New Testing Methods Could Boost Air Safety

Nondestructive techniques are no guarantee against DC-10 crashes, but ways to put more science into such testing are on the way

No one yet knows exactly what caused the crash of an American Airlines DC-10 shortly after takeoff in Chicago last May. But in the aftermath of this tragic disaster enough questions have been raised concerning the McDonnell Douglas Corporation aircraft's design, the Federal Aviation Administration's (FAA) airworthiness certification procedure, and the airlines' maintenance practices to cause the grounding of all DC-10's in the United States until the plane can be proved to be safe. The economic consequences of the grounding will surely make the crash the most expensive in history.

One finding made public by the National Transportation Safety Board was the existence of a 10.5-inch-long crack in the aft pylon bulkhead before the crash occurred. (Pylons are the structures that hold the DC-10's engines to the wings.) Similar but smaller cracks have now been found in a total of eight DC-10's, and safety board chairman James King told Congress that these defects arise from an improper maintenance procedure. It has not been proved, however, that this crack was the cause of the Chicago disaster. For one thing, the aft pylon bulkhead consists of two steel plates, each of which is designed to carry the full load in the event the other fails, but the cracks found have all been in one plate, not both, in the eight planes.

A question that is worth asking is why there are so many DC-10's that not long ago were flying and now are sitting around with cracks in a critical part that are several inches long. That is, why were the defects not detected and the affected parts replaced or repaired? The not so subtle answer is that aircraft are just not thoroughly inspected very often. Moreover, although the available techniques are usually adequate in the laboratory to find cracks of the order of 1 millimeter long, these same techniques are frequently subject to misinterpretation by human operators, are not very quantitative, and are not easily calibrated or standardized when used in the real world.

Nondestructive evaluation is the process of inspecting the quality of parts that is used, not only by aircraft builders and airlines but by all makers and users of almost any product, ranging from nuclear reactors to microelectronic circuits. Nondestructive means that, after inspection, the part is undamaged and can be used, provided that no defects are found. As a recognized discipline, nondestructive evaluation is at most a decade old. According to Harold Berger of the National Bureau of Standards (NBS), universities now provide minimal professional education in the field. Moreover, says Mike Buckley of the Defense Department's Advanced Research Projects Agency, significant funding from federal agencies for research into new and improved methods based on science and not art or tradition has become available only in the past 5 years.

With a lot of catching up to do, research in nondestructive evaluation is just beginning to be appreciated, and the availability of funding is drawing some top-notch people into the field. Gary Dau of the Electric Power Research Institute, the R & D arm of the nation's utilities, estimates that in 1978 about $25 million was spent to improve old or develop new methods of inspection. Not one observer, however, believes that any conceivable inspection system could detect all structural flaws. There is no such thing as zero defects, says Buckley.

Although any electromagnetic, thermal, or mechanical property can serve as a probe of a material's state, for structural materials, mainly metals but increasingly ceramics and composites of metals and organics, widely used nondestructive techniques fall into about a half dozen categories. The first is the simple use of the eyeball and possibly a flashlight, as can be seen in reference to aircraft inspections. The first DC-10 inspections ordered by the FAA after the Chicago crash were visual.

A visit to the FAA revealed that, in addition to the normal preflight walk-around, there are four classes of inspections, A through D. The most thorough or D check is made after from 12,000 to 30,000 hours of flight. It is only in the D check that parts of the plane are regularly disassembled and scrutinized. Even at this level, however, the testing is on a statistical, sampling basis (one out of four planes selected randomly).

(In the case of the DC-10, which was certified by the FAA in 1971, the long interval between the D check and the statistical sampling mean that, as Frank Taylor, director of accident investigation for the safety board has said, it is likely that the aft pylon bulkhead was never inspected on many planes.)

There are several reasons for this approach. As maintenance people widely recognize, there is often as much chance of damaging a part during disassembly as there is of finding a defect during the inspection. The current wrangling between McDonnell Douglas and American Airlines over the proper method of removing the engine and pylon from the DC-10 more than adequately justifies this reservation. A second reason is that aircraft are simply too large to inspect in detail. Rather than wasting time and money in this fruitless task, the thrust of the inspection process is directed toward areas expected or designed to carry large loads and areas that have proved to be troublesome. Thus, said an FAA spokesman, although the whole process may sound unsophisticated, it is in fact quite effective, except in the case of isolated, random defects, which would not be caught by sampling.

It is primarily but not necessarily only in the D check that the other five categories of nondestructive evaluation find application in aircraft inspection. These methods include:

▶ Dye penetrants. A dye that can be brushed or sprayed over the area to be inspected will seep into surface cracks. After a suitable period, the surface dye is washed off, and a powdery developer is applied. The developer partially draws the dye back out of the cracks. Dyes are either brightly colored and visible to the eye or they fluoresce under ultraviolet light. Dye penetrant inspections found the cracks in the aft pylon bulkheads that FAA Administrator Langhorne Bond used to justify the grounding of the DC-10.

