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QUANTITATIVE NONDESTRUCTIVE EVALUATION - REQUIREMENTS FOR TOMORROW'S RELIABILITY

Joseph S. Heyman
NASA Langley Research Center
Hampton, Virginia 23665-5225

ABSTRACT

Quantitative Nondestructive Evaluation (QNDE) is the technology of measurement, analysis, and prediction of the state of material/structural systems for safety, reliability and mission assurance. QNDE has impact on everyday life from the cars we drive, the planes we fly, the buildings we live/work in, literally to the infrastructure of our world. In this paper, we will highlight some of the new sciences and technologies that are part of a safer, cost-effective tommorow. Specific technologies to be discussed are: thermal QNDE to aircraft structural integrity, ultrasonic QNDE to materials characterization, and technology spin-off from aerospace to the medical sector. In each case, examples will be given of how new requirements result in enabling measurement technologies, which in turn, change the boundaries of design/practice.

INTRODUCTION

In our ever increasingly complex world, we must rely on the integrity of our surroundings for safety, reliability and economy. That is equally true for ballpoint pens, computers, cars, power plants, or hypersonic vehicles. Although all premature failures are undesirable, the associated risk can range from annoyance to catastrophe. A critical vitalized technology, quantitative nondestructive evaluation (QNDE), is bringing new reliability to industry starting with design concepts, prototype verification, process control, end point inspection, and in-service inspection leading to maintenance repair, or retirement-for-cause. In this paper, several recent NASA developments are highlighted, which are ready for technology transfer and application.

Design takes advantage of QNDE in the fine tradition of concurrent engineering. Using CAD (computer-aided design) tools, a proposed design can be evaluated for inspectability based on realistic QNDE techniques: for example, ultrasonics, magnetics, thermal, or radiography. In addition, a probability assessment for missing a flaw can be established and used for fracture mechanics predictions of safe-life. Therefore, before metal is cut (or polymers are cured), one can start with a basis of design reliability.

A second stage in most product development is prototyping. Again, QNDE plays a critical role helping to characterize fabrication problems, stress profiles, design shortcomings, and degradation occurring in accelerated life testing.

The third stage is process monitoring, which is a key cost-effective approach to catching problems before and during fabrication by applying feedback to the process thereby raising overall quality. For example, ultrasonics can monitor the degree of cure and viscosity of polymer systems during manufacturing.

After fabrication, for critical structural elements, it is often desirable to verify integrity. Such verification may require geometry or material property tests. Again, QNDE can check detailed geometry with data from a three-dimensional x-ray CAT (computer axial tomography) scanner compared to CAD design drawings. Material properties can be assured through physical measurements of stiffness (using ultrasonics and x-ray), density (CAT), and fiber orientation (ultrasonics or thermography). Flaws can be found, sized, located, and assessed using structural mechanics to predict the impact of such findings on performance.

Finally, life cycle costs can be reduced while safety and reliability is improved if QNDE is applied during appropriate intervals throughout the element's service life.

QUANTITATIVE NDE TECHNOLOGIES DEVELOPMENT/TRANSFER

In this paper, several recent developments in QNDE are highlighted. In each case, these developments resulted from well defined needs. Typically, physical models of the proposed concept were developed to guide and focus the experiments needed to verify the approach. The models permit optimization of approaches before major investments are required for experimental hardware. During the evolution of these concepts, there is a constant interplay between experimental data and model predictions--moving step-by-step through the process of development. If tests are successful, a prototype instrument is built and tested on real (or realistic) hardware.

Technology developed in this "model first" fashion holds great promise for transfer to industry. First, the data generated by this process is quantitative, science based and therefore more readily interpreted through the model. The market potential is usually broad since the solution tends to be generic--that is, it can be applied to other similar problems by changing elements in the model to identify how to modify the instrument. In contrast, correlative development approaches tend to work only on the problem at hand and require extensive testing if any of the variables are changed. The technologies highlighted here have been brought through the outlined process and as such represent reduced risk opportunities for U.S. industry. The successful transfer is of benefit to NASA as well as to the company involved. New QNDE developed by NASA is of maximum value when it is commercially available to NASA and its contractors through a company source. The applications of these technologies is usually to a broad sector of which aerospace is but a small part. Thus, there is benefit to all parties involved.

