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AEROSPACE TESTING INTERNATIONAL

SHOWCASE 2012

2012 SHOWCASE

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Fueling a new generation

What has been the prime theme in aerospace over the past 12 months? Economic troubles? No. Military build-up? No. It is eco/green fuel. United Continental was the first airline to take flight commercially using a biofuel-powered aircraft when Flight 1403 flew from Houston's George Bush Intercontinental Airport to Chicago's O'Hare International on November 7, 2011. Its green fuel, produced by Solazyme, was derived partially from genetically modified algae.

As this issue went to press, Alaska Airlines/Horizon Airlines was set to make the first of 75 biofuel-powered commercial passenger flights scheduled to fly across the USA in 2011. Its fuel is made from recycled cooking oil.

Reports say that Sir Richard Branson aims to introduce a 'green aviation fuel' on Virgin Atlantic airplanes within three years. Others say it is more of a stunt, but he does state that the use of aviation biofuel is "one of the most exciting developments of our lifetime and a major breakthrough in the war on carbon". According to Virgin, it hopes to convert waste gases from industrial steel production into a jet propulsion that could ultimately account for nearly one-fifth of the present annual global consumption of aviation fuel. A demonstration flight is planned within 12 to 18 months, the airline announced in October 2011.

In the Far East there are new attempts to follow the green trend with a Chinese demonstration flight. UOP LLC, a Honeywell company, announced that Green Jet Fuel, produced jointly with PetroChina, powered China's first biofuel flight. A spokesperson for Honeywell said, "The Air China demonstration flight, which took off and landed in Beijing, used a 50% blend of petroleum-based fuel and Green Jet Fuel made from the plant jatropha in one engine of a Boeing 747-400 aircraft." The Civil Aviation Administration of China (CAAC) has committed to a 22% reduction in aviation emissions by 2020.

In another surprise report, the US Department of Agriculture (USDA) has issued a loan guarantee that will enable a biofuels firm to construct a facility in New Mexico to produce 'green crude' oil from algae, which can be refined into transportation fuel. The USDA said, "Producing fuel from algae is seen as one way to provide for domestically produced fuel for commercial and military use." It has also signed a Memorandum of Understanding with the FAA and US Navy to help the commercial airline industry use biofuels as jet fuel. Under the MOU, the USDA and FAA are working together with the airline industry to develop appropriate feed stocks that can be most efficiently processed into jet fuel.

Airbus is also right in the green zone. In October 2011, a flight from Toulouse-Blagnac to Paris-Orly using an Airbus A321 was able to demonstrate the halving of CO_2 gas emitted compared with a regular flight. "The commercial flight combined for the first time the use of biofuels (50% in each engine), optimized air traffic management (ATM), and efficient Continuous Descent Approach (CDA) to minimize CO_2 emissions," Airbus said in a statement. Keep it green!

On an entirely different note, I started editing *Aerospace Testing International* in 2004. Trying to swim with my head above water on a subject I knew little about, I turned to my father, a retired senior captain with British Airways, for help. Over the seven years since, he supplied me with anecdotes, inspiration, and facts used in these and many previous pages. Sadly, he died in October. At his funeral were many dozens of people from across the flying fraternity, military and civil. None of my family had any realization that his influence had been quite so far-reaching. He flew DC-6s to 707s, BAC1-11s to Tiger Moths, DC-10s to Bristol Freighters. He was one of the first British pilots to go to Toulouse and fly the earliest generation Airbus civil aircraft in the early 1980s.

The poem *High Flight* by Pilot Officer Gillespie Magee was read during the service, a mantra to pilots, and my father kept copies in his study and flight bag. A moving tribute to human flight, and his small, but significant part within it. Dedicated pilot, Captain John Hounsfield.

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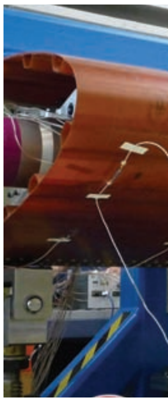

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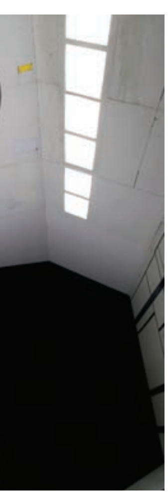


OLD AIRCRAFT, NEW TECHNOLOGY

The German Aerospace Center, DLR, has been able to investigate the handling qualities of a new concept flying wing under real flight conditions using a research tool that began operating 25 years ago

BY JANA EHLERS

The Advanced Technologies Testing Aircraft System (ATTAS) research aircraft belonging to the German Aerospace Center (DLR) provides the opportunity to simulate other airplane configurations during flight. The DLR Institute of Flight Systems has used this capability to analyze the dynamics of a flying wing under real flight conditions and to assess its handling qualities by means of pilot evaluation.

The unconventional concept of flying wings provides some favorable characteristics that make these airplanes potential candidates for future civil aircraft. Their large cargo capacity would enable them to transport large amounts of freight or passengers, which makes them especially attractive in light of the predicted increase of air traffic over the coming years.

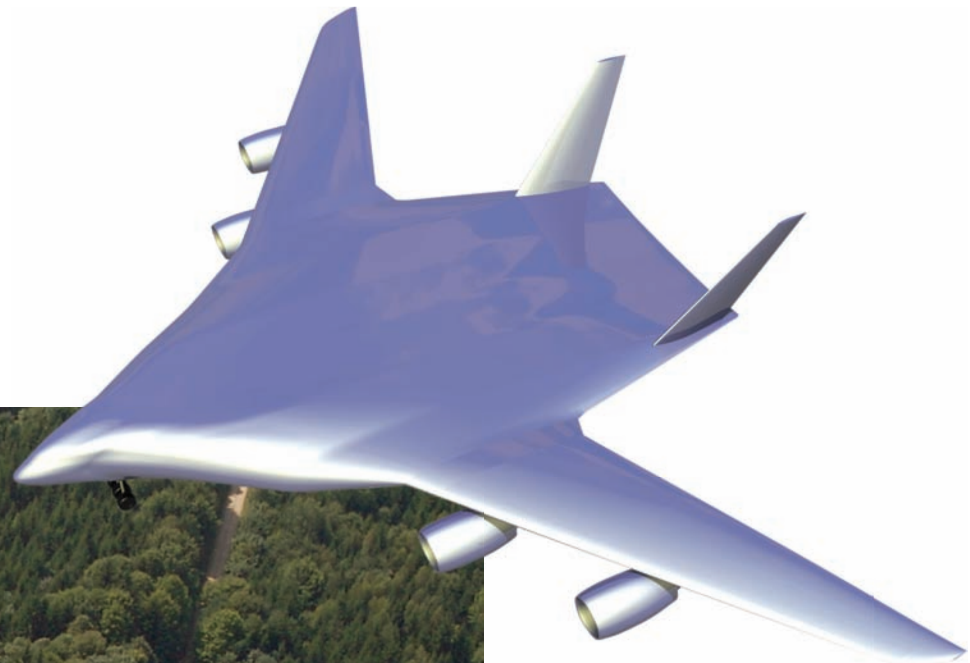
Other major benefits of flying wing configurations are their good aerodynamic efficiency due to a high lift-to-drag ratio and significantly less fuel burn per seat than conventional airplanes. This new aircraft concept can, however, only be realized if the flying wing can be easily and securely controlled by the pilot. Unfortunately, the assurance of satisfactory handling qualities is in general a critical issue for flying wings. A detailed handling quality analysis is therefore an essential part of the design process of such a new aircraft. The inflight simulation carried out with ATTAS was aimed at fulfilling this analysis.

The 'considered flying wing' is based on a configuration that was developed during the former European Union project NACRE (New Aircraft Concept Research). It is a large, long-range aircraft with a maximum take-off weight of approximately 700 tons and a capacity of 750 passengers. Instead of a conventional fuselage, it possesses a large center wing that significantly contributes to the overall lift of the aircraft. Two relatively small vertical tails replace the single vertical tail of conventional airplanes. There is no conventional horizontal stabilizer.

ATTAS inflight simulator

Even after 25 years of operation as a research aircraft at the DLR, ATTAS represents a unique tool for aerospace research in Europe. At more than 30 years of age, the ATTAS is the last flying example of the type VFW 614. Only 19 aircraft of this short- to medium-range 44-seater with a wing-span of 21.5m had been produced before serial production was stopped in 1978 for financial reasons.

DLR took over the VFW 614 at the beginning of the 1980s and started extensive modifications in cooperation with the manufacturer VFW/MBB. Within four years the captain's side was converted to the workplace of the experimental pilot. This included the additional integration of a complete electrical control system and a sophisticated data acquisition and recording system. The left-hand side of the cockpit was equipped with configurable displays and required devices for fly-by-wire control. Some years later, an



LEFT: **DLR research aircraft ATTAS (Advanced Technologies Testing Aircraft System)**

additional modification opened up the possibility of using a side-stick as an alternative to the conventional column/wheel for the controls of the experimental pilot.

The electrical control system provides an interface from the experimental pilot's controls to the experimental computer, which has full access to the actuators of all control surfaces and the engine controls. The safety concept of the ATTAS guarantees a switching from the experimental electrical flight control system to the basic mechanical flight control system by de-clutching the actuators from the control surfaces within 120ms. In that scenario, the safety pilot on the right-hand side takes over control of the aircraft using the conventional controls of the VFW 614. Therefore a separate certification of the experimental software is not been necessary, which means that the engineers are able to integrate experimental software within a very short time.

For the execution of inflight simulations, a non-linear model-following controller has been developed and integrated into the experimental computer by the DLR Institute of Flight Systems. This enables the ATTAS to expose the flying qualities of other aircraft within its dynamic and performance limits. For this purpose, a mathematical model of the simulated aircraft defines the dynamics of the output

"DLR took over the VFW 614 at the beginning of the 1980s and started extensive modifications in cooperation with the manufacturer VFW/MBB"

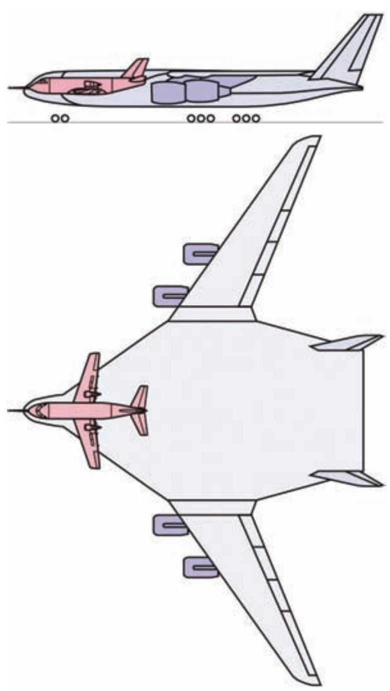
variables that are used as the control variables for the model-following controller.

The most important output variables for the assessment of flying qualities in the longitudinal motion are the load factor at the pilot's seat and the pitch rate. In order to allow an independent control of these two variables, the ATTAS was equipped with direct lift control flaps at the trailing edge of the conventional high-lift flaps. These flaps can be deflected at a maximum rate of 90°/sec, providing the ability to control the heave motion as an additional degree of freedom. Therefore, the model-following controller is capable of using five independent control surfaces: the elevator, the direct lift control flaps, the ailerons, the rudder and the engines, enabling the control of five output variables.

The controller matches the bank and pitch angles, the side slip angle, the airspeed and the load factor at the pilot's seat of the real aircraft with the corresponding outputs of the mathematical model of the aircraft that has to be simulated. In this way the experimental pilot is able to experience and assess the flying qualities of a new aircraft design in the real world.

Performance of flight tests

The inflight simulation performed at DLR included flight tests with the original baseline configuration of the flying wing without any automatic control and a modified model of the aircraft that had been extended by the



ABOVE: DLR research aircraft ATTAS (Advanced Technologies Testing Aircraft System)

LEFT: Despite the huge differences in size and geometry, ATTAS simulated the dynamics of the flying wing in a realistic manner

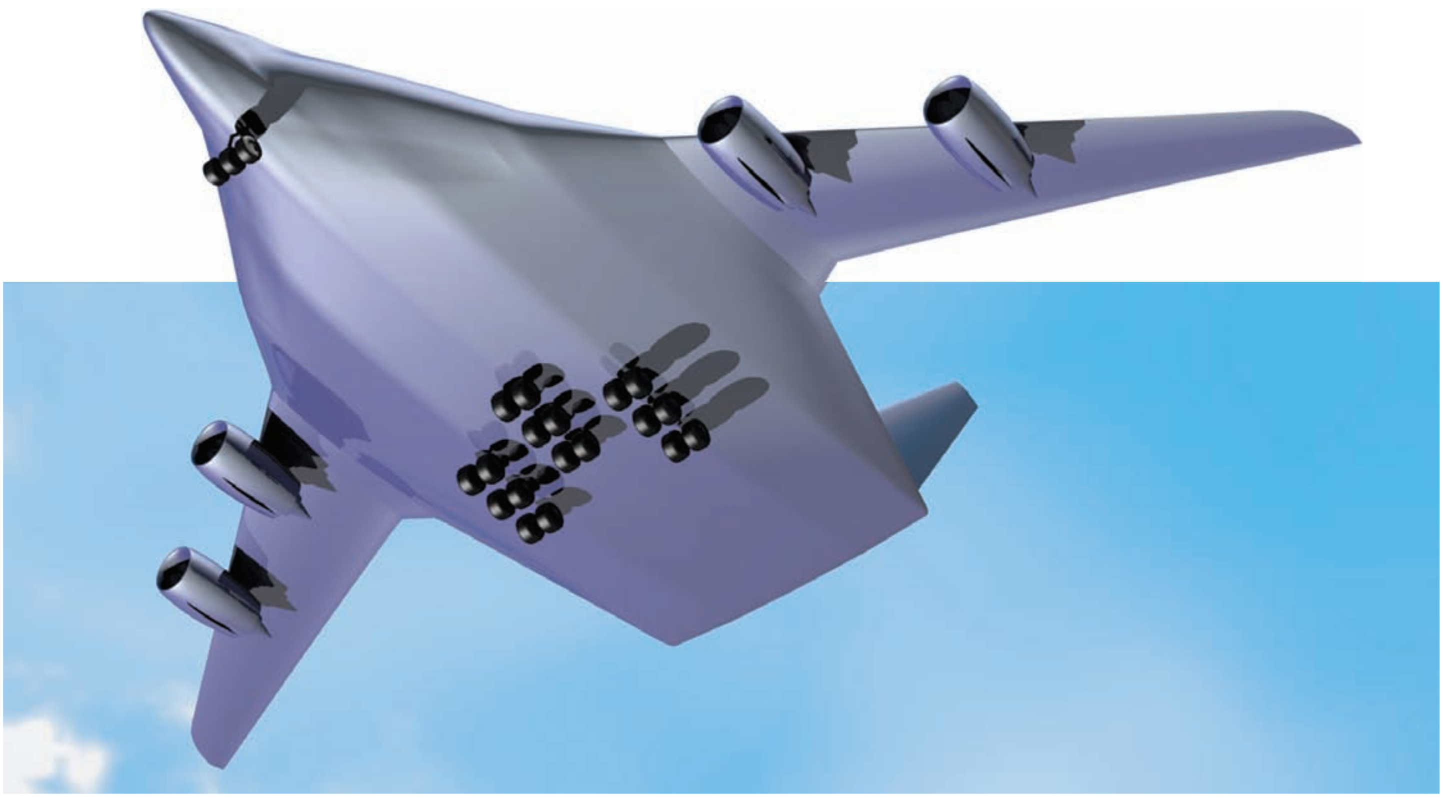
BELOW: The cockpit of ATTAS: The left-hand side of the cockpit where the experimental pilot sits is equipped with configurable displays and a side-stick. The safety pilot sits on the right seat and sees the unmodified original cockpit of the VFW 614

implementation of a control and stability augmentation system. Altogether, three flight tests have been conducted on ATTAS.

The first flight test aimed at the familiarization of the pilot with the unconventional dynamics of the flying wing configuration to provide a first qualitative impression of the flying qualities of the aircraft. For this purpose, the natural modes were excited by small control inputs and simple flying tasks were conducted.

During the subsequent two flights, the handling qualities of the flying wing were evaluated quantitatively by applying the Cooper-Harper rating scale. This scale is a common means used during flight testing to evaluate handling qualities. It ranges from 1 to 10 where 1 indicates that the flying qualities of the aircraft are satisfactory without any improvement and 10 describes an uncontrollable behavior of the airplane. In this way, test pilots can express their subjective perceptions of the flying qualities of the flying wing during the different maneuvers in a quantitative way that can later be analyzed and compared to ratings of other pilots. The pilots who performed the inflight simulation were two DLR test pilots. Both of them have comparable flight experience and are mainly flying the VFW 614 and Airbus A320.

The maneuvers were chosen on the basis of an analytical handling qualities analysis that had been conducted in preparation for the flight tests. In this theoretical handling qualities assessment, analytical handling qualities criteria had been



applied and showed that the dynamics of the flying wing during turns were particularly difficult to handle.

The investigation identified the unsatisfactory Dutch roll characteristics with too low damping and natural frequency, the build-up of large side slip angles during turns and a pitch-up tendency at high side slip angles as major deficiencies of the handling qualities of the aircraft. The inflight simulation consequently also focused on turn maneuvers in order to get further insight into these critical dynamics of the flying wing.

The flight test maneuvers included a bank angle capture, a coordinated turn, a heading capture, and a simulated instrument landing system (ILS) approach. During the bank angle capture, the task of the pilots was to match the target bank angle of 20° as closely as possible. The deviation from this target value as well as the workload to achieve this is evaluated by the Cooper-Harper rating scale. In case of the coordinated level turn, a similar turn maneuver was performed as before but the maximum side slip angle was evaluated instead of the bank angle. During the heading capture, the pilots had to terminate a coordinated turn at a predefined target heading.

In all these maneuvers the test pilots assessed the workload during turn maneuvers. The purpose of the last maneuver, the simulated ILS approach, was the evaluation of the ability of the flying wing to perform tracking tasks. The test pilots therefore had to follow a virtual glideslope and localizer and evaluated the longitudinal and lateral deviations from the given track. All flight tests were flown with the open-loop baseline model of the flying wing first and with the closed-loop model afterward.

"The most important output variables for the assessment of flying qualities in the longitudinal motion are the load factor at the pilot's seat and the pitch rate"

ABOVE: The flying wing configuration investigated during the in-flight simulation

Results of inflight simulation

The inflight simulation demonstrated that the turn dynamics of the considered flying wing can only be handled appropriately if the pilot is supported by an automatic control system. During the maneuvers with the open-loop model of the flying wing, the fast build-up of side slip angle in combination with the strong pitch-up tendency of the flying wing at high side slip angles clearly prohibited a satisfactory handling of the aircraft. The test pilots faced a very high workload and were not able to keep the deviations of the target values for the different tasks within the desired limits. Moreover, they had to be very careful to only apply smooth control inputs because otherwise pilot involved oscillations (PIOs) occurred and the system became unstable.

The maneuvers performed with the closed-loop model showed that the implementation of the control and stability augmentation system led to a significant improvement of the flying qualities of the flying wing. Both pilots agreed that the workload was much lower during these maneuvers because the active control system strongly reduced the side slip angles and consequently also the pitch-up motion induced by the side slip angles during turns. Furthermore, the inflight simulation showed that the improvement of the handling qualities of the considered flying wing by active control is limited due to physical boundaries such as low control authority in the yaw axis due to relatively small vertical tails and the sluggish behavior of the aircraft in the lateral axis. Further optimization is therefore required before the flying wing can fly safely – even without the help of the DLR ATTAS. ∎

Jana Ehlers is a research scientist at the Institute of Flight Systems of the German Aerospace Center. Ehlers had contributions from Dominik Niedermeier, research scientist at the Institute of Flight Systems, and group leader, Cognetics, and research scientist Dirk Leißling

CLOSE INSPECTION

The rapid rise in the use of composites in aircraft is driving the development of technologies to inspect these materials, both during manufacture and in service

BY THIERRY LAFFONT

Composite structures and components are increasingly being used in aviation as manufacturers strive to reduce aircraft weight to increase fuel efficiency or payload. Initially, composites were used only in relatively small components, such as flaps and fairings. Now they are also used for major structural parts. These new materials and the change in function of components made in the new materials set new challenges for inspection, both during manufacture and in service.

In some of the latest aircraft, composites account for more than 50% of material weight. Their increase in use has been quick: they accounted for only 25% of the material weight in aircraft such as the A380. All these composite components and structures demand inspection during manufacture for quality control purposes. Composites must also be inspected during service, especially when they have incurred damage.

What are composites?

When two or more materials with different properties are combined, they form a composite material. Engineering composites are produced by combining plastic resins with a matting or tape of glass fiber or carbon fiber.

Formerly, composite components were manufactured by applying the carbon or glass fiber matting to a mold and then painting on the resin. Today, most components are produced from pre-preg material, where the resin is already incorporated, or pre-impregnated, within the matting. The pre-preg is applied to the precisely engineered mold in a slightly tacky state in a cleanroom and the plies are built up as with wet lay-up. However, before consolidation takes place in the autoclave, the resin must be activated and this is usually done under vacuum.

It is mainly during the lay-up stage that the errors occur that lead to subsequent flaws (such as delamination, porosity, and voids) in the finished composite component. For example, a slight wrinkling of the pre-preg material as it is applied, either manually or by robot, can cause air to be trapped, which can lead to defects later.

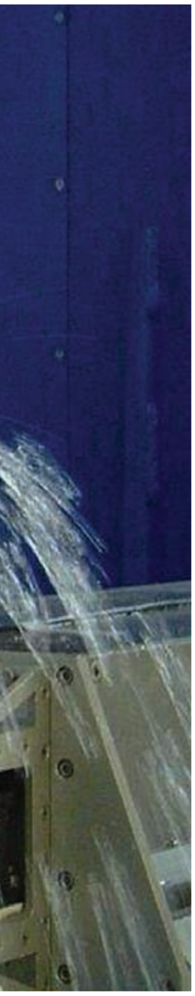
The same defects can also be caused in so-called honeycomb structures, where to achieve bulk within a component such as a panel, two lamellar sides, produced by conventional lay-up methods, are bonded onto a honeycomb structure, made with a material such as Nomex, to form a sandwich. This process can also lead the composite sides and the honeycomb to disbond.

Non-destructive testing

By their very nature, composite materials preclude many conventional non-destructive testing (NDT) techniques or, at best, limit their application. For example, although carbon fiber composites are conductive, eddy current has very limited application and x-ray cannot detect a delamination, except when there is an inclusion of substantially different density. Tap testing is still applied primarily as an in-service check, rather than as a quantitative manufacturing inspection tool.

Other techniques have also been applied, such as heat pulse laser holography and thermal imaging, but the technology that is most commonly used in the inspection of composite components and structures is ultrasonic. There is still an important place for portable ultrasonic equipment

CENTER: **Through-transmission squirter system**



TOP: **The Bondtracer device for detecting and sentencing minor composites damage**

BELOW: **Ultrasonic phased-array inspection**

on the production line. Typically, portable ultrasonic flaw detectors are used to inspect small components or to provide more precise identification of indications identified by automatic inspection systems, to obviate the need for re-passing the components through the larger machines.

For example, thickness meters, such as the DM5E from GE, are often used following machining operations to confirm thickness compliance with specification. Phased-array thickness meters, such as the Phasor DM, which was originally developed for detecting corrosion spots, are also used to detect discontinuities. The instrument's phased-array probe has 28 adjacent and discrete elements to allow extensive linear coverage, while the software allows the user to select and display thickness measurement in each discrete beam.

Portable phased-array instrumentation is widely used to reduce inspection times and to improve probability of detection over conventional flaw detectors. Offering the capability for rapid, large surface area inspection, phased array also affords better, clearer visual imaging.

Phased-array instruments, such as the Phasor XS, can provide inspection images in four modes: A-scan; A-scan and sector image; sector image; and Topview, which is similar to a C-scan. Snapshots of the sector images and the associated A-scans, which are used for defect sizing, are displayed in real time on a high-resolution TFT panel and can be stored on an onboard SD card for subsequent analysis and archiving. Inspection data can also be downloaded via USB connectivity; reports are in JPEG or BMP format, with no need for special reading software.

Fixed ultrasonic inspection systems

Ultrasonic inspection is also the preferred quality assurance technology for inspecting larger composite structures. Inspection is typically carried out in a scan gantry and configurations can be conventional pulse-echo, through transmission multiple channels in parallel or multiplexed, as well as phased array. Immersion tanks can have squirter coupling, bubbler coupling, and contact transmit/receive coupling, and are designed to handle a wide range of aerospace components of various sizes, materials, and geometries.

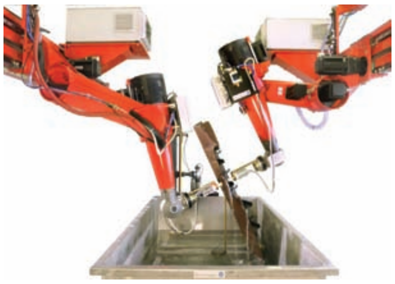
For example, with a squirter system, water jets carry the ultrasonic beam from the transmitting transducer to the composite structure; the beam then passes through the structure to the receiving transducer. Scan images detect any foreign object inclusions, interlaminar delaminations, skin-to-core disbands, and regions of excessive porosity. Recent advances in fixed systems have been in component handling systems, in transducer manipulation heads, and in the extended use of phased-array technology. Robotic arm component-handling systems are now available with up to 11 axes of movement, so that they can automatically handle the largest and most complex components. Machines can accept input data direct from the operator or from CAD/CATIA files, and certain processes can be carried out automatically. Inspection data can be displayed in a variety of formats, including A-, B-, C-, and D-scan, as well as 3D imaging.

Transducer manipulation heads can also be designed to suit specific applications, such as angle and surface inspection and the inspection of stringers and stringer roots. Phased-array technology has significantly increased inspection times and has improved inspection versatility with concepts such as 'reverse delay'. This allows inspection of radii and corners with the same array probe, with no need to change over to specific geometry probes. It does this by shooting all elements on the radius, measuring the radius curvature from the response time back to each array probe element, and then virtually transforming the radius into a flat surface, using the reverse delay times to allow easy interpretation of the defect.

Parallel B-scan is another phased-array technique that allows high inspection speeds and provides excellent inspection data even under difficult inspection conditions. It uses a phased-array probe, with a number of elements being larger than the ultrasonic aperture of an individual synthetic probe. All elements are fired at the same time in phased or non-phased mode; the return signals are detected at the same time and immediately digitized, so that a real-time B-scan can be displayed. The major advantage of the parallel B-scan technique is that its wide aperture means it receives signals from the pitch/catch and dual elements (V-reflection) simultaneously.

Inspection in service

Airlines can potentially lose millions of dollars a year through minor accidents that occur on the flight line, such as collisions with baggage loaders. For



> **"By their very nature, composite materials preclude many conventional non-destructive testing techniques"**

ABOVE: Robotic ultrasonic inspection system

BELOW: The phoenix v|tome|x system

every accident, an aircraft must be grounded while extensive tests are conducted to confirm its integrity and airworthiness. When carbon fiber composites sustain damage, it can cause subsurface delamination, which is difficult to gauge with visual inspection alone.

Barely visible impact damage is a major challenge for composite manufacturers. However, GE has developed a simple ultrasonic device for ramp personnel to determine whether there is any damage to the composite aircraft skin. This involves mapping the suspect area, and based on OEM procedures, deciding whether the aircraft can fly 'as is' in accordance with the aircraft's maintenance manuals, or if NDT is required for further evaluation.

The device is as easy to use as a common stud finder. It has a simple display, with green indicating consistent skin thickness and red indicating an unanticipated thickness change. This will help operators to dispatch airworthy aircraft quickly, preventing unnecessary grounding or flight delays, and providing significant savings.

Computed tomography

During the past decade, computed tomography (CT) has progressed to provide higher resolution and faster reconstruction of the 3D volume. High-resolution x-ray CT allows the 3D visualization and failure analysis of the internal microstructure of composite materials, where 2D x-ray microscopy would give only the integral information of the overlaying bundles of fibers. Consequently, CT is fast becoming ideal to accompany the manufacture of composite structures and components from development to final quality control.

From the laboratory…

Specifically designed for laboratory applications, the phoenix nanotom from GE is an ultra-precise, high-resolution CT system for scanning samples of up to 3kg and 240mm diameter with unique voxel resolutions down to <300nm. The nanotom is the first 180kV nanofocus CT system in the world, set up for the highest-resolution applications in a variety of fields.

The nanotom uses the principles of cone beam CT: the high-power nanofocus tube, with a maximum acceleration voltage of 180kV and a maximum tube power of 15W, generates a cone-shaped x-ray beam that images the sample onto a fully digital detector. Without any preparation, a sample is easily fixed between an x-ray source and a detector, and the part is rotated 360° in steps. In this way, the sample size determines the achievable voxel size, i.e. highest magnification can be reached for smallest samples.

Generating tomographic images starts with the acquisition of a stack of 2D x-ray images. The acquired data is a collection of images acquired while progressively rotating the sample step by step through 360° within the field-of-view at angular increments of about 0.25-0.5°. These projections contain information on the position and density of absorbing object features within the sample. This data is then used for the numerical reconstruction of the volumetric data using a filtered back projection algorithm.

Laboratory power up to 500W is provided by the phoenix v|tome|x, which offers excellent magnification and resolution. Its optional dual-tube configuration allows high-resolution nanoCT of low-absorbing samples. This versatility ensures the new system a wide spectrum of applications in materials science, industrial failure analysis, process control, and 3D metrology, in industrial sectors ranging from castings and electronics to plastics, geology, and aerospace, including turbine blade inspection.

…to the production line

In-line CT is a current development project and a prototype is now available, featuring a modified GE medical scanner. Work pieces are conveyed through the tomography system simply and continuously on a conveyor belt, with no need for robotic handling. Utilizing Helix multiline technology, the work pieces are scanned at speeds of up to several centimeters per second, and automatically assessed with the aid of GE's speed-optimized evaluation algorithms. These include, for example, automatic porosity analyses, or the classification of incorporated extraneous material. Because the 3D position, shape, and size of the defects can be analyzed with reference to subsequent processing steps, fast in-line CT can lead to a reduction in the reject rate.

Aerospace is the largest single user of composites, both in terms of weight and value. Both the military and the civil sectors have committed to composites, as demonstrated by the 40% plus composites content of the Joint Strike Fighter and the Eurofighter and the 50% plus content of the A350 XWB and Boeing 787. The reasons are well documented and well proven. Composites offer a better strength to weight ratio than conventional metals, They are almost free from fatigue problems. They are cheaper to manufacture.

All this means better power and maneuverability in the military sphere, and lower fuel costs and higher payload capability in the civil sector. Inspection of these new materials has presented considerable challenges in NDT. These challenges have been met and will continue to be met as inspection needs evolve with newer technologies and materials. ∎

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MEETING AERONAUTICAL DEMANDS

Why wireless telemetry is an ideal choice for aerospace ground and flight test applications

BY BRIAN DUFFY

There is no room for error when testing in aerospace ground and flight test applications. The working environments of aerospace are simply too demanding and too grueling to miscalculate structural integrity or performance capabilities of any component. This is why wireless telemetry – or the transmitting and receiving of data via radio frequency (RF) technology – is an ideal fit in aerospace.

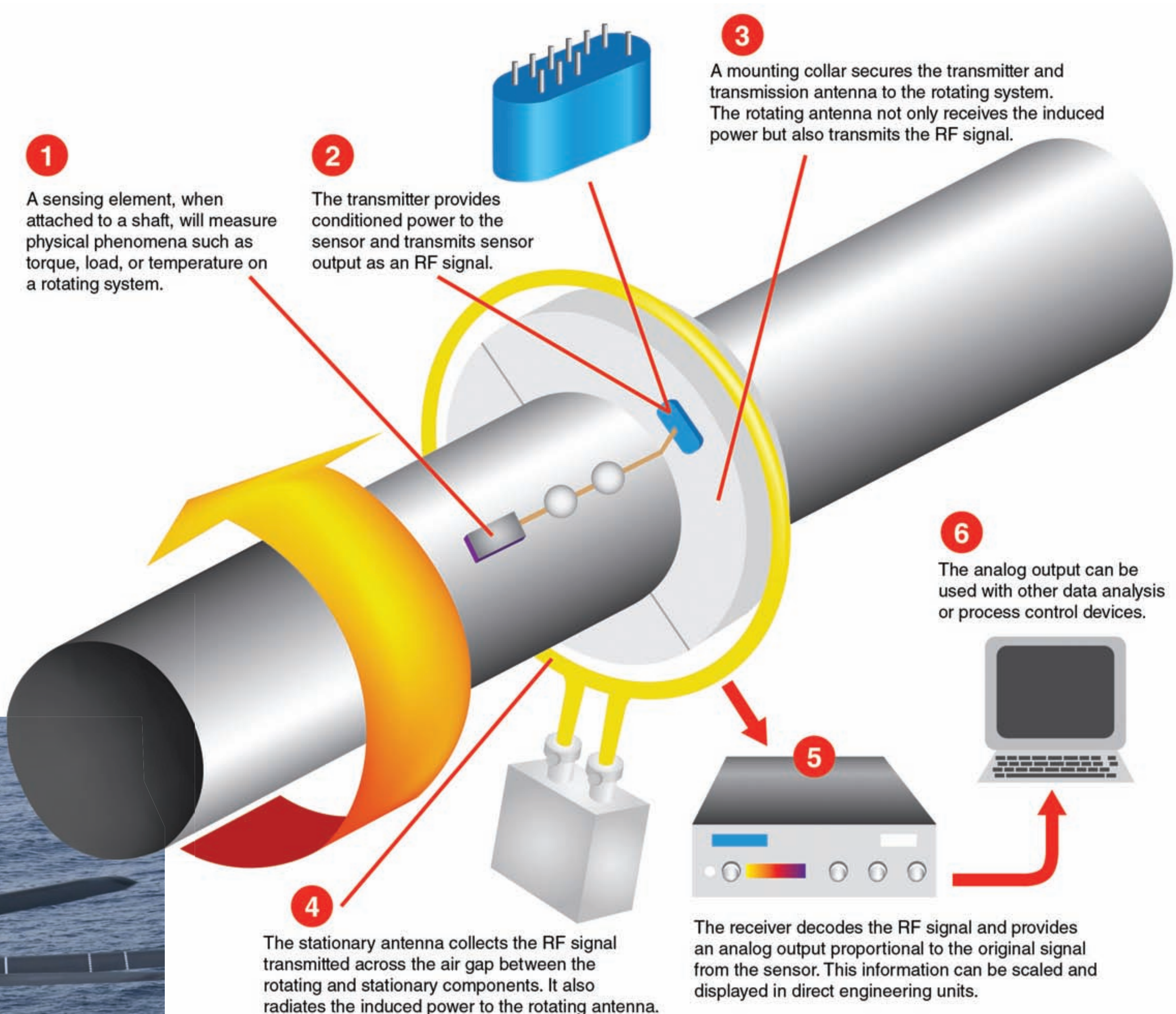
The advantages of wireless technology are numerous, including low maintenance and the ability to operate in tight spaces; essentially, RF technologies can be used where slip ring or contact systems simply cannot.

