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Sensitive Stress Analysis via Reliability Enhancement Test for Mechanical Aerospace Products

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***Abstract*—With advancements in aerospace technology, the development goal of future mechanical aerospace products is to create low-cost, high-reliability, and generalized products to satisfy the requirements of different mission profiles. However, traditional development tests for mechanical products are typically not implemented under environmental conditions or operational stress beyond the design limit. Hence, they cannot obtain the design and working limits of the product. Consequently, providing quantitative support for the adaptability of the developed product is difficult. With the increased development needs of mechanical aerospace products, sensitive stresses affecting product quality have been identified in this paper by analyzing historical quality problems of similar products and promoting FMEA analysis. The analysis of sensitive stress via a reliability enhancement test for mechanical aerospace products has been proposed to fully stimulate weakness of mechanics and improve the inherent reliability of products through design improvements.**

Keywords*—aerospace; mechanical products; reliability enhancement test; sensitive stress

I. INTRODUCTION

The aerospace industry uses several types of products such as structures, mechanisms, pyrotechnics, electricals, and electronics. Statistical analyses show that the quantity of non-electrical products accounts for approximately 44.3% of the total required products. Improving the reliability of non-electrical products and reducing the probability lower quality products needs to be analyzed during product design considering current high-density emission and high development requirements of high quality, low cost, and generalization. Traditional development tests for mechanical products are not typically implemented under environmental conditions and working stress beyond the design limit. Hence, the design and working limits of the products cannot be obtained. Consequently, providing quantitative support for product adaptability is difficult. With the progress of aero-space technology, development goal for future aerospace mechanical products is low cost, high reliable and generalization that satisfies the requirements of different mission profiles. Therefore, identifying the environmental and working stresses that have a significant impact on the reliability and safety of the mechanics before test implementation is necessary. By applying environmental or working stress to the developed products, potential defects can be rapidly stimulated and addressed via design improvement, resulting in improved product reliability.

The reliability enhancement test (RET) has been widely implemented in electronic and electromechanical fields because of lower cost, shorter test time, easy simulation of defects, etc. By applying temperature step-stress, vibration step-stress, and temperature-vibration stress, previous design defects of electronic products will be stimulated [1,2].

However, only a few studies have been conducted on non-electrical product RETs. Since RET stimulation efficiency is determined by sensitive stress, identifying the sensitive stress affecting the entire task profile of the product is the basis for formulating RET implementation plans. By analyzing historical quality problems and promoting FMEA analysis of corresponding products, sensitive stress will be identified through statistically considering the primary influencing factors leading to the failure of non-electrical products. This is intended to guide RET implementation and method studies.

II. OVERVIEW OF RET

A. Development of RET

An RET is a type of accelerated reliability test designed to rapidly stimulate product weaknesses and expose flaws in product designs. This test is different from design verification or qualification tests as they are implemented to verify successful product operation under the specified environmental and working conditions. They emphasize more on design compliance verification, and failures are not expected. In the early 80s of the last century, although environmental stress screening (ESS) saw rapid development and wide implementation, several potential design defects in products could not be stimulated. Accordingly, G. K. Hobbs, K. A. Gray, L.W. Condrad et al. proposed the

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highly accelerated life test (HALT) and highly accelerated stress screening (HASS), which aimed at stimulating design and process defects by progressively increasing stress and making design improvements to eliminating these defects and improve product reliability [1]. The methods mentioned above can be attributed as the predecessor to RET.

The Boeing Company conducted the RET on Boeing 777 aircraft equipment in 1955 and achieved remarkable test effects. By implementing step stress and accelerated life tests to 40 LRUs, 239 faults were stimulated. Statistical analysis showed that 64.85, 30.54, and 4.6% of these faults were stimulated by step stress tests, accelerated life tests, and workstation failure, respectively. Further statistical analysis concluded that design defects, process defects, and component failures could result in 34.1, 36.36, and 15.9% of faults respectively.

By analyzing 1,000 cycles of engineering tests of the Boeing 777 aircraft, The Boeing Company quantitatively evaluated the effect of RET implementation. The replacement rate of 217 sets of LRUs with RET implementation was only 4%, which is much lower than the 35% replacement rate of the 173 sets of LRUs without RET. A lower replacement rate significantly reduced product maintenance rate, shortened product development cycle, lowered product cost, and improved the reliability level of the Boeing 777 aircraft [3,4,5]. This practice demonstrates that RET can effectively stimulate product design and process defects.