SPECIFIC TECHNOLOGIES - THERMAL QNDE

Thermal QNDE has many benefits for inspection [1,2]. It can be noncontacting, view large areas at a single time, and result in cost-effective measurements for practical structures. The method finds flaws through their effect on heat flow in objects. In one rendition of the technique, some form of heat energy is injected into a surface--optically, electrically, with hot water or with some other method. Only a few degrees temperature difference is required. The infrared (IR) radiation emitted from the heated surface as a function of time is monitored with an IR camera and its image is stored. The acquired data is processed based on a physical model of the tested object to interpret the temperature data to reveal hidden internal structural information. Techniques have been developed to minimize spurious effects such as background reflections, nonuniform heating and surface emissivity variations (related to the efficiency of a surface to emit radiation).

A typical measurement setup is shown in figure 1. In this situation, quartz lamps are used as a heat source and a digital image processor is used to acquire and process the data. The system is under computer control such that the heat input/data acquisition has been optimized based on simulation analysis using material properties and geometry of the tested structure.

An example of the utility of this approach is shown in figure 2. The image is of a flat aluminum plate of 0.040" thickness bonded to a second plate that has been cut to form letters spelling out "NASA LaRC NDE." The letters simulate hidden damage as might occur from fatigue or corrosion.

Figure 2a is a normal photograph of the plate while figure 2b is an image obtained from LaRC's thermal QNDE system clearly "seeing" through the plate to the hidden back surface letters.

Figure 3 demonstrates a practical application of this system for imaging the internal structure of an airplane fuselage. Figure 3a is a mechanical drawing of the internal fuselage showing the waffle-like design while figure 3b shows the ability of the QNDE approach to help assess the integrity of structural elements by "seeing" through the outer skin to the hidden internal structure.

LaRC has developed and applied thermal QNDE approaches to a wide array of problems ranging from diamond film coatings on electronic materials to solid rocket motor insulation adhesive bonds. In each case, the problem is first analyzed, then modeled, and a testing approach developed/optimized. Many problems are so similar that test protocols can be developed by a simple modification of previous approaches. This technology has high promise for development, sales, and service.

SPECIFIC TECHNOLOGIES - BOLT TENSION MONITOR

The lowly bolt may seem to be a strange component for advanced high technology--until one realizes its importance in many critical applications. From bridges to aircraft, integrated power circuits to power plants, bolts are transformed from crude mechanical devices to precise "instruments" required to do their job. In many situations, a bolt failure can have catastrophic consequences. The difficulty in tensioning fasteners is that one cannot easily and directly measure the clamping force exerted by a bolt. Instead, that value is inferred from other measurements such as torque. Torque in particular does not measure what a bolt does: it only measures "twist." Frictional variations make torque an inaccurate tensioning method resulting in errors that can be appreciable [3]. Shown in figure 4, is a plot of a space-quality fastener tensioned 20 times to a desired load of 46,000 pounds force. Note that the torque to achieve that load varies by over 200 percent during the tensioning sequences!

To overcome these problems, NASA LaRC has developed a bolt tensioning monitor that more directly measures the force in the bolt [4]. The technique is based on ultrasonic propagation inside the bolt. In contrast to some ultrasonic systems which measure time, this device measures the acoustic phase shift which accompanies bolt tension as the bolt gets longer (similar to a rubber band, a bolt doesn't perform its function unless it is stretched). Figure 5 shows the superior accuracy of ultrasonics over torque for the tensioning of fasteners using different lubricants to vary friction. Whereas the torque curves vary dramatically for each lubricant tested, the ultrasonic curves are nearly identical for all tests.

The LaRC system, shown in figure 6 is a computer-based ultrasonic instrument ready for field applications. Important data is taken during bolt clamp-up and is archived in the device's memory. After the day, the memory card can be removed and the records of all fasteners tensioned can be stored for future reference to insure integrity. Furthermore, at some later time, the fastener tension can be recertified to insure it has not relaxed in-service. The technique is fairly forgiving of bolt geometry since it uses a frequency wave which propagates more "well behaved" than a pulse which contains all frequencies. This system is at the prototype stage and will be transferred to industry through one of our technology transfer mechanisms such as licensing or a joint development agreement.

