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Recent Developments in Health Appraisal and Life Extension of Mechanical Systems

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Abstract—Learning from the failure of mechanical systems is a necessity, given that it is the understanding of how and why things fail that generates effective redesign. This subsequently enables the technology that surrounds us to become more reliable, safer, and more economical by extending component life and minimizing the wasteful decisions made to replace systems that are either sound for continued operation could be easily repaired. Considerations for cost-effective decision making, so as to promote healthy machinery, equipment, and structures, are discussed in terms of learning from failure analysis, improving via reliability engineering, and achieving longevity through integrated diagnostics.

1. Introduction

For as long as there have been engineered structures and systems, there have been maintenance issues, uncertainties regarding reliability, and unanticipated failures. The impact of such problems can be devastating, and may be worse today than in past centuries because more can go wrong in our technology-driven society. Airplane crashes and railway disasters, for instance, would not be possible without the scientific breakthroughs enabling jets and trains to exist.

The cause of most mechanical faiures is generally attributed to either a) negligence during the design, manufacture or operation of the system or structure, or b) application of a new material or design that produces an unexpected result. For the former, existing procedures are sufficient to avoid catastrophe, but are not followed due to human error, ignorance, or misconduct. The latter cause of failure is much more difficult to prevent. When an improvement is introduced, there are invariable factors that the designer did not anticipate.

Fortunately, advances in reliability engineering have offset some of the potential dangers posed by engineering creativity. The understanding of how materials fail and the ability to prevent such failures has increased considerably since World War II. The purpose of this treatise is to review the progress which has been made in reliability through the recent decades, and offer insights into those technologies that offer promise in enabling the health of mechanical systems to be monitored in real-time throuth integrated predictive diagnostics.

2. Learning from Failure Analysis

When something fails, the limitations of a design may be quickly understood. Success tells little of the limitations. It only enables one to see possibilities for reducing conservatism by subjecting the system to more demands. It is only in failure that boundaries are defined and it is typically because of failure that the approach to design is altered. Much can be learned from probing failures to their root cause. The knowledge gained can be used to increase safety and reliability, and decrease manufacturing and operating costs.

Failure analysis methodologies have progressed to the point of becoming somewhat routine. Many books have been written and many short courses have been offered to teach how to conduct a failure analysis. The basics are straight forward. It is imperative that evidence be catalogued and all steps and parts be fully documented to preserve a thorough record.

Before defining the analytical steps required for a particular analysis, one must first determine why the analysis is to be performed and what will be done with the information gained. For instance, will the failure mode information be used to model the failure, such that time-to-failure can be predicted for other, similar designs? This may enable the implementation of a more effective maintenance schedule. Or, is how the component behaves in its environment the objective? This may lead to a longer service life. Perhaps, results from a study may suggest that the component or system needs to be redesigned. Given the right objective, there are many different techniques available for an analysis and someone trained in conducting one will know which are best suited for a particular cause.

Upon meeting the objective of a failure analysis by identifying the source or mechanism of failure, the results should ultimately impact some aspect of the product's design, manufacture, or use. Three such areas of significance include the development of new design approaches, the creation of redesigned configurations for improved safety and reliability, and the justification for service life extension.

2-1. Developing a New Approach

Based on historical successes with mechanical systems, designers will tend to push-the-limits on new systems or structures, so as to improve functionality or decrease cost. Through failures and subsequent analysis, the real behavior of a new design is better understood.

An analysis that changed the approach to the mechanical design stategy of ships was attributed to the failure of Liberty ships during World War II. Liberty ships were designed to be built quickly and at a low cost by using welds instead of rivets. Large sections of steel plate were welded together to form the ship hull. The all-welded structure was a resounding success, until one of the vessels broke in two while sailing between Siberia and Alaska. Subsequent fractures occurrred in other ships. Investigations revealed that the failures were caused by a combination of three factors: 1) the welds, produced by a semi-skilled work force, contained crack-like-flaws; 2) most of the fractures were initiated at local stress concentration sites; and 3) the steel used had poor toughness. The steel in question had always been adequate for riveted ships because fracture could not propagate across panels that were joined by rivets. A welded structure, however, is essentially a single piece of metal; hence, propagating cracks encountered no significant barriers.

Development of the field of fracture mechanics and the incorporation of fracture mechanics analysis into the design phase of components and structures came about largely because of the failure of Liberty ships. Test methodology (to fully identify the brittle fracture characteristicdes of materials) and stress analysis techniques (to better predict brittle behavior conditions) are stuctural behavior that led to catastrophic failure in conditions that were not understood at the time of the inital design.