Another benefit of RF technology is its 'robustness'. It can be used in high vibration areas and can endure high g forces, a norm in aerospace applications. RF technology can operate at high rpm for extended periods of time (due to having no bearings or slip rings), and it accommodates axial play. With a modular design, RF components offer both customization and flexibility within applications, as well as the capability of capturing data at high bandwidth (up to 30 KHz). RF technology also lends itself to having multiple channels per device, another common need in aerospace testing applications. To better understand how all these benefits are possible, a basic knowledge of wireless technology is a must; and that starts with the electromagnetic spectrum.

Electromagnetic spectrum

The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation. The electromagnetic spectrum of an object is the characteristic distribution of electromagnetic radiation radiated, or absorbed, by a particular object. The span within the electromagnetic spectrum is often

Wireless telemetry systems allow accurate torque measurements in main rotor and tail rotor testing while withstanding intense vibrations



called the radio frequency spectrum and includes frequencies from 3kHz to 300GHz. Typically, devices in industry operate between 107 and 108, which is the Industrial, Scientific, and Medical (ISM) band for data transfer.

Wireless telemetry and RF

Wireless telemetry uses electromagnetic waves within the radio portion, or RF, of the electromagnetic spectrum. The primary purpose of wireless telemetry systems is to transmit and receive (collect) data from rotating equipment.

Rotating and stationary antenna schemes are determined by the application, but in general: the rotating antenna transmits the RF from the transmitter; the stationary antenna picks up the RF for the receiver; and the stationary antenna is typically within 25mm of the rotating antenna for the entire circumference. RF is an electromagnetic wave consisting of a carrier frequency and some type of information or data. The carrier frequency is generated by a transmitter and the data is embedded in the carrier by a process called modulation. Modulation is a way of encoding data into wavelength form where the waves can differ by height (amplitude) and frequency (how close together the wave peaks are). The wavelength is the distance (in meters) for one complete cycle of the wave.

The RF is transmitted at a known frequency through the airwaves, where it is available to be picked up by any receiver tuned to the same frequency. The receiver or demodulator strips away the carrier wave, leaving only the data. As a result, the data has traveled wirelessly from point A to point B.

Transmitters use various modulation techniques depending on the data being transferred. These include: frequency modulation (FM), pulse width modulation (PWM) and frequency shift keying (FSK).

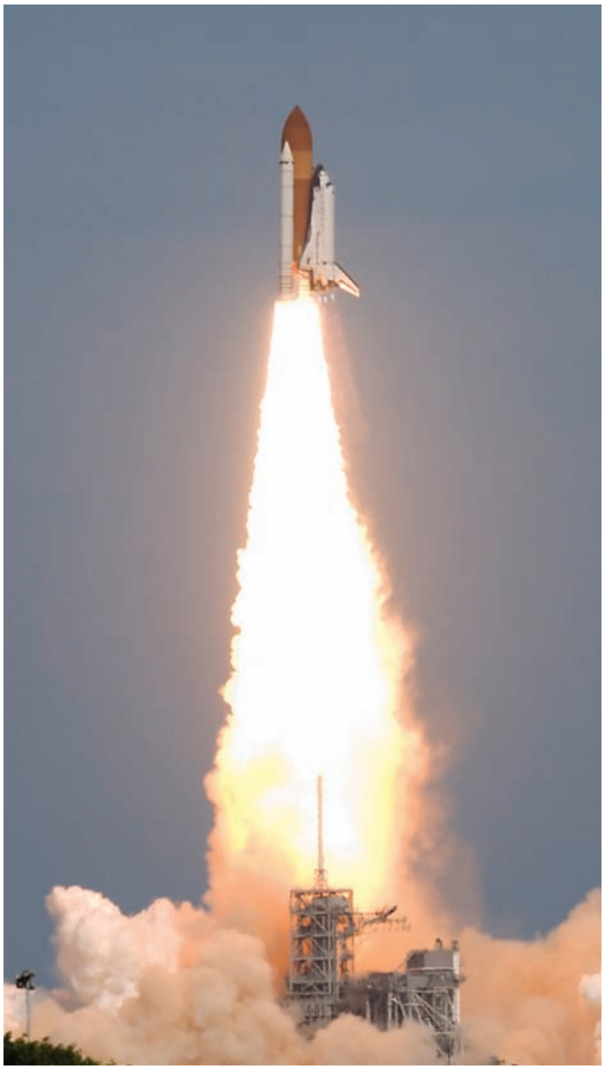
Frequency modulation (FM)

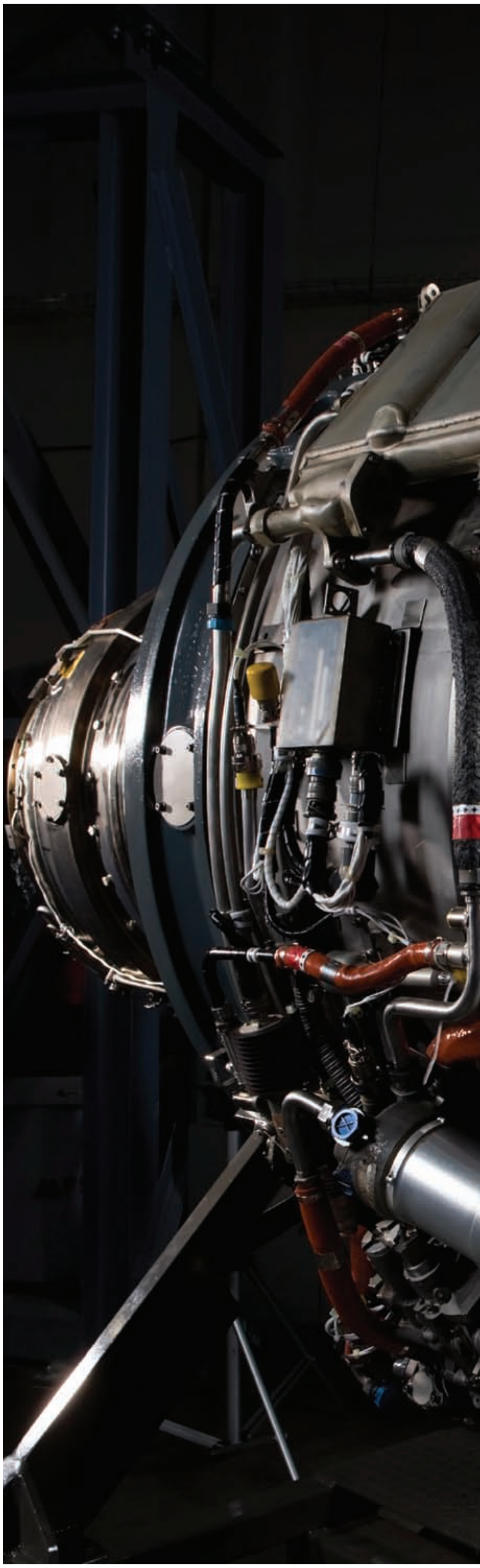
Essentially, FM conveys data over a carrier wave by varying its frequency. FM is typically the RF data transfer choice when a high bandwidth is utilized. Specifically, it is used for dynamic strain testing, or the collection of vibration data.

One example within the aerospace industry is rotor blade testing. FM is ideal for vibration measurement because it captures both properties that occur during vibration – magnitude and frequency. There could be noise implications when using FM, so it may not be the best RF data transfer choice in every situation.

Pulse width modulation (PWM)

PWM offers cleaner output data and inputs less noise into the receiver than





FM. As a result, it is used for static strain measurements, or torque. One example would be evaluating the torque characteristics of a fuel pump. Typically, static strain receivers will provide high-level analog outputs. In PWM, the data generates a square wave analog signal, which makes any noise on the magnitude of the square wave insignificant.

Noise levels would have to be strong enough to change the duty cycle of the square wave to have an impact on the data. PWM is limited on the maximum throughput signal, or how many times the signal can be updated on the bandwidth.

Frequency shift keying (FSK)

FSK is a technique used to send digital data by shifting the carrier's frequency among a set of values in which digital information is transmitted through frequency changes of a carrier wave. This is the transmission choice used for digital data measurement, or when one wants to convert serial data into visual data (e.g. temperature). Jet engine dynamic strain and temperature testing is an example. While FSK works well, it is generally slower than FM or PWM, as it is typically less than 100Hz.

The interfacing portion of wireless telemetry, or how RF and its modulation are put to work, is perhaps best understood visually (see previous page).

Aerospace test applications

One aerospace application that showcases RF technology's ability to withstand intense vibrations and high g forces is in the testing of jet engine dynamic strain and temperatures. Mostly conducted in wind tunnels or on the ground (preflight tests), the purpose of a jet engine dynamic strain and temperature test is to determine the life expectancy of the turbine blades. This information is vital because most turbine blades are retired after realizing 50% of life. Dynamic strain measurements are typically vibration measurements on strategic points of the jet engine's turbine blades, with the neck of the blade being most important. Because there are several strain and temperature measurements, the ability of the wireless system to provide multi-channel outputs is essential.

Dynamic strain data will result in an AC analog output with a bandwidth of 30kHz. Temperature data will have a 0-3VDC output with a maximum bandwidth of 50Hz each for up to six channels. FSK and FM are the types of modulation most often used on jet engine testing. Again, this is where wireless telemetry demonstrates the ability to deliver a multichannel output while operating under high *g* force. The maximum g load for low mass transmitters is 40,000 g.

Space shuttle fuel pump testing illustrates the customization and flexibility benefits of RF technology. This application involves taking the actual torque measurement on the shaft of a space shuttle fuel pump. One example utilized wireless telemetry components, which are modular in concept. Special rotary and stationary antennas were combined with a customized gauged fuel pump shaft to gain real-life data and torque output. A hybrid transmitter was used in the high-speed application, which operated in 100°F ambient temperature. PWM was the technique used.

Space shuttle fuel pump testing involves taking the actual torque measurement on the shaft of the fuel pump. This application showcases radio frequency technology's customizability

Radio frequency technology's ability to withstand high *g* forces is showcased in the testing of jet engine dynamic strain and temperatures

When it comes to showcasing the vibration resistance and general robustness of RF technology, main rotor and tail rotor torque measurement test applications are leading examples. These testing situations involve a wireless telemetry add-on to customer-gauged drive shafts, typically a static strain application. In one instance, the customer used RF telemetry components and built their own system with their gauged shaft. Assisted by the manufacturer, a custom rotary antenna and corresponding stationary antenna were designed and implemented to meet customer requirements, minimizing the overall mass of the system. The wireless components withstood the system vibration and axial displacement using existing customer parts. There was no need to break apart the equipment to measure and capture the data.

This application also highlights the customizability of wireless telemetry systems, as products are available that offer flexibility in design to best fit customer equipment. PWM was the technique used for this application as well.

Accuracy is crucial

In aerospace testing, accuracy is essential. Components simply must be structurally proven to meet the operating requirements. Wireless telemetry products that utilize RF technology offer the features and benefits to meet the aerospace industry's unique demands. And they can do it with a multitude of standard product designs, as well as through custom designs built specifically for customer applications and needs.

Availability, component options and customization offerings differ from supplier to supplier. The keys to finding the right wireless telemetry system – one that will offer versatility, flexibility, dependability, and testing accuracy – include a thorough understanding of the application at hand and a carefully selected manufacturer partner. ∎

Brian Duffy is the global applications engineering manager for Honeywell Test & Measurement Products

SEEING BELOW THE SURFACE

Laser light shearography non-destructive testing (SNT) is providing a cost-effective and faster inspection capability

BY JOHN W. NEWMAN

High quality and lowered costs are essential goals for competing in today's aerospace supply chain. Traditional non-destructive testing (NDT) methods such as ultrasonic testing (UT) C-Scan are highly effective but are expensive and slow. Today's lean manufacturing demands high-throughput inspection as well as a means for near-real-time process control to ensure product quality and reliability at the lowest possible cost. In programs for the F-22 and F-35 as well as the next generation of civil aircraft and spacecraft, shearography non-destructive testing (SNT) systems provide a cost-effective and swifter inspection capability.

The traditional methods for NDT such as UT C-Scan and tap testing are not only slow but they may not provide the best defect detection capability for new designs using carbon fiber composites, low-density Nomex and foam core materials. Composites allow complex net-shape geometries that present enormous and expensive challenges for inspection for critical bond defects.

UT C-Scan, with a typical throughput of just $10ft^2$/hr ($1.1m^2$/hr), uses water jets as a couplant to get the ultrasonic signal into the part and to pick up the signal on the opposite side. Drops in signal amplitude or shifts in phase can reveal internal defects, but the absorption of water in laminates and honeycomb can mask signals and require further delays for drying cycles. The complete inspection can take many hours or days to complete.

Laser light

Shearography uses laser light, a non-penetrating radiation, to create images of critical surface and subsurface defects such as impact damage, delamination, disbonds, foreign object damage (FOD), porosity, wrinkled fibers and fiber bridging. Shearography detects slight phase shifts in the laser light to create images of minute changes in the surface contour of an aircraft part subjected to a low-level stress. The stress change required to image these flaws is in the order of

CENTER: Inside a shearography test chamber, dual 32ft gantry scanners provide fast, highly repeatable scan coverage of a 9m long carbon fiber/ Nomex core fuselage for a UAV. Two robotic digital shearography cameras provide simultaneous imaging. This system can inspect composite structures up to 32ft long at 500ft²/hr

TOP RIGHT: The external tanks of the Space Shuttle (Picture courtesy NASA)

Image courtesy of NASA

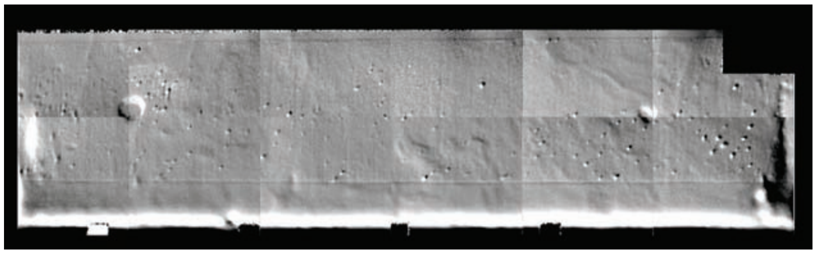
only several degrees of temperature change, 10 to 100 millibar partial vacuum or a low-level vibration that can be mechanically or acoustically coupled to the part. These low stress change levels are truly non-destructive yet allow deep defects over large areas to be imaged and measured accurately and with unprecedented speed. In many aerospace programs today, laser shearography is providing a large part of the solution for low-cost, high-quality aerospace manufacturing.

Robotic scan gantry

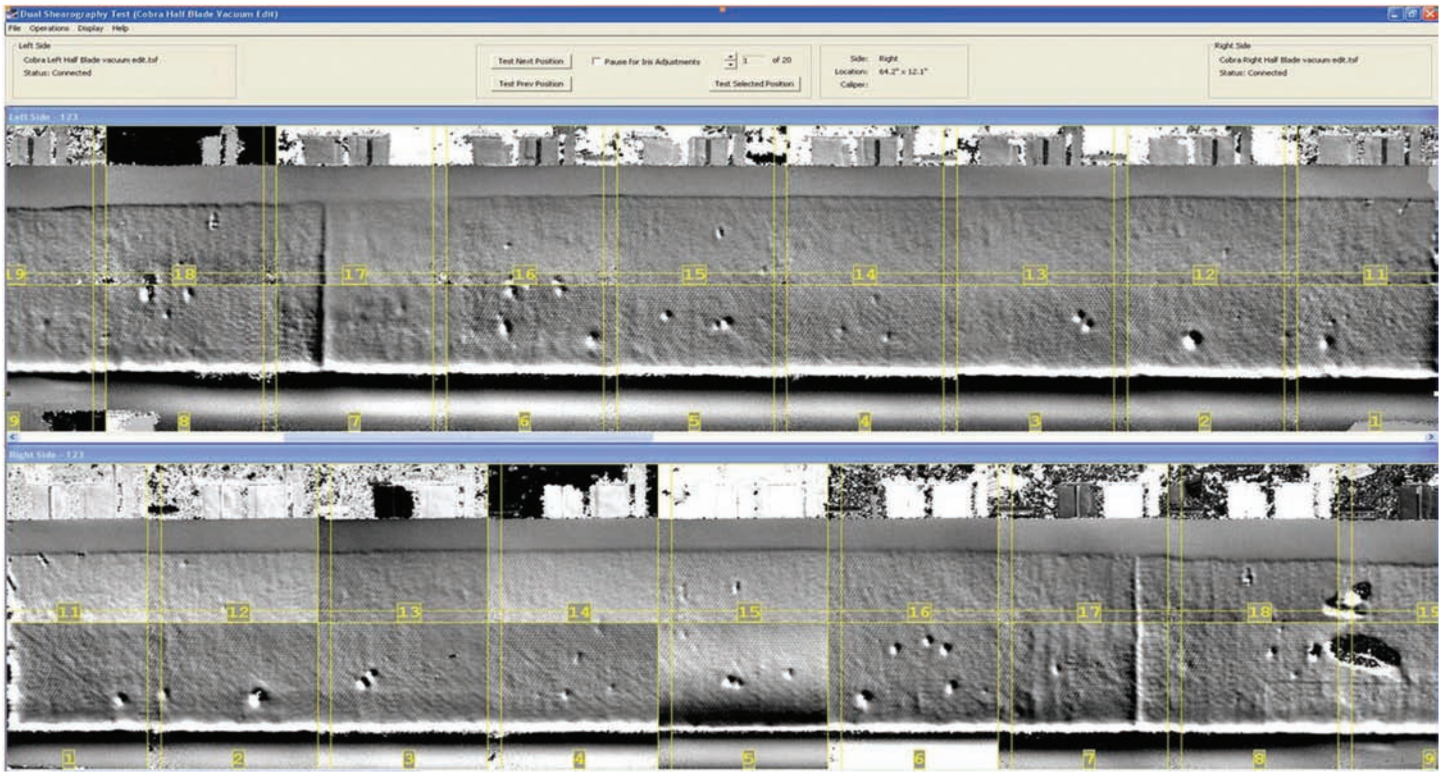
At Bell Helicopter's new rotor manufacture facility, the newest addition to its inspection toolbox is a dual robotic scan gantry, vacuum/thermal system with a 32in chamber. This advanced system enables the company to inspect 429 blades at a rate 400% faster than the current process, says Bell engineer Jeffrey Nissen. Further shearography images of blades can be archived and compared with changes during maintenance.

The world's first production electronic shearography NDT system was delivered to Northrop Grumman in 1987 for the manufacturing of the US Air Force B2 Stealth Bomber, the first aircraft to incorporate shearography in the manufacturing of highly complex composite structures. Today, shearography is widely used in many aerospace programs.

In the past 20 years, more than 1,200 shearography systems have been



LEFT: **A major US aircraft depot 'heritage' aircraft flap measuring 4 x 1.4m, made of aluminum honeycomb core and aluminum face sheets is inspected with a gantry shearography system in 12 minutes. More than 120 disbonds are detected, sized and located for repair. Before shearography, inspections with ultrasonic C-Scan systems required several days to set up, run and analyze the data**



ABOVE: **Shearography results for both sides of a honeycomb core main rotor blade, which was inspected in nine minutes. Indications of defect size, area and location are marked on the blade for repair**

"As with all NDT methods, the strengths and weakness of the inspection technology must be completely understood"

integrated into the manufacturing process for aircraft metallic and composite structures, aircraft tires and high-reliability aerospace electronics. For older 'heritage' aircraft, shearography is highly effective for detecting disbonds due to damage or corrosion – especially when parts have seen multiple repairs and have excess adhesive or doublers. Such parts can be extremely difficult for traditional methods such as C-Scan.

As with all NDT methods, the strengths and weakness of the inspection technology must be completely understood, and applications qualified. Written procedures and rigorous training is required for both operators and engineers.

Operators of shearography NDT systems or instruments can be qualified to EN4179, ASNT SNT-TC-1A or NAS 410. Shearography systems can operate with extraordinary efficiency, reaching throughputs from 25-1,200ft^2/hr, 2.5-120 times the typical 10ft^2/hr inspection rate for UT C-Scan.

Vacuum shearography is highly effective for imaging disbonds, delaminations, core damage and core splice-joint separations and offers a strong inspection capability on foam cored materials that usually have very low thermal and acoustic conductivity, which precludes the use of thermography and ultrasonics.

Thermal shearography

Other shearography NDT techniques that are frequently used include thermal shearography (Figure 2) for non-visible impact damage, face sheet delaminations, disbonds, FOD and core damage. Thermal and pressure shearography is excellent for fiber bridging defects and damage to composite wrapped pressure vessels, and rocket engine components such as nozzles and combustion chambers. Vibration shearography using audible acoustic energy has been highly developed over the past few years to inspect the foam on the external tank of NASA's Space Shuttle.

BELOW: A thermal shearography camera being used to inspect a helicopter blade for damage

"Shearography instruments of many configurations, including endoscopic systems, provide on-vehicle inspections for operational damage"

ABOVE: A high-performance planform design with advanced materials, the Bell 429 main rotors are inspected with vacuum/thermal shearography NDT during manufacture

Shearography provides inspection results in minutes, without any part contamination or wetting of the test part. System features such as Teach/Learn part-scan programming, automatic image stitching creating a single image of the entire part, image analysis and defect measurement tools and automated operation are comparable to C-Scan systems. For helicopter blades, the dual camera scan gantry configuration allows simultaneous shearography inspection of both the upper and lower sides of the blades. Leading-edge erosion strips can also be inspected. A main rotor blade with honeycomb core was inspected in nine minutes for both sides. Voids, impact damage and entrapped water were detected (Figure 3). Interpretation of the shearography test data may be accomplished during the shearography testing in real time at the system control console, or off-line. The calibrated shearography images are stitched together to show the entire helicopter blade and the analysis allows the operator to zoom in, measure defect dimensions and areas and even precisely indicate the location on the blade for repair.

Large composite structures with complex geometries can be shearography inspected. Shearography cameras do not require part contour following, greatly simplifying gantry designs, test part programming and reducing costs. In UT C-Scan, the transducers must be maintained on the surface of the structure and precisely aimed so the ultrasonic signal transmitted through the part is received on the opposite side. In shearography, no such contour following is required; surfaces can be inspected at an angle and images stitched together based on camera coordinates.

Finally, shearography instruments of many configurations, including endoscopic systems, provide on-vehicle inspections for operational damage. Typically, the shearography instruments are vacuum-attached to the surface to be inspected and apply a partial vacuum or thermal stress.

Throughputs of up to 15m^2/hr are typical and it is particularly recommended for radomes, rotor blades, metal honeycomb and composite surfaces applications.

NDT technology

In conclusion, laser shearography is a mature and highly cost-effective NDT technology for many large-area aerospace applications, especially for metal or composite sandwich structures. Shearography can provide a large productivity and quality gain over traditional NDT methods such as UT C-Scan, thermography or tap testing.

Automated shearographic systems provide very rapid inspection, such as the 400% increase in throughput for the Bell 429 main rotor blades. Results are provided as digital image data with defect location, size, and area. Recent publication of industry consensus documents such as ASTM E 2581-07 *Standard Practice for Shearography NDT of Composites in Aerospace Applications*, inclusion of shearography under Laser Shearography methods in EN4179, ASNT SNT-TC-1A and NAS 410 Rev 3, has brought considerable recognition of the technology as a means for aerospace manufacturers to gain a competitive edge. ∎

John Newman is the president and founder of Laser Technology Inc in Norristown, Pennsylvania, USA. He is chairman of the Laser Methods Committee of the American Society for Nondestructive Testing (ASNT) and vice chairman of the Emerging Methods Committee for ASTM, E07. He can be contacted at jnewman@laserndt.com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SCALE THE POWER

The challenge for powered wind tunnel testing lies in the large power density that is necessary to realistically simulate the propulsion system

BY DR MICHEL GUILLAUME

An important step in aircraft development is the aerodynamic integration of the propulsion system. This is particularly true when the aircraft is powered by propellers or open fans, when interaction effects between the aerodynamic surfaces and the slipstream can be important.

Wind tunnel tests are used to understand these installation effects, to validate the theoretical predictions, to optimize the integration, and to map the configurations. RUAG Aviation's Large Wind Tunnel Emmen (LWTE) has been used extensively for the development of numerous passenger, transport and trainer propeller aircraft. Recently, in collaboration with Boeing and Rolls-Royce, a test with a generic counter-rotating open rotor (CROR) powered airliner was successfully completed. Especially for multi-engined aircraft configurations, the challenges for powered wind tunnel testing lie in the large power density that is necessary to realistically simulate the propulsion system and the geometrical constraints, for example for the sensors within the given scaled aerodynamic nacelle lines.

The driving force

The common choices to drive the propellers or fans of wind tunnel models are electrical motors, air turbines and hydraulic motors. Each of these has their specific advantages and disadvantages. From a technical and economical point of view, hydraulic motor technology provides the best compromise.

Advantages of hydraulic motor technology include: robust engines that provide abundant power; precise RPM control; favorable temperature characteristics that allow continuous operation; reasonable investments in infrastructure and model hardware; low operating cost; and high productivity. RUAG Aviation has extensive expertise in the development and operation of these specialized hydraulic motors and their associated control and measurement systems for wind tunnel model applications.

> **"Special emphasis is put on the tailoring of the blade characteristics to the specific testing requirements"**

LEFT: **HISAC environmentally friendly high-speed aircraft in the RUAG wind tunnel**

As the outlines of the aircraft and nacelle, and the power and RPM requirements, differ from one aircraft to the next, only rarely can a wind tunnel model propulsor system used in a past test campaign be reused for other customers without modifications. Therefore, it is important to have the basic technology and test benches for the customer-specific 'scaling developments' available in-house.

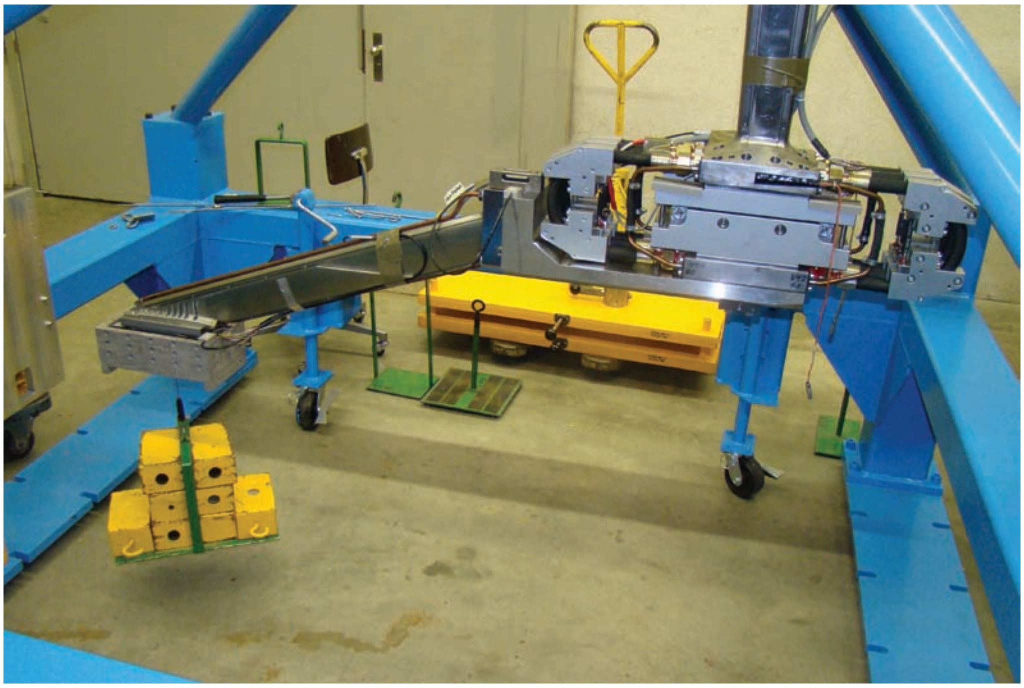
Critical technologies such as motor, RPM control, data transmission, rotary shaft balance, and shaft design and rotor dynamics need to be readily available to design a customer-specific solution in a timely and economical manner. As wind tunnel occupancy time is expensive, it is of prime importance that the systems perform reliably during a test campaign. Therefore, it is mandatory to realistically test the complete equipment a priori and outside the facility. This can be accomplished through the use of a number of test benches and calibration equipment for the hydraulic motors, the rotating shaft balances, the balance crossing system and the telemetry.

In the past few months, RUAG Aviation's corresponding capabilities have been further increased by the commissioning of yet another test stand.

High power tests

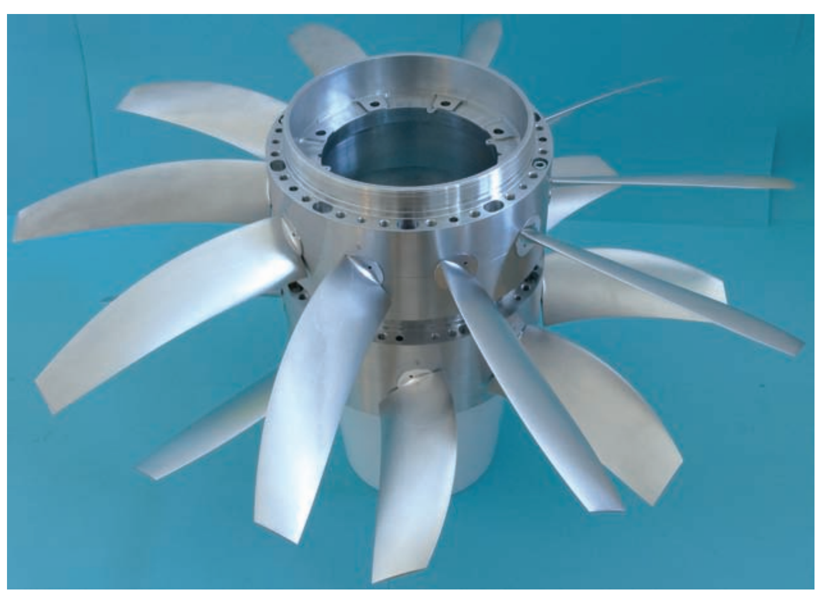
It is now possible to safely test the full propulsor system, including the propellers – also counter-rotating – at high power settings in the flow of a small wind tunnel. This test bench is designed and will be crucial for reproducible shakedown and endurance tests, propulsor calibration, as well as development tests to further extend the operational limits on power, torque, RPM, and durability of the propulsors. The first application will be the testing of RUAG-designed generic pusher and tractor CROR configurations.

The main goals of the test are to validate the design and manufacturing process of new metal and composite fan blades, to confirm



ABOVE: **Isolated test rig during calibration and propulsion system elements**

RIGHT: **Counter rotating open fan**



the predicted lifetime of the motors (greater than 500 hours) and to boost the power to 160kW with an increase in RPM and/or torque. In addition, the sensitivity of the rotating six-component shaft balances on RPM, limiting the sensor's accuracy, or the potentially serious effects of rotor dynamics, reducing the usable speed range, can be better studied under the realistic and well controlled conditions of this test stand.

Recent high power wind tunnel tests at RUAG were mostly performed using fan blades provided by a third party. A RUAG research project aims to improve its own manufacturing capabilities of complexly shaped composite blades for wind tunnel model testing applications.

The goal is to create design and manufacturing processes for both aluminum and carbon blades, which allow the delivery of high-quality blades at competitive prices. Special emphasis is put on the tailoring of the blade characteristics to the specific testing requirements (rigidity, eigenfrequencies) and on the integration of embedded instrumentation for health and status monitoring.

The accurate transmission of signals from the rotors to the data acquisition system, for example for measurements from the rotating shaft balance and blade stresses, is another complexity that comes with powered testing. Slip rings can be an excellent choice and are normally used for simpler propeller-driven models while telemetry, for topological reasons, provides considerable geometrical benefits for CROR configurations.

Precise information for data

The data from the rotor usually needs the addition of precise angular position information at many positions per revolution for later data processing. This results in a high data rate in the order of up to many megabytes per second and, therefore, high requirements for data processing power, intelligent

ABOVE: **Dual engine propulsor and telemetry**

processing algorithms, and clever storing concepts. This data must not only be analyzed and stored but also, in real-time, be synchronized with the slow standard measurements, for example from the main balance. This is especially true in the LWTE because RUAG commonly uses the more time-efficient 'measure while in motion' continuous data acquisition method instead of a 'move-stop-measure-move' approach.

For environmental and economic reasons there is a renewed interest in the variety of propellers and open fans for powering future transport aircraft. The Aerodynamics department of RUAG Aviation, with its decade-long expertise in powered wind tunnel tests and its in-house motor and measurement technology, is ready to provide the complete aerodynamic testing infrastructure indispensable for the development of these future ultra-green aircraft and propulsion generations. ∎

Dr Michel Guillaume is the departmental manager, Aerodynamics, for RUAG

THE FUTURE OF UNMANNED SYSTEMS

New testing techniques and procedures are some of the cutting-edge concepts that will make today the 'New Golden Age of Aviation'

BY RICK GAETA & JAMEY JACOB

There have been several periods of rapid innovation in aviation history, each accompanied by a flurry of flight testing. The first of these occurred during the trial and error period around World War I, when flimsy and slow strut-and-wire bi-planes gave way to stronger and faster designs that had dramatically improved aerodynamics, structural design, propulsion, and control. Arguably the greatest period of aviation innovation occurred during the early years of the Cold War, when designs incorporating jet propulsion with aluminum skin structures generated numerous unique concepts in manned aircraft. The attitude and willingness to experiment with novel and often questionable designs will probably never be witnessed again, at least for manned aircraft. However, with the advent of unmanned aircraft, we are in the midst of another 'Golden Age of Aviation', with opportunities to design and test cutting-edge concepts that push the boundaries of the possible. New testing techniques and procedures are part of this endeavor.