SPECIFIC TECHNOLOGIES - MEDICAL TECHNOLOGY TRANSFER

NASA scientists and engineers are made aware of critical non-aerospace problems affecting other sectors of the national infrastructure to maximize Agency technology transfer opportunities. One mechanism for that awareness is the Technology Utilization Program which circulates listings of problems brought to NASA's attention by other agencies, industry, and universities. Often, when an expert in another field identifies a problem, it is identified as a request for a specific measurement rather than a well defined problem statement. Working with the individual, however, the measurement science people help identify the nature of the problem and thus focus on a direct path to its solution.

Bladder incontenence is an example of a medical problem brought to our attention that afflicts millions of Americans today. The problem was identified as a requirement for measuring the diameter of the bladder to determine its fullness to alert a wearer of the need for elimination. In looking at the problem, it was determined that the stated solution based on bladder diameter was already in use, but additional unstated complexity compromised its success. The problem needed to be approached differently.

The bladder is not a simple inflating sphere. Therefore, a measure of the front to back surface diameter is not a reliable indication of fullness. Instead, the bladder is more like a slightly elastic pouch whose geometry differs from person to person. One of the major changes that occurs during distension, is the tension in the bladder material itself. It varies from a flaccid film to a stretched membrane. Ultrasonics, incident on the bladder, is transmitted to back surface tissue easily when the bladder is full. When empty, the bladder wall scatters/attenuates acoustic energy resulting in a reduction in the reflection/reverberation at the back wall. This, in turn, reduces the measured signal amplitude which is identified as an empty bladder.

Figure 7 shows a block diagram of the bladder monitor developed for this program [5]. It is a self-contained ultrasonic system. It launches an ultrasonic wave into the bladder, digitizes the returning signals, stores the waveform in multichannels, compares the signals with stored patient training signals, and, if necessary, alerts the wearer to bladder fullness. In actual practice, the device spends most of its time "asleep" extending its battery life, waking up to take measurements on a periodic basis.

The wearer can be alerted by several modes of communication: audio, visual, tactile, and remote. When triggered, the audio device sounds a small alarm, the visual device lights a small LED in the wearer's glasses, the tactile device taps the skin, and the remote device sends a radio wave to a separate station (operated by a care-giver) and sounds an alarm remotely.

Figure 8 shows the bladder distension device concept interrogating a nearly empty bladder (top) and a full bladder (bottom). As the back wall undergoes tension, it results in an increase in reverberation which is detected in the ultrasonic response. The monitor takes several features into account in alarming for a full bladder. The device determines a scan value which is a function of the distance from the bladder front surface to the back surface multiplied by a weighing constant modified by the energy return in the reverberation signal. The scan value is computed for each wearer as an alarm threshold thereby personalizing the operation of the system. In operation, the threshold must be achieved several times in succession to indicate bladder fullness. Such redundnacy reduces the potential of false calls.

In another medical technology transfer, a problem was identified requiring measurement of internal body temperature during hyperthermia treatment of cancer patients. The current practice involves multiple invasion of the region with thermocouples, often repeatedly, to determine the temperature profile around the tumor. Instead, LaRC suggested using ultrasonics to monitor the phase transformation of a wax material injected near the tumor site [6]. The wax can be prepared to melt at the desired treatment temperature and to remain at the tumor site during the entire treatment period. As the wax melts, its acoustic impedance changes which can be determined noninvasively as a large ultrasonic signal fluctuation indicating that the heating has reached the desired treatment level.

Figure 9 shows a concept drawing of the temperature monitoring device with data indicating the effect of heating the tumor to the wax melting point. The top part of the figure shows the ultrasonic data for unmelted wax. The high difference in impedance between the wax and the surrounding tissue reduces the amplitude of the signal reflecting off of the tumor. In contrast, after the wax melts, as is shown in the lower part of the figure, the reflection off of the tumor is large. Therefore, the proper temperature for treatment can be maintained by observing the state of the wax and controlling the heating power accordingly.