2-2. Creating a Redesigned Configuration

Analyses of failures typically do not result in far reaching changes in the approach to design. Information is most often incorporated into newer, more failure-safe redesigns of the components.

A high-profile analysis that changed the design of aircraft in the early 1950's was conducted on several de Havilland Comets. This was the first passenger aircraft built to fly at altitudes great enough to require pressurization of the cabin. Several of these aircraft failed in mid-flight after only flying 900 to 1250 flights. This was well under the amount thought at the time to be required for enough accumulation of fatigue damage to cause failure. At first, severe weather was blamed, but as pieces of one of the failed aircraft were recoverd and examined, fatigue crack initiation at a rivet hole near the corner of one of the squarish windows on top of the aircraft was observed. Cracking proceeded aft from the window to a circumferential stiffener, then followed the stiffener circumferentially until the skin peeled off the aircraft causing catastrophic failure of the structure. Stress analysis of the window and rivet geometry showed stresses were increased at this location. Subsequent fatigue testing showed that fatigue failure could occur at even low numbers of cycles with this particular design. The information was used to redesign the aircraft to include only round windows and to increase the safety margin at rivet holes.

2-3. Justifying an Extended Service Life

In designing a system, the engineer usually begins with a goal for the length of time in which the system is expected to function safely with little maintenance. Geometry and material are then specified to satisfy this target. By making assumptions as to flaw sizes, the environment, and conditions of operation, predictions concerning the behavior of the system over its lifetime are made.

Extension of life beyond this early goal is becoming common practice as a better understading of material behavior and test methods to simulate service conditions occurs. This suggests the importance of basic studies associated with the effects of long-term cyclic or static loading, and of the role that environmental variations have on failure mechanisms. By conducting failure analyses, the increase in expected failure-mode knowledge can be incorporated into models and databases, so as to enable more accurate predictions of component behavior over time. Improving the accuracy of such models permits one to determine when inspection intervals should be conducted, and safely stretch the service life of aging systems without a major increase in cost.

Examples of items having life extension programs include nuclear power plants, bridges, aircraft, and manufacturing equipment. Such diverse systems depend on accurate failure analyses, permitting a course of action to be taken with respect to inspection, modeling, and diagnosis.

3. Improving VIA Reliability Engineering

Reliability is concerned with failures during the life of a product. To evaluate it, one needs to know when and why systems or structures fail. Because of the uncertainty associated with applied stress and strength, the concept of probability is often used to describe reliability. Reliability is usually defined as the probability that an item will perform a required function without failure under given conditions for a period of time.

Reliability engineering, as an engineering discipline, originated in the aerospace industry during the 1950's when failure rates of military electronic systems resulted in limited supply and high life-cycle costs. With an emphasis on data collection, statistical analysis, and reliability testing, methods for analyzing life data advanced. Probabilistic risk assessment was developed, utilizing the event tree, fault tree, and various risk-consequence techniques. This methodolgy found favor with the nuclear power industry during the 1970's.

Recent emphasis in reliability engineering has been placed on robust design. By definition, a robust design is one where its performance is minimally sensitive to uncontrolled variables. Therefore, one must have an understanding of which parameters have a major effect on the system's performance. Given complex and competing failure modes, sufficient insight to identify these factors is difficult; hence, a statistical design of experiments approach is often recommended. Engineering judgment is used to develop a factorial experiment, where data, provided by computer simulation and/or actual hardware testing, is analyzed using variance techniques. Through the mathematics, an understanding of the sensitivity of the design to each factor or interaction of factors results. By being attentive to the identified characteristics which significantly impact the product, reliability improvement and life extension may be achieved.

Most reliability studies have shown that failures are frequently induced through manufacturing processes. Stresses and temperatures during manufacture often exceed the maximum values for which the system is made. A basic design may be adequate on average to withstand design stresses, but variations may sufficiently increase the variance of strength so as to increase the probability of failure. This is particularly true for the effect of dimensional tolerances. Hence, and objective of reliability engineering is to have control of the process through quality inspections and screening.

Reliability demonstration testing has often been required for military systems; however, as reliabilities increased, test time correspondingly increased and demonstration testing became less practical. An alternative to demonstration testing is to continuously monitor the system or structure during the development stages so that weaknesses are quickly identified. The process enables misapplied parts to be found and replaced, design errors to be corrected, and defects associated with workmanship or manufacture to be eliminated. Accumulating test data from different environments during the design process is not simple, but is necessary to provide insight into the behavior of the item of interest.