Currently, several research reports in China have conducted RET on electronics. Liu Wenxing et al. summarized the use of RET in the development of aero engines, resulting in the discovery of 70 faults including the falling off of the temperature sensing element shell, controller FLASH reading and writing abnormality, de-welding of the speed sensor, the fuel pump regulator valve breakage, and start-transmission gear system cracking. The statistical analysis discussed further in this paper indicate that 40, 35.7, 18.6, and 5.7% of the failures result from improper manufacturing process, design defects, material defects, and other problems, respectively. By implementing targeted improvement to products, the reliability of the areo-engine was significantly improved [6].

Considering non-electrical RET research, Yanfeng Yang [11] and Junqi Qin [12] from Ordnance Engineering College used numerical simulation methods to analyze an RET of a pulley mechanism and cylindrical coil spring. Yanfeng Yang [11] et al. considered the wear fatigue failure mode of the pulley mechanism as the research object and used the numerical simulation method to study the reliability enhancement tress effect of the pulley mechanism by increasing the spring stiffness and changing the contact load between the pulley and the shaft. The simulation results show that the applied enhancement sensitive stress could be effective in stimulating fatigue failure and provide technical support for the implementation of RET.

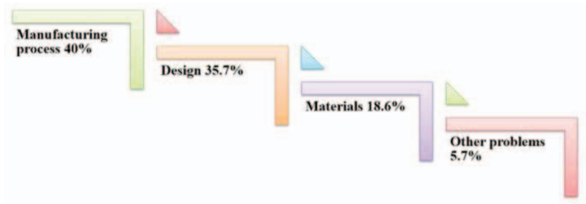

Fig. 1. Proportion of failure in aero-engine RET [6]

B. *Theoretical Basis of RET*

RET is a type of special accelerated test generally studied based on the failure physics theory. Robert W. D. and Qual Mark extensively worked on reliability enhancement stress efficiency and research techniques [7, 8]. GB/T 29309 (Accelerated stress test procedures for electrics: Guidelines for highly accelerated life tests) has been formulated in China to guide RET implementation. In addition, IEC 62506 (methods for product accelerated testing, 2013) provides guidelines on the application of various accelerated test techniques for the measurement or improvement of product reliability and can be used to identify product defects caused by manufacturing processes or design errors. In addition, it can be used to evaluate the effect of RET implementation.

Contemporarily, stress-intensity interference theory and cumulative damage model are widely used in RET studies [10]. Products suffer from various environmental stresses during practical application such as temperature, vibration, thermal/mechanical impact, humidity, salt spray corrosion, and vacuum (see Table 1). Typically, both stress and intensity distributions are random, and failures will occur when a product is subjected to more stress than its intensity limit. In addition, if the product has defects, it may lead to local stress concentration, accelerating fatigue damage accumulation. The structural integrity of the product will gradually deteriorate upon. Once it is lower than the stress it experiences, the probability of failure of the product increases.

Based on these theories applicable to RET, the stimulating effect of RET can be improved by identifying the sensitive stress that affects the reliability of products and designing proper application steps and methods for the sensitive stress.

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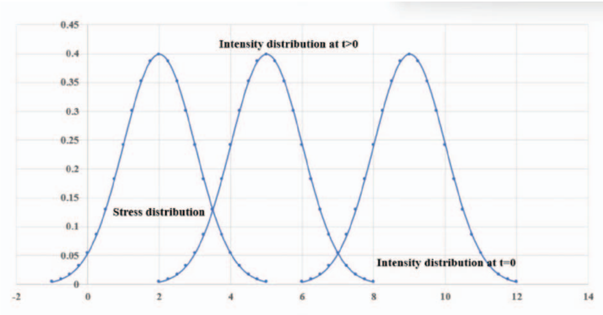

Fig. 2. Stress-intensity distribution vs. time-to-failure mode

TABLE I. TYPICAL ENVIRONMENTAL STRESS EFFECTS AND CORRESPONDING CONTROL MEASURES

Stress	Effect	Control measures
high temperature	Accelerating metal surface oxidation, evaporation, decreasing viscosity, material stiffness/intensity decreases/ expansion	Cooling design, thermal insulation design
cryogenic	Material embrittlement/ shrinkage/ stiffness increase, rubber cured/ elasticity losing, conductivity/ magnetic permeability decreasing, viscosity increasing, freezing	Thermal protection design, insulation design, cryogenic adaptability design, moisture-proof design
temperature cycling	deformation results from different material expansion coefficient, reduced mechanical and vibration damping properties of rubber and organic plastics, accelerated aging	Selecting materials with the same expansion coefficient for the matching components, thermal insulation design
vibration	Fatigue failure, loosening, accelerated wear, transient failure	Intensity design, anti-vibration design
Thermal impact	Cracking, delamination, mechanical failure	Heat-resistant design, Thermal protection design
Mechanical impact	Structural failure, deformation, displacement	Vibration damping design, intensity design
humidity	Short circuit, freezing, accelerated oxidative expansion	Sealing design, protective coating, other protection design
drying	Embrittlement, evaporation (lubricants, etc.)	Sealing design, protective coating, environmental protection
vacuum	Insulation breakdown, air leakage, container damage, inability to dissipate heat	Intensity design, active cooling
Salt spray	Electrical erosion, insulation degradation, oxidation acceleration	Sealing design, protective coating, contact avoidance design between different metal and non-metal parts