As autonomous technologies continue to advance, unmanned systems will change the flight space of tomorrow, both military and civilian. Test requirements for evaluating unmanned vehicles, their autonomous systems, and associated payloads must be sufficient to meet the unique technical challenges, particularly related to the unmanned nature of the vehicles. Although there are benefits to flight testing unmanned systems, such as lower costs than flight testing similar manned systems, there are also distinct disadvantages. Due to the low cost and incorrectly perceived unregulated nature of UAS, a 'Wild West attitude' has emerged in UAS flight testing. Additional challenges arise due to the nature of the mission of UAVs, including long endurance, high altitude, and other persistent surveillance requirements. Much like manned aircraft, different UAS designs require different flight testing standards, ranging from agile and frangible micro aircraft to airliner-sized HALE systems.

Failing faster – the key to rapid response

A key feature of previous Golden Ages of Aviation was a willingness of both government and industry to build and test ideas that were not 100% proven. Indeed, looking back to aviation's beginnings, this feature was the hallmark of the celebrated role models of aerospace engineers: the Wright brothers. By testing and ruling out ideas quickly, it enabled them to focus on aspects that worked, even if they weren't successful the first (or even second) time. Perhaps the lack of computational power and other modern crutches was the origin of this approach, but it had an interesting by-product: it enabled them to fail faster. Research and development is a cycle that is characterized by failed tests, re-engineering, rebuilding, and re-testing. It is impossible to build new designs without failing along the way. The key is to shorten this cycle by emphasizing engineering innovation.

The UML-OSU model

The University Multispectral Laboratories (UML) is a national

ABOVE: **Preparing for flight test; providing students with hands-on and relevant flight tests is a critical part of the UAS education process**

"It is impossible to build new designs without failing along the way. The key is to shorten this cycle by emphasizing engineering innovation"

center supporting the defense, intelligence, security, and energy sectors. It is a government-owned (by Oklahoma State University (OSU)) contractor-operated entity (GOCO). This enables UML to be a trusted agent of the government. Attracting government agencies that are focused on rapid needs is a key feature of UML. With its reach-back into academia, UML can respond rapidly and cost-effectively to relevant problems. In this way the UML can fuse government, industry, and academia to focus on specific problems on an as-needed basis rather than building a dedicated rigid infrastructure for narrow, long-term research.

To meet this challenge, UML and OSU have cultivated a unique set of research capabilities with a foundation of relevant educational curricula. UML and OSU operate facilities for composite fabrication, test rigs for engine performance including a special simulated flight dynamometer for simulated inflight propeller testing, acoustic data acquisition equipment for noise characterization and design, wind tunnels, dedicated airfields, state-of-the-art autopilot hardware, and software for flight simulation and GNC design. Finally, UML and OSU have developed a range of research and development, test and evaluation (RDT&E), as well as training and education tools to produce rapid response and innovation in the UAS arena.

One aspect of this is the synthesis of modeling, rapid prototyping, propulsion testing, airframe integration, and flight testing. Development time has been greatly reduced by using accurate flight models and computer flight simulators coupled with hardware-in-the-loop testing of autopilot and control systems. Unavailable decades ago, cheap computational hardware works on board the modern UAS and also simulates the system. This enables designers to quickly test and modify platform configurations with little cost prior to build. Developing the capacity to rapidly model and construct composite airframes is the next piece of this puzzle.

Eschewing traditional construction methods for small aircraft in favor of all-composite airframes provides multiple advantages, including small lead times, high strength, and limitless outer mold lines, and the added benefit of training students in modern aerospace manufacturing techniques. This is coupled with detailed propeller testing to provide optimized performance data prior to flight testing. Another crucial piece is testing of the integrated vehicle for electrical interference. Unlike systems of the past, modern UAVs are hardware intensive and contain multiple RF sources and other generators of electromagnetic signals. The use of anechoic and reverb chambers to isolate problem spots in communication and payloads prior to testing in the field substantially reduces likelihood of failure.

The challenge of UAS propulsion

Propulsion testing for unmanned vehicles involves the accurate measurement of thrust (from either a reciprocating or gas turbine engine), torque (for engines driving a propeller by producing shaft horsepower), and rotational speeds of propellers and shafts. Much of the focus in aerospace propulsion since the 1950s has been on high-performance jet engines, neglecting the reciprocating driven propeller systems. In addition, it has become increasingly more important to measure and characterize the noise of the propulsion system. There are several reasons why these measurements are very challenging to acquire.

First, if propeller performance is desired, static tests are of limited benefit. The performance of a fixed pitch propeller changes dramatically whether operating statically or under flight conditions. Thus, testing propellers in a wind tunnel or flight test is required. A suitable wind tunnel must include enough test section area so the walls will not affect the performance. Another tried-and-true approach to this problem is to use a simulated flight rig. UML and OSU have done precisely this by mounting a dynamometer in the back of a pickup truck. Flight speeds for many relevant UAS can be simulated by the truck riding over flat ground.

Second, if the acoustic signature of the propeller is to be measured (amplitude, frequency, and directivity) this poses another set of constraints. If one is trying to characterize the propeller noise, using an internal combustion (IC) engine will make it difficult to isolate. Using an electric motor can help, however there may still be a problem at high frequencies. Furthermore, the propeller will exhibit a different noise signature at different

inflow velocities so static tests alone will not fully characterize propeller noise. Proper acquisition of far-field noise data requires an anechoic environment. If a wind tunnel is used, it must be properly treated to absorb frequencies as low as 50Hz. Limiting reflections coming off walls and other structures will more likely approximate anechoic environments. These test conditions are very difficult and expensive to achieve.

Finally, if the IC engine noise or electric motor noise needs to be characterized, a known load should be applied. Instead of a propeller, a water brake should be used to simulate a propeller load on the engine. However, this results in the engine having to be cooled without the benefit of the propeller slipstream. Using a 'slave' fan to blow air over the engine can accomplish this, but can contaminate any acoustic measurements that are also needed. The key requirement for acoustic testing of propulsion systems is to simultaneously measure the engine performance while measuring the noise signature. This gives the engineer valuable feedback and helps trade-off performance and low-noise solutions.

With flight testing being the ultimate arbiter of successful designs, ground-based propulsion testing (for both performance and acoustics) can be used to great effect to down select configurations. In the case of acoustic test in lieu of an anechoic wind tunnel, portable acoustic walls can be cheaply fabricated to minimize sound reflections.

Flight testing

Flight testing of unmanned systems is crucial. It represents the culmination of many ground and component tests that have led to an integrated flying system. However, legally flight testing UAVs under the best conditions is difficult in the USA. Assuming airworthiness has not yet been demonstrated through flight testing, obtaining a COA from the FAA is difficult. This leads to waiting in long queues for the limited commercial flight test space available to the UAV industry. Unfortunately, this limits the ability to fail faster and becomes the development bottleneck for all UAS.

To circumvent this problem, UML has signed an MOU with Fort Sill to allow limited access to its restricted airspace. Although advantageous to UML, enabling it to test new platforms and payloads quickly, it also provides value to the Army at Fort Sill by slowly training staff in the integration of UAS into the battlefield. Recognizing that conflicted airspace is part of the future, this permits crucial preparation in learning how to safely operate manned and unmanned aircraft in the same airspace. This also provides valuable data on UAS operations needed by the FAA prior to integration into the NAS.

Acoustic testing in the flight environment

It has become increasingly clear that characterizing and controlling the acoustic signature are very important parts of the UAS mission effectiveness and detection. Controlling this aspect of the flight vehicle is an enabling technology that opens up the concept of operations for many UAS. Accurately measuring the noise emitted from a UAS in flight is a very challenging task. Variations in meteorological quantities and terrain greatly affect measurements as it pertains to amplitude and directivity. It is critical that a good measure of the pressure, temperature, relative humidity, and windspeed and direction is made at relevant locations where data is recorded. Even under the most benign weather conditions, a constant sound source can vary by up to 10dB over the course of minutes due to ground reflections and atmospheric irregularities. Moreover, acquiring data above the human audible range is also important due to the increased use of animals for early detection.

UML has a suite of high-quality condenser microphones that can measure sound accurately in an outdoor environment. Frequencies

ABOVE: Students constructing a composite airframe

ABOVE: **Propulsion testing in relevant environments is critical – to this end, propellers and motors can be tested on an automotive mounted dynamometer prior to flight tests**

RIGHT: **Network of microphones in field to measure acoustic signature**

from 10Hz to 80kHz can be acquired and analyzed with state-of-the-art multichannel signal processing hardware. Microphone stands should be unobtrusive and have no hard, flat surfaces to produce reflections, and microphones should be set approximately 2m above the ground.

At certain frequencies ground reflections might become important. Another important feature is the ability to stamp the microphone time histories with GPS time in order to correlate with the GPS time and position of the UAS. Therefore, the acoustic 'observer' location can be correlated with the UAS location at a given time. These measurements are also valuable for validation of acoustic propagation models. Perhaps the most critical element to acoustic testing in a flight environment is the ambient background noise, including local wind conditions. Wind affects microphones by introducing a random or broadband noise at low frequencies, usually below 200Hz. IC engine fundamental frequencies and some first blade passing frequencies are below 200Hz, which means that if the wind strength is high enough, the microphone will be saturated and unable to clearly pick up the fundamental frequencies. This can be mitigated by placing wind socks on each microphone to reduce the wind effect on the diaphragm. Additionally, cross correlation of multiple microphones can be used to extract a coherent acoustic source. The latter requires more processing time, which may prove difficult with the speed of the moving source. The former is a passive technique that usually works well enough under most conditions, and is recommended.

Educating the UAS test engineer of the future

Although aircraft design has always required a systems-engineering-orientated approach that combines aerodynamics, structures, propulsion, and control, designing unmanned systems – by its nature – requires a heavier dose of avionics than most aerospace engineering programs currently provide. The interaction of the onboard autopilot, ground control system, communication system, and payloads necessitates that students are provided a more in-depth education in unmanned avionics.

To provide aerospace engineering students with the capability to contribute to unmanned aircraft design, testing, and operation on day one of employment, OSU has developed a UAS option at the MS and PhD level. The program requires students to perform a complete UAS design from the ground up, including design of the airframe, autopilot, ground control and communications systems, and payload.

Each vehicle must be designed to perform a particular mission, and flight testing is required to demonstrate system capabilities compared to predicted performance. Other program requirements include courses in UAS propulsion, certification of unmanned aircraft, and integration of UAS into the NAS. Finally, UML brings the student closer to the real world user of UAS technology. The close relationship between UML and government customers and in turn the close relationship between UML and OSU provides students with unique insight into relevant design issues that need to be solved.

With UAS, the new golden age of aeronautics has begun. As issues with integrating UAS into the NAS are resolved, new uses for UAVs that have not yet been considered will appear and their promise is as strong, if not stronger, in the commercial sector than it is in the military. With the continuing advance and use of technologies in both the systems and the development and testing of the systems, this age can be expected to last longer and burn brighter than those before. ∎

Dr Rick Gaeta & Dr Jamey Jacob are faculty members of OSU

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SHAPE DYNAMICS

The development and measurement of an 'adaptive wing leading edge' for high-lift applications

BY KATHARINA KRAUS

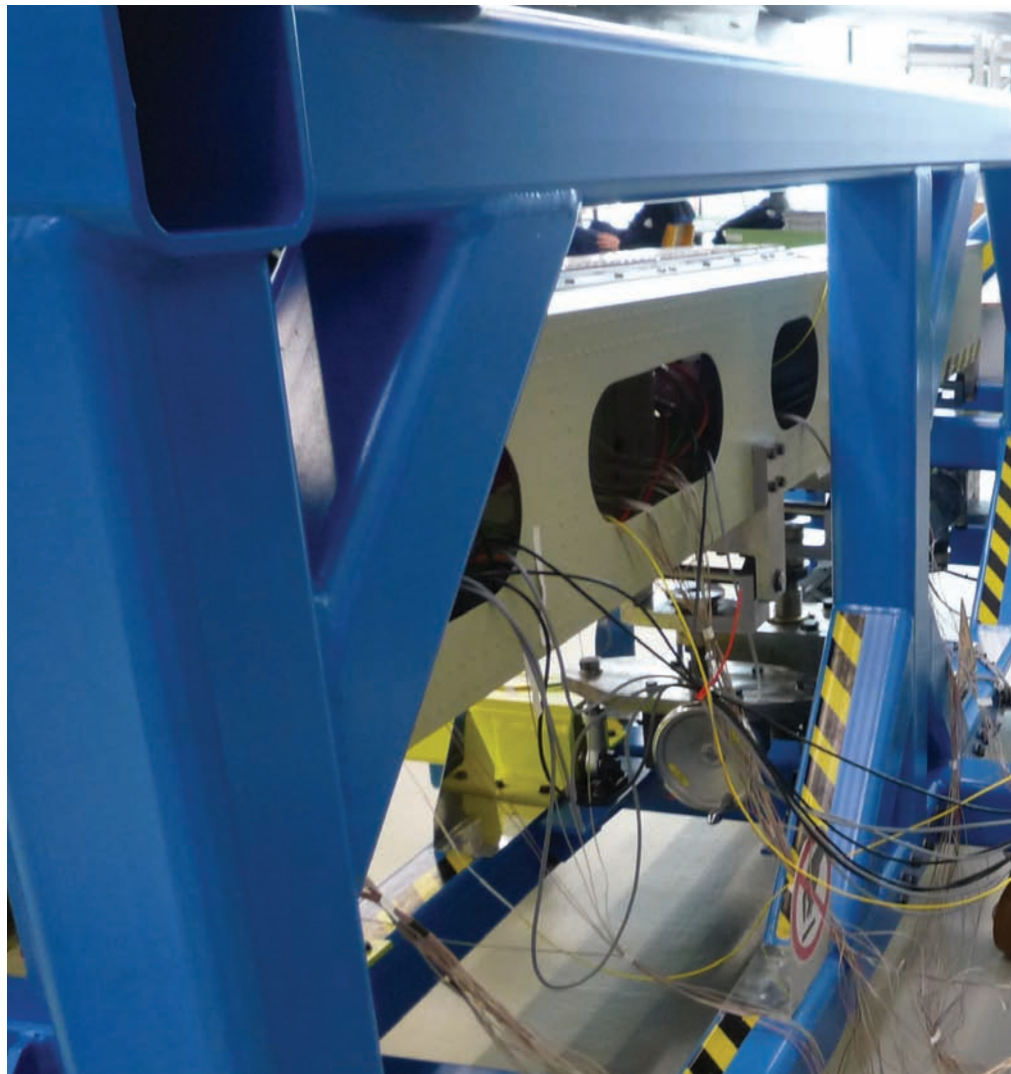
The increasing economical and ecological demands within the aircraft industry call for an improved aerodynamic performance, especially in the civil sector. To accomplish this, shape-variable structures have been identified as a key technology. In the framework of a German research project called 'HIT – SmartLED' (High-lift Technologies of the Next Generation – Smart Leading Edge Device), this technology was used for the development of an adaptive leading edge for high-lift applications on commercial aircraft. The project partners include Airbus Operations GmbH, Cassidian, DLR (German Research Center for Aeronautics and Space) and EADS. Innovation Works designed and set up a test carrier for the experimental verification of numerical computations.

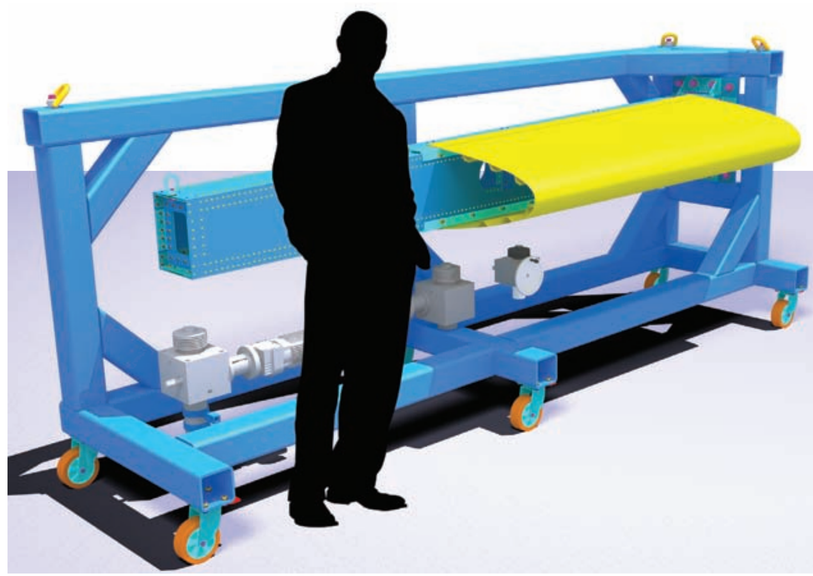
For the testing, the Fraunhofer Institute for Structural Durability and System Reliability (LBF) carried out the sensor application and measurements of this lightweight structure. Four measurement methods appropriate for the evaluation of geometric deformations and mechanical strains were used. Finally, important qualitative and quantitative statements on the stress of the structure under loading could be made after the measurements.

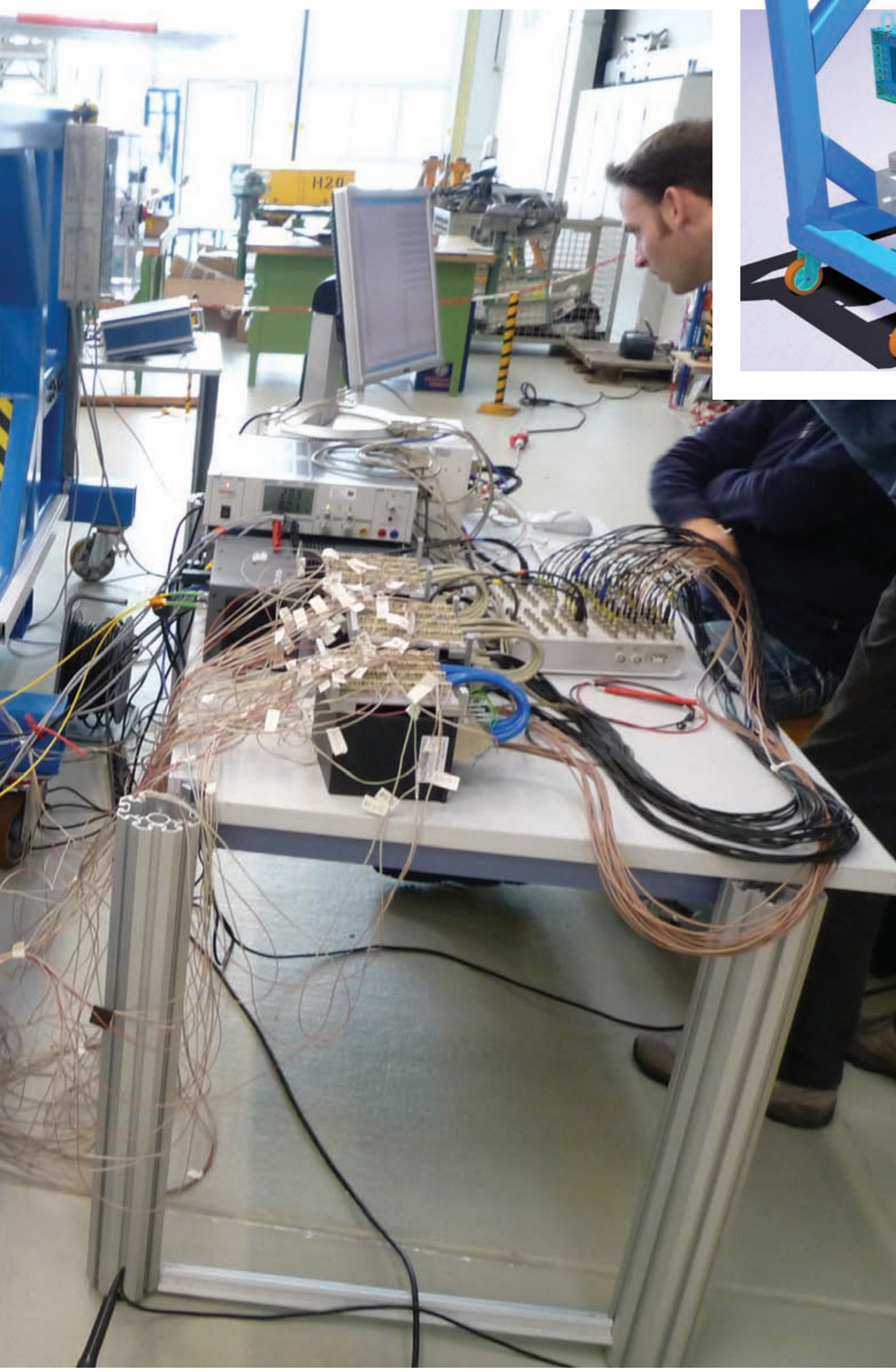
Selection of measurement methods for experimental verification

This is especially pertinent for the leading edge high-lift system of a wing when it has been exposed to high operational loads throughout the aircraft's service life. In addition, the adaptive, smart leading edge device has to support the laminar flow over the wing, which is directly associated with high aerodynamical demands. Based on these facts, the three most important requirements of the leading edge are contour accuracy, functionality and internal loading.

These criteria and their degree of fulfilment must be experimentally evaluated with suitable measurement







methods. Because of this, a geometrical measurement via the digital image correlation (DIC) offers two major benefits, among others: it captures the surface quality, and it supports a comparison between theoretical and actual profile shape. For this, the test object is recorded by a system of two cameras in a calibrated position. After that, the computer calculates the three-dimensional surface via triangulation. Furthermore, the deflection of the inner kinematics is determined through inclinometers, which are designed in MEMS-technology suitable for minimal installation space and power consumption.

Aside from the geometrical deformation, the structural strain is best measured locally via electrical strain gauges due to their high accuracy. Also, optical strain gauges, such as fiber Bragg grating sensors, are taken into account at critical positions of the structure. They show an excellent fatigue life even under high loads and strain and are therefore well suited for structural durability testing of composites.

Sensor operation and measurement performance

Both strain gauge types are mounted on the inner and outer surface of the test carrier. Internal loading is dominated by bending. Therefore, mechanical and thermal in-plane stress is negligible as confirmed during the tests. Additionally, the global strain measurement is possible via the image correlation system and

ABOVE: Computer model of test carrier: rig and smart leading edge device. © Cassidian

CENTER: Compilation of heterogeneous measurement signals on a measurement computer © Fraunhofer LBF

LEFT INSET: Test carrier with applied electrical and optical strain gauges

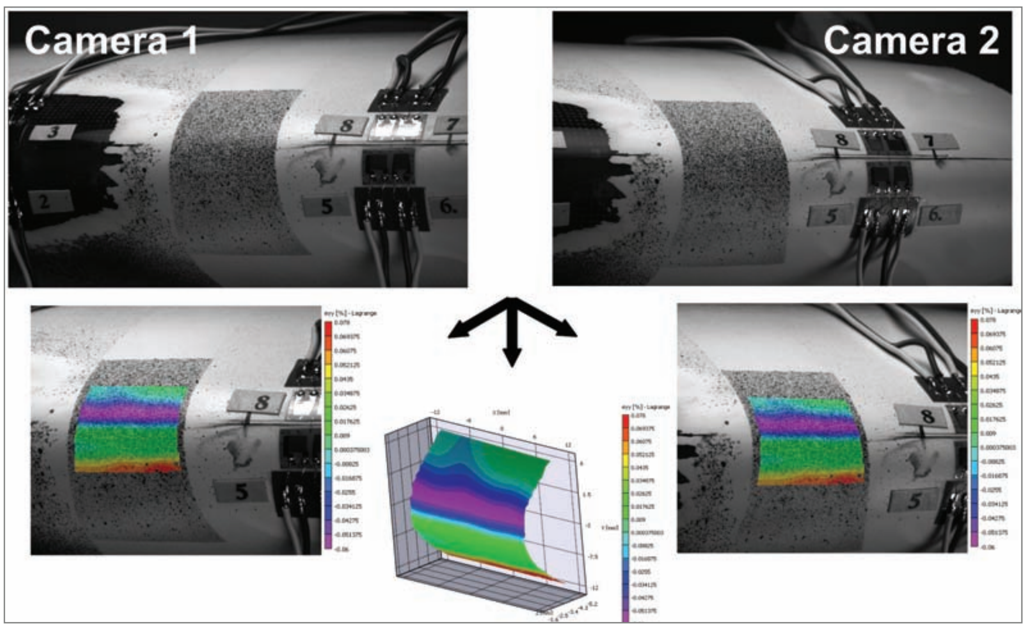
"Verifying a system's structural durability under its expected loads through ground testing is a major part in its development"

BELOW: Geometry and strain analysis by digital image correlation method. © Fraunhofer LBF

provides stress information on the complete outer surface.

The synchronous data collection of strain gauges, inclinometers and image recording simplifies the later interpretation. For this purpose, Hottinger Baldwin Messtechnik GmbH (HBM), with which the Fraunhofer LBF works in close cooperation, provides the hardware and software for a combined measurement of electrical and optical strain sensors.

These strain sensor technologies output the data in real time and therefore allow for a quick intervention if necessary. Digital image correlation with a stereo system and large measurement areas, on the other hand, is not real-time capable. Its calculated results showed a good representation of the three-dimensional geometry and a realistic strain distribution on the surface.



Stereo digital image correlation

For the 3D image correlation method, two cameras synchronously capture an object from different angles. Individual points on the object's surface are projected and digitized on both CCD sensors. With the known positioning of the cameras to each other it is then possible to determine the spatial position of a surface point via triangulation.

For the application, a high resolution of the object is achieved by a high-contrast, stochastic speckle pattern. An included angle of 60-120° between the cameras provides the best spatial results. Also, the relevant measurement area should be screen filling since the accuracy depends on the used number of pixels, among other things. Beside this, it is necessary to maintain a not-too-flat angle of incidence between the camera axes and the surface tangent, otherwise a successful point recognition is not guaranteed.

The correlation itself works in the way that identical image points from the left and right camera are related to each other. For this, an algorithm is used, which compares the patterns of grey values around a pixel to clearly identify it within the images. Thus, the displacement of the digitized object points can be followed throughout consecutive image recordings. Finally, the occurring strain is calculated from the gradients of the spatial displacement.

Ground testing of smart structures in general

Testing and measuring a component under laboratory conditions gives a first insight of the structure's behavior and the critical elements within. However, the reaction of the matured component under the expected operational loads – in other words, its structural durability – must be evaluated in further ground tests. For this, suitable methods for fatigue testing must be applied to gain comparable and reliable results.

The knowledge Fraunhofer LBF brings to the field of structural durability has been developed since the 1930s. While at the beginning the tested systems mainly presented passive structures, today's research includes fatigue assessment of smart structures and system reliability analysis of active systems, such as adaptive structures with sensors and/or actuators.

Verifying a system's structural durability under its expected loads through ground testing is a major part in its development. Next steps will include the assessment of a component's fatigue during its service life under realistic operational loads and environmental conditions.

This requires in-flight measurement and data analysis as it is expected by structural health monitoring (SHM) systems in the near future. For their development, the verification of structure-based sensor signals is essential. Fraunhofer LBF tests SHM systems and sensors/actuators for adaptive structures under relevant loads or artificial damages in the lab, while the sensor signals are verified with non-contact measuring technologies such as laservibrometer, x-ray technology and also optical or thermal cameras. ∎

Katharina Kraus is a research assistant in the department of lightweight structures at the Fraunhofer Institute for Structural Durability and System Reliability. Within the context of her studies she works on topics such as aeroelasticity and structural health monitoring on aircraft

THE ADVANCE OF ROBOTICS

Next-generation Industrial robotics with different types of coupling fully integrated in an NDT suite has many advantages for the ultrasonic inspection of composite aeronautical components

BY JOSÉ ROMÁN FERNÁNDEZ

Non-destructive testing (NDT) of aircraft parts made of CFRP or sandwich materials by using the ultrasonic method is a challenge for every manufacturer of testing machines. This type of aircraft component requires cutting-edge technologies to deal with the requirements of the inspection task, in terms of part handling, mechanics' accuracy, ultrasonic capabilities, and data processing.

For a long time, ultrasonic testing systems for aircraft components have been customized to adapt mechanics (typical gantry or bridge designs) to match the customer needs. This requires a major effort, which can ultimately have collateral effects on price, delivery time, system flexibility, and maintenance cost.

Therefore, manufacturers of aeronautical components and suppliers of inspection systems have focused their attention on industrial robotics as a way to simplify and cheapen quality control processes in manufacturing. Unfortunately, the specific requirements of the different ultrasonic inspection (UT) techniques have not attracted the attention of robot manufacturers in the past, and these peculiarities and differences with respect to habitual and traditional robot applications have so far made it impossible to obtain satisfactory results for the users.

Tecnatom has been committed to quality in the application of NDT techniques for more than 50 years, primarily focused on the nuclear power industry and for more than 10 years in the UT inspection of aero components. These two sectors share the demand for zero defects and zero failures. The company has succeeded in adapting its inspection technology and knowledge to the industrial inspection of carbon-fiber components, the manufacture of which requires absolute reliability and safety combined with practical optimization of the manufacturing process, particularly focusing on quality control and quality improvement.

But there are challenges to be faced, including the creation of new designs, demands to inspect more regions of the aero parts, larger components, more complex shapes, high curvatures, multilayering, and a combination of monolithic and sandwich structures.

The machine

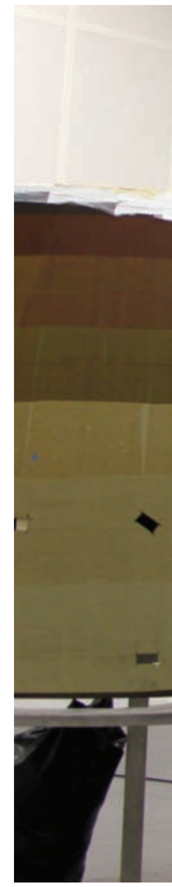
A testing machine consists of the mechanical part, UT software and hardware (SW-HW), and computer peripherals. 'Mechanics' includes control of positioning, and coupling for proper and stable ultrasonic scanning. The electronics comprises the transducers, the pulse generation and beam forming, and the signal processing. The software includes powerful tools for calibration, scan path generation, data evaluation, storage, and post-processing. In the past, each of these elements had to be set up separately and used step by step.

Tecnatom's solution has made it possible to powerfully and simply integrate all these elements in order to facilitate a quick and simple operation that may be carried out by a single operator, who does not require a high degree of training. All the phases of the process are controlled from a single NDT Inspection Suite: preparation, calibration, surveying of the part, calculation of trajectories, post-processing and simulation, control of the robot-operated cell, data acquisition and processing, evaluation of data in real time, and reporting. In particular, the new NDT suite is ready for use on an industrial-robot-based inspection system. A powerful wizard incorporated in the process enables the operator to control all the necessary tasks from his own conceptual language, without the need to learn the SW user interfaces specific to each of the components (robots, ultrasonic equipment, control and generation of trajectories, etc.).

The flexibility required for adapting to different parts, accuracy, reliability, and robustness are guaranteed by an integrated SW-HW architecture that includes the most advanced industrial components and tools.

Robot integration

Customers purchasing a UT testing machine can benefit from robot implementation on the inspection systems to achieve lower prices. Also, robot manufacturers offer a worldwide maintenance concept that provides short response periods. This shortens downtime of the equipment and keeps up productivity. Technically, standardized robots bear challenges in electric noise and synchronization accuracy when scanning 3D parts.



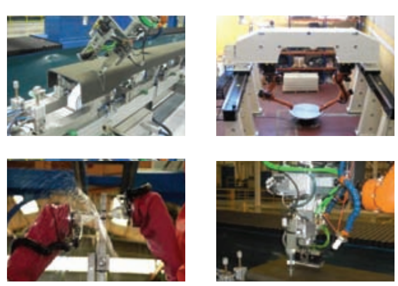
ABOVE: Examples of robot integration in aero components

RIGHT: Industrial robots are new solutions in aero-parts inspection

Tecnatom has maintained a close collaboration with suppliers of industrial robots. In some cases it has developed new versions of its control. These new modules provide the position and orientation of the inspection point in real time and generate the trigger and synchronization signals required by the ultrasonic data acquisition system (DAS-UT). This way, the team has arrived at a solution that gives a SW-HW full process integration between its UT systems (conventional or PA) and robots in true real time. In this way, robot integration on an NDT system provides a solution optimized on UT scanning capability, and reduces the cost, time delivery and maintenance needs of the system.

Robot configuration

The control platform enables flexible configuration, based on one or two robots on linear tracks and/or gantries, rotating tables, etc. These can be implemented, working simultaneously on one same part or on different parts, with pulse-echo or transmission techniques indistinctly and in a manner completely transparent to the operator, without the need to carry out HW-SW adaptations in the system.



The platform considers multi-robot cell management. The control is able to manage the independent operation of the robots (mode RT1 or RT2), or joint operation of the robots in a synchronized-cooperative way (mode RT1+RT2). The advantage is full flexibility when applying the system to a specific application: in PE inspection, one robot is devoted to one part while the other is devoted to a different part, or both robots are devoted to different areas of the same component, or both robots collaborate in TTU inspection. Furthermore, due to the optimized layout configuration, the space required for the cell is smaller than it was for configurations in the past (gantry, tower).

Another important advantage is that the graphic operating interface is independent from the hardware used (regardless of the supplier or model of the robot) and can be customized by the operator. Finally, the interface uses standard Ethernet communication protocols and buses, making it independent of proprietary tools.