▶ Magnetic particles. Fine iron particles in the form of a dry powder or a liq-

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uid suspension are applied to the surface of the part to be inspected, which has been magnetized for this purpose. Defects on or near the surface interrupt the magnetic field lines in the magnetized part and likewise disrupt the particles as they try to align themselves with the field. As with dyes, the magnetic particles may be brightly colored or fluorescent.

▶ Eddy currents. A coil in a probe placed near the part to be inspected generates an alternating magnetic field. The field in turn induces eddy currents in the metal. Defects affect the electrical conductivity of the metal and thus also the eddy currents. The probe producing the magnetic field also detects these defect-caused changes in the eddy currents.

▶ Ultrasonics. In the simplest mode of ultrasonic inspection, a piezoelectric transducer launches a pulse of ultrasonic waves. Each time the pulse crosses an interface between materials with different sound velocities, part of the pulse is reflected back to the transducer, where it is sensed. Thus, there will be large reflections from the front and rear surfaces of a part. Most importantly, there will also be a smaller reflection from a defect such as a crack inside the part.

▶ Radiography. Most often x-rays, but sometimes gamma rays or neutrons are used in radiography. Defects such as cracks or pores show up as dark spots on film because the radiation passing through them is not attenuated as much as through defect-free material.

Observers agree that none of these methods is sensitive enough to detect all small flaws. Aircraft maintenance manuals recommend one or a combination of methods for the inspection of different parts of a plane. As a general rule, the FAA specifies a particular method only for certain critical areas, largely determined on the basis of accumulated service experience.

Often the techniques complement one another. For example, x-rays usually are best at detecting three-dimensional defects such as pores but are not good at finding cracks unless they are oriented in the same direction as the x-ray beam. Ultrasonics, on the other hand, detects cracks best when the crack is oriented normal to the direction of the ultrasonic pulse. Similarly, x-rays and ultrasonics can best detect internal defects, whereas dye penetrants, magnetic particles, and eddy currents are restricted to surface or near-surface flaws.

One of the principal limitations of these techniques is that they are so dependent on the operator, according to Ed Caustin of Rockwell International. Thus, the burden is on the inspector to react on the spot and make a go or no go decision on the basis of not altogether unambiguous information, such as a trace on an oscilloscope screen. But as the author of a recent book on the engineering of strucutures wrote, "Where a human life is concerned it is clearly desirable that a 'safe' crack should be long enough to be visible to a bored . . . inspector working in a bad light on Friday afternoon."* And, according to Berger at NBS, training and certification of the inspectors is mainly the responsibility of the employer.

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Automation is a way to reduce operator dependence that has become increasingly viable as the costs of mini- and microcomputers drop. A case where automation would be of immense help is the use of ultrasonics to inspect the quality of complex-shaped parts such as forgings. One problem with such parts is that, in order for the ultrasonic technique to work, the transducer must be normal to the surface of the part, clearly a difficult task if the surface orientation is continually changing.

Engineers at the Fort Worth Division of the General Dynamics Corporation have constructed a computer-controlled ultrasonic testing system for inspection of newly fabricated parts of the F-16 fighter's vertical stabilizer. The system uses a minicomputer programmed to act something like a terrain-following radar and thereby control the orientation with respect to the surface by controlling the motion of the transducer around five axes of rotation. The ultrasonic test does not begin until the computer has established that a normal orientation has been achieved. The test data are also recorded by the computer. The system is suitable for inspection of parts only after they have been removed from the aircraft or before they are put in place during manufacture.

For in-service inspections, a hand-held search unit built around a microcomputer is being developed, according to Francis Chang of General Dynamics. There is no provision for automatically orienting the transducer, but the microcomputer contains a preprogrammed inspection criterion, drives a graphics display of the test data, and stores the data on a tape cassette.

Use of computers can also help automate the interpretation of the ultrasonic signals. Although not necessarily typical, inspectors of piping in nuclear reactors have found that only about 1 in every 1000 indications of a flaw in ultrasonic testing is actually traceable to a defect. The other 999 signals are due to welds and geometrical factors. It would take a dedicated and vigilant inspector to overcome what must be a tremendous "boy who cried wolf" effect.

Researchers at Adaptronics, Inc., of McLean, Virginia, are working on a concept called an adaptive learning network aimed at overcoming this problem and thereby sort out signals from defects. By analyzing properties of the acoustic pulse other than its amplitude, such as the distribution of energy in the various frequencies in the waves in the pulse, by using signal-processing techniques to enhance the reflection of the ultrasonic signal above background noise, and by using the adaptive learning network, Adaptronics has shown the feasibility of identifying and measuring the size of cracks as small as 0.3 millimeter in the area around fasteners in aluminum aircraft parts. Moreover, the ability of this system to automatically differentiate between cracks and benign reflectors in pipe welds has been demonstrated. Now, says Tom Mucciardi of Adaptronics, field testing has begun of a hardware prototype of the Adaptronics system.