SUMMARY

These are but a few of the many opportunities in the field of quantitative nondestructive evaluation for technology transfer through one or more of the many mechanisms available through NASA. Such transfer is of value to the receiving industry tapping the intellectual resources of our National labs. In addition, the transfer is of value to the Agency bringing needed technology to commercialization so that it can be widely utilized by NASA and its contractors. In addition, the access to state-of-the-science QNDE technology brings value to the public sector through improved safety, reliability, and cost-effectiveness in addition to the synergism of accelerating applications for non-aerospace industries.

ACKNOWLEDGEMENTS

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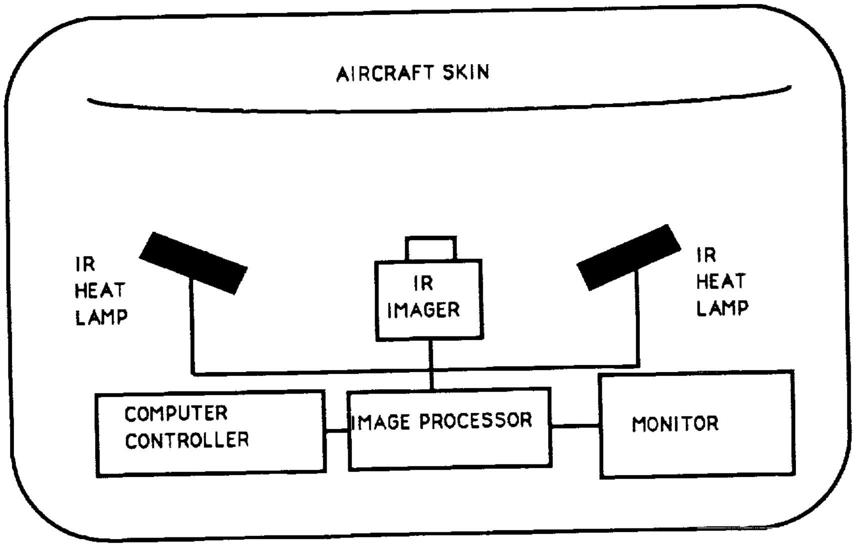

Figure 1: Thermography NDE Measurement System

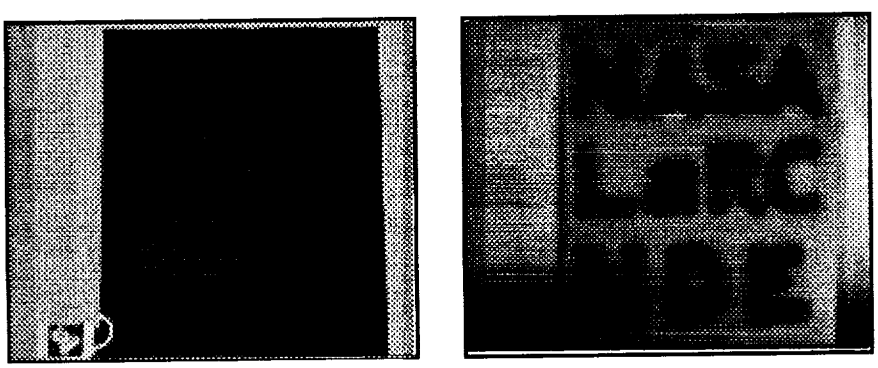

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Figure 2: Front Surface of a Test Panel.

(A) Normal Video Camera

(B) LaRC Quantitive Thermal NDE Measurement System

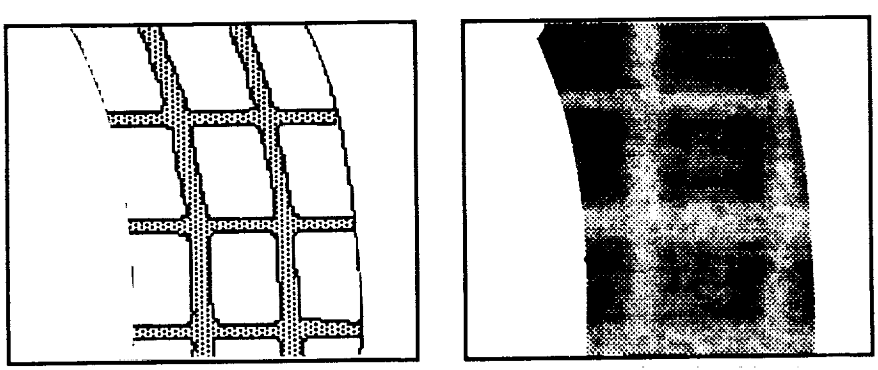

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Figure 3: Aircraft Fuselage Subsurface Structure.