ABOVE: Example of robot integration in aero components ultrasonic inspection (courtesy of Airbus-Nantes)

LEFT: Some examples of different configurations based on robots

UT electronics

UT electronics are implemented in one of two ways, depending on customer requirements and needs: conventional UT or phased array electronics.

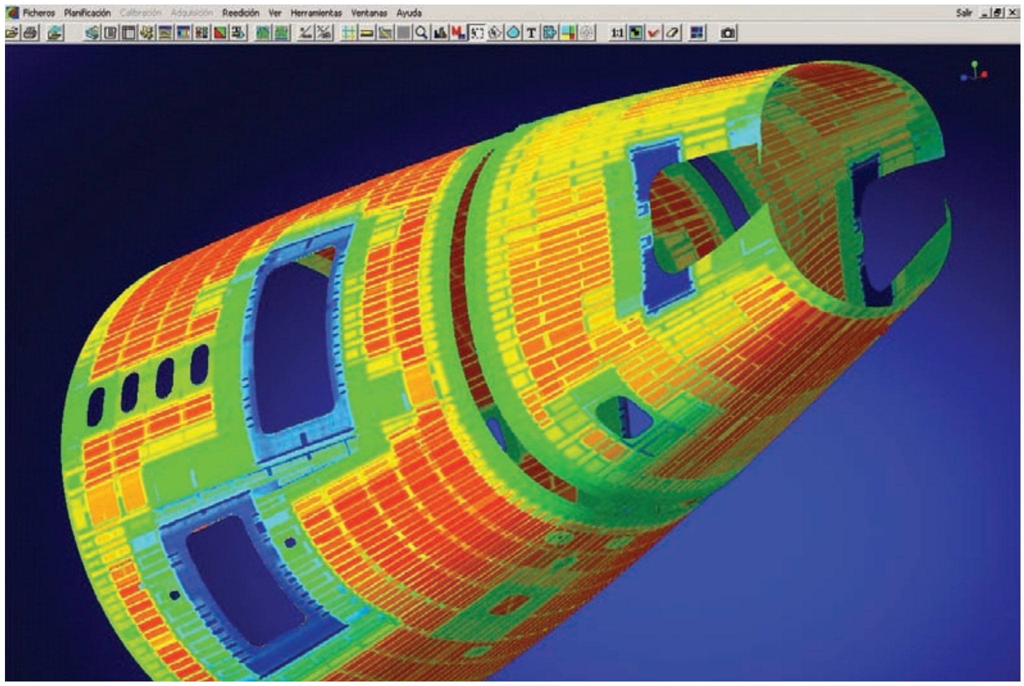
In the case of conventional UT electronics, an innovative and modular digital UT technology enables signals to be acquired closer to the probe and transmitted to the operating computer by fiber-optic connection. It achieves excellent robustness and UT signal dynamic margins, and excellent signal-to-noise ratio. Its main characteristics are designed especially for remotely controlled automated inspections, and the basic UT parameters are perfectly adapted to cover the needs of the aero components inspection. Another important improvement is its modular design, which enables the expansion of UT channels for easy adaptation to any number of machine axes.

For complex geometry shapes, or just to improve the productivity of the system, the use of phased-array electronics is an excellent option. The possibility of dynamic triggering and focusing provides important advantages during the scanning process. If it is connected to a modular concept, it satisfies a range of applications, from laboratory to industrial.

Fully integrated NDT suite

An NDT suite has to include a powerful software that is used through all the phases of an inspection process: planning, UT calibration (including focal laws calculation for phased-array) and data acquisition, data evaluation, part geometry capturing and processing, inspection programming, robot control, and reporting of results. The Tecnatom DAS system enables an easy adaptation to user necessities and requirements. The software program covers all the basic functions required by the system operators.

The interface takes advantage of Windows OS by means of icons and menus accessible by mouse, and is ready for a client's customized design. It is also compatible with commercial devices (printers, optical disks, etc.). The different applications use a common data repository, exchanging information via Ethernet and therefore allowing for the concurrent running of programs without any risk of losing information.



ABOVE: **UT plot of color-coded amplitude signal versus linear position (Bscan) and color-coded time arrival of UT echo**

> **"Some mechanical restrictions for robot movements could physically impede the theoretic solution, which, if not detected, could frustrate the right scanning"**

The SW package also enables the generation of automatic reports, which may be configured depending on the client requirements (f.i. 2D-3D data reconstruction and analysis).

Regarding the connection with the UT electronics, the software includes functions associated with the parameterization and calibration when using conventional ultrasonic or phased-array electronics. In both cases, the UT inspection techniques (PE, TTU) are also considered, and easy configurable pre-defined setups are available, saving operator time.

Another important advantage of the NDT suite is the integration of tools for the planning and control during the scanning: 2D-3D Automatic Trajectory Generation SW. It is able to import geometries from DAC files, mainly generated by CATIA software, or, in a different approach, from points clouds obtained by a learning system (laser pointer following the real part geometry). Once the geometry is known, the SW selects the areas to be explored, and with pre-defined criteria and strategies for the performance of the inspections, it generates the scanning trajectories to be applied in a fully automatic way.

Even with a powerful tool for automatic trajectory definition, the implementation of the optimized trajectories in a specific inspection cell has to be checked. Some mechanical restrictions for robot movements could physically impede the theoretic solution, which, if not detected, could frustrate the right scanning. The integrated NDT suite also includes a simulator of the robot movements following the proposed trajectories. Therefore, some problems can be detected, such as infringement of articulation limits/working area and collision detection. In such a case, a feedback with the right solution is given and transmitted to the CNC. The advantage is that, this way, any online problem related to robots' behavior can be simulated and solved without damaging the real system. Additionally, it offers the possibility to change the reference system, rotary translations calculation, and modeling of probe-holder, and simplifies the management of additional external axes (linear tracks, rotary tables, etc.).

In addition, the NDT suite can include an Automatic Defect Analysis module, which, with pre-defined criteria, is able to directly detect defects or mark questionable areas where a second check is needed. This package can reduce by a factor of 2-3 the time used by an operator during the data analysis phase.

LEFT: Automatic charger for probes and other devices

Automatic changing of inspection

An automatic charger reduces the scanning time-out periods, improving productivity. The different inspection modules and devices are automatically picked up and interchanged when exchange is needed or is convenient. Also, auxiliary devices can be automatically picked and assembled in the main inspection modules using the automatic tool changer. This is the case of laser pointers, defect marking devices, etc.

For UT testing, industrial robots have several advantages over customized mechanics solutions in terms of flexibility, overall cost, delivery time, and maintenance. As a standardized mechanical component, robot implementation offers a worldwide maintenance concept that provides short response periods, shortens downtime of the equipment, and keeps up productivity, and, in general, drives lower prices for the equipment. Currently, robots based configurations are compatible for PE or TTU testing, and all previously introduced coupling mechanics. This makes the robot approach very versatile and powerful.

Plus, in order to facilitate a quick and simple operation by a single operator who does not require a high degree of training, a fully integrated NDT suite provides a powerful software that helps in all the phases of an inspection process: planning, UT calibration (including focal laws calculation for phased-array), data acquisition and evaluation, part geometry capturing and processing, inspection programming, robot control, reporting of results, etc. ∎

José Román Fernández is the director of technological development at Tecnatom, Madrid, Spain

GOOD VIBRATIONS

Airbus and LMS develop a streamlined flutter analysis process to handle the huge amounts of inflight testing data generated by the A380

BY ELS VAN NIEUWENHOVE

Along with the aircraft characteristics, modal identification methods used during flutter testing have evolved to assure correct parameter identification. Frequencies and damping value estimations have to be as accurate as possible to define the aircraft fluttering margins used during those first mission-critical inflight test campaigns.

In a nutshell, flutter testing can be broken into three segments: real-time; near real-time; and off-line. Inflight real-time test campaigns acquire live data during the test flight mostly as a safety check to continue the flight envelope. Near real-time testing focuses on rapid modal estimation to determine the overall safety of the flight and the flutter test program. Off-line deals with the finer analysis of the recorded flight data and final report production.

To validate data efficiently and effectively off-line, Airbus choose LMS Test.Lab Modal Analysis. It offers all the required functionality, such as data preprocessing, modal parameter estimation, mode shape animation, and result validation.

Bigger airplanes, new flutter requirements

The Airbus flutter team in Toulouse, France, faced some challenges working on the A380 campaign, but there were issues they had encountered before with the A340 flutter campaign: high modal density and similar mode shapes, both placed in a low narrow frequency band.

In terms of modal identification, these new precise requirements called for a better-defined and better-equipped testing installation. This meant digging a bit to find the right kind of process. Measured data needed to be recorded at enough locations with high enough quality to improve power spectra and transfer function estimates, and avoid spatial aliasing when working out aircraft deformed shapes. This required some innovative thinking and serious process validation with regard to current techniques.

> "We found that the exponential window, which allowed for cross-correlation calculations, was a good de-noising tool for our inflight data"

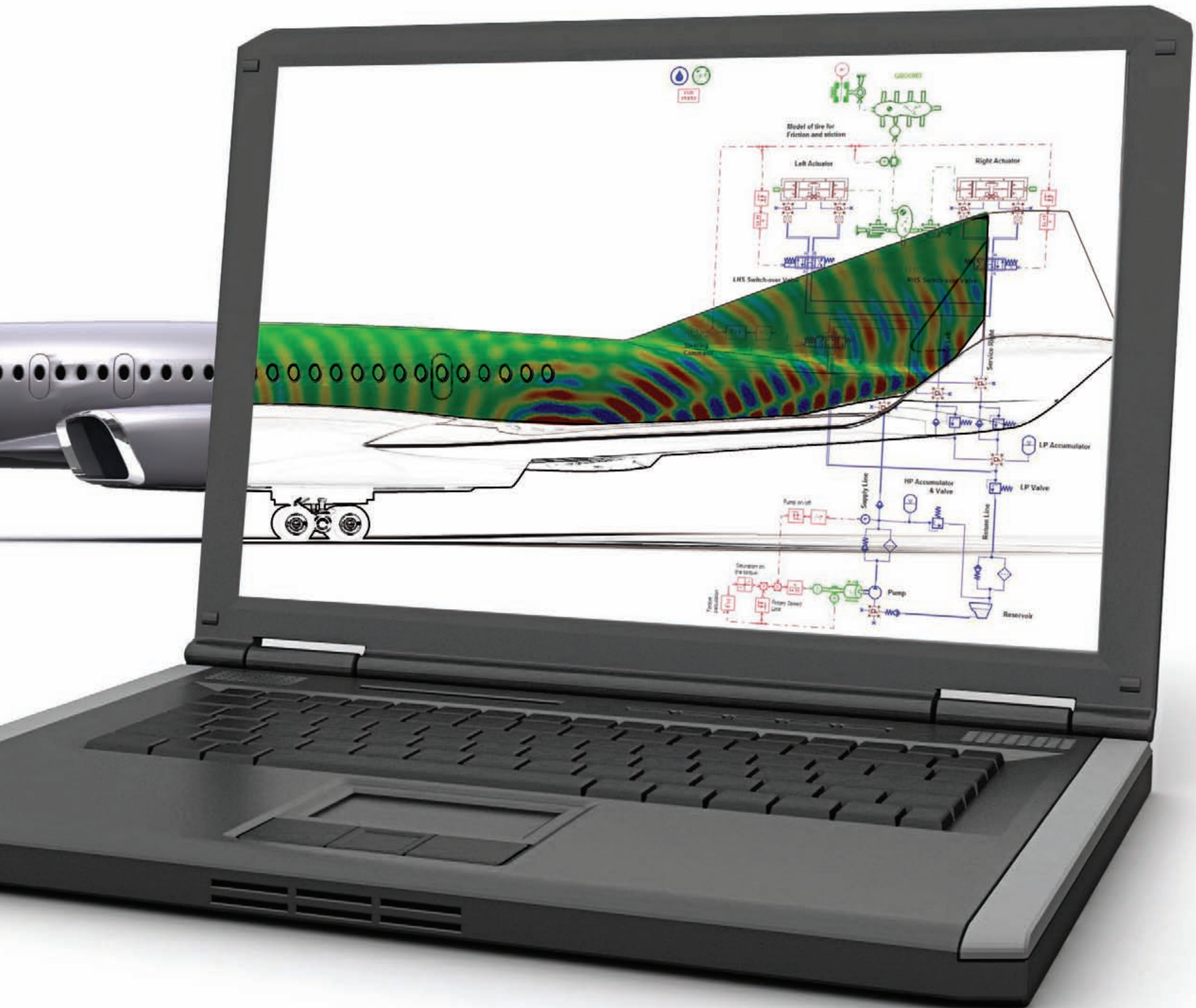
Building on Eureka Flite projects

Since 2001, Airbus France and LMS International have been cooperating on several Eureka projects called 'Flite' (Flight Test Easy). An intergovernmental initiative to support market-oriented European R&D, the Eureka Flite projects focus on bringing new and powerful tools to structural engineers and aircraft designers, improving the quality and usefulness of data gathered during flight testing.

The Flite consortium gathers world-ranking aircraft manufacturers and technology providers from France, Belgium, and Poland. The Flite projects offered a unique opportunity to confront new advanced algorithms with challenging real-life aircraft data.

Finding the right data

In late 2007, LMS and Airbus agreed to start a project to evaluate LMS PolyMAX, an integrated part of the LMS Test.Lab Structures suite as a key solution to achieve high-quality off-line inflight data processing for flutter testing. The LMS Test.Lab Structures suite is a complete solution for modal analysis, combining high-speed multichannel data acquisition with a



suite of integrated testing, analysis, and reporting tools. LMS is renowned for its modal testing experience and scalable solutions, from supporting impact testing on small structures right up to large test campaigns using multiple shakers and hundreds of measurement channels.

In the past, the flight test departments of Airbus France performed data analysis using their in-house near real-time analysis package and transferred the results, together with the raw data, to Airbus Germany, where the numerical flutter predictions were correlated with actual flight tests. However, Airbus France wanted to carry out more in-depth data processing, so that it could transfer more complete results to Germany.

"Clearly, we needed a solution that would improve the alignment between online inflight analysis occurring in Toulouse and the post-processing completed in the design center in Airbus Germany. At this stage, we are very pleased with the results. LMS Test.Lab is able to provide us with the right type of results," says Jean Roubertier, flight test department aeroelasticity expert at Airbus.

Record-breaking data acquisition

Considering that the 525-seat Airbus A380 is the largest commercial passenger aircraft in the skies today, it is not surprising that because of its size, the acquired inflight testing data is also record breaking.

"With more than 100 sensors, this was one of the largest setups for an inflight flutter test campaign I have ever seen," says Bart Peeters, LMS research project manager. "Also, the amount of tests under different flight conditions is impressive. The resulting database is immense and efficient

“Even with projects of this scale, there is always noise in the data that needs to be managed”

ABOVE: **Measured mode shapes estimated from in-flight sensor data. A wing bending mode (left) and a fuselage bending mode are shown (right)**

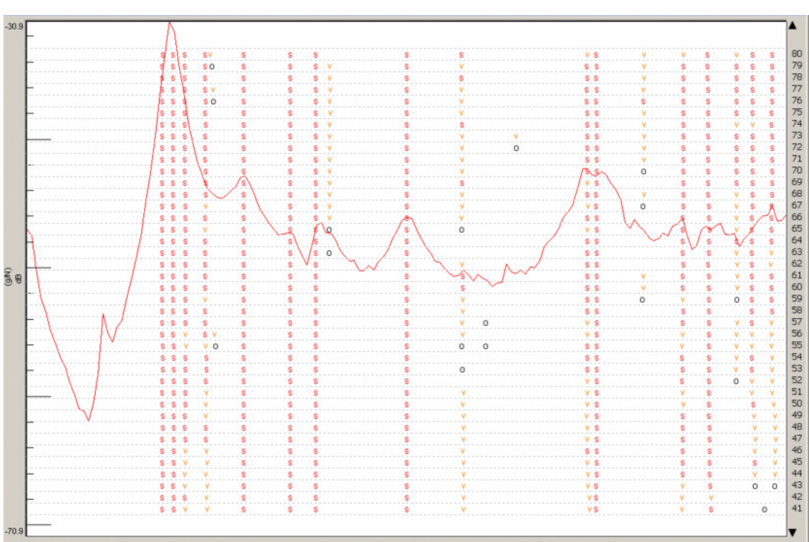
BELOW: **The very clear LMS PolyMAX stabilization diagram allows an easy identification of the many modes in the considered frequency band**

processing and report generation capabilities are required.”

The Airbus Flutter team in Toulouse performed a variety of excitations, including control surfaces sine sweeps and pulses. Pulses are currently used to assure crew and aircraft safety, whereas sweeps are used to work out more accurate results, allowing theoretical FE models to be updated. Flutter flights duration time has been considerably reduced by integrating pulses into the process,

Technically speaking, the basic concept behind the project was to compare classical experimental modal analysis (EMA) with LMS Test.Lab’s operational modal analysis (OMA) technique. In classical EMA, the control surface excitation and aircraft response signals are converted to frequency response functions (FRFs). During the actual flight, other excitation sources, such as turbulence, are present. Sometimes, this results in noisy FRFs. For example, an aircraft tail response sensor receives a rather limited contribution from the wing excitation. Therefore, the idea arose to neglect the excitation signal and apply OMA to the aircraft acceleration signals.

“We actually achieved better results using OMA than with classical EMA. We found more modes. The synthesis was better with higher correlation and fewer errors. And the inflight mode shapes looked much nicer,” adds Miquel Angel Oliver Escandell, a member of the Airbus Flutter team, who was dedicated to the project for a year. “This was thanks to the amount of sensors we used and the OMA capabilities of LMS Test.Lab.”



De-noising the data

Even with projects of this scale, there is always noise in the data that needs to be managed. LMS Test.Lab paints a clear picture with techniques that produce clear analysis results, even from rather noisy data. This feature offers clients such as Airbus a competitive advantage when it comes to off-line test processing.

“We found that the exponential window, which allowed for cross-correlation calculations, was a good de-noising tool for our inflight data,” says Escandell. “And the validation tools such as correlation levels, MAC matrix, mode shape complexity (MPD and MPC criteria) are very complimentary in regard to real-time identifications performed during flutter tests.”

During the comparison testing, the flutter team at manufacturer Airbus used LMS PolyMAX during sweep excitations of the aircraft. Results, using an exponential window of 5%, appear to be good, supplying high synthesis correlations (98% using only two references) and clear stabilization diagrams.

“We’ve been extremely impressed by the flutter analysis results and the way the LMS Test.Lab software can handle the challenges of processing the immense amount of Airbus A380 inflight data during the off-line analysis,” concludes Roubertier. ▮

Els Van Nieuwenhove is the marketing manager test for LMS International

FLUID APPROACH

Aerospace industry users should consider a number of factors when choosing a technology to measure the flow of fluids on board aircraft

BY LADD HOWELL

Measuring the flow of fluids used on board aircraft or in component test stands demands superior instrument performance. From measuring the fuel consumption of rotary and fixed-wing aircraft, missiles, and drones, measuring coolant flow to advanced avionics and radar systems, to evaluating the performance of hydraulic fluid and lubricants, aerospace applications present difficult flow metering challenges.

Among today's common liquid and gas flow meter technologies are widely differing designs, such as turbine, coriolis, magnetic, differential pressure, and vortex meters. Every technology offers particular strengths and weaknesses in relation to a given application. This is especially true in the aerospace industry.

For example, a manufacturer prototyping a helicopter platform may need to test the performance of an orifice or pump, or monitor engine heating, under various flight conditions. Flow measurements must not only be extremely accurate, but provided in real time. Once the flow data is collected, the manufacturer will make the necessary design changes to keep the aircraft within specified performance tolerances.

In addition to initial prototype flight testing, manufacturers often employ flow meters for a host of recurring tests. A flow meter may be mounted along with other sensors on a panel installed under the helicopter's engine cover. The helicopter is taken through its flight envelope and the flow of various engine or hydraulic fluids is measured and recorded. The wide range of temperatures encountered during these tests requires that the meter be able to compensate accurately for the temperature changes that significantly affect fluid viscosity.

Another application is to measure fuel consumption as part of an aircraft's onboard fuel management system, or as part of a ground-based engine test stand. These applications often involve aircraft designed for military, commercial, and industrial service.

Aerospace component manufacturers across the world require the best available test equipment to optimize their flight-critical components. Whether it be a fuel pump, hydraulic pump, heat exchanger, or simply a valve, accurate flow measurement is absolutely critical to ensure component performance.

Selecting the right technology

End users contemplating the purchase of a flow meter should take time to study the characteristics of respective measurement technologies, and analyze their advantages and disadvantages for different environments. This will ensure the selection of a meter with the performance and reliability to meet the user's particular requirements.

In some aerospace flow applications, specialized metering devices may be needed to obtain accurate flow measurements over wide ranges of temperature, pressure, vibration, shock, and other variables. Certain applications have unique requirements for sensor size, weight, material of construction, and mounting.

For this reason, end users must not only identify the correct flow sensing technology, but also select a manufacturer with proven experience in their industry, and the knowledge to provide sound application guidance and advice.

LEFT: Turbine flow meter used for fuel on load and off load to aircraft

ABOVE: Broad Area Maritime Surveillance Unmanned Aircraft System (BAMS UAS). BAMs in flight over reef courtesy of Northrop Grumman Media Gallery

One of the most versatile flow meters – and one of the most popular among aerospace engineers – is the turbine flow meter. This is regarded by many as the meter of choice for obtaining precise flow measurements in clean liquids. Unlike more costly and complex metering techniques, the versatile turbine meter can be designed and manufactured based on almost any custom specification.

Precision turbine meters can be used to measure the flow of fuel, hydraulic fluid, cryogenic fluid, lubricants, coolants, and other fluids crucial to aircraft performance. In these applications, the meters can withstand a variety of environmental conditions as specified by TSO C44a, RTCA/DO-160, and a host of military specifications.

Operating principle

Turbine flow meters employ a proven, high-precision measurement technology that provides exceptionally reliable digital outputs. The meters incorporate a freely suspended turbine or rotor, rotated by the flow of the fluid (liquid or gas) through the meter body. Since the flow passage is fixed, the rotor's rotational speed is a true representation of the volumetric flow rate. The rotation produces a train of electrical pulses, which are sensed by an external pick-off mounted on the surface directly above the rotor. The frequency of the pulses can be converted to an analog current or voltage, or displayed in any engineering units.

The advent of small, powerful microprocessors that can be easily packaged in an electronic pick-off has resulted in a 'smart' turbine flow meter. These advanced turbine meters – so named because of their built-in linearizing electronics – eliminate the need for external temperature sensors, signal conditioners, and linearizers by providing real-time compensation for measurement variables (for example, viscosity and density). This feature increases the meter's rangeability by extending turndown to as much as 100:1 at 0.1% linearity. Total system uncertainty utilizing smart electronics can achieve values of less than 0.12% reading at 2 sigma.

Linearized turbine meters can be configured so that multiple units output an identical K-factor, thereby providing complete interchangeability of the flow meters. Moreover, the data acquisition device does not have to be rescaled or reconfigured if the meter is changed or recalibrated. The linearized output can be amplified to a 0-5V DC pulse and scaled in units of volume, such as gallons per minute and liters per minute. Analog and digital outputs are also widely available.

Coupled with the typical 2-3msec response times of turbine flow meters, users are able to detect changes in flow instantly. Updating measurement variables at microprocessor speeds ensures that calculations are made with current temperature, pressure, viscosity, and density values. Utilizing calculated density values, turbine flow meters can be configured to output flow values in mass units.

Advantages in application

Turbine flow meters are ideally suited for aerospace applications requiring a fast response time and accurate total volume determination after a step change in flow rate. Turbine meters also have a relatively high turndown ratio, with a repeatable range of up to 100:1. This capability often enables a single turbine meter to replace multiple meters with a lesser turndown capability, and can significantly reduce cost in applications requiring accurate rate and totalization measurement over a wide flow range.

> **"The high resolution of the turbine meter also makes it ideal for the detection of leaks in aircraft fluid systems"**

Another inherent turbine meter strength is its design simplicity and ruggedness. Stainless steel is most frequently used in the construction of turbine meters for its exceptional strength and resistance to corrosion. But depending on size and weight requirements, temperature ranges, fluid characteristics, and other variables, optional materials such as Hastelloy C and aluminum can be utilized for the machined housing and internal systems.

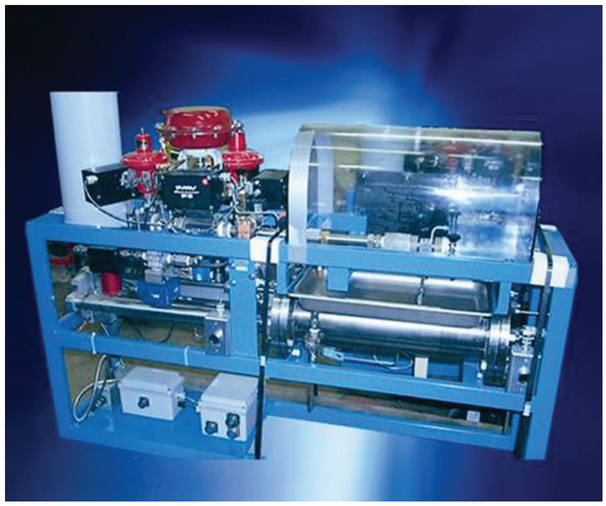
The turbine's compact size and packaging flexibility make it suitable for use on board aircraft to measure fuel, coolants, lubricants, and hydraulic fluids. In these environments, the flow meter is durable enough to withstand the high levels of vibration, shock, and g-force loads encountered during flight. Successful testing to shock loads as high as 4,000g and extreme random vibration levels have been performed.

The high resolution of the turbine meter also makes it ideal for the detection of leaks in aircraft fluid systems. With resolutions up to 48,000 pulses per gallon for small turbines, minute fluid flow can be detected.

The relative simplicity of the turbine meter's required signal processing allows linearizing and temperature conditioning circuits to be adapted to military levels of temperature and EMI noise immunity. All the signal conditioning electronics can be packaged with the turbine in a compact, rugged housing that is quiet to EMI susceptibility and emissions.

Another key difference between turbine meters and other common flow sensors is their compatibility with remote electronics: paired with a heat-tolerant electronic pick-off and amplifier, turbine meters can be located in areas where extreme temperatures are normal, while data acquisition electronics are safely mounted elsewhere.

These attributes make turbine flow meters the instrument of choice for use in the extreme conditions and demanding performance requirements of the following aerospace applications.



ABOVE: **Primary standard flow calibrators provide the necessary traceability to ensure performance requirements**

Fuel management

Many aerospace companies rely on fuel flow transducers to provide accurate, instantaneous fuel flow rate and consumption data as part of fuel management systems. Paired with cockpit displays, turbine flow meters offer easy installation and high reliability utilizing this demanding application.

Flight test

From piston engine aircraft to the latest military fighter jets, flow measurement equipment is a key component of systems that monitor critical fluid flow on board today's advanced aircraft.

Flight test applications for turbine flow meters are diverse and demanding. Intelligent flow metering devices provide temperature compensation for changes in viscosity and density, as well as scaled frequency, voltage, or current outputs for use by fuel management systems and other controls.

Test stands, test cells, iron birds

A turbine meter, paired with a flow computer or smart transmitter, can perform precise metering of fuel flow in engine test cells, fuel and hydraulic fluid flow in component test stands and iron bird assemblies, and hydraulic fluid flow in hydraulic mules. The accuracy of these measurements improves the overall performance of test regimens and reduces the chance of rejecting a compliant component.

Available in standard and ultra-low-flow designs, turbine meters utilize a proven technology to provide exceptionally reliable digital outputs. This capability, combined with response times as short as 2-3msec, allows for precise monitoring of transient responses during tests. The high-speed response enables the data to be accurately time stamped for comparison with events occurring during the test. This enables the design engineer to know exactly what is occurring to the flow at all times during the test, which is critical for optimum system design.

UAVs, drones, missiles

Today's smart military and government platforms, including UAVs, drones, and missiles, are frequently called upon to stay in flight for extended periods, or even to loiter over an area. Such demanding requirements make fuel totalization a mission-critical task. Aerospace industry designers developing these and other advanced platforms seek instantaneous fuel flow rate data that can be used as feedback to control engine performance.

Turbine fuel flow transducers offer a high turndown capability, as well as exceptional repeatability and speed of response. The meters can be employed to measure precise amounts of fuel and oxidizer throughout the flight envelope.

Hydraulic fluid measurement

Measuring hydraulic fluid during a flight test requires a compact and rugged flow meter. Turbine meters answer the size, safety, and durability concerns of flight test engineers by offering flared tube or beam seal fittings, positive retention of internal parts, and reinforced rotors. Subjected to vibration, shock, and pressure impulse tests, the meters are suitable for the most difficult environments.

ABOVE: This custom-designed turbine flow meter provides viscosity and density corrections over wide flow and temperature ranges

Calibration

Aerospace users with critical flow measurement applications must maintain their instrumentation in optimal working order. To obtain the greatest accuracy from the device, calibration is a critical component in all flow meter technologies. This requires periodic meter calibration using a system that is traceable to recognized government and industry standards, such as those established by the National Institute of Standards and Technology (NIST).

The extent to which a flow meter calibration is NIST-traceable depends on whether the system used is a primary standard or a secondary standard. A primary standard calibration is one based on measurements of natural physical parameters (mass, distance, and time). This calibration procedure ensures the best possible precision error, and through traceability, minimizes bias or systematic error. A secondary standard calibration is not based on natural, physical measurements. It often involves calibrating the user's flow meter against another flow meter, known as a master meter, which has been calibrated on a primary standard.

A growing number of flow meter customers are specifying that their meters be serviced by calibration facilities accredited under the National Voluntary Laboratory Accreditation Program to perform ISO/IEC 17025 liquid calibrations – the 'gold standard' for absolute accuracy and repeatability.

As with all sensors, the device is only as good as its latest calibration.

The popularity of turbine flow meters is attributable, in large part, to the demanding flow measurement requirements of today's high-technology aircraft. Like many other sensor technologies that originate in the aerospace industry, these reliable flow meters are finding acceptance in a host of other applications where high accuracy, extended range, fast response time, compact size, and rugged construction are required. ∎

Ladd Howell, aerospace market manager, Flow Technology Inc

RECORD BREAKERS

Land speed record vehicles owe much to aerospace technology, which continues to dominate today's supersonic designs

BY WALDO E. STAKES

The first horseless carriage land speed record was set in 1898 by a Frenchman driving an automobile powered by batteries and an electric motor. The record, which marked the beginning of automobile racing, was set at 39mph. The car employed a new scientific concept called air streamlining. A noted scientist of the day claimed, "It did not matter how fast a horseless carriage can be made to go as no human being can withstand speeds greater than 60mph!"

Of course, modern cars now reach speeds somewhat in excess of 60mph, and it is difficult to predict how quickly they will travel in 50 to 100 years' time. Today, one can buy a stock 200mph motorcycle and a nearly 300mph automobile from a dozen manufacturers direct from the showroom.

The performance of most of these vehicles is derived from land speed record vehicles, which have been closely linked with the developing aircraft/aerospace industry since the 1920s. At this time, speed record car and motorcycle designers began using aircraft engines (mostly from bombers) to power their vehicles. In the 1930s, as fighter aircraft engines became more powerful and reliable, they were also used.

Aviation pioneer Glenn Curtiss was the fastest man on Earth for a short time when he rode a motorcycle to 136mph in 1907 at Florida's Daytona Beach – a speed greater than any land speed record automobile had reached at that time. The motorcycle was powered by a 4,000cc V8 aircraft engine of his own design. Curtiss used his speed record fame to generate financing to fund his aircraft engine manufacturing company, which later became aligned with the Wright aircraft company. Together they produced some of the most reliable aircraft of their day.

Three-pointer configuration

In fact, the wheel layout of most modern land speed racing vehicles can be traced back to fighter and light fighter/bomber aircraft developed during World War II. The tricycle wheel configuration proved to be the best arrangement for aircraft with high-speed take-off and landing requirements. The first

> **"The ramjet engine is probably the best choice for a land speed record car propulsion system"**

operational twin-jet fighter, the German Messerschmitt Me 262, was originally put into production and deployed as a tail dragging design. It was soon converted into a tricycle wheel arrangement when it was noted that its Jumo turbojets were damaging and sometimes igniting runways when the aircraft took off, landed, or taxied.

The tricycle wheel arrangement is known to land speed record designers as the three pointer and was originally employed by Craig Breedlove for his 1962 version of the Spirit of America jet cars. This car was powered by a General Electric J47 turbojet engine, as used in the North American F-86 Sabre jet. The cars' aerodynamics were refined by aerospace engineer Rod Chapelle and the intake ducts were designed by Lockheed Skunk Works engineer Walt Sheehan, who had designed the intake ducts for the Lockheed F-104 Starfighter.

The first supersonic three-pointer design was the 1967 Bluebird CMN-8 rocket car designed by Ken Norris for Donald Campbell. Unfortunately, the design had only reached the mock-up stage when Campbell was killed on Coniston Water in 1967, while attempting to set a water speed record with his turbojet-powered boat, Bluebird.

My current three-pointer, Sonic Wind LSRV, is a supersonic automobile built for the purpose of gathering data from a human-controlled vehicle traveling at speeds greater than Mach 1 (760mph) on the ground. LSRV stands for 'land speed research vehicle.' I say 'automobile' because the United States Air Force rocket-powered test sleds running on rails have already exceeded Mach 9 or more than 6,000mph during testing of military components.

Pushing the envelope

Human beings have ridden rocket-powered sleds to speeds that set the standards for the kinds of loads a military pilot or land speed record car driver can sustain. Dr John P. Stapp rode the Northrop-built 'Sonic Wind' rocket sled at Holloman Air Force Base in New Mexico in 1954 and reached a terminal velocity of 632mph. This was the highest speed achieved on land by a man and was not was eclipsed until 1969.

Stapp endured an accelerative force of +15*g* for 3.5 seconds, and in stopping, his body endured -42*g* to -45*g* for 1.5 seconds. This equates to accelerating from a standstill to 632mph in 3.5 seconds and then coming to a complete stop in 1.5 seconds. Stapp was injured on this run, but did survive, and today these statistics remain the standard *g* load figures for what the human body can endure and 'probably' survive.