Perhaps the ultimate nondestructive test would be the ability to continuously monitor a structure as it is in service. At Battelle's Pacific Northwest Laboratories, work is under way to develop a method of doing this by means of a technique called acoustic emission. A crack emits sound waves as it grows. Cracks below a certain critical size, which depends on the material, the geometry of the crack, and the load carried by the part of the material the crack is in, are not dangerous. These so-called subcritical cracks can, over a long period of time, increase in size by fits and starts, until the critical crack size is reached and the part fractures. One way to use acoustic emission is to extend a part's life. If a subcritical crack can be lo-

*J. E. Gordon. *Structures, or Why Things Don't Fall Down* (Plenum Press, New York, 1978).

cated by some other nondestructive technique, then acoustic emission monitors can be located near the defect to listen as, or if, it grows. Only when the crack reaches a dangerous size, would the part be replaced or repaired. The problem, as always, is discriminating and quantitatively characterizing acoustic signals from growing cracks as compared with other sounds.

According to Jerry Posakony of Battelle, one experiment in progress involves a jet trainer in Australia. A plane with a known defect, which is being monitored by acoustic emission, is flown about with the object of learning what flight conditions put a load on the craft and make the crack grow.

One reason aircraft are not taken apart and inspected more often is the cost. Consider the case of fasteners. All planes are put together with hundreds of thousands of fasteners, such as rivets and bolts. The areas around certain fastener holes are highly stressed and therefore natural places to look for cracks caused by fatigue. The most reliable method of inspection is to remove the fastener and use a special eddy current technique. But in some planes, estimates Don Forney of the Air Force Materials Laboratory (AFML), the cost per hole inspected can amount to over $150, a prohibitive expense where there are thousands of critical fastener holes per plane and hundreds of planes. Moreover, fastener removal always incurs the risk of damaging the hole.

Researchers at Systems Research Laboratories in Dayton, Ohio, recently developed an ultrasonic technique that can detect cracks as small as 0.7 millimeter in the area under fastener heads, but only in the upper layer. The problem is that the area around fastener holes consists of two layers separated by a sealant, which strongly attenuates ultrasonic waves.

To penetrate beneath the sealant, AFML scientists are working on a new eddy current technique. They hope to be able to detect cracks as small as 2 millimeters long in the second layer, says Forney, by using a much lower than normal frequency, a specially designed coil, and a microprocessor to analyze the eddy current signal.

For more sensitive crack detection, ultrasonics must eventually be used. To overcome the problem with the sealant, AFML researchers are also studying a computerized signal-enhancement technique that operates in a manner similar to some advanced radars. The ultrasonic pulse sent out by the transducer is in the form of a code. On reflection, the transducer recognizes only signals containing that code, so that even the highly attenuated reflection of ultrasonic pulses passing beyond the sealant layer can be extracted from the background noise.

These and other new techniques on the way will without doubt considerably improve the sensitivity and reliability of nondestructive evaluation. Everyone agrees, however, that there are limits imposed in part by the requirements that humans must know where to look before any of the methods can be used. There is, therefore, always the possibility of a disaster because people will never be able to think of everything. Furthermore, knowledge about when a structural material will fail has an inherently statistical character, and the probability of failure can be made small but never zero.

—ARTHUR L. ROBINSON

Einstein Pictures the X-ray Sky

New satellite telescope has capabilities on par with those of the best optical telescopes

This is the second of two articles on the early results of the Einstein Observatory.

Launched only last November, the second High Energy Astronomy Observatory (HEAO-2, "Einstein") is revolutionizing x-ray astronomy just as its namesake revolutionized physics. Earlier x-ray observatories, including HEAO-1, were designed to scan the sky for x-ray emitters. With Einstein, the challenge has shifted from discovering x-ray sources to understanding the processes producing the x-rays. But having 500 times the sensitivity of previous detectors, Einstein makes more than its share of discoveries, too. For example, it sees distant quasars and clusters of galaxies that can barely be detected by the largest optical telescopes.

Einstein has opened the field of x-ray astronomy of ordinary stars. Previously only a handful of ordinary stars were observed to emit x-rays, and only one, the sun, could be studied in detail. Einstein reveals that stars of virtually all types and ages, from hot to cold and from birth to death, are x-ray sources. A big surprise is that many stars that are quite hot may have coronas, like the sun. If they do, this observation conflicts with astrophysical theory.

With only half of Einstein's intended 1-year mission completed (x-ray astronomers hope the satellite will operate longer) and only some of the data analyzed, many of the results are preliminary. Nonetheless, a variety of astrophysical insights are emerging already.

Is the universe closed, or will it continue to expand forever? This question has been boggling cosmologists for many years. According to generally accepted theory, the universe is expanding. It will reverse its expansion only if the gravitational attraction between the objects in the universe is strong enough to overcome their motion away from each other. Cosmologists would be convinced that the universe is closed if they determine that it contains at least ten times the amount of mass thought to be included in all galaxies.

To see whether there is a lot of extragalactic mass, Einstein has been taking a close look at the seemingly diffuse x-ray background radiation of the universe—radiation that comes from all directions. Evidence gathered by HEAO-1 within the last $1^1/_2$ years suggested that the background was produced by vast amounts of intergalactic gas at a temperature of 500 million degrees Kelvin. It was thought that this hot gas might be five times as massive as all the galaxies—nearly enough mass to ensure a closed universe. But Einstein has not found the gas.

Einstein looks at the background by peering at patches of sky where there are

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