(A) Shaded Areas are Structural Strengtheners

(B) Doublers as Imaged by QNDE System for Integrity Assesment

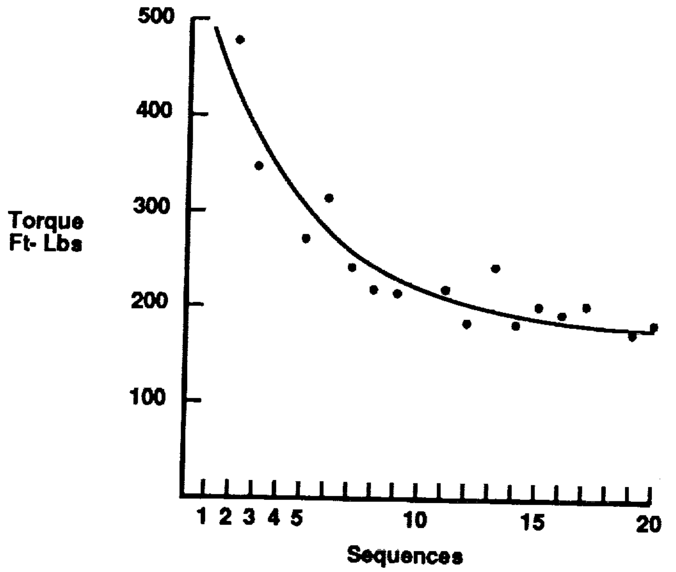

Figure 4: Effect of Multiple Tensioning Sequences on Friction

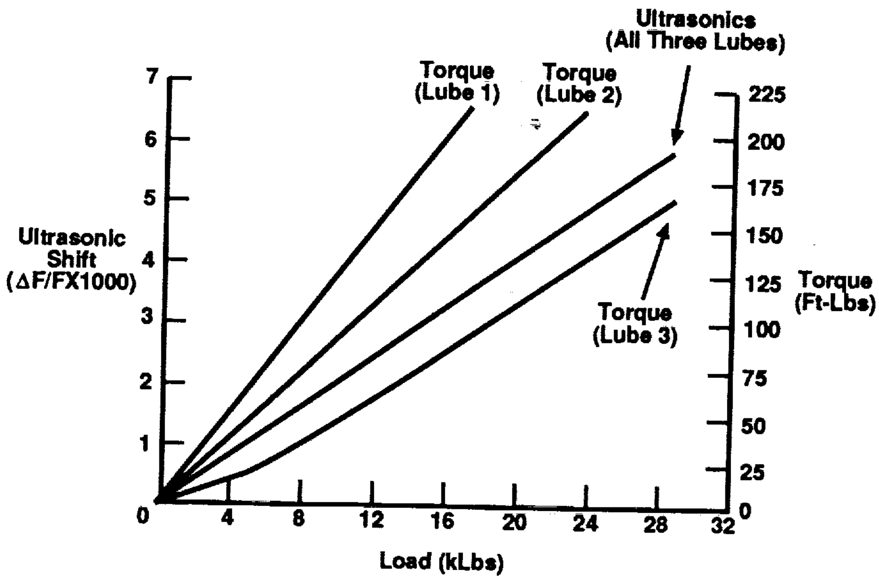

Figure 5: Comparison of Tensioning with Torque Versus Ultrasonics for Different Lubricants

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Figure 6: Field Portable Bolt Monitor Shown with Testing Apparatus