A supersonic car needs to accelerate at between 3*g* and 5*g* so that the driver can maintain physical control over his vehicle. During deceleration, a maximum of -10*g* is considered acceptable. Stapp was simply strapped to his 45,000 lb thrust rocket sled and because of the high g load was essentially incapacitated during his run.

As a result of Stapp's experience, human-ridden rocket-powered sled test runs were banned by the military. The countless number of test sled runs at the tracks owned or contracted by the military to this day are mostly used for ordnance proficiency, development tests, and materials survivability studies.

In the late 1950s, chimpanzees rode rocket sleds wearing standard Air Force issue Nomex flight suits and helmets, which were exposed to wind ram pressures and frictions at speeds greater than 2,000ft/sec. Most of these test subjects did not survive and some even caught fire from the air friction at such high velocities. The results of these tests initiated the development by military contractors of safety capsules to protect pilots.

Rocket technology

The land speed record currently stands at 763mph; to exceed this, more powerful engines are required. As in the past, land speed record car designers turn to aerospace technology to supply the power plants. Most are powered by turbojet, turbofan, or rocket engines, with rockets being the most popular as they offer the greatest power.

Curiously, ramjet engines have never been used in land speed racing. The ramjet engine is probably the best choice for a land speed record car propulsion system because it is light, generates tremendous power, and is simple to fuel

LEFT: Rear view of the Sonic Wind ice racer, Waldo Stakes' first land speed car, powered by an LR-11 rocket engine

ABOVE: Sonic Wind the ice racer and Sonic Wind LSRV side by side

and prepare. The Marquardt M-43 ramjet engine as used in the Bomarc surface-to-air missile uses low-grade, low-octane pump gasoline as its fuel.

Ramjets offer a lot more in specific impulse (I_{sp}) than a rocket. Ramjets develop 800-3,000 plus I_{sp} and rockets 100-465 I_{sp}. This is because ramjets use the air they are running through to burn their fuel. Rockets have to carry their own oxidizer, which lowers their I_{sp}. The only drawback in using a ramjet is that they must be accelerated to near transonic speeds before they can be lit and sustain combustion, but that is simple enough to achieve using a smaller solid-fueled pusher rocket engine.

Record-breaking origins

The Sonic Wind LSRV rocket car design now under construction is based around a highly modified Thiokol XLR-99 rocket engine, which was originally used in the North American X-15 aerospace plane. In 1967, the X-15 set the absolute speed record of 4,519mph for an aircraft, which still stands to this day.

Our modernized XLR-99 design uses the original injector, which is mated to a new technology combustion chamber and nozzle fabricated from composite materials. The fuel has been changed from ammonia to methanol for performance and safety reasons.

One curiosity about land speed vehicles that is not shared with aircraft is that nearly all land speed vehicles have fallen short of their predicted target top speeds. This is because even though vehicle aerodynamic drag can be accurately calculated, wheel rolling resistance can only be speculated. As a car attains a high velocity, the wheels in effect fly over depressions or cavities in the running surface rather than traveling down into them. As the wheels fly over these cavities, air drag slows them down by hundreds of RPM. When the wheel regains contact with the running surface, it is spun up to current RPM in a fraction of a second. The drag this produces is unpredictable and can only be estimated.

The only way to minimize these forces and their resultant drag is to keep the wheel mass as low as possible, so that it takes less horsepower to return the wheels to running speed. There are dozens of ways to do this. I chose to design my wheels as simple, thin rings running around the outside of an extremely large diameter internal axle. This high-speed wheel design has been unchanged since I conceived it more than 20 years ago and is employed in all my rocket car designs.

Frontal area is also one of the most important aspects in designing a land speed record vehicle. The larger the vehicle, the more air it has to move out of its way and the greater the shockwaves it will generate as it exceeds Mach 1 and accelerates that air mass. Shockwaves are a product of vehicle size, vehicle mass, velocity, and air density.

Ideally, the vehicle should be no larger than the largest component in the vehicle and that largest component should be the driver or pilot. All the other components can be laid out in a line behind and in front of the driver.

My first unlimited land speed record vehicle attempt was a rocket-powered ice racer I named 'Sonic Wind' after Stapp's rocket sled. It used blades and a ski to run on frozen lakes. Minuscule by land speed record vehicle standards, it is powered by a single thrust chamber from a Reaction Motors LR-11 rocket engine, as used on the Bell X-1 rocket plane.

The Sonic Wind LR-11 rocket engine uses ethanol/water and liquid oxygen as propellants and generates 2,200 lb of thrust for 22 seconds. The vehicle weighs 780 lb loaded and expends 220 lb of propellants during a maximum speed run. It has a subsonic drag coefficient of 0.12 and a total frontal area of 2.8ft^2.

My current automobile design, Sonic Wind LSRV, has a frontal area of 8ft^2. By comparison, Thrust SSC, the current automobile land speed record holder, has a frontal area of nearly 60ft^2.

Sonic Wind LSRV is a three-pointer automobile that uses a unique new ground effects system to negate supersonic lifting. This three-pointer design puts the front wheels close together at one point at the very front center of a vehicle, so that as the vehicle goes over a bump, the front end will only lift up in a vertical moment. By mounting the front wheels in trail, they realign themselves with the direction of motion when they reconnect with the running surface, helping the car to travel in a straight line. Most jet fighter nose wheels are designed in a similar fashion.

A four-wheel car with wheels at the four corners is a very stable design, but better suited to cornering than traveling in a straight line. The problem is that as the two front wheels encounter bumps, they roll inward as well as upward, which generates forces that pull the vehicle in different directions. This complicates the design by adding extra workloads for the driver to deal with.

Designers need to avoid over complicating vehicles with too many systems, subsystems, or back-ups, because every component added is another component that can and probably will malfunction at a crucial time. Land speed sites tend to be very hostile environments in which to run a vehicle and maintain a team.

Currently there are a half a dozen unlimited land speed cars being built around the world using the latest in aerospace technology, as well as developing their own technology. One could say that without the aircraft and aerospace industry, there would have been no land speed record cars, but equally, the aerospace industry might well be less advanced if it weren't for the early popularity of the land speed record. ∎

Waldo E. Stakes is a land speed racer, builder and the designer of the LSRV

SYSTEM SYNCHRONIZATION

How can large and distributed data acquisition and test and measurement systems over standard Ethernet cables be synchronized?

BY DR FRED BLÖNNIGEN

Test engineers are always faced with the problem of how to synchronize all their data acquisition and control channels. In older systems, this requirement translated to a centralized 'data acquisition room', where all channels were concentrated.

Here, the signals were conditioned and digitized. This was done at least for the high-speed channels and translated into long cable lengths, which in turn generated EMC noise and therefore deteriorated measurement accuracies. Furthermore, as mathematical models get better, test engineers are increasingly looking to synchronize slow and fast data, i.e. to correlate the temperature measurement with the vibration data for turbine tests.

Here, using long cables becomes a nightmare. How do you accurately measure microvolt signals with such long cables? The Ethernet approach would be the logical choice, but what about synchronization?

You could put your distributed data acquisition subsystems close to the actual point of measurements, and by using the newly released IEEE 1588 synchronization mechanism, achieve synchronizations down to 25ns over normal Cat 5 Ethernet cables.

In rotating machinery, this would translate to an angular mismatch of less than 0.05°. Most standard measurement cards could not provide such a good phase alignment. Bustec was able to demonstrate successfully to NASA synchronization via IEEE 1588 down to 25ns in a large and widely distributed 3,600-channel real-time monitoring system.

Today, product development in the aerospace and test industry faces significant economical pressures. This translates to short development cycles, on the one hand, and on the other, demand for high measurement accuracy to verify new designs.

Let us take the example of a new airplane. Structural as well as engine designs are pushed to limits not known before. One of the reasons is the need to construct very fuel-efficient aircraft. These economic pressures change the world of data acquisition and test and measurement.

BELOW: **Typical large data acquisition system**

> **"Companies such as Rolls-Royce, Boeing, and Airbus are asking for their next-generation test systems to be based on Ethernet with IEEE 1588"**

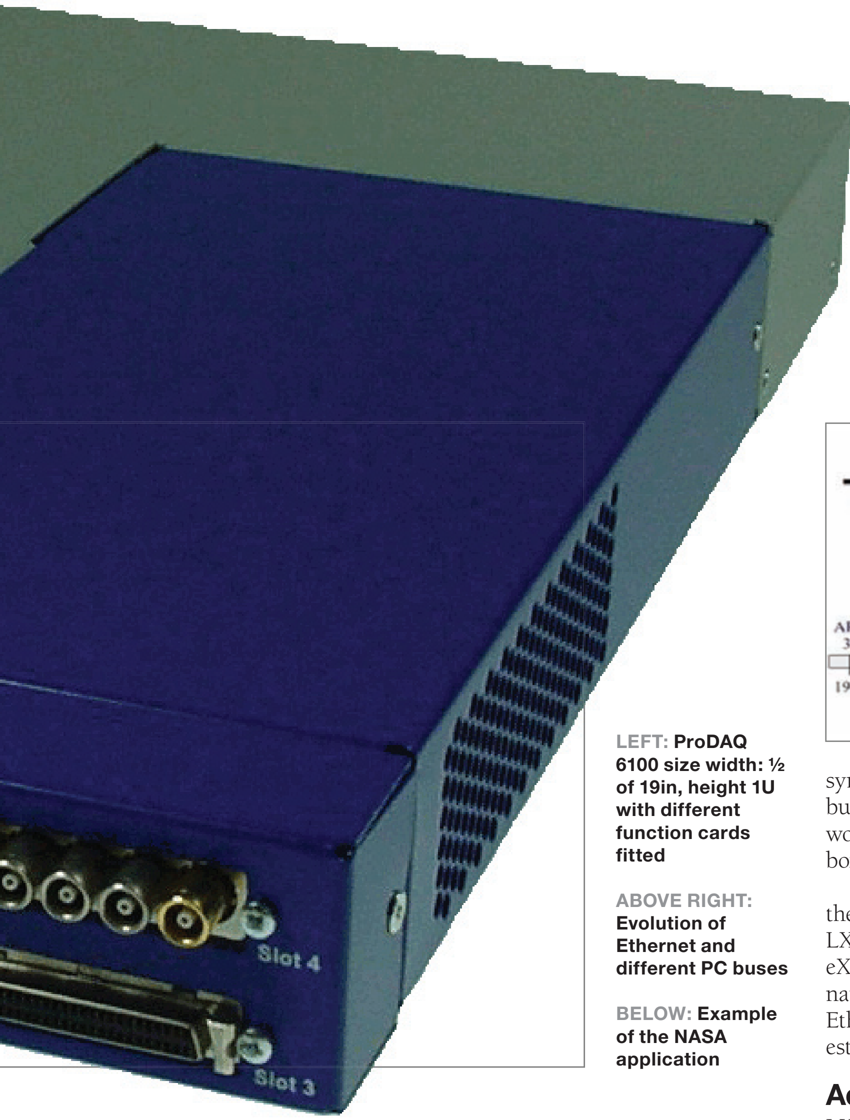
Historical approach

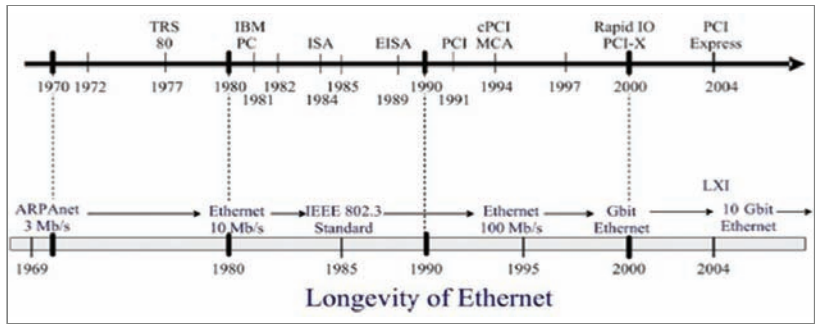
Data acquisition systems are built increasingly as distributed systems with input/output points distributed between large distances, as, for example, in the structural test of large airplanes. Up to now, each sensor was connected with sometimes very long wires to signal conditioning units, which in turn were connected to central data acquisition units and computers.

These classical setups had two major problems. First, and quite obviously, the high cost of cabling would normally use one-third of the total system budget. Second, was the deterioration of signal quality due to these long cable lengths. Signals from sensors are often in the microvolt range and are sensitive to electromagnetic noise. Induced errors resulted in orders of a couple of percent of the measured values. Considering the cost of actual data acquisition systems and the measurement accuracy better than 0.01% that can be easily achieved with modern data acquisition systems, these older solutions are no longer effective.

Ethernet or LXI?

Therefore a logical choice would be to use distributed systems with integrated signal conditioning based on standard Ethernet (IEEE 802.3). Contrary to a myriad of short-lived PC buses with





LEFT: **ProDAQ 6100 size width: ½ of 19in, height 1U with different function cards fitted**

ABOVE RIGHT: **Evolution of Ethernet and different PC buses**

BELOW: **Example of the NASA application**

new and incompatible versions every three to four years, Ethernet has been commercially available for 30 years.

Every new revision was always backward compatible to the former ones. Obsolescence problems, as in the world of PC buses and their derivatives, such as PXI, never existed. Furthermore, the TCP/IP protocol is well established and in widespread use.

Another important factor in modern data acquisition systems is data throughput. With the standard 1G or 10G ports sustaining 100MByte/sec or 1 GByte/sec, even very large systems with thousands of channels can easily be handled. For even larger applications, multiple ports can be put into one PC or server. In the above-mentioned example at NASA, a four-port 1G interface card was used and up to 400Mbytes/sec throughput to the PC was achieved. The 3,600 channels were running at 10kHz per channel with 24-bit resolution. The total data volume was 144MB/sec. This proved to be no challenge for the system.

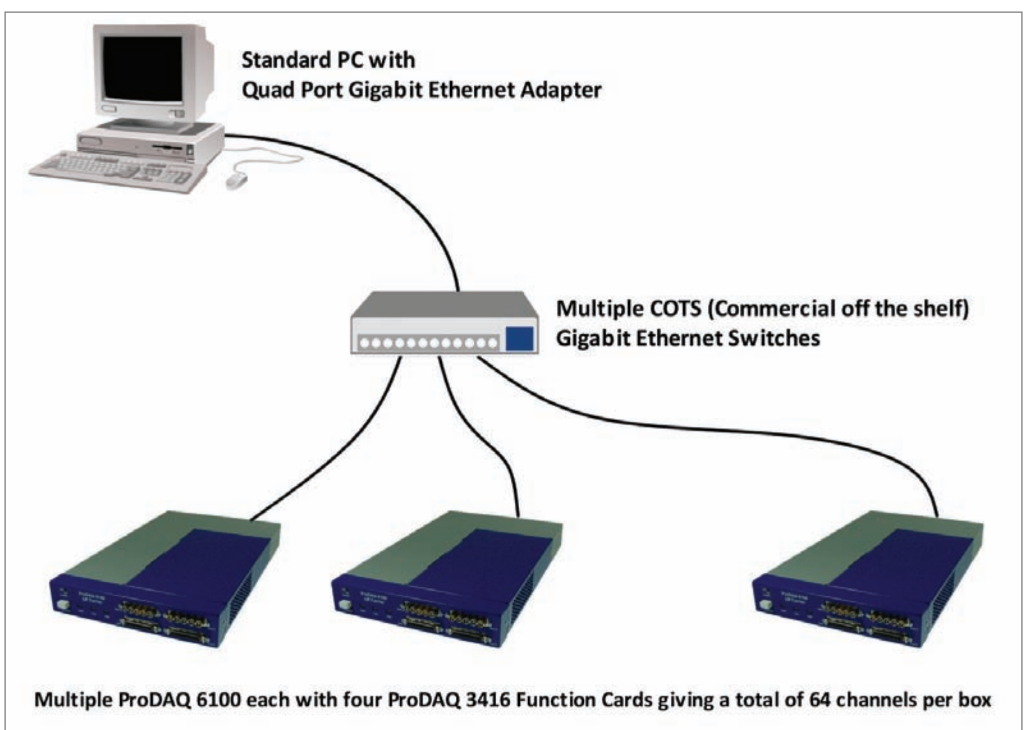
Currently missing from normal Ethernet is the ability to synchronize all data channels in a distributed environment. One can do this synchronization through external cables, but this creates two problems: the user would need trigger/timer distribution boxes and specialized, expensive cables.

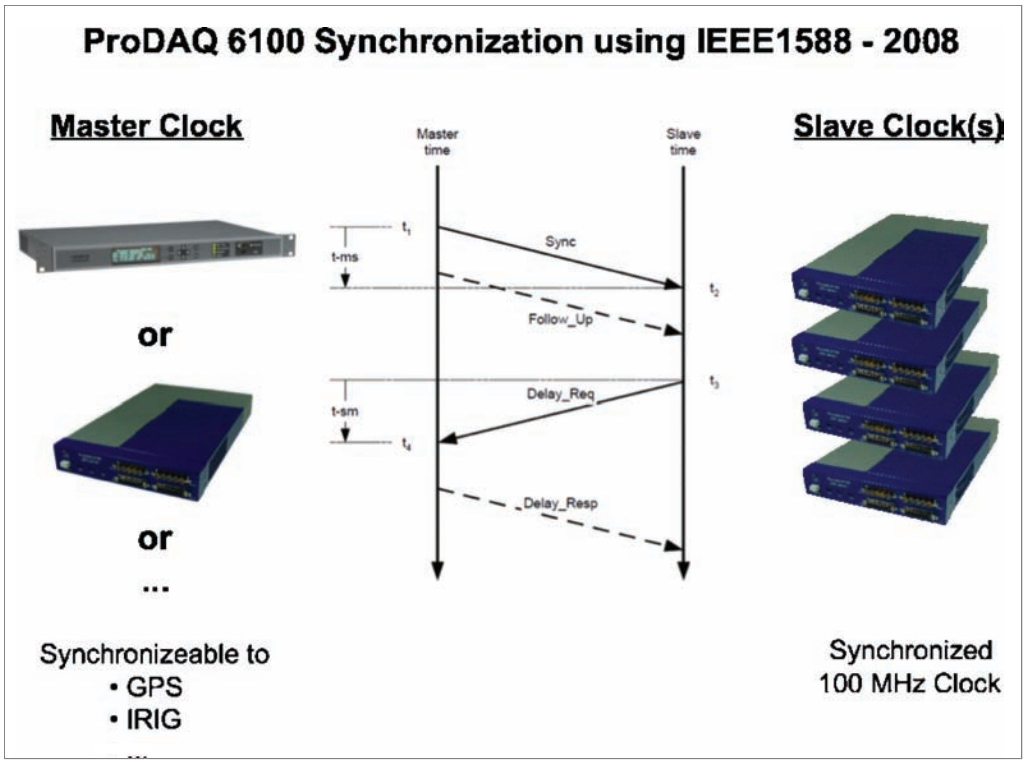
It would be better to synchronize via the normal Ethernet cable. This brings LXI into the picture. LXI stands for LAN eXtension for instrumentation. As the name suggests, it is based on standard Ethernet (IEEE 802.3) and the well-established TCP/IP protocol.

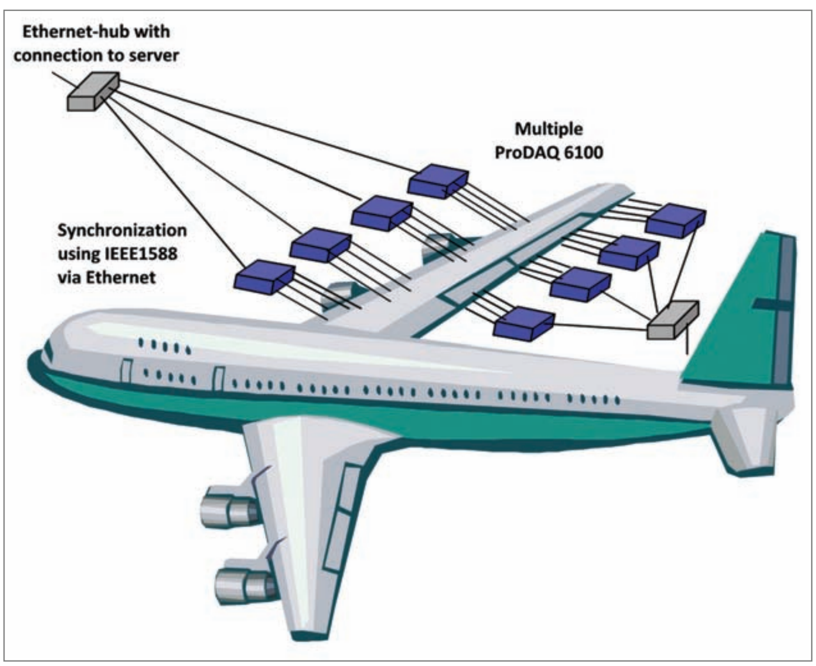
Additional LXI advantages

LXI devices consist of normal Ethernet devices with a built-in web server. You can discover all instruments with the 'discovery protocol' and the web interface allows the user to configure the units. An additional advantage is the serviceability of the units via the web server from any location. The quality of the synchronization depends on the quality of the implementation.

Of all the companies in the market today, Bustec is offering a clock synchronization with a clock uncertainty of only 25ns in fully distributed systems. This time was achieved using a standard 1GB Ethernet switch, available in any computer store.







ABOVE: Synchronization mechanism

RIGHT: Multiple ProDAQ 6100s located around the aircraft and wired to different strain gauge sensors

In all environmental measurements such as temperature, pressure, vibration, or strain, acquisition is normally run between 100Hz and 100kHz per channel, and in wind tunnels at up to 200kHz, which corresponds to clock intervals of 50µs. This is a factor of 2,000 smaller than the speed at which data is sampled. Even in turbine tests, an angular error of less than 0.05° is negligible. With the introduction of IEEE 1588, the user solved the remaining problem in today's Ethernet based data acquisition and test systems: namely, synchronization of all data channels in distributed systems via a standard Ethernet cable, hence overcoming the cost issue of expensive cabling. With cable prices at a couple of cents per meter, cabling costs can be reduced to a marginal percentage of the total cost of the system.

Typical applications for Ethernet

It comes as no surprise that companies such as Rolls-Royce, Boeing, and Airbus are asking for their next-generation test systems to be based on Ethernet with IEEE 1588. Boeing has already installed the first large stress test system based on LXI. Airbus is even asking to bring all onboard data acquisition and test systems up to the new LXI standard. For Airbus, all measurement devices must use the IEEE 1588 mechanism.

The hardware solution

Bustec delivers a small LXI carrier box, called ProDAQ 6100, which is about the size of a laptop. Up to four function cards can be installed in each of these ProDAQ carriers. These cards can have different functions, such as ADCs or counter for measurement, or DACs – digital or serial cards for control functions. For example, the picture overleaf/below, shows a 16-channel, 24-bit card with an independent ADC per channel, programmable filter, and 10kHz maximum digitizing speed. A user can install up to four of these cards, giving 64 channels with a measurement accuracy of up to 0.0012%. This corresponds to the accuracy of a 6.5 digit DMM, but here with 10,000 readings/sec on each of the 64 channels, instead of one channel with two readings/sec for the DMM.

It should be noted that the volume of the ProDAQ 6100 is less than half the volume of the DMM. The units can also be fitted into 19in racks. Bustec is proposing rack-mounting kits for fitting two units into 1U of the rack.

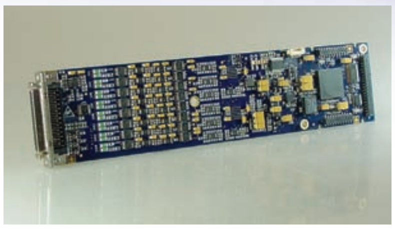
As described above, even in large systems such as NASA's, with more than 3,000 distributed channels, ProDAQ 6100s can work successfully. Applications ranging from turbine and engine testing, structural analysis, and wind tunnel measurement, to inflight data acquisition and monitoring are ideal candidates for Ethernet with IEEE 1588.

Signal conditioning units

In addition to the data acquisition and control cards, Bustec offers the test engineer a complete set of signal conditioning units, from temperature measurements with RTDs or thermocouples, to full high-end bridge completion units for different bridge types or for ICP sensors.

This unit supports TEDS class 1 and 2, and also provides the possibility of ICP measurements. All these options are selectable on a channel-by-channel basis. For the excitation, a 16-bit DAC is used independently on the positive and negative side of the bridge. Together with the ADC cards, the absolute measurement

ABOVE: **16-channel bridge signal conditioning unit**



RIGHT: **ProDAQ 3416 function card, 24-bit, from 1Hz to 10KHz sampling rate, gain 1 to 2,000, one ADC per channel**

accuracy for a full bridge measurement in a full-scale range of 100,000µE is better than 5µE. This is a value never achieved before in the industry.

System architecture

An important feature of a test system is the analog measurement accuracy that can be achieved with the equipment provided, including the sensors and the cables. The user should always start with good cabling. This means twisted-pair shielded cables.

BNC cables are inadequate for today's requirements, offering a maximum signal-to-noise ratio (SNR) of only 70dB. In addition, they tend to pick up noise levels of more than 1mV. This is quite normal in industrial environments. While this seems acceptable if you measure 10V signals, it is no longer true if the signal is in the order of 10mV – a normal voltage for bridge measurements. In this case, a noise level of about 1mV translates into an error of 10%. This is neither acceptable or desirable.

If you compare this with the SNR of more than 100dB that modern analog-to-digital cards can deliver, the need to invest in a good cabling infrastructure becomes apparent. By using twisted-pair differential cables, you can take advantage of the extreme low noise levels of 1-3µV provided by Bustec cards, giving a total error in the 10mV scale of about 0.05%.

Calibration concerns

With the unit under test often located in environments where stable temperatures cannot be guaranteed, for example, in hangars, it is important to be able to calibrate the entire system at any given moment.

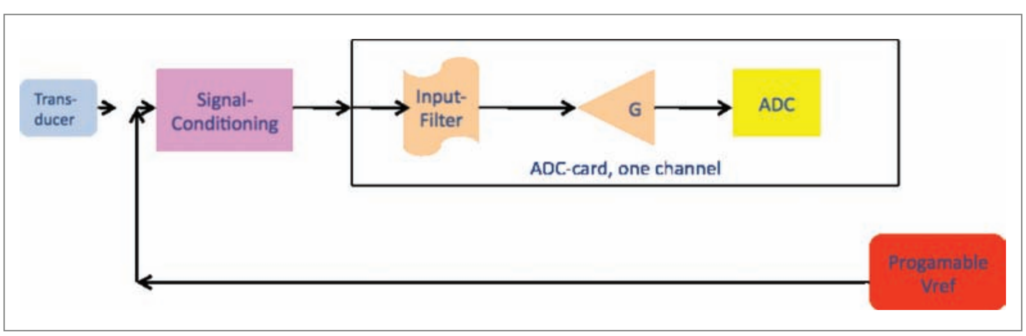
Until now, calibration required a voltage calibration source to be applied to all measurement channels. This involved unhooking the cables and hooking up the voltage reference, calibrating the given channel, and had to be performed for every channel. In large systems with more than 1,000 channels, calibration could therefore take several days – a time-consuming and costly process.

Bustec changed this procedure drastically. By inserting a programmable voltage source into the LXI carrier, the user can now inject a voltage reference value that corresponds to the range of any given channel.

This programmable voltage reference is connected to all signal conditioning units through the connecting cable. Having a relay at the input of every channel allows the user to switch in the right reference voltage to every channel, abolishing the need to hook any voltage calibrator to your inputs. The measurement is called 'on-the-fly' calibration.

The programmable voltage reference is extremely temperature stable, with a temperature drift of as low as 2ppm/°C. Now the whole system can be calibrated in a couple of seconds. As every ProDAQ carrier unit has a built-in ability to monitor the programmable voltage reference with a DMM, the data is always traceable to NIST standards.

BELOW: **'On the fly' calibration**



Shorten test cycles

More and more aerospace companies are switching to LXI. It is the standard all major test and measurements companies are adopting. Bustec supports these efforts and believes products based on this new standard offer the user, in this case aerospace companies, a real advantage in cost as well as in performance.

Being based on standard 1Gbit Ethernet with TCP/IP stacks, they are by definition built for distributed systems and are connected to the workstation or server via standard 1Gbit switches. They provide the same advantages already present in former company systems, namely accuracy and data bandwidth.

In the aerospace industry, Ethernet with IEEE 1588 is the logical choice for data-acquisition or test and measurement systems. All measurement and test applications in the industry can be handled. Obsolescence problems are no longer of concern because backward compatibility is assured.

The distribution of data sources is handled by Ethernet, which by definition provides a distributed environment.

Synchronization via IEEE 1588 even solves demanding clock synchronization requirements. The measurement accuracy, as in the case of Bustec, is on a level never seen before. Data throughput to a PC or server can scale to your need and is almost unlimited. The maximization of channels per measurement card, as in the case of Bustec's ProDAQ 3416, brings the total volume of measurement systems down considerably. This translates into lower system cost, as the space needed for the systems is also minimized.

Last, but not least, the cost of cabling will be significantly lower, because expensive signal conditioning and data cables are mostly replaced by cheaper Ethernet cables. As a result, the user benefits from lower costs but better performance. ▮

Dr Fred Blönnigen founded Bustec in Ireland and opened a branch in 2000 in the USA. He is still working as CEO of Bustec


XL Go

SENSING THE MOTION

The use of high-end MEMS motion sensor technology is becoming more widespread in industrial and instrumentation applications

BY JEAN-MI STAUFFER

CENTER: **MEMS capacitive accelerometers are certified for the latest civilian airliners**

TOP RIGHT: **MEMS accelerometers are certified for the latest generation of high-speed trains**

MEMS motion sensors have prompted major revolution in the automotive, IT, and consumer markets. Indeed, MEMS accelerometers are used on a daily basis in our cars, computers, and cell phones.

And now MEMS motion sensors are also invading high-end applications in the military aerospace and advanced industrial and instrumentation markets. MEMS motion sensors, and more specifically MEMS accelerometers, are starting to replace established, expensive, and fragile high-end electromechanical devices, offering same or even better performances at lower cost, lower power consumption, smaller size, and much better environmental survivability. Today some of these sensors are already fully qualified in civilian and defense programs. They offer advantageous opportunities, for example as back-up systems on the most recent Airbus and Boeing airplanes or as new and innovative solutions for harsh environment applications such as borehole drilling or gun-launched smart munitions.

High-end accelerometers

The industrial and instrumentation markets benefit largely from existing fully qualified MEMS accelerometer products from Colibrys.

Driven by military aerospace requirements, the validation and demonstration of product performances is systematically done across the full range of environmental conditions, including wide temperature ranges, vibrations, and shocks, which is mandatory to demonstrate long-term validity of the critical parameters.

All the major specifications are achieved through the design of the products themselves and through a very precise and well-controlled manufacturing process performed under close statistical control, avoiding lengthy and expensive screening.

This approach enables Colibrys to offer repetitively and constantly high-end accelerometer products to the industrial and instrumentation markets as well. The company does not have to produce high quantities of accelerometers to select only the best one for military/aerospace applications and classify the remaining products as lower-end product performances for the industry.

Industrial & instrumentation requirements

The approach of these markets is very different to the military/aerospace market and the diversity of products required is somehow larger. The basic technology platforms available to Colibrys, as well as the targeting of the right product for the right application, are fully compatible with the high-end requirements of the industry and instrumentation.

By combining existing technology platforms based on capacitive MEMS silicon sensors, open loop or closed

Typical MEMS applications in the railway market

- Bogie monitoring and diagnostics system for security and comfort;
- High-speed train tilt control system for improved passenger comfort;
- Position monitoring of magnetic levitation train;
- Control system;
- Health and Usage Monitoring System (HUMS);
- Shock monitoring during transportation;
- Precise train positioning;
- Railway track monitoring system for safety and maintenance.

loop electronics, and high-grade assembly in hermetic ceramic packaging with dedicated platforms specifically developed for the industry (i.e. wide bandwidth product for vibration measurement), Colibrys offers a full range of inertial, tilt, vibration, and seismic sensors with performances and advantages developed to meet the specific sensing objectives detailed below.

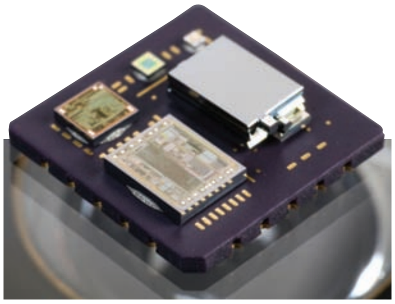
Inertial sensing

Very precise measurement of acceleration and rotation is key to determine accurately and without external reference the position, the orientation, and the velocity of a moving object. This principle is used extensively in inertial measurement units (IMU) and attitude heading reference systems (AHRS) for high-precision guidance and navigation in the air, on the surface of the earth or under water, and is generally implemented as a complement (short-term data), a replacement, or a backup of GPS in the event of jamming or loss of signal. Extensively used in military/aerospace, the products (Colibrys MS8000, MS9000, HS8000 product families) are also used in interesting civilian applications, such as guidance of blind people and the locating of firemen in buildings.

> "Accelerometers are extensively used as tilt sensors or inclinometers to determine a slope, an elevation or a depression of a reference plane in terms of gravity"

Tilt sensing

Accelerometers are extensively used as tilt sensors or inclinometers to determine a slope, an elevation or a depression of a reference plane in terms of gravity. The applications differentiate themselves through the required resolution and the absolute accuracy or combined total error, taking into consideration the linearity, the hysteresis and the stability under environmental conditions (vibrations, shocks, temperature). Tilt or pitch and roll indicators (Colibrys MS8002,



ABOVE: MEMS manufacturing using advanced equipments under clean room conditions

ABOVE RIGHT: Open view of Colibrys MEMS capacitive accelerometer (MS9000)

MS9001 or MS9002 products) are used for high-precision platform stabilization in various markets such as military/aerospace, industrial and instrumentation or energy.