4. Achieving Longevity Through Integrated Diagnostics

As systems and structures age, opportunity for replacement is often discouraged due to financial constraints. As a result, and expectation of keeping aging systems in service using probabilistic techniques has emerged. This, in turn, has elevated concern that poor performace, inadequate safety, and increasingly expensive maintenance will result.

To respond to this technological challenge, pending failures must be identified before disastrous consequences occur. Incipient failures, are hard to locate, and current maintenance systems have only limited capabilities to do so. Today's systems rely mainly on time-based inspection, which requires that items of interest be inspected at specified intervals, and be replaced when deemed unfit for service. A more effective and efficient alternative to time-based inspection is to continuously monitor critical components. This necessitates an understanding of Integrated Diagnostics, a term associated with the technologies and methodologies used to determine how mechanical failures occur, and how they can be detected, predicted, and diagnosed in real-time.

Activity in this area has primarily focused on mechanical fault diagnoses and lubricant degradation studies. For the former, mechanical vibration sensors, attached to critical components, provide signals which can be assessed through automated pattern recognition. A sudden change in the signal implies a change in system performance. For the latter, the severity of wear debris is determined through oil analysis. Both tehniques have limitations, and may not be the best indicators of pending mechanical failure.

In order to have progress in real-time health monitoring, the physics and chemistry of moving components subjected to high temperature, and corrosive environments need to be better understood. In addition, and assessment must be made as to which variables of state (temperature, pressure, etc.) play a role in signaling the onset of a given problem. Sensors and signal processing methodology must also be developed for providing information to an intelligent decision support system (perhaps utilizing neural network technology) and/or a human operator.

Such research needs could be categorized as follows:

(1) Failure Detecton and Identification - the study of deterioration mechanisms and techniques to detect the initiation of fractures and other failures.

(2) Failure Prediction Methodology - the study of methodology for failure prediction in real-time, including modeling fault initiation and failure signatures, and observing the propagation and fracture phases of fatigue-based failure.

(3) Direct Sensing, Analysis and Diagnosis - the study of responses to signals early in fault inception, including research of sensors that can be placed at critical sites on mechanical systems for response to changes in variables of state or vibration.

Since many vehicles in the U.S. armed services are approaching middle age, the U.S. Department of Defense through the Office of Naval Research has invested in two research centers for the purpose of focusing attention on the aforementioned thrusts. Based at the Georgia Institute of Technology, a Multi University Center for Integrated Diagnostics (CID) was formed in March 1995, supported by faculty and staff from Georgia Tech, the University of Minnesota, and Northwestern University. A second center is housed at the Pennsylvania State University with team members from Penn State and the Rensselaer Polytechnic Institute.

4-1. MultiUniversity Center for Integrated Diagnostics

Organized by thrust area and project, twelve research activities are presently being pursued by the Georgia Tech MultiUniversity Center in failure mechanics, ground-based maintenance techniques, and real-time failure mechanical, civil, selectrical, and materials engineering disciplines. Education of graduate students in this cross-disciplinary area, and collaboration with industry are priorities of the Center. Themes of the individual projects being pursued are listed below.

- Study of Acouctic Emission and Transmission from Incipient Fatigue Failure
- Crack Detection in Annular Structures through Ultrasonic Guided Waves
- Detecting Mechanical Seal Failure in Turbomachinery
- Development of a Fiber-Optic Technique for Flaw Characterization
- Acoustic Emission Modeling
- Failure Prediction Methodology
- Propagation Behavior of Cracks
- Integrated Microsensor Development (MEMS

Technology)
- Eddy Current Microsensor Development
- Monitoring of High Harmonic Oscillations in Rotating Machine Elements
- Dynamic Metrology as a Wear Diagnostic
- Sensor Development using magnetic-Electrical-Impedance Tomography

5. Conclusion

Any study associated with the longevity of a mechanical system should first identify the critical elements that are bound to fail. For each critical element, one must consider the mechanism of failure, and if possible, develop a general failure model which could serve as a guide in selecting the best sensors to detect faults or pending failures. Then, one must develop a means to analyze and correlate sensor output, so as to provide the human operator and/or intelligent decision support system with reliable information about the state of the system in real-time.

It is hoped that, upon reading this review, some will be encouraged to carry out additional work to further extend the knowledge of failure detection and identification, failure prediction methodology, and direct sensing, analysis, and real-time diagnosis. It is also wished that some will recognize the value of what has already been achieved, and will thereby be encouraged to apply the current technology associated with failure analysis, reliability engineering, and integrated diagnostics to developing innovative health appraisal and life extension plans for mechanical systems.

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