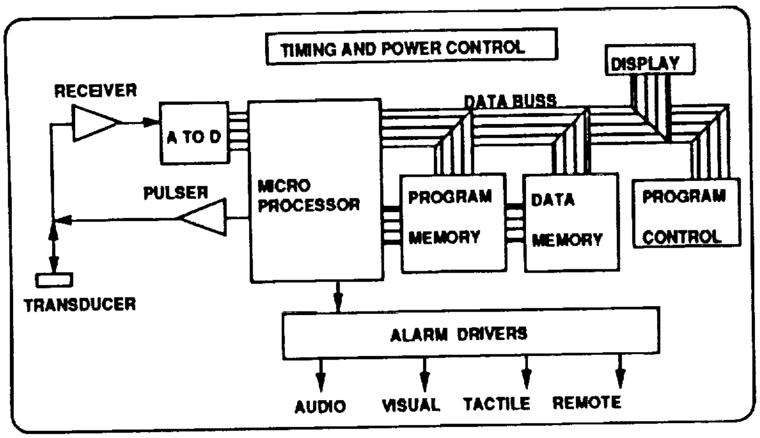

FIGURE 7 ULTRASONIC BLADDER DISTENSION MONITOR BLOCK DIAGRAM

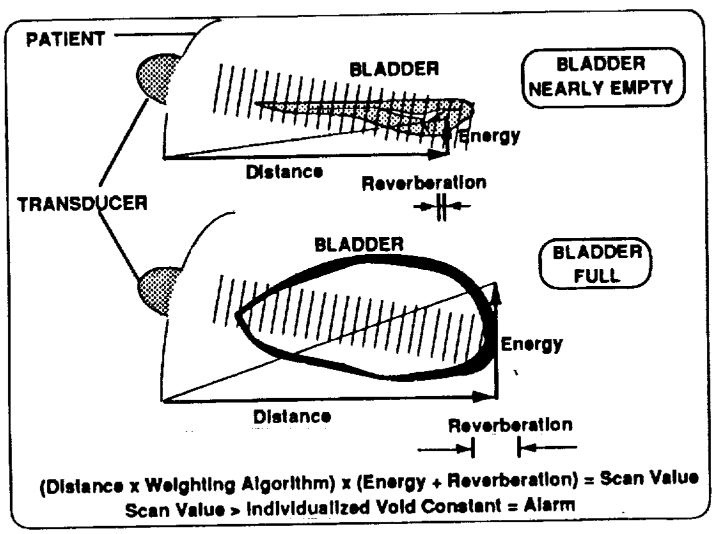

FIGURE 8 ULTRASONIC BLADDER DISTENSION MONITOR CONCEPTIONAL DIAGRAM

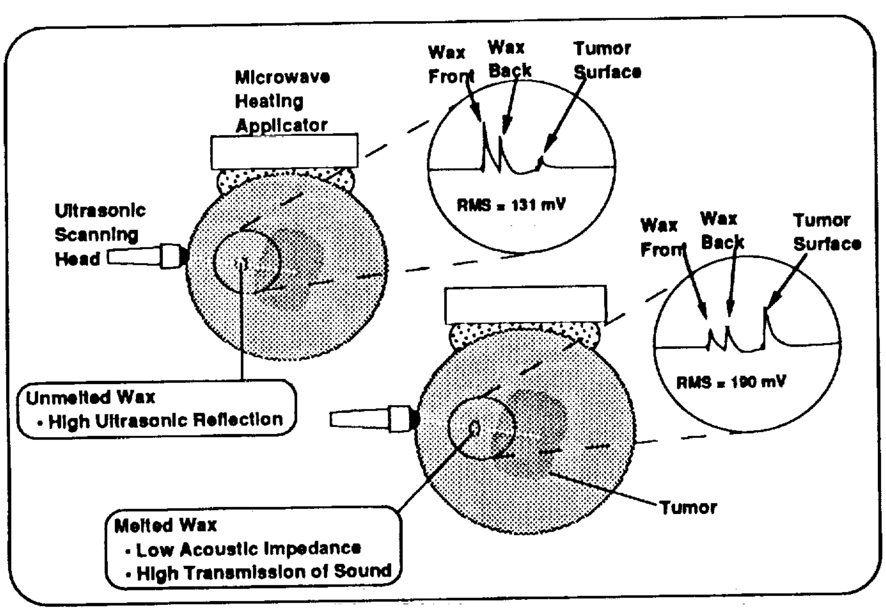

FIGURE 9 ULTRASONIC TUMOR TEMPERATURE MONITOR CONCEPTIONAL DIAGRAM

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