Vibration sensing

Precise and stable vibration measurements (Colibrys VS9000 product families) are required in many applications, ranging from civilian and military aircraft or helicopters to land vehicles, large structures (bridges, buildings, dams), and industrial equipment. The aim of these wide dynamic measurements is to assess a modal shape and its stability, or to monitor and measure a given vibration level to be able to reduce its impact and improve comfort, increase durability, or anticipate preventive maintenance in the fields of research, development, production, or test.

Seismic sensing

Sophisticated MEMS capacitive sensors (Colibrys SiFlex product families) combined with advanced electronics are replacing traditional geophones or seismometers for different types of seismic measurements. Numbers of applications outside the traditional strong motion earthquake monitoring are using these seismic motion sensors for their extreme low noise, high resolution, and large dynamic range. These applications are characterized by low-amplitude signals produced by natural (earthquake, volcano, subsidence or even wind) or human-induced (explosions, shock, constructions) movements.

In the building industry, seismic accelerometers in the form of structural health monitoring (SHM) systems are increasingly being installed throughout the world. This is especially so in areas vulnerable to high-level seismic activity for seismic pre-mapping and intensity measurements, but is also the case within large structures such as buildings, dams, bridges, nuclear plants, etc, that are subject to subsurface landslip or externally induced stress and vibrations to determine the structural integrity.

Strong motion seismic sensor technology is evolving in response to these emerging demands, and traditional electromechanical solutions, such as forced balanced accelerometers (FBA), are increasingly being displaced by more cost-effective and robust MEMS-based solutions. The growth of SHM systems in many regions of the world is driven by both the preventive measurement and the prediction of unquantifiable and subjective ageing of many large structures such as dams, bridges, high-rise buildings, etc, and the increasing pressure on many governments to provide effective civil protection, control, and intervention solutions through comparative analysis of structures before, during, and after major earthquakes, as seen in recent years in Indonesia, Italy, Haiti, Chile, New Zealand, Spain, and Japan.

It has been reported that earthquakes are responsible for almost 60% of all deaths caused by natural disasters, which heightens government and public awareness of the devastating consequences of such events.

High-speed train market

The fast-growing railway market of high-speed lines in most countries and the deployment of new-generation high-speed trains, which will be increasingly equipped with onboard safety control equipment, require reliable and high-spec accelerometers. The desire to increase the sophisticated technologies used to guide and control the trains while reducing maintenance costs, facilitating repair planning, and improving passenger and driver safety and comfort means that a variety of sensors needs to be incorporated into modern trains. (See box, on previous page for a list of typical applications of MEMS in the railway market).

The company

Colibrys is a supplier of standard and semi-custom high-end MEMS-based motion sensors in the energy, military aerospace, industrial, and instrumentation markets. Its products are designed for use especially in harsh environments and/or safety-critical applications. Its accelerometers, developed for a broad spectrum of functions, include extremely low-noise and shock-resistant seismic sensors, high-stability and high-shock inertial accelerometers, low power tilt accelerometers, and DC coupled capacitive vibration and shock sensors. ∎

Jean-Mi Stauffer is vice president of sales and marketing at Colibrys

BUS BOOST

Improved interface boards for avionics buses, combined with hardware-in-the-loop simulation, are ideal for developing and testing components and systems for aerospace applications

DIPL.-ING BJÖRN MÜLLER & DR-ING. ANDREAS HIMMLER

Through a number of interface boards, dSpace is addressing the unique and demanding requirements of aircraft and satellite development and testing. Recently, extra channels and features, and new blocksets, have been added to the interface boards for avionics buses ARINC 429 and MIL-STD-1553. And there is now a new interface board for ARINC 717. These solutions are ideal in modular dSpace real-time systems for hardware-in-the-loop (HIL) testing and rapid control prototyping (RCP) in the aerospace industry. HIL testing is especially useful in cases involving bus communication. One of its benefits is restbus simulation.

Using HIL simulation for communication tests

As communication scenarios change and communication develops, the tests and the tools also have to be adapted. Years ago, developers and testers focused on the behavior of a single control unit. Now effects of each control unit on the behavior of the network of the aircraft or spacecraft must also be tested. If it is not correct, error propagation and error reproduction can occur. The changes require new tests, which can be subdivided into two main types: tests without real-time simulation, mainly concentrating on physical characteristics; and tests focusing on communication above ISO/OSI Layer 1 with and without a link to a real-time simulated application.

ISO/OSI reference model

The first type of test is necessary during the early stages of control unit and/or network development, especially during the hardware phases. It is used to analyze the slew rate, the signal level or the eye pattern of a bus system. The test systems used for this type are based on oscilloscopes. Most protocol testers can also be used for this type of verification. These can also be oscilloscopes and support the higher abstraction layers of the ISO/OSI model. Most are able to manipulate or modify the transmitted data from the physical layer up to the presentation level, and data is displayed and interpreted reliably. Well-established tools also belong to the first type. These tools can perform restbus simulation, and bus and protocol analysis. They are mainly used during development for initialization, configuration, and testing of communication networks.

The second type of communication test does not have the capabilities for testing the physical level in detail but it has other advantages. Tests without a link to a real-time simulation of an application are mainly used for developing and analyzing bus systems. They can read or generate communication matrices and change or create signals or messages. They can also work with protocols, and analyze and display communication data, and are very useful tools for developing and validating bus communication. However, most of them are not able to connect additional digital and analog inputs or outputs. These capabilities are required for the last of the above test types. This test type is essential for the validation of a control unit because it is the only one that combines application testing with bus communication in a real-time environment. This is fundamental because the application needs the additional connections and information in order to work properly. The real-time simulation of the application is the primary aspect of the combination. Typical questions for such tests are:

- Is the correct information being transmitted? (e.g. implausible signals);
- Is the transmission timing correct (dependencies on the environment)?;
- Are messages expected?;
- Are signal- or message-specific features preserved, e.g. data length code (DLC), acknowledgements, message counters, check-sums.

These questions relate only to ‘positive testing’ – the reaction of the device if the input signals are within the specification. As well as positive testing (i.e. testing the functionality with correct input data by stimulating or simulating the bus), ‘negative testing’ also has to be performed. This is done by insertion of errors (failure of the bus, the control unit, or individual messages, etc) into the transmission process or into the signals. Thus, to test the behavior of distributed or networked functions in the event of a fault, it may be necessary to manipulate messages between real control units.

CENTER: Cabin view with in-flight entertainment

Validating communication via restbus simulation

The proven method of control unit software verification is the HIL simulation. This is used to validate the required functionality under varying operating conditions when the control units in a network must be tested separately or if all the control units are not present in a test setup. In restbus

simulation, the simulator emulates the missing nodes in the communication network using the communication databases or matrices, which are necessary for operating a control unit. Simulating the environment (the control units that are not present in reality) in this way makes it possible to put the device under test (DUT) into the conditions defined for the tests. If network testing has to be performed on several or even all of the control units on a communication bus, or even in a whole aircraft or satellite, bus nodes can be either simulated or integrated physically. For many tests it is not sufficient to transmit or exchange, in restbus simulation, synthetic signals that are independent of the environment. This is particularly the case when the device under test has to perform plausibility checks between message signals and signals from further inputs such as I/O channels. To satisfy this requirement, the transmitted message signals must be coupled with a simulated environment. To show the features needed to simulate typical communication networks, some of the above requirements for restbus simulation are described below.

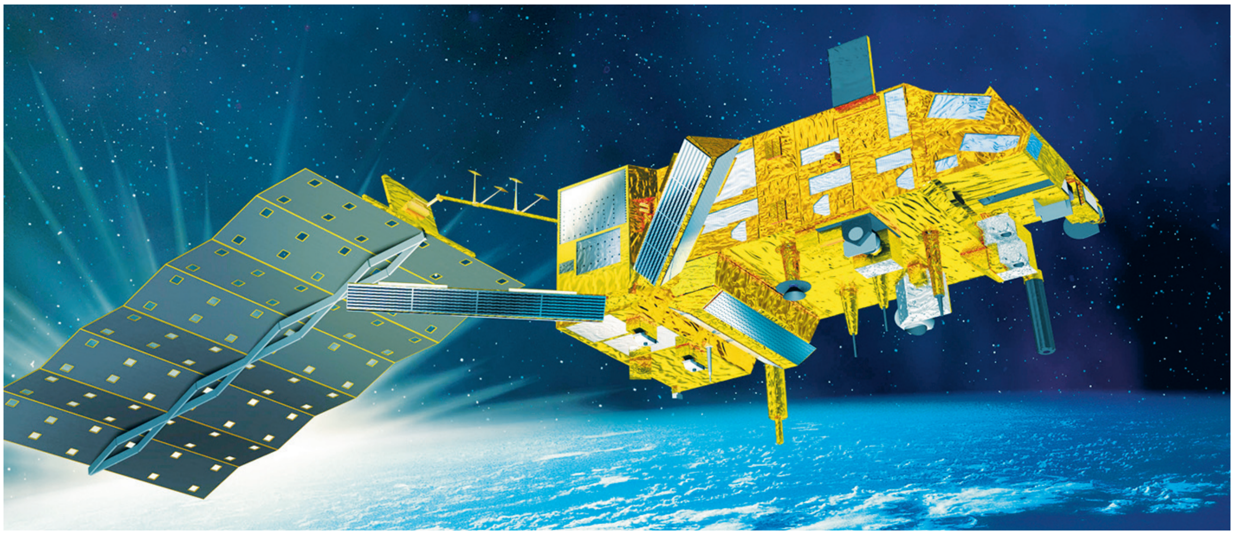
A basic requirement for restbus simulation is the ability to generate all the messages and signals that are normally transmitted by the real control unit in the aircraft or satellite. If negative testing needs to be performed, the simulator must also be able to manipulate these signals. Although standardized bus systems are used, generating the signals and messages is not a trivial task.

Testing aerospace buses flexibly and easily

To run integration tests of several electronic control units (ECUs) with HIL simulators in aerospace applications, a large number of bus channels are required on one interface board. Configuring the bus communication for the tests has to be made as easy as possible, and all the properties of the buses under test must be supported. Component tests with one control unit on an HIL simulator partly have different requirements, because bus nodes that are not available during the tests have to be simulated additionally. Here too, though, there needs to be an easy way to define the bus communication. With MIL-STD-1553, the special bus structure also has to be taken into account, as it includes a bus controller, up to 32 remote terminals, and a bus monitor. In HIL tests for components, the bus controller has to be simulated, and for integration tests it is mainly the remote terminals. The new aerospace bus solutions from dSpace fulfill all these requirements. This is because they were developed in close cooperation with leading aerospace component and system manufacturers. The new interface boards are being used successfully in the Joint Strike Fighter (F35) program, the NPOESS program (National Polar-orbiting Operational Environmental Satellite System), and other projects.

Solution for an integrated development process

The new solutions for MIL-STD-1553, ARINC 429, and ARINC 717 from dSpace are based on industry-proven modules from GE Intelligent Platforms, in PMC, and IP form factor. These modules are integrated into the dSpace Peripheral High-Speed (PHS) bus via dSpace PMC and IP carrier boards, which are optimized for high-performance real-time operation. This configuration means that developers can use the very short latencies of dSpace's modular hardware with the advantages of industry-proven bus system boards from other providers. This constellation can be employed to set up seamless, traceable development processes running straight through from model-based development to release tests for controllers on an HIL simulator. For easy connection of the bus interfaces, dSpace provides special blocksets. These are the interfaces to the real-time model (plant model for HIL tests or controller model for RCP applications) and provide a graphical environment for intuitively configuring communication. It is not necessary to program the interface boards at the deep protocol level. Their functionality can be used conveniently for the individual buses with the help of the appropriate dSpace Real-Time Interface (RTI) blocksets. One feature that



RIGHT: US environmental satellite NPOESS (© ESA - D. Ducros)

"ARINC 717 buses are another frequent component in network tests"

deserves a special mention is the use of configuration files to configure bus communication, which makes it easy to change the parameterization of the models in Simulink.

MIL-STD-1553

The new interface board has four doubly redundant channels that comply with the current MIL-STD-1553 A/B Notice II. Each of the four channels can be user-configured independently of the others as one of the terminal devices specified in the standard: bus controller, remote terminal, and bus monitor. Thus, the new interface board can be optimally used for developing sophisticated components and for testing complex networks.

An essential component is the RTI blockset. Newly developed by dSpace, this contains a library with send and receive blocks for remote terminals. The blocks give users complete access to the channels' functional behavior, their physical level, the transmitted messages, and status information. In addition to the message contents, the outputs of the receive blocks also make time stamps, commands, status messages, and message counts available in the real-time model. The blocks can be used to simulate up to 32 remote terminals on an MIL-STD-1553 bus, and enable users to set sub-addresses, the word count, mode codes, and broadcast messages for each remote terminal. Both the physical bus level and the transmission behavior can be manipulated to perform error testing. For physical tests, the bus output voltage can be either predefined or fed in from the outside.

For tests on the transmission behavior, the times for no-response timeout and late-response timeout can be set. A special feature is that if a channel is configured as a bus monitor, the messages to be monitored are not only available in the real-time model, but can also be sent to a PC via Ethernet.

BELOW: Eurocopter EC 145 (© Eurocopter)

ARINC 429 and ARINC 717

dSpace's new interface solution for ARINC 429 is ideal for testing entire avionics networks, including communication between a very large number of bus nodes. With up to 32 send and 32 receive channels, it has twice as many channels as its predecessor. One outstanding feature is the completely redeveloped blockset, which facilitates the configuration of bus channels enormously. The configuration files define all the properties of the ARINC labels: data format, start bit, data length, scaling factor, and SDI filter. This makes it very easy to change the labels. With the data from the configuration files, the ARINC messages are generated automatically in the real-time models by means of encode and decode blocks, and payload data can also be extracted from the received ARINC messages. To perform the all-important tests for erroneous bus transmission, errors can be inserted for bit count, inter-message gap, and parity.

ARINC 717 buses are another frequent component in network tests with ARINC 429 buses, enabling data transmission between the Digital Flight Data Acquisition Unit (DFDAU) and the Digital Flight Data Recorder (DFDR) to be tested. There is now also a dSpace interface board for these buses, offering the same advantages as the ARINC 429 interface board.

The new interface boards for MIL-STD-1553, ARINC 429, and ARINC 717 are ideal for rapid control prototyping and for HIL testing. The latter applies to integration testing and component testing using HIL simulation. It also applies to restbus simulation, which is the proven method of testing bus communication during HIL testing.

The interface boards have graphical user interfaces and work with a database, making communication configuration intuitive and easy. Used in conjunction with dSpace's fast, modular real-time systems, they are ideal for developing and testing components and systems for aerospace applications. Not surprising, as they were developed in close cooperation with leading aerospace companies. ∎

Dipl.-Ing. Björn Müller and Dr-Ing. Andreas Himmler are product managers for HIL simulators in the dSpace product management department in Paderborn, Germany, responsible for the aerospace market and bus system products respectively

ICE RESEARCH

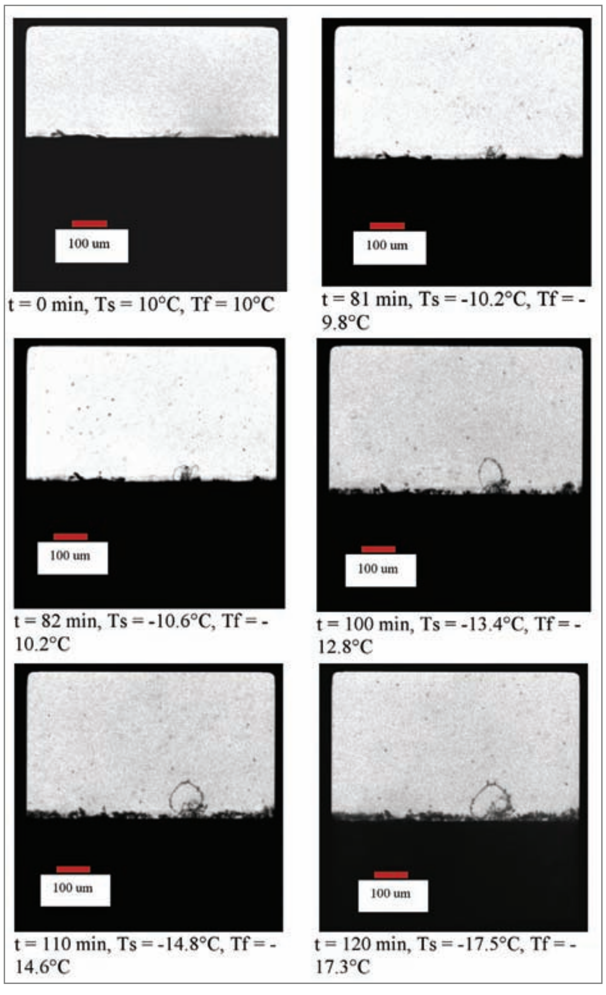
The UK's leading university specializing in aerospace studies has initiated a project to look into the formation of ice in aviation fuel

BY PRIYA SINGADIA

At the forefront of aerospace technology, the UK's Cranfield University takes a practical and holistic approach right across the business of flying and aerospace. Using a multidisciplinary approach, Cranfield brings together aeronautical engineering, materials, and manufacturing with expertise in aviation business processes and practices. Commercial relationships include partnerships with the companies, Airbus, BAE Systems, Boeing, and Rolls-Royce.

Earlier this year, Cranfield's successes in the aerospace sector were recognized and honored by the Royal Aeronautical Society when the university received the Aeronautical Heritage Award. The Heritage Awards scheme celebrates and commemorates British technical or operational achievements that have made an original and unique contribution to aeronautics of world importance. The Aeronautical Heritage Award specifically recognizes the many globally significant contributions to aerospace science and technology that originated at the university since its establishment as the College of Aeronautics in 1946.

BELOW: Water/ice deposition on a subcooled surface



Improving air safety

Back in 2008 a Boeing 777 crash-landed at London Heathrow Airport after flying in from Beijing. The aircraft suffered reduced thrust in both engines while coming in to land and fell short of the runway. It was initially believed that the cause of the accident was ice forming in the fuel lines, which was difficult to prove and a problem that is not well understood.

This low level of understanding could be about to change, however, as Cranfield recently embarked on two collaborative projects commissioned by a major aircraft manufacturer.

The first project is lab-based and has seen Prof. Hoi Yeung team up with his colleagues from the School of Engineering and Cranfield Defence and Security. The team recreated formation of ice in fuel. Having developed a model section of a wing tank, Hoi's team have been able to reduce the temperature of the tank containing aircraft fuel to -40°C/°F so that ice forms in the fuel and they can record how the ice builds up over time.

"Overall, we're interested in a number of things – how the ice forms, its strength, and how it breaks down into small particles and flows away naturally in the systems without causing problems or it blocks the fuel system," explains Prof. Yeung.

The second project aims to achieve a fundamental understanding of the problem of the development of ice in

ABOVE: **Speedbird 38 landed short of the Heathrow runway in 2008. The cause was found to be ice crystals in the fuel clogging the fuel/ oil heat exchanger**

fuel and to develop a model to predict the impact of different conditions on ice formation in fuel.

"This initial research has given us a good knowledge base that we're now going to apply to the European Air Safety Agency project that we're involved in, looking at other factors that may affect ice buildup," continues Professor Yeung.

Ice investigation

For the investigation, Cranfield has constructed a model fuel tank, to study the accretion of ice on subcooled surfaces. The top and bottom plates of the tank are cooled by a purpose-built unit to imitate the conditions experienced by the skins of a wing fuel tank. The temperature of the plates can be cooled to below -40°C/°F. The sides of the tank are made from double-glazed glass panels with embedded demisting elements to facilitate visual observation and imaging. A pulsed laser is used to provide the necessary illumination. Images are recorded using a CCD camera equipped with a long-range microscopic lens.

As the temperature of the fuel drops below the saturation temperature of water, dissolved water in the fuel will come out of the solution, forming micron-sized water droplets. They can remain as water droplets in temperatures below -30°C. However, if they touch a solid surface, they could transform into ice particles and begin to accrete on the surface. The figures, far left, show the initial stages of ice accretion. The image size is 0.8mm. The properties of the surface and flowing conditions have considerable impact on the amount of ice accretion. Ice properties such as density, adhesive, and cohesive strength are measured.

Ultimately, this understanding and knowledge will help aircraft manufacturers better manage water in the fuel systems of aircraft. ∎

Priya Singadia is CPD marketing manager for the School of Engineering and Hoi Yeung is Professor of Flow and Process Assurance and head of Process Systems Engineering Group at Cranfield University, UK

DIGITAL SWITCHOVER

It's not only in daily life that analog film cameras have almost disappeared. Airborne military applications have largely switched over to digital too, and the remaining installations will soon need to make the move to digital high-performance streaming cameras

BY RETO HUBER

High-speed film cameras have been steadily replaced across many industries in recent years, due to the lack of film available and the desire/need for immediate availability of image data.

However, many analog film cameras are still in use for airborne high-performance and lengthy recording applications, as an airplane cannot easily be modified to accommodate the latest generation of digital cameras. Even the slightest modification of the wiring or the test routine would require a recertification of the aircraft.

There is a wide range of possible applications for high-performance streaming airborne cameras, and aerial reconnaissance is the most popular. An example of such a camera system is the KS-121A. Developed to improve the reconnaissance capability of the RF-5 aircraft, the KS-121 70mm Frame Camera System offered high resolution in a relatively small format. Its compact size allowed four cameras to be mounted in the aircraft nose. Technology-specific disadvantages, such as film processing time and the need to digitalize the film, were accepted.

CENTER: Aerial reconnaissance on fighter aircraft

Replacement parts

As most manufacturers of film for these cameras have ceased production or announced the phasing out of specific materials, all parties affected will have to think about replacement of their existing systems in the near future. The change from film to digital will be eased by the advantages of this new technology: immediate access to digital image data with no lengthy processing time; and a range of new, advanced functions, such as multiple digital inputs and outputs to integrate external signals, and GPS information of every frame with the image data.

Digital cameras for reconnaissance applications must feature a very high resolution of 14 megapixels or more to get similar results as a 70mm film camera. The camera controller must be able to stream this massive amount of data from multiple cameras for several hours at a stretch.

An airplane is not like an industrial assembly line where modifications to reposition a camera are usually simple to accomplish. How are extra data and control cables installed in an aircraft? Or maybe it could be a camera connected to the airplane's power system? And the test routine itself: does it need to be modified to accommodate digital cameras, and how easily will it be adopted by the pilots and camera operators?

Controllers for digital streaming cameras from a company such as AOS Technologies offer fully customizable control software that enables customer-specific configuration of the input and output signals and the functionality. This keeps the necessary modifications to the airplane and the test routine to a minimum.

Adapting to the system

A number of external input and output signals are used to operate the analog system, including IRIG-B time-stamping. AOS's digital streaming controller can be configured to accept the same input signals and to simulate the output signals, as well as marking each digital frame with the correct time stamp as received from the IRIG-B source.

In addition, malfunctions of the controller due to failure of the airplane's power system or electromagnetic noise can be avoided with the built-in UPS that bridges power failures for about two minutes. The recordings are stored on non-volatile solid-state drives (SSD), which are immune to the high vibration in airborne applications. Needless to say, the system does not contain any fans or other moving parts.

Besides its customizable software, the other basic features of an airborne streaming system are its compact size

LEFT: **AOS H-EMA - high-speed streaming camera**

BELOW: **AOS H-EMA Airborne controller – MIL controller to stream from up to two high-speed or high-resolution cameras**

and design: it will fit into the existing space, which is in most cases limited, and its ultra-solid design and structure will withstand the harsh environmental conditions of flight, such as shock, vibration, and changes of temperature and moisture.

With an analog camera system, access to the film cassette is required when replacing it. Digital controllers, however, can be installed in a distant part of the aircraft as the cameras are tethered through Ethernet cables, which are not restricted in length and have small diameters. No direct access to the controller is required, as the sequences can be downloaded from the controller via a permanently installed Ethernet or eSATA cable.

High-performance streaming controllers can not only operate with high resolution but also with high-speed streaming cameras. These systems are used for in-flight component testing where the whole flight must be monitored. Other applications include aircraft flight behavior testing, or recording the various instruments in an aircraft or helicopter cockpit.

These are just some examples of the variety of smart features of the AOS H-EMA streaming system.

"An airplane is not like an industrial assembly line where modifications to reposition a camera are usually simple to accomplish"

Specialist needs

In demanding environments, such as the airborne test and measurement world, it is sometimes necessary to adapt the digital camera to the specific needs of the test setup. This has led to an emerging range of applications for which digital streaming systems can be used.

AOS Technologies takes on turnkey responsibility in such projects: from close interaction with customers at the start of the concept to developing special mechanics and, where necessary, add-on electronics, and of course providing the necessary software. In the final project phase, the company works closely with customers when installing the system and preparing for the mission. It has a proven track record in installing camera systems and successfully implementing projects with major aircraft manufacturers.

Last but not least, experience in airborne applications is essential to guarantee not only the best fit of camera and accessories to meet customers' requirements, but also to match the budget. In many cases, specific requests can be answered by a special software configuration in the controller, eliminating the need for additional hardware.

Since airborne camera systems have to perform reliably over a long period of time, after-sales service and long-term availability of spare parts must not be overlooked during the evaluation process. Specially trained partners and subsidiaries around the world and on all continents offer ongoing technical service and support not only during installation and integration, but also for user support, repairs, system extensions, and upgrades. ∎

Reto Huber is the engineering manager with AOS Technologies AG, based in Switzerland

TEST STAND DESIGN

In a competitive environment, the design and development of innovative products can be challenging. Adapting an existing product line rather than designing a totally new one can be a cost-effective way to achieve success

BY THOMAS TRAXLER & THOMAS FLICKER

A large European MRO had a requirement for a universal test station for lube and fuel components. The design brief demanded a single test solution that would test a large number of units. Cost, time, space, and reliability were the important issues.

An Austrian company, Test-Fuchs, took on the challenge, and to help reduce costs and improve reliability it used as a basis the design for its modular test stands. The concept is currently used for hydraulic test stands, but with a little innovation from the company's design team, it has been adopted for lube oil test stands.

The Universal Lube Oil Test Stand can accommodate a range of rotating and non-rotating components from Airbus and Boeing aircraft, such as lubrication units, fuel/oil heat exchangers, oil tanks, and pressure fill valves, that are currently being used in most civil airlines. The test stand's user-friendly design saves space in the workshop while enabling excellent access for testing and maintenance. Components can be adapted very quickly and easily, saving time and reducing costs.

The heart of the Universal Lube Oil Test Stand is the deposit for the hydraulic fluid, which can be heated to 90°C – required for certain tests. The integrated heating system is not the only special feature; the tank can be pressurized up to 2 bar as well as vacuumized. The fluid deposit's compact design means it can be adapted inside the test stand. As a result, the length of all pipes and hoses is reduced to a minimum, which is important for reducing pressure drop at high flows.

The test stand includes high-pressure circuits with a flow of up to 5 l/min and a pressure of up to 400 bar, and low-pressure circuits with a flow of 235 l/min at up to 40 bar. Independent measuring circuits can operate with a flow band of 0.5 l/min to 450 l/min at a pressure range of 0 bar to 40 bar.

Another special feature is the integration of six scavenge connectors, which widen the range of components that can be tested on the stand. In these scavenge lines flow measuring can also reach up to 450 l/min.

Universal adaptable pressure transducers enable pressure measurements directly on the outlets and inlets of the unit under test (UUT).

RIGHT: Test stand for fuel components

BELOW: Lube oil test stand

A four-quadrant electromotor up to 14,000rpm powers the machine rotating lubrication units. Additionally, an energy recovery system is installed as well as a calculated torque measuring device via the required current.

The safety-glass protection cover enables perfect access and visibility, and the monitor and keyboard on a telescopic swivel arm with a hanging bar is also a design highlight that enables many possibilities and is very comfortable for the operator. The operating system is a computer-aided unit that is easy to use and enables manual test runs, and semi-automatic and fully automatic test runs to be carried out. The Test-Fuchs software enables the operator to choose freely between the three different modes.

Wherever tests are made with lubrication oil, fuel tests also have to be done – especially on fuel/oil heat exchangers. As a result, a Universal Fuel Test Stand complements the Universal Lube Oil Test Stand.

This Universal Fuel Test Stand is also made to save customers time and workshop space, thus reducing the costs considerably. Because of its universal nature, a large number of Airbus and Boeing components, which, again, are in use at the moment in most civil airlines, can be tested. These include fuel booster pumps and oil heaters. The test stand has also been developed in accordance with the new explosion protection directive ATEX and on special request of the customer it is

"The operating system is a computer-aided system that is very easy to use and enables manual test runs"

> **"The levels inside the tanks, which are monitored via level indicators, can be varied by pumping the fuel from one tank to the other"**

ABOVE AND RIGHT: **Lube oil test stands**

also TÜV-certified. On this test stand the fuel tests of fuel/oil heat exchangers and of other fuel components can be arranged. But this is not the only special feature. An integrated swiveling tank within the system enables the testing of components that need to be tested below fuel level (such as fuel pumps, flow dividers and refueling valves). The swiveling of the tank is fully automatic.

The heart of this Universal Fuel test stand is the tank system, which consists of two reservoirs, one being the main reservoir, the other is the swiveling tank, which can be pressurized up to 2 bar. The levels inside the tanks, which are monitored via level indicators, can be varied by pumping the fuel from one tank to the other.

The test stand includes a high-pressure circuit with a flow of 20 l/min at up to 250 bar and a low-pressure circuit with a flow of 200 l/min at up to 16 bar. Independent measuring circuits can operate within a flow range of 1 l/min to 400 l/min at a pressure range of 0 bar to 250 bar.

This Universal Fuel Test Stand also has a hot fuel circuit, in which it is possible to heat the fuel up to a temperature of 55°C, and use it for tests with a flow of up to 20 l/min at a pressure of up to 16 bar.

As with the Universal Lube Oil test stand, the operating system is computer-aided, very easy to operate, and enables manual test runs and semi-automatic and fully automatic test runs. Again, the software here also enables the operator to choose freely between the three modes.

Test-Fuchs manufactures test stands that have an operator-friendly and ergonomic layout, which guarantees an easy component installation with short setup times and freely accessible connections. An important common feature of all the company's test stands is the similar layout of the mechanics, hydraulics, and software. This means that operators can be trained easily on different Test-Fuchs test stands, saving training costs and times.

The modern design reflects the new line of products, which was developed especially for the new Test-Fuchs modular test stands. Of course, this was not only done for the visual appearance but to reduce the production costs of the test stands that would otherwise be custom built.

Therefore the elements of the frames, coverings, safety coverings, user console, and telescopic swivel arm with hanging bar were directly taken from the less cost-intensive Modular Test Stand line. ∎

Thomas Traxler and Thomas Flicker are both based with Test-Fuchs in Austria

PHASED ARRAY INSPECTION OF CFRP

The ongoing development of ultrasonic phased array technology and its increasing use is bringing new levels of reliability, efficiency, and documentation to CFRP inspection

BY DAN KASS

The use of composites in aero structures continues to increase. The development of advanced composite materials was driven by the high performance requirements in military aircraft to reduce weight to maintain performance and offset the demands of cargo, onboard armaments, and/or dense material required for radar absorption for stealth performance. Commercial aircraft's initially limited use of fibrous composites for secondary structures in the 1980s has evolved with the advent of these high-performance composites.

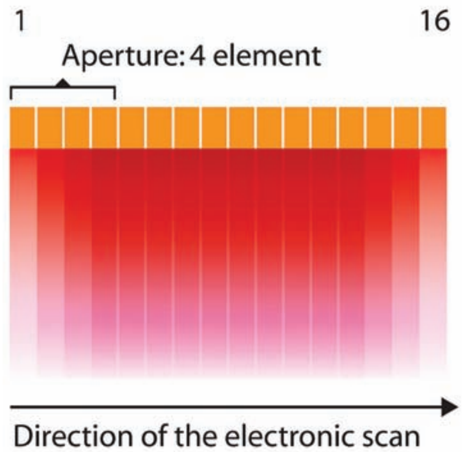
One such category, carbon fiber reinforced plastics (CFRP), not only offers the advantages of reduced weight and high strength to commercial planes, but leveraging the ability to mold complex shapes reduces the complexity and number of parts that would be required using their metal counterparts, and has complete resistance to corrosion.

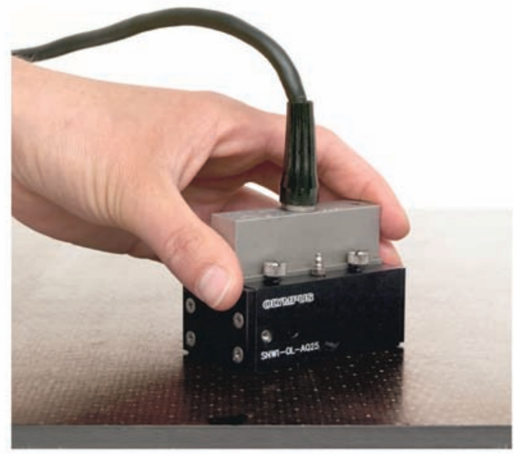
These materials have progressed to the point where both small and large commercial aircraft are now using CFRP for primary structures. This increase in CFRP use and the accompanying evolution of its fabrication processes have placed new demands on non-destructive inspections in materials development, manufacturing, and in-service inspections. As such, ultrasonic phased array inspection tools have been developed to enable rapid inspection and full data recording.

Conventional UT inspections

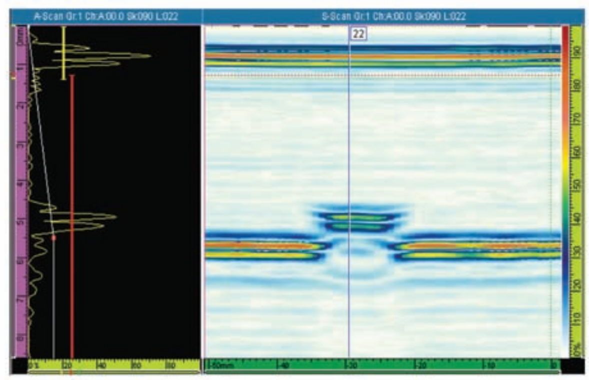
While the size, geometries, and thickness of CFRP parts vary significantly, the nature of commonly occurring defects is ideally suited for compressional wave pulse echo ultrasonic inspection. Laminar defects caused by improper lay-up of materials or impact damage, unintended ply drops, and embedded structures largely occur in a plane normal to the surface.

The technology of ultrasonic flaw detection in composites is based on a simple principle of compressional wave physics. A high-frequency sound wave





ABOVE: Element steps of a linear array, Linear array probe with wedge



RIGHT: Live Linear scan with A-scan showing delamination near bottom of CFRP

LEFT: 2 Axis scanner, linear array probe, and Omniscan MX2 Portable phased array instrument for flat /near flat large area CFRP inspection

that has been launched in a solid medium such as composites will travel in a straight line perpendicular to the surface until it encounters a material boundary, for example a far wall, another material interface, or a lamination.

At that point, the sound wave will be reflected in a predictable way. Ultrasonic flaw detectors generate short bursts of sound energy through small, hand-held probes that are coupled to the surface of the test piece with a liquid medium such as glycerin or even water. The instrument then displays the pattern of sound reflections referred to as an A-scan, which will change as material conditions change. Transducer frequency and element size are selected based on the material being inspected and critical defect parameters. In general, higher frequencies and smaller element diameters are required for resolution of smaller defects. Lower frequency probes are used to penetrate deeper into materials and offset scattering and attenuation of sound in materials with lower density or inhomogeneous structures. Typical CFRP inspection is done with 2.25MHz to 5MHz delay line probes with element diameters typically ranging from 6-12mm.

Phased array scanning

As an A-scan represents the volume of the material encompassed by the generated sound beam directly underneath the transducer, it provides only live point data and relies heavily on the operator hand scanning appropriately to achieve coverage. The end result is often hand marking on the part or point A-scan data captured with commentary on the location and defect parameters. It does not provide a full record of the inspection.

Advanced techniques can be used to organize, visualize, and improve defect recognition and archive data. With conventional single element probes this usually entails using a 'raster' scanning device to encode position over two axes. Signal amplitudes from a gated region are plotted as associated color levels and as a function of position, creating a planar image referred to as a C-scan. This C-scan shows areas free of defects as represented by lower scale colors corresponding to minimal signal reflections, and higher signal reflections from defects are plotted to colors approaching maximum on the color scale. Defect sizing can be performed on this image data.

While this approach can be implemented on flat, near flat and tubular structures, it is difficult to inspect corners of components such as spars, stringers, and top-hat structures. One conventional single element approach would be to fix multiple probes along the radius so as to overlap and remain normal to the surface. Amplitude and time responses are

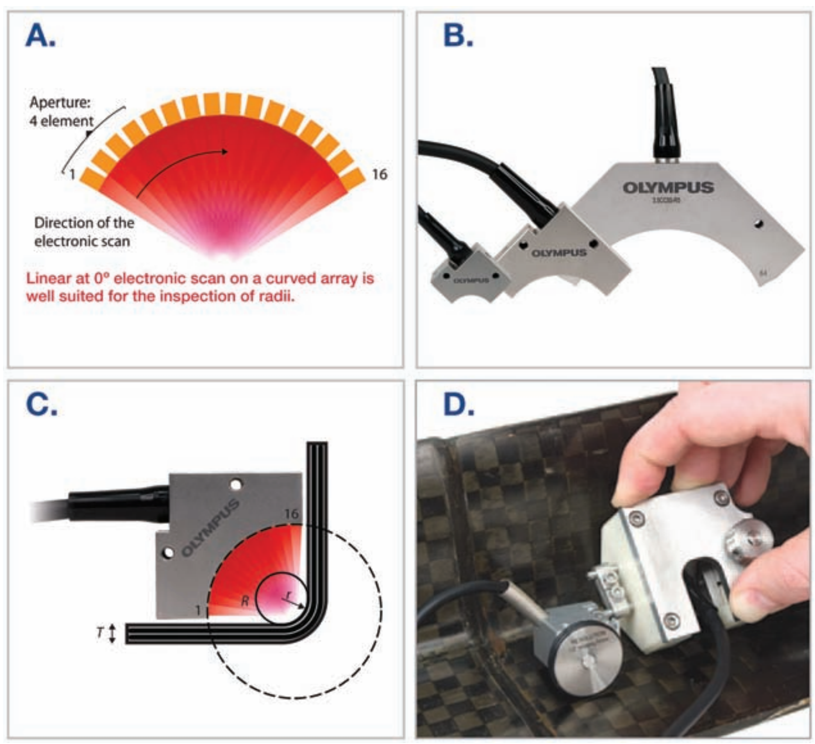
recorded along with transducer position to produce a map from each probe. Trying to manage multiple probes from a fixing and image stitching perspective, however, makes the entire setup complex.

As full C-scan records are becoming an inspection requirement as CFRP use continues to increase in commercial aircraft, phased array inspection has been increasingly adopted to increase speed and simplify inspections for both flat and radiused CFRP parts. Phased array instruments use multi-element probes in which elements are individually pulsed and time-delayed.

Beam steering enables one transducer to generate an image across a sequence of angles (a sector scan) or to produce an image from a fixed angle that travels over the length of a probe (a linear scan). Furthermore, beam parameters such as aperture (element group size) and focus distance can be controlled to provide flexible setups and superior results with a single probe.

For CFRP inspection, linear array probes are used to produce a series of compressional waves by moving the acoustic beam along the major axis of an array without any mechanical movement. This is accomplished by defining the number of elements that are pulsed together (referred to as a virtual aperture) to produce a 0° beam that is then multiplexed in steps across the larger group of elements the probe contains. Typical linear array phased array probes for inspection of CFRP with thickness of 3-25mm are 3.5 or 5MHz with 24 to 128 total individual elements.

ABOVE: **Portable phased array inspection of a radiused aerospace component (photo courtesy of Avior, Produits Intégrés)**

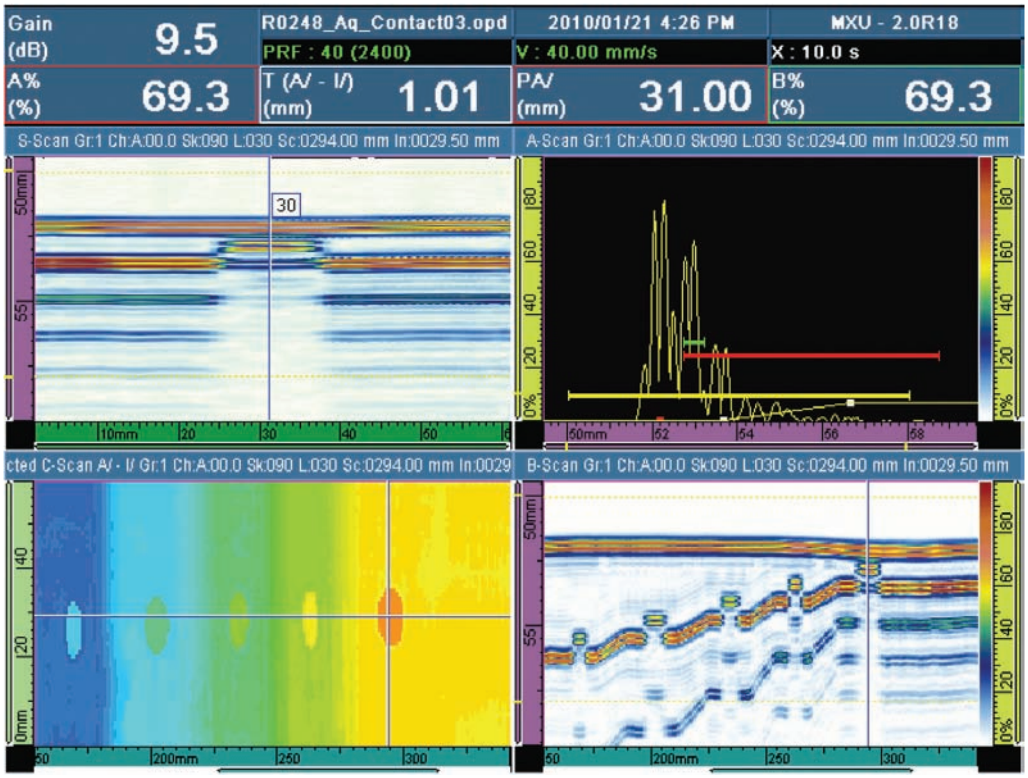


ABOVE: **A: element steps of a curved linear array B: Curved linear array probes of varying radius C: Conceptual acoustic beam for ID inspection D: Actual Probe fixture and single encoder for ID scanning**

Cross-section view

In addition to the ability to select and display A-scans across various apertures along the probe, a live cross sectional image (linear scan) can be displayed, dimensionally accurate to the probe's length. This cross-sectional view allows visualization of ply to ply interface abnormalities, especially delamination depth measurement, and single axis length sizing. A typical linear scan may consist of the user defining an 8mm aperture (eight elements grouped together), stepping one element at a time over 128 elements resulting in a 120mm cross-section view.

Although larger numbers of elements enable a wider inspection area within a single pass, smaller element count linear arrays enable better access and coupling to curved and restricted access areas while still providing cross-sectional visualization. Phased array



TOP: **Live A-scan and Linear scan from current transducer position**

BOTTOM: **Accumulated phased array C-scan and cross sectional B-scan over encoded scan length at a selected aperture**

> **"With complete storage of inspection data, test results can be reviewed and analyzed after the inspection"**

probes can be designed to minimize the dead zone (approximately 1.5mm) from the side of the probe to the last element to allow maximum inspection area as close to the edges as possible. As with single UT element probes, linear array probes are often used with plastic delay lines or with water irrigated wedges to provide more consistent coupling while scanning large areas. Schemes are available which minimize water use and flow, and provide an acoustic impedance match to the material, which deadens the front surface interface reflection to improve near surface resolution.

Since linear scans provide multiple data points, a C-scan image can be produced by adding a single encoder to track probe movement while scanning in one direction. This combination of electronic and mechanical scanning is often referred to as a one line scan.

This simple scanning method is fast, fully portable and easy to implement with today's portable phased array instruments. As the footprint of the probe and encoder is quite small, this method can be used to accumulate swatches of data from a variety of part shapes. When inspecting large flat or near flat CFRP panels, a two-axis mechanical scanner can be used. More capable instruments will automatically stitch together linear scans that are position encoded in two axes, dramatically increasing the speed of inspection as compared to conventional single element C-scanning. Scanner designs are lightweight, water resistant, and have mounting options to allow horizontal, vertical or upside-down operation.

Radius inspection

Radius inspection of CFRP using conventional UT can be challenging. Using a linear curved array allows the acoustic beam to be stepped around either an ID or OD while maintaining normality to the part radius, producing live cross sectional visualization. As described earlier, adding a single encoder produces a C-scan image of delaminations in the radius over the entire length of the part.

This method is fast, provides full coverage, improves probability of detection, and results in an inspection with full traceability. The choice of the appropriate probe depends on the geometry of the part. The main factors that need to be considered are the inspection type (ID or OD), the radius of the corner, and the angle of the corner.

Once the choice of probes has been narrowed, the thickness of the part as well as the footprint of the probe and wedge must be taken into consideration to ensure access to restricted areas that may exist. Probes are available to accommodate a variety of radii. 'Fixturing' to enable adjustment of probe to material radius alignment and maintenance of alignment during scanning is required.

Analysis

With complete storage of inspection data, test results can be reviewed and analyzed after the inspection. When collected, fully linked A-scan, Linear scan, B-scan and C-scan data provide a permanent record of inspection that can be recalled, reviewed, and analyzed. As with linear scans on flat panels, indication size for length of radii defects in the scan direction can be directly measured.

The length of the defect from the linear scan following the radius, however, requires a geometric conversion. This sizing takes into account the radius of the phased array probe, the radius of the corner, the depth of the indication, the thickness of the part and the uncorrected indication size. This conversion is also dependant on the type of inspection (ID or OD). Along with manual indication sizing, PC software is often used to automate the analysis process. Defects can be clustered and sized based on inspection requirements. A common scenario is to determine statistical variation of a 'clean area' to establish a reference point or noise level. Defects are then automatically characterized on similar areas via a user-specified signal to noise allowance, minimum defect size and per cent area restrictions.

The development of ultrasonic phased array technology and its increasing acceptance in the aerospace industry is now showing higher levels of reliability, efficiency, and documentation to CFRP inspection. As with other areas of modern digital NDT, this evolution is likely to continue. ∎

Dan Kass is the portables technology specialist from Olympus Industrial Systems Group

SHOCK TACTICS

Selecting accelerometers for and assessing data from mechanical shock measurements offers a range of benefits

BY PATRICK L. WALTER, PHD

After first clarifying what mechanical shock is and why we measure it, basic requirements are provided for all measurement systems that process transient signals. High-frequency and low-frequency dynamic models for the measuring accelerometer are presented and justified. These models are then used to investigate accelerometer responses to mechanical shock. The results enable rules of thumb to be developed for shock data assessment and proper accelerometer selection. Other helpful considerations for measuring mechanical shock are also provided.

What is mechanical shock?

The definition of mechanical shock is 'a non-periodic excitation of a mechanical system that is characterized by suddenness and severity, and usually causes significant relative displacements in the system'.

The definition of suddenness and severity is dependent upon the system encountering the shock. For example, if the human body is considered as a mechanical system, a shock pulse of duration of 0.2 seconds into the feet of a vertical human due to impact resulting from a leap or a jump would be sudden. This is because vertical humans typically have a resonant frequency of about 4Hz. The amplitude of the shock would further characterize its severity. By contrast, for most engineering components, this same shock would be neither sudden nor severe.

The effects of mechanical shock are so important that the International Organization for Standardization (ISO) has a standing committee, TC 108, dealing with shock and vibration; a *Shock and Vibration Handbook* has been published and routinely updated by McGraw-Hill since 1961; and the Department of Defense has sponsored a focused symposium on this subject at least annually since 1947. Figure 1 provides an example of a component and gunnery system experiencing mechanical shock.

Package drop projectile firing train/truck crash

Mechanical shock can specified in the time and/or frequency domains or by its associated shock-response spectrum. Figure 2 is an example of a shock pulse specified in the time domain. This pulse is used as an input to test sleds to enable the qualification of head and neck constraint systems for National Association for Stock Car Auto Racing (NASCAR) crashes. Its duration of approximately 63ms produces 68g at 43.5mph.

Figure 3 shows an example of a mechanical shock described by its amplitude in the frequency domain. This representation shown is particularly useful in linear analysis when the transfer function of a system is of interest (for example, mechanical impedance, mobility, and transmissibility). It provides knowledge of the input-excitation frequencies to the mechanical system being characterized.

Figure 4 (overleaf) is an example of a shock-response spectrum (SRS). The SRS is one method to enable the shock input to a system or component to be described in terms of its damage potential. It is very useful in generating test specifications. Obviously, the accurate measurement of mechanical shock is a subject of great importance to designers.

Measurement system requirements

There are a number of general measurement requirements that must be dealt with in measuring any transient signal that has an important time history. The more significant requirements are listed below. The frequency response of the measuring system must have flat amplitude response and linear phase shift over its response range of interest. The data sampling rate must be at least twice the highest data frequency of interest.

Properly selected data filters must be able to constrain data signal content so that the data does not exceed this

> **"Mechanical shock measurements provide the basis for component and system test specifications, mechanical transmissibility studies, and the determination of mechanical forces"**

ABOVE. FIGURE 1: **A naval firing system experiencing mechanical shock**

highest frequency. If significant high-frequency content is present in the signal, and its time history is of interest, data sampling should occur at 10 times this highest frequency. The data must be validated to have an adequate signal/noise ratio.

It is assumed that the test engineer has satisfied the above requirements so that this paper can focus on accelerometer selection.

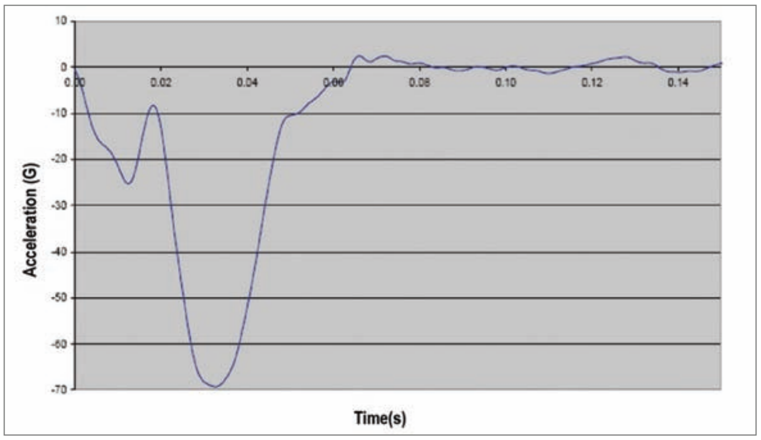
Accelerometer mechanical and electrical models

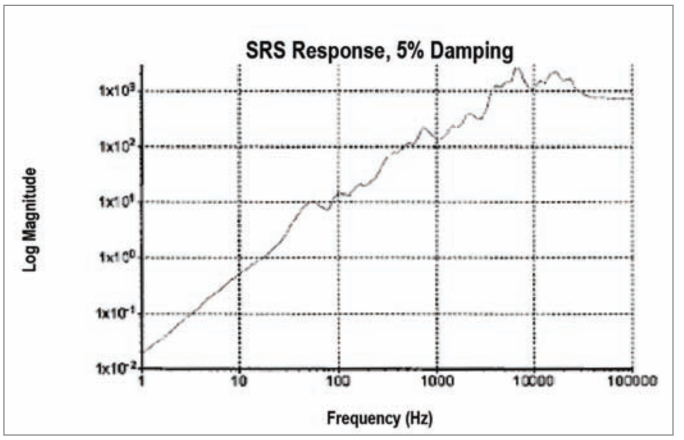
The two types of accelerometer sensing technologies used for mechanical shock measurements are piezoelectric and piezoresistive. Piezoelectric accelerometers contain elements that are subjected to strain under acceleration-induced loads. This strain displaces electrical charges within the elements and the charges accumulate on opposing electroded surfaces. The majority of modern piezoelectric accelerometers have integral signal-conditioning electronics (ICP or IEPE), although such 'onboard' signal conditioning is not mandated. When measuring mechanical shock, ICP conditioning enhances the measurement system's signal/noise ratio.

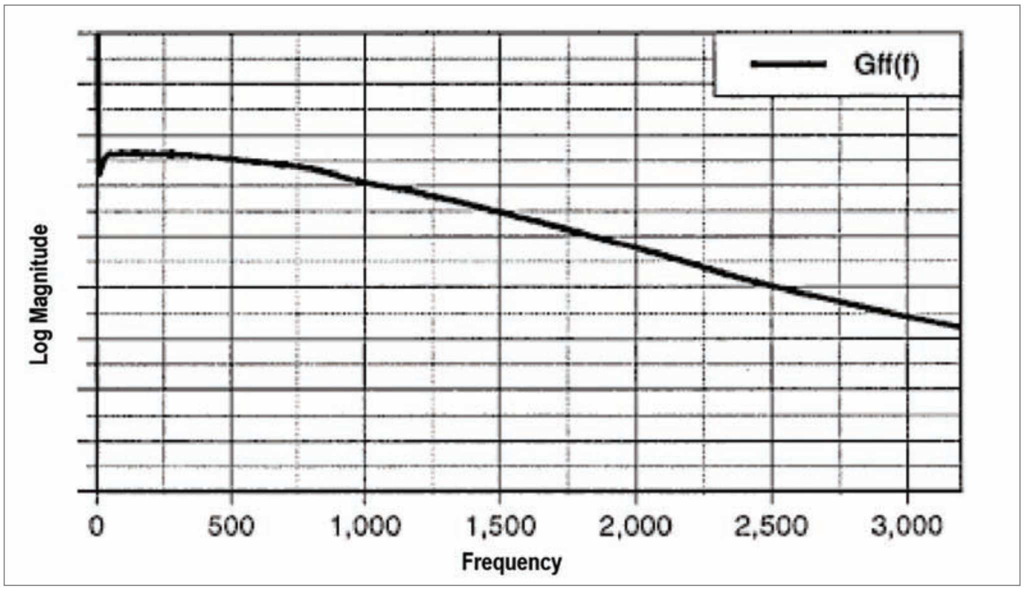
Today, the term 'piezoresistive' implies that an accelerometer's sensing flexure is manufactured from silicon as a microelectromechanical system (MEMS). MEMS shock accelerometers typically provide an electrical output due to resistance changes produced by acceleration-induced strain of doped semiconductor elements in a seismic flexure. These doped semiconductor elements are electrically configured into a Wheatstone bridge. Both of the preceding technologies will be discussed further in a subsequent section of this paper.

Accelerometers themselves are mechanical structures. They have multiple mechanical resonances associated with their seismic flexure, external housing, connector, and more. If the accelerometer structures are properly designed and mounted, their response at high-frequencies becomes limited by the lowest mechanical resonance of their seismic flexure. Because of this limiting effect, the frequency response of an accelerometer can be specified as if it has a single resonant frequency. Figure 5 pictorially shows a mechanical flexure in a piezoresistive accelerometer and figure 6 shows a cutaway of a piezoelectric accelerometer. In figure 6, the annular piezoelectric crystal acts as a shear spring with its concentric outer mass shown. Thus, a simple, spring-mass dynamic model for an accelerometer is typically provided as in figure 7.

The various curves in figure 7 represent different values of damping. These curves are normalized to the natural frequency ω_n: ($r(\omega) = \omega/\omega_n$). For low damping values, the natural frequency and the resonant frequency can be considered synonymous. For a shock accelerometer to have a high natural frequency ($\omega_n = (k/m)^{1/2}$), and







TOP LEFT FIG 2: **Shock time history used in NASCAR testing**

ABOVE FIG 3: **Frequency spectrum of a shock used to excite a structure**

TOP RIGHT FIG 4: **Shock response spectrum of acceleration pulses due to gunfire**

as a by-product a broad frequency response, its flexure must be mechanically stiff (high k). Stiff flexures cannot be readily damped; therefore, shock accelerometers typically possess only the internal damping of the material from which they are constructed (typical value of 0.03 critical damping, which is the highest curve of figure 7).

Piezoresistive accelerometers have frequency response to zero Hertz. Piezoelectric accelerometers do not have response to zero Hz. At low frequencies, piezoelectric accelerometers electrically look like a high-pass RC filter. Their -3dB frequency is controlled by their circuit time constant (RC = τ). Typically this time constant is controlled within the aforementioned ICP circuit. Figure 8 shows this frequency response curve. The plot is normalized to the low frequency -3dB frequency ($r(\omega) = \omega/\omega_{-3dB}$).

Before beginning to measure any shock motion, the test engineer has to understand accelerometer theory, accelerometer mounting techniques, cable considerations, and more. Fortunately, this information is readily and effectively available in an IEST document RP-DTE011.1: Shock and Vibration Transducer Selection. In going forward, we will assume that a properly mounted and signal-conditioned accelerometer is being used. This enables us to focus on understanding the measurement limitations on shock pulses imposed by the high and low-frequency response constraints of the accelerometer. Conversely, it enables one to establish frequency response requirements for an accelerometer measuring mechanical shock.

High-frequency limitations

The key to selecting a shock accelerometer, based on its high-frequency performance, is knowledge of its resonant frequency. This resonant frequency f_n (in Hz) is related to its equivalent value ω_n (in radians/second) as: $\omega_n = 2\Pi f_n$. Typically, an accelerometer should not be used above 1/5th its resonant frequency. At that point on the graph, the device's sensitivity as a function of frequency is 4% higher than its value near zero Hz. Since shock pulses are composites of all frequencies, the total error due to this sensitivity increase will always be much smaller than 4%.

Conversely, if the shock pulse is analyzed in the frequency domain, and if considerable frequency content is found above 1/5th of the accelerometer's resonant frequency, increasingly greater errors will exist in the data. (This comes as no surprise since the accelerometer is operating outside of its flat frequency-response range. Operation within the flat frequency-response range has been previously stated as a requirement for all measurement systems and their components.)

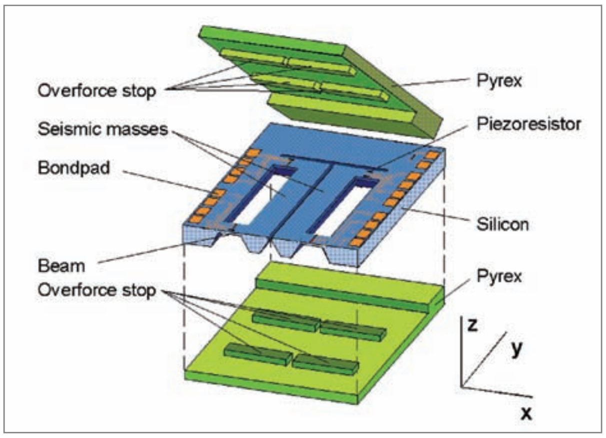
Since most shock pulses are first viewed in the time domain, it is important to establish a relationship as to the credibility of the observed shock pulse based upon knowledge of the resonant frequency of the accelerometer. The natural period T_n of the accelerometer will be defined as $T_n = 1/f_n$. For example, if an accelerometer has a resonant frequency of 50,000Hz, its natural period T_n = 20µs. T_n is introduced at this time because rules of thumb will next be provided based on this natural period.

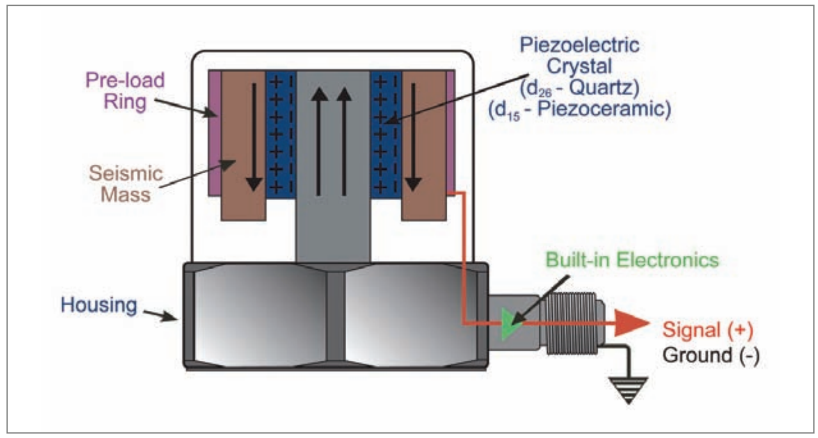
Results of analysis show that at T/T_n equal to 5, the peak error of the measured shock pulse is always less than 10%, and for T/T_n equal to 10 almost perfect reproduction is achieved. Thus, the rule of thumb when selecting an accelerometer or assessing all ready recorded shock data is: $T/T_n > 5$

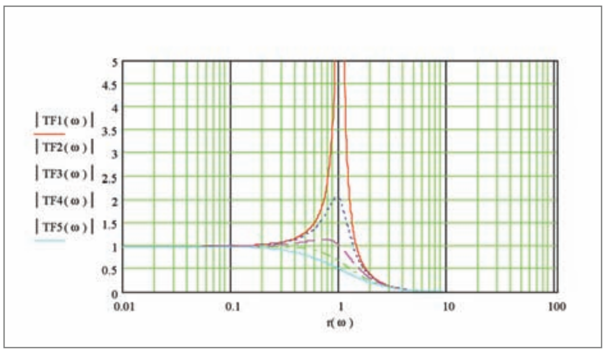
Real pulses typically do not have symmetric rise or fall times. The terms rise and fall time t_r, as used throughout this paper, refer to the 10-90% time from zero to or from the pulse peak.

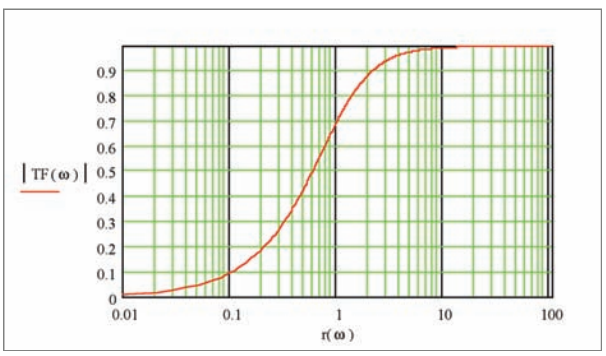
By analogy to the preceding rule: $t_r/T_n > 2.5$.

When applying these rules, the test engineer can prescribe any additional amount of conservatism that is thought to be needed based upon the intended use of the data.









TOP LEFT FIG 5: Mechanical flexure for a MEMS accelerometer

TOP RIGHT FIG 6: Cutaway of a shear-mode piezoelectric accelerometer

ABOVE FIG 7: Simple spring-mass accelerometer model

ABOVE FIG 8: Low-frequency response of piezoelectric accelerometer

Low-frequency limitations

It is necessary to consider low frequencies only when selecting a piezoelectric accelerometer for mechanical shock. (As stated earlier, piezoresistive accelerometers possess a frequency response to zero Hz.) However, if for example a piezoresistive accelerometer is ac-coupled to eliminate thermal drift, the following considerations also apply to it.

Figure 8 showed the low-frequency limitation of a piezoelectric accelerometer. The circuit time constant of the accelerometer is related to the low-frequency -3dB point as: $\tau^{-1} = \omega_{-3dB}$. That is, an increased time constant provides greater low frequency response. When looking at data in the frequency domain, a simple rule of thumb to use is: $f\tau > 0.5$.

This rule guarantees less than 5% attenuation in frequency content above the frequency f (in Hz). For a given time constant, this rule allows you to select the lowest frequency at which you should begin to use test data based upon this criterion. Alternatively, it allows you to select an appropriate circuit time constant in advance of testing.

Again, it is important to establish the credibility of the observed shock pulse in the time domain based on knowledge of the circuit time constant. This relationship will be parameterized as a function of the ratio of the time constant Tau (τ) to the pulse width T.

There is a way to plot the response in the time domain of an RC circuit to a theoretical square pulse. As the ratio of the time constant to the pulse duration reaches 10 ($\tau/T = 10$), there remains a 10% droop (error) at the end of the pulse. This would be a worse-case assessment, since most real pulses trail off significantly before pulse termination. The haversine and half-sine pulses show more practical situations. This same ratio of $\tau/T = 10$ would result in a 2.4% error for the peak value determination of a haversine pulse and a 3.4% error for a half-sine. The corresponding error for the peak of a triangular pulse would be 2.6%. Thus, a rule of thumb when selecting an accelerometer or assessing already recorded shock data is: $\tau/T > 10$

Again, the test engineer can apply as much additional conservatism as the application warrants.

Piezoelectric versus piezoresistive

The majority of piezoelectric accelerometers use ceramic sensing materials. At sufficiently high frequencies, the resonance of any accelerometer can be excited, but a unique characteristic of ceramic materials is that this excitation can result in a zero-shift of the signal. This remained a mystery until 1971, when the cause-effect relationship of the zero-shift in ceramic materials was established, and this work brought about an increased focus on MEMS accelerometers for shock applications. Theoretically, MEMS accelerometers do not zero shift.

A limitation in MEMS accelerometers in shock work is their tremendous amplification at resonance (for example, 1,000:1), which can lead to breakage in response to high-frequency inputs (for example, metal-to-metal impact, explosives, and so on). Figure 9 shows one example of a MEMS shock accelerometer that attempts to incorporate a small amount of squeeze film damping to minimize this problem.

High-frequency electronic limitations

To mitigate the aforementioned zero-shift problems in piezoelectric accelerometers, certain models (such as PCB Model 350) contain mechanical isolation to mitigate high-frequency stimuli. To minimize frequency-response aberrations due to this isolation, the accelerometers are electrically prefiltered. Feedback components (resistors and capacitors) internal to the accelerometer and around the signal-conditioning amplifier enable a two-pole Butterworth filter to be developed. The high-frequency roll-off of this filter, as opposed to the resonant frequency of the accelerometer, now becomes the measurement system's upper frequency constraint.

In other instances, this same type of frequency limitation may occur outside of the accelerometer. For example, in flight test instrumentation only 2-3kHz maximum frequency response per channel is typically allocated. In addition, at shock levels below 2,000g, damped accelerometers might be used. The response of properly damped accelerometers appears as the intermediate or 'flattest' of the curves in figure 7. This curve shows negligible gain and is attenuated approximately -3dB at the natural frequency of the accelerometer.

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ABOVE FIG 9: PCB Model 3991 MEMS Shock Accelerometer

BELOW FIG 10: Complex mechanical shock pulse

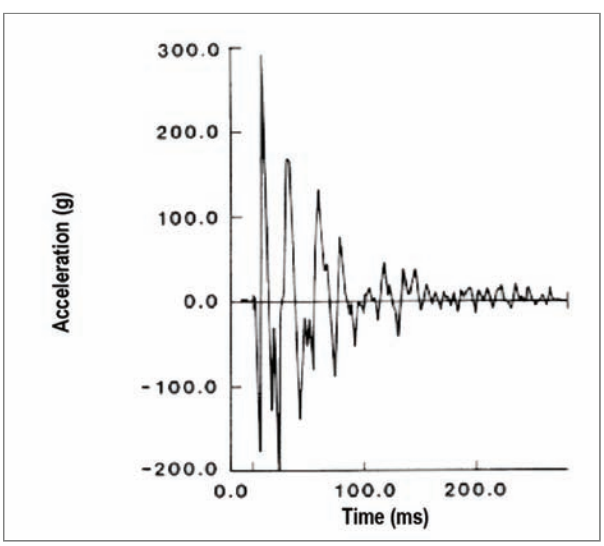
The commonality of the examples of the preceding paragraphs is that amplification (i.e., gain) approaching the resonant frequency of the accelerometer no longer limits the response of the measurement system. Instead the limitation becomes the system's high-frequency attenuation. Due to this attenuation, another rule of thumb can be applied. Here again we base this rule on the shortest duration of the pulse's rise or fall time t_r to or from the pulse peak. By analogy to the preceding observations: $t_r f_{-3dB} > 0.45$

This rule states that the rise or fall time of the shock pulse is guaranteed valid only if the product of its duration multiplied by the high-frequency -3dB frequency in Hz exceeds 0.45. Again, this rule is helpful for both pretest planning and data assessment.

Complex pulses

As opposed to the simple pulses shown to date, real shock pulses can be quite complex (figure 10). A question then arises as to how we apply the preceding simple rules of thumb to complex pulses. The answer is that we dissect the pulse for its shortest and longest positive or negative-going excursions as well as its shortest positive or negative rise time. Since today all data is recorded in digital format, these simple rules can be readily programmed into a software data analysis package.

> **"The capacitor has the effect of creating a second RC time constant in the circuit"**



Cable frequency limitations

In ICP circuits, if very long cables are used, the cable capacitance can become an upper frequency limitation. For example, 4mA of supply current driving 100ft of cable supporting an ICP circuit with cable capacitance of 30pF/ft will begin to attenuate full scale signals above 40kHz. Other drive-current-versus-cable-operating trade-offs can be assessed using manufacturers literature. Frequency attenuation due to cable length can usually be overcome by simply increasing the supply current.

Low-frequency oscillations

If an ICP accelerometer is selected properly, the effect described next should never be a consideration. However, since the effect is sometimes observed in test data where the shock pulse is excessively wide and/or the accelerometer signal conditioning is overranged, it is described for clarity.

Aside from a constant current diode, the signal conditioning for ICP circuits typically includes a coupling capacitor for blocking the bias voltage on the signal return. The capacitor is always selected so as to avoid affecting the accelerometer's low-frequency performance. However, the capacitor has the effect of creating a second RC time constant in the circuit. The effect of this second time constant is to transform a first-order, high-pass system into a second-order one. The signal now returns to zero typically in hundreds of milliseconds and an oscillation is observed, indicating one or more problems with the data.

Conclusions

This paper has presented simple rules of thumb to enable test engineers to select accelerometers efficiently and accurately for mechanical shock measurements or to assess data resulting from those measurements. Whereas the rules of thumb are based on theory, they result in a number of practical rules that a test engineer, designer, or data analyst can readily apply. ∎

Patrick L. Walter, PhD, is measurement specialist at PCB Piezotronics Inc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VOLCANIC ASH AND SAFETY

A university study into the impact of volcanic eruptions on aviation looks at the melting and resolidification behavior of volcanic ashes

BY HONGBIAO DONG & LEWIS BURTON

Throughout history volcanoes have both fascinated and frightened. Many erupt explosively and produce ash plumes that loft through the troposphere and commonly the stratosphere. The plumes spread laterally to form an umbrella cloud, which are commonly blown by winds hundreds to thousands of kilometers.

Airborne volcanic ash consists principally of highly angular silicate glass particles (pyroclasts) of basaltic, andesitic or rhyolitic composition and presents a serious hazard to aviation, particularly jet aircraft, because it can cause jet engines to fail rapidly. The hazard has increased considerably with increased encounters between jet aircraft and volcanic plumes over recent decades as the result of increasing intercontinental aviation, and this is expected to increase further.

Explosive volcanic eruptions are common worldwide, with potential for aircraft-ash plume encounters in many regions (e.g. Europe, Alaska, Southeast Asia, and the Pacific). The 2010 phreatomagmatic eruption of Eyjafjallajökull in Iceland highlighted two issues: the potentially severe financial effects of flight cancellations extending for durations of several days and weeks, possibly months, and affecting flights to and from locations far away from the volcano; and an urgent need for improved understanding of the effects of ash particles on jet engines, such as how different types of pyroclast behave at high temperatures, and how this behavior is affected by different particle concentrations in the air. The zero-tolerance policy recommended by manufacturers has been questioned and amended.

The aviation hazards

The aviation industry is at risk from the 550 (approximately) historically active volcanoes worldwide. For example, the 1989-90 eruption of Redoubt volcano in Alaska disrupted aviation in the south-central part of the state and damaged five jet passage aircraft, including a new Boeing 747-400, which cost in excess of US$80 million to repair. Over the past 30 years more

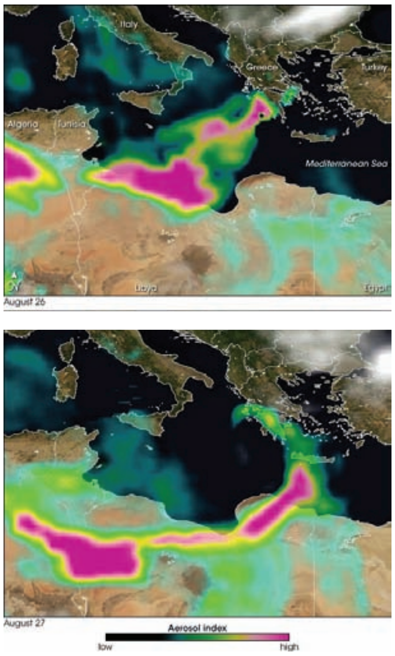
BELOW: **Volcanic ash plume, Cleveland (picture courtesy NASA)**

Volcanic Ash Advisory Centre, UK

The UK Met Office's London Volcanic Ash Advisory Centre (VAAC) aids flight safety for the northeast Atlantic routes by providing reports and forecasts for the movement of volcanic ash plumes within its area of responsibility, and covers the UK, Iceland, and the northeastern part of the North Atlantic Ocean.

The London VAAC provides forecast guidance up to 24 hours ahead to support decision making. This guidance is provided to the Civil Aviation Authority as the lead agency, the UK's National Air Traffic Service (NATS), airports, and airline operators in order to support their decisions on whether aircraft can fly safely.

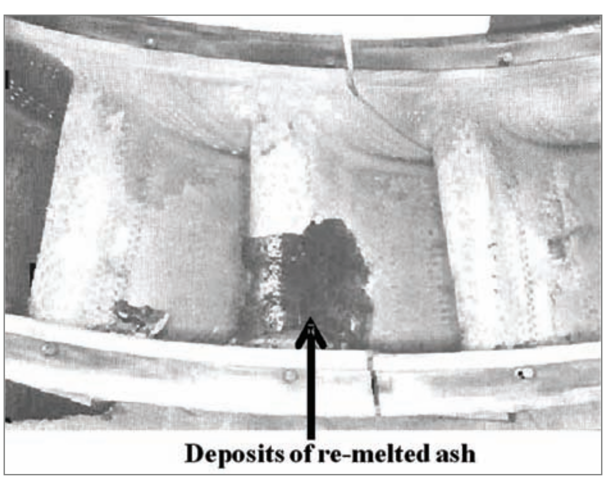
The center uses a range of technologies and expertise to predict the movement of volcanic ash. The Met Office dispersion model forecasts are routinely validated and verified against all available observations, such as from satellite, radar, lidar, and aircraft,



NASA satellite

NASA's newest Earth-observing satellite will orbit 800km above the planet. The environmental satellite, the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP), was successfully launched from Vandenberg Air Force Base, California, on October 28, 2011. The satellite will also be used to track ash plumes from volcanic eruptions to help ensure aviation safety.

BELOW: Deposits of melted and re-solidified ash on the first stage nozzle guide vanes



> **"The primary cause of engine thrust loss in these events was the accumulation of melted and resolidified ash"**

than 80 jet airlines have been damaged in flight and at airports as a result of encounters with drifting clouds of volcanic ash. Seven of these encounters caused inflight loss of jet engine power, which nearly resulted in the crash of the airplane. The repair and replacement costs associated with airplane/ash cloud encounters are high. More importantly, passengers' lives are at severe risk when the thrust on all engines is lost during an approximately one-minute exposure to the volcanic ash as evidenced with Redoubt?

The primary cause of engine thrust loss in these events was the accumulation of melted and resolidified ash on the Stage 1 turbine nozzle guide vanes in the engine, as shown in the image bottom left. These deposits reduced the effective flow of air through the engine, causing the compressor to stall.

The aim of this study is to investigate the melting and resolidification behavior of volcanic ashes of the different glass compositions found in typical circum-Pacific and European volcanoes, including the glass transition temperatures and the kinetics (speed) of the transitions. These characteristics will provide detailed information critical to better understand how contrasting volcanic plumes interact with jet engine components.

The studies

In experiments carried out at the UK's University of Leicester, it was found that volcanic ashes are extremely complex and volatile in nature. The size of ashes ranges from 10µm to 400µm and the ash has powder-like morphology. Composition analysis provided evidence that the ash came from a silicate-based rock compromising of about 55wt% silicate dioxide as well as a host of other elements, including aluminum oxide, iron oxide, calcium oxide, sodium oxide, magnesium oxide, potassium oxide, titanium oxide, phosphorous pentoxide, manganese oxide, and sulphur trioxide.

Results from thermal analysis experiments revealed that the melting and resolidification temperature of ash ranges from 1,007°C to 1,233°C (1,844°F to 2,251°F). The resolidified ash was completely welded to the ceramic container, which has the similar chemistry and microstructure of the ceramic coatings on the airplane engine turbine components. The welded ash surface appeared smooth in texture and proved extremely difficult to remove from the substrates.

The ongoing research at the University of Leicester aims to provide thermodynamics and kinetics of the melting and resolidification behaviors of different types of volcanic ash to develop novel methods to remove and clean ash from substrates. It is hoped that the results will help inform research to determine minimum levels of ash concentration that are capable of damaging aircraft and engines. ∎

Further details on the volcanic ash project are available from Dr Hongbiao Dong, reader in engineering materials, Department of Engineering, University of Leicester (h.dong@le.ac.uk). Lewis Burton also works in the Department of Engineering

COMPONENT QUALITY

Subassemblies can now be trialed during the manufacturing process, saving time and money and improving quality

BY ROBERT M. BROWN & BERNIE LANE

In the aerospace industry, component quality is of paramount importance. Making sure that these components meet specifications and are reliable can be a major challenge. Typical power for aircraft runs at a frequency of 400Hz. Therefore it is essential that the power source on board the aircraft is stable and reliable. Components and subassemblies running on aircraft power are subject to a variety of dips, drops, transients, and frequency shifts. Having a way to simulate this during testing can be extremely helpful to ensure the best quality possible when manufacturing components and subassemblies.

In all industries, manufacturers strive for the highest level of quality possible from their components and systems. In the aerospace industry this is even more important, since a failure of a device or system in the air could lead to catastrophic consequences. Being able to test these components and systems in a way that simulates actual use conditions has its challenges, but with the use of programmable AC/DC sources and software, manufacturers can get one step closer to accomplishing this task. Aerospace products are required to meet test specifications such as MIL-STD-704, DO-160 and ABD0100. These standards are industry regulated and products are tested to these standards to ensure they are acceptable for use in various applications. Meeting these standards can be difficult, time consuming and costly. Engineers can spend hours of time generating the test setups. Implementing these solutions in a manual mode would require multiple setups of equipment, requiring hours of setup time, each and every time the test is recreated – and would drive up testing costs.

Being able to control each phase independently and vary the frequency for testing is a must in complying with requirements such as MIL-STD-704F and DO-160. With the use of programmable AC/DC sources this is possible to accomplish and with custom software, it becomes even easier to test and achieve the desired results at the touch of a keyboard.

DO-160 identifies the input requirement for three-phase equipment with balanced and unbalanced phase inputs as follows: Operate the equipment at maximum duty cycle for at least five minutes for each test with the primary power adjusted first for a phase balance, then for a phase unbalance. At the end of each test and with the equipment still energized, adjust the average voltage at equipment terminals to 115V RMS and determine compliance with applicable equipment performance standards.

Most software features all the basic modes of operation, such as list, step, pulse, harmonic synthesis, and waveform editor. As a reference point for this discussion, this particular version of software softpanel uses the basic modes of operation of an AC source with a transient generator to create the complex tests called out in MIL-STD-704, DO-160 and ABD0100.

Once the user selects the appropriate standard from a pull-down list, all predefined tests for that standard are shown and can be selected for testing. These tests can be modified and saved based on the user's testing needs. This is quite important since having the flexibility to create,

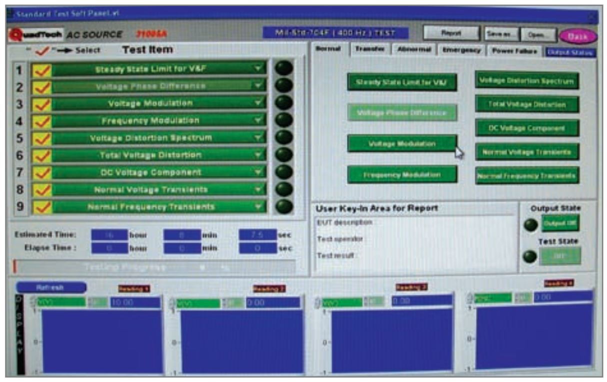
MIL-STD-704F identifies the following for one typical test setup for AC frequency:

Steady-state characteristics	Limits
Steady-state voltage	108-118V, RMS
Voltage unbalance	3.0V, RMS maximum
Voltage modulation	2.5V, RMS maximum
Voltage phase difference	116-124°
Distortion factor	0.05 maximum
Distortion spectrum	Figure 7
Crest factor	1.31 to 1.51
DC component	+0.10 to -0.10V
Steady-state frequency	393-407Hz
Frequency modulation	4Hz
Transient characteristics	**Limits**
Peak voltage	±271.8V
Voltage transient	Figure 3
Frequency transient	Figure 5

TABLE 1 **AC normal operation characteristics – 400Hz**

Steady state characteristics	Limits
Steady state voltage	108-118V, RMS
Voltage unbalance	3.0V, RMS maximum
Voltage modulation	2.5V, RMS maximum
Voltage phase difference	116-124°
Distortion factor	0.05 maximum
Distortion spectrum	Figure 7
Crest factor	1.31 to 1.51
DC component	+0.10 to -0.10V
Steady-state frequency	360-800Hz
Frequency modulation	4Hz
Transient characteristics	**Limits**
Peak voltage	±271.8V
Voltage transient	Figure 3
Frequency transient	Not to exceed steady-state values of 360-800Hz
Maximum rate of change of frequency	250Hz/sec

TABLE 2 **AC normal operation characteristics – variable frequency**



RIGHT: **MIL-STD-704F test screen**

TEST	Equipment category	Phase A/B/C voltage (V RMS)		
		Phase A/B/C Voltage (V RMS)	Phase B	Phase C
1	All	132.5	132.5	132.5
2	All	98.5	98.5	98.5
3	A(CF) and A(NF)	134	134	128
3	A(WF)	134	134	126
4	A(CF) and A(NF)	97	97	103
4	A(WF)	97	97	105

TABLE 3 **Equipment performance standards**

Test and standard selection
Waveform editor
List mode
Step mode
Pulse mode
Interharmonics
RTCA DO-160D test
MIL-STD-704F (400Hz)
MIL-STD-704F (360~800Hz)
ABD0100 (115V/60Hz)
ABD0100 (115V/360~800Hz)
ABD0100 (115V/400Hz)
ABD0100-A350 (VF)

TABLE 4 **Features of the 30000TG–MSA softpanel application**

modify existing, save, and recall these programs at any time has become a powerful solution for aerospace manufacturers. Another area of interest for manufacturers is the ability to set up a test or import a waveform profile from an Excel spreadsheet. This helps to make a complete solution for all AC/DC power testing requirements.

With a wide range of power options to choose from, testing simple things such as steady voltage and frequency, as well as more complex testing of complete dropout and transients, can be accomplished. These requirements fit the needs of all products from the smallest of components and subassemblies all the way up to complete, finished products. This solution can be used in all areas of the product lifecycle, including: early investigational stages, development and prototyping, manufacturing assembly and test, and service and repair. It is also a great solution for long-term testing in quality, reliability, and fault analysis.

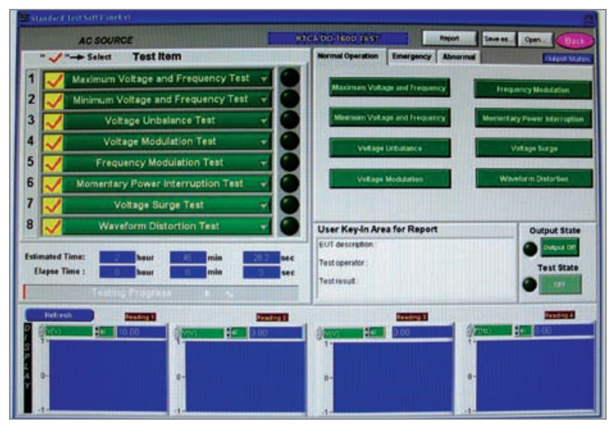
In addition to the AC requirements for testing, DO-160 has a requirement for DC transient testing. The sources used in this case also have the capability of outputting DC and can be used to perform dip and drop testing to DO-160 for systems operating at 28V DC as well as other voltages. Figure 3 is a sample test and output of a QuadTech 31005A AC programmable source. The test was created using the list mode in QuadTech's Military Aerospace Softpanel.

This is a three-step test:

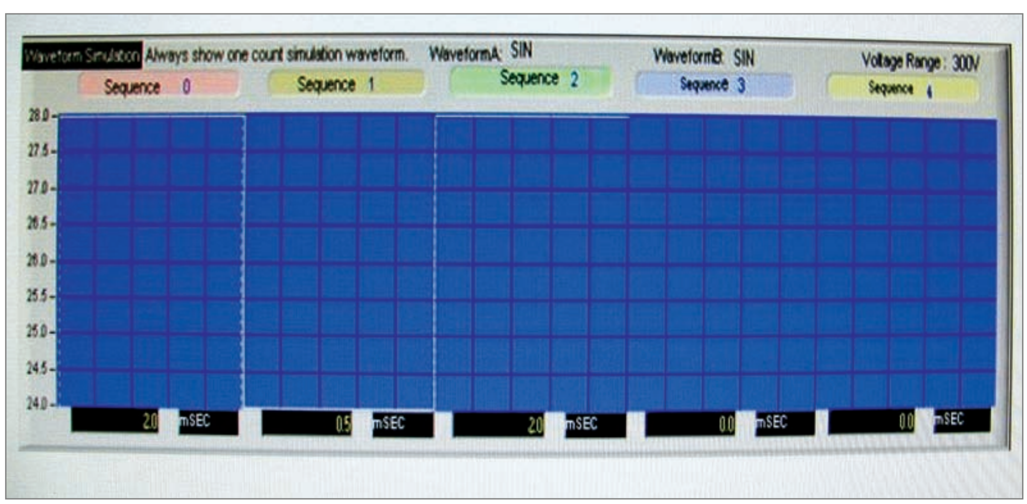
- Step 1 for 28V DC for 2ms;
- Step 2 for 24V DC for 0.5ms;
- Step 3 for 28V DC for 2ms.

More and more manufacturers and suppliers are realizing that having both testing hardware and software to assist in this testing can be beneficial. It provides a simple and easy way to accomplish repeated testing, saving both time and money. Additionally, testing supported by software provides a more robust system, helping to ensure products are at a level of quality that is acceptable for these types of applications. ∎

Robert M. Brown is vice president of technical operations and Bernie Lane is an applications engineer at QuadTech



ABOVE: **DO-160 test screen**



ABOVE: **The waveform captured on a Tek TDS 210 Scope. The trace shows response with a 24V DC dip for 0.5ms in the 28V DC nominal voltage**

GAP MEASUREMENT SYSTEM

The Gapman Gen3 is in the final approval stage at several major European aircraft manufacturing plants. The plants are performing final assembly and producing large components for the next-generation aircraft platforms that will launch over the next few years

BY ROBERT L. FOSTER & BRYAN MANNING

Gapman Gen3 technology was introduced in the March 2011 issue of *Aerospace Testing International* in an article entitled *Filling the Gap*. The article covered the Gapman Gen3 electronic gap measurement system for aircraft applications with higher resolution, longer battery life, and an extremely easy-to-use operator interface.

In the commercial aircraft designs currently in process, there are new standards required for gap measurement accuracy, data capture, and documentation of the shimming (packer) process. The applications where thousands of gaps are measured are found in more complex aero structures. There is also a considerably higher proportion of structural and skin components made from carbon-fiber reinforced polymer (CFRP). Difficult-to-access gaps, tapered gaps, and hidden gaps also raise the bar for the choice of the best gap measurement solution.

Several sites in Europe have performed Gauge R&R and ANOVA testing on the Gapman Gen3. Typically in these tests, three different operators measure a minimum number of different target material types of well-defined locations with successive repeat trials (three tries is typical). The individual results are tabulated, yielding a score that indicates the measurement variance of production measurement methods. The target material combinations in the tests includes aluminum/aluminum, aluminum/CFRP, titanium/CFRP, and CFRP/CFRP. The Gapman Gen3 has passed these rigorous tests at at least six sites.

Aircraft gap measurement and shimming applications

The most critical application where repeatable gap measurements are required in aircraft assembly is during the packer and shim selection process. Liquid and solid shimming is necessary during the fabrication of aircraft components such as the wing and fuselage

"The shimming process is also critical during the production of an aircraft's fuselage sections"

The very flexible non-contact gap measurement wand

sections as well as during final assembly of aircraft.

By using the traditional precision metal feeler gauge method of measuring tapered or uneven gaps, manufacturers are significantly handicapped in identifying the actual true gap topology in any given shimming location. Remember that the 'feel' in feeler gauges represents a minimum gap.

In wing production, the outside aircraft skin is attached to ribs and spars. Due to variable dimensional tolerances, and partially as a result of the stiffness of the CFRP, the two mating surfaces do not perfectly match. This creates voids between the CFRP or metal surfaces. To enhance structural integrity and retain aerodynamic design, these voids must be filled with shims. A liquid shimming technique is used for smaller voids, while solid shims are typically used to fill voids of more than 0.6mm.

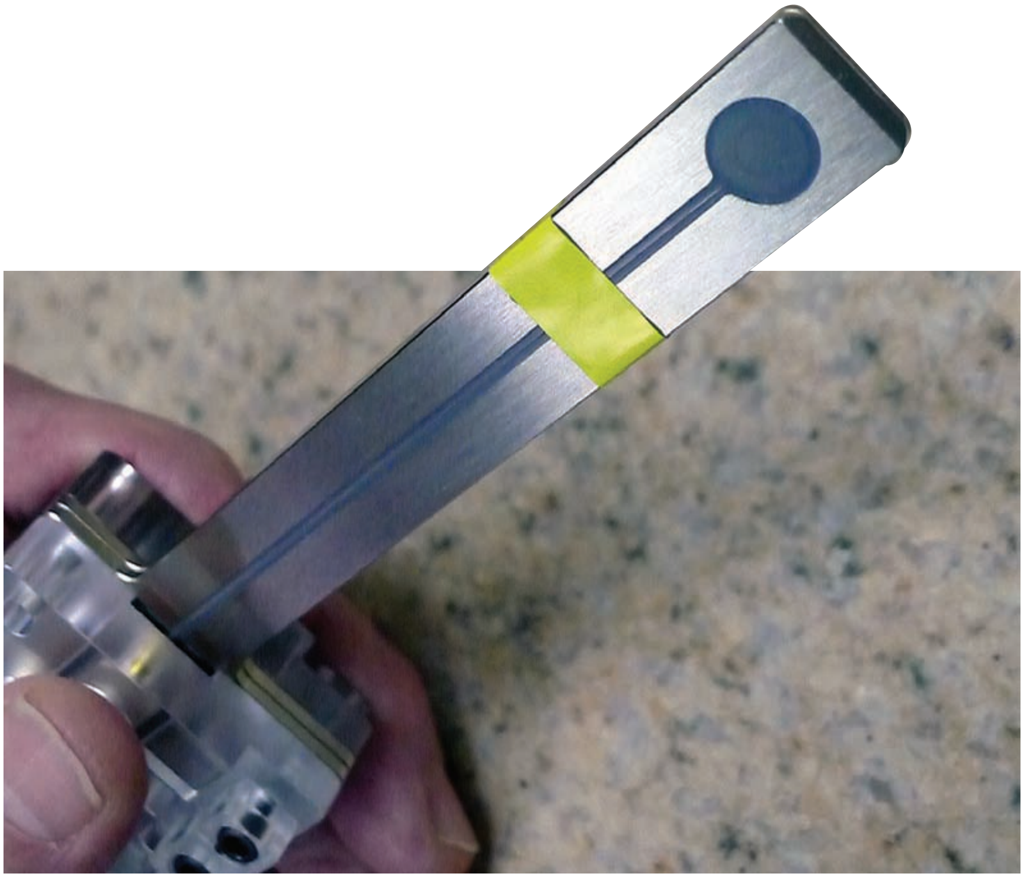
The shimming process can be very time-consuming due to the combination of gap measurement, gap data collection and transfer and selection of standard shims. Filling larger and more complicated shaped voids can require custom-machined shims that add significantly more time to aircraft production, especially if this process is performed using manual methods.

The Gapman Gen3 is popular among aircraft manufacturers worldwide due to the multiple hours of repeat labor saved using the 'electronic feeler gauge', with its built-in data collector and a wireless option that provides more direct measurement data transfer (see Figure 1 for typical aircraft gap measurement applications).

Below are some specific examples of gap measurement requirements on the latest aircraft designs.

Aircraft main wings

New wing designs use CFRP on the upper and lower outer skins to provide enhanced aerodynamics and lower weight, contributing to the improved fuel efficiency of the aircraft. The skins are attached to ribs, spars, spar joint plates, hinge ribs and L brackets made



> "The fabrication method of a vertical tailplane (VTP) has similarities to that of an aircraft's main wings"

from a variety of materials including CFRP, titanium, and aluminum alloys. Depending on the aircraft size, the gaps measured range from 0.2-3.5mm.

Studies have shown that using a Gapman Gen3 versus precision metal shims has reduced the shimming process by a factor of four. This is a significant time saving considering the thousands of gap measurements taken during the shimming process of the wing assembly. These huge time savings contribute to very favorable returns on investment for aircraft producers.

Vertical stabilizer

The fabrication method of a vertical tailplane (VTP) has similarities to that of an aircraft's main wings. From start to finish, this component requires a few thousand gaps to be measured during the shimming process. Often, the VTP shell is manufactured horizontally, making gap measurement and shimming more practical.

Typical gaps in assembly of VTP shells are between the outer skins (now using CFRP material) to the shell, ribs and spars fabricated in CFRP, titanium, and other metals. Gaps in this application can range from 200 microns to 4mm. The gaps are mostly flat, but some are tapered.

Fuselage sections

The shimming process is also critical during the production of an aircraft's fuselage sections. Repeatable gap measurements are required here in applications of filling voids between a variety of connecting surfaces such as the outer skins, stringers, panels and splints. Materials are similar to those used in wings, and gaps run from 200 microns to 3mm.

There are also many difficult to access gap locations such as behind the splints, where a measurement wand must be flexed to 90°. The very flexible sensor wand of the standard Gapman Gen3 has been found to be an ideal solution in this application (see Figure 2).

Engine pylons

Another application in which gap measurements are required is during engine pylon production. These gaps are located between the pylon and an assembly of engine ribs positioned into a reference on a bench fixture. About 30 gap measurements are taken around the jig to ensure that the outer shape dimension matches the specification. The materials here are titanium and steel. The typical gap range is 3.5-6mm. Based on the requirements of this application, a rigid thicker sabre is used in conjunction with a Gapman Gen3.

Final assembly applications

The most critical fastener applications in aircraft production are during final assembly. The join between the main wing assembly and the center wing box is critical as these junctions undergo significant stress during flight. This holds true for the rear portion of the aircraft as well, which includes the horizontal and vertical stabilizers. These locations by design can use very large shims to match where these surfaces meet.

The body of large aircraft can be assembled in barrel-like radial sections or longitudinal half or quarter sections. These are jointed together in a critical seaming operation. These joint sections need to be fastened and bonded together using unique processes that require a large number of gap measurements. This is a highly stressed area of the aircraft and needs special attention in locations several centimeters inboard near fastener locations. ∎

Robert L. Foster is president of Capacitec and Bryan Manning is commercial director of Capacitec Europe

AIR SUPPLY

Arguably the most advanced fighter in the world, the F-22 Raptor was grounded after problems with its oxygen supply. Now it is airborne again

BY KENJI THULOWEIT

When Air Combat Command directed a stand-down of the F-22 fleet on May 3, 2011, the 411th Flight Test Squadron had already begun working around the clock to test and collect data on the Raptor's oxygen system in order to get it airborne again.

That critical work culminated in Secretary of the Air Force Michael Donley and Air Force Chief of Staff General Norton Schwartz announcing an Edwards-supported implementation plan that will allow the F-22 Raptor to resume flight operations.

Air Combat Command ordered the stand-down following 12 reported incidents since April 2008, where pilots experienced hypoxia-like symptoms.

In conjunction with the System Program Office and contractor team, the 411 FLTS played the key role in providing the data to the Air Force's Safety Investigation Board and Scientific Advisory Board needed to recommend a return-to-flight solution.

"We're the responsible test organization here and were tasked to develop the tests and execute them," says 1st Lt Austin Curtis, 411 FLTS lead subsystems engineer.

Two-pronged approach

As the Air Force's primary developmental flight test and evaluation center, Edwards had the necessary assets to collect data required for the SIB and SAB report to the chief of staff.

"We have instrumented airplanes and the ability to modify them to look at particular questions the SIB and the SAB wanted answers before they recommended putting the F-22 back in the air," says Major Chris Keithley, 411 FLTS F-22 test pilot.

According to Keithley, the squadron spent the first 12 weeks evaluating the problem, designing the test, and modifying the airplane.

"We had a two-pronged approach," Keithley explains, "that looked at potential contaminants in the air that are normally provided to the pilot, and diminished oxygen production out of

LEFT: The 411th Flight Test Squadron played a critical role in getting the Air Force's fifth-generation fighter cleared to return to flight

> "We're the responsible test organization here and were tasked to develop the tests and execute them"

ABOVE: An Edwards F-22 Raptor screeches through the sky following a nearly five-month stand-down (Lockheed Martin photo)

the onboard oxygen generation system. For the contaminants, we had several instrumentation apparatuses on the airplane, along with Summa canisters to collect air samples that were tested in a lab."

The 411th team used specialist desorption tubes and carbon canisters to collect air samples, and a systems monitor to detect volatile organic compounds (VOCs).

"We looked at several different regulatory standards to see what (constituted) good and bad levels of VOCs," says Keithley.

Oxygen system

The onboard oxygen generation system, known as OBOGS, is designed to produce a certain amount of oxygen at various altitudes. Instrumentation on the test F-22 monitored and transmitted real-time data on the levels of oxygen it was producing. Also, as the F-22 engine provides bleed air to the environmental control system and OBOGS, test missions sought to stress the environmental control system and engine to see if any anomalies occurred within either system.

After each test, an expediter drove the samples to the lab to turn data quickly. A local lab analyzed the samples for toxins and contaminants.

The squadron flew 15 sorties in four weeks to collect real-time oxygen data from the Raptor's test instrumentation. The 95th Aerospace Medicine Squadron also examined test pilots before and after flight tests and, as Curtis notes, the test airplane flew with components taken from Raptors that previously reported incidents to help rule out potential root causes.

"Basically we turned over every single rock we thought to turn over; we wanted to take a real broad brush approach to ensure we answered all

Friendly fighter

Earlier in 2011, an F-22 Raptor successfully flew at supercruise on a 50/50 fuel blend of conventional petroleum-based JP-8 and biofuel derived from camelina, a weed-like plant not used for food.

The flight was the capstone of a series of ground and flight test events conducted by members of the 411th Flight Test Squadron. The Air Force selected the F-22 weapons system to be the biofuel blend flight test pathfinder for all fighter aircraft.

The overall test objective was to evaluate biofuel fuel blend suitability in the F-22 weapons system, according to officials. Testing consisted of air starts, operability, and performance at different speeds and altitudes throughout the flight envelope. The F-22 Raptor performed several maneuvers, including a supercruise at 40,000ft, reaching speeds of Mach 1.5. Supercruise is supersonic flight without using the engine's afterburner.

Officials say the flight marked another milestone for the Alternative Fuels Certification Division in support of the Air Force's 2016 goal to cost-competitively source 50% of the domestic aviation fuel requirement from alternative blends. This requires that the alternative component be derived from domestic sources produced in a manner that is 'greener' than fuels produced from conventional petroleum.

The camelina-derived synthetic fuel falls into a class of hydroprocessed blended biofuels known as hydrotreated renewable jet fuels (HRJ). HRJ fuel can be derived from a variety of plant oil and animal fat feedstocks.

90 Raptors have been delivered to the Air Force to date. The 478th Aeronautical Systems Wing is overseeing the production, delivery and fielding of additional F-22s (US Air Force photo)

Test background

The Advanced Tactical Fighter entered the demonstration and validation phase as early as 1986. The prototype aircraft (YF-22 and YF-23) completed their first flights in late 1990. Ultimately, YF-22 was selected as best of the two and the engineering and manufacturing development (EMD) effort began in 1991, with development contracts to Lockheed/Boeing (airframe) and Pratt & Whitney (engines).

EMD included extensive subsystem and system testing, as well as flight testing with nine aircraft at Edwards Air Force Base, California. The first EMD flight was in 1997 and at the completion of its flight test life, this aircraft was used for live-fire testing.

The program received approval to enter low rate initial production in 2001. Initial operational and test evaluation by the Air Force Operational Test and Evaluation Center was successfully completed in 2004.

questions," says Keithley. Of the roughly 250 members in the 411 FLTS, 80% worked on the project at one time or another.

"It has been a non-stop work schedule. It has been one of the busier times at the 411th," recalls Keithley.

In August, the squadron hosted an F-22 commander's conference, where pilots and engineers interfaced with SIB and SAB members and developed a tool to speed up data reduction and analysis.

According to Curtis, 411 FLTS engineers developed a software program that broke down raw data, extracted irrelevant information, and provided usable data faster and in a graphical format that proved extremely useful to the SIB. The tool allowed the SIB team to analyze massive quantities of data more quickly, ultimately decreasing the Raptor downtime by increasing the speed in which testers and evaluators found a return-to-flight solution.

The 411 FLTS passed all data to the SIB and SAB, which reported their findings to Air Force leadership. From the reports, Air Combat Command developed a return-to-flight solution.

"We now have enough insight from recent studies and investigations that a return to flight is prudent and appropriate," Schwartz said. "We're managing the risks with our aircrews, and we're continuing to study the F-22's oxygen systems and collect data to improve its performance." ∎

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