III. NECESSITY ANALYSIS OF IMPLEMENTING RET FOR NON-ELECTRICS

The aerospace industry uses several non-electrical products such as structures, mechanisms, pyrotechnic products, and rocket engines, as shown in Figure 3. Although the rocket engine is always treated as a stand-alone products for the launch vehicle system, it is a synthesis of various products. Hence, it is not within the scope of discussion in this paper. The necessity analysis of RET implementation on non-electrical products is discussed as follows:

1) Although the forms of structural products are diverse, their failure mechanism is relatively simple, typically manifesting as structural intensity and stiffness failure. Thus, the structural design should be focused on improving load resistance capacity of the products. Further, stimulating defects in structural products by implementing load/hydraulic stress, displacement, and random vibration-temperature stress is efficient. For large structural parts, the strength destruction test is used to obtain its residual intensity. Hence, the RET has been integrated into its reliability design process, and the enhancement test for specific failure modes can be carried out according to actual needs.

2) Different combinations of igniter, explosion transmitter, and pyrotechnic terminals comprise various types of pyrotechnic systems. Typically, by adjusting the components' design characteristics (dosage of powder, fire gap, etc.), expected operating stress can be obtained and used to stimulate strength/functional failure or other defects can be observed. Series standards such as GJB5309 have a detailed description regarding the test methods for pyrotechnics, which meet the reliability assurance requirements of pyrotechnics. Hence, further research on its RET is not discussed in this paper.

3) The reliability of products with actional functions such as valves, servo motors, and other mechanics is extremely significant to the success of the launch vehicle owing to their compact structure, complex function, higher importance, changeable application environment, complex failure mode, etc. While traditional development tests are more similar to environmental adaptability tests, some overstress conditions occur on the products. Hence, defect stimulation is not satisfied, and problems such as stuck, leakage and other failures occur during use. In the context of developing generalized and highly

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reliable products, performing the RET of these mechanics is greatly significant.

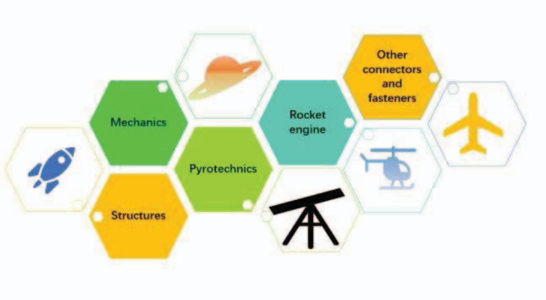

Fig. 3. Classification framework of aerospace mechanics

IV. Historical Failure Analysis and Sensitive Stress Identification of Mechanics

RET stimulating stress interpretation for electronics are consistent nowadays, primarily focusing on two types of stress i.e., temperature and vibration. Through the RET of electronics, failure modes of mechanics with similar structure form and historical quality problems must be analyzed first to identify and obtain the primary sensitive stresses that have an important role in the RET implementation of mechanics.

By analyzing historical quality problems of mechanics such as valves and servo motors, causes of failure can be categorized into 8 categories, as shown in Figure 4, including design, manufacturing process, operation, components, materials, management, software, and overdue use.

Statistical analysis indicates that the proportion of manufacturing process, design, and operation have the highest share of failure modes at 33.33, 32.83, and 23.23% respectively, while the total proportion of the other five categories is only 10.61%. Thus, reducing the quality problems of mechanics such as valves and servo motors can be facilitated by improving product design methods, strengthening manufacturing process control, and refining operating procedures. Since operation is not directly related to product reliability, the inherent reliability of the product is determined by design factors, and manufacturing process reliability is guaranteed by the process. Thus, reliability improvement of the mechanics should be primarily implemented by identifying sensitive stress in design and manufacturing process.

Further analyzing the causes of failures and sensitive stresses of mechanics, the failure modes that frequently result in quality problems of valves and servo motors are categorized in Table II, and the following inferences have been obtained:

a) The failure mode with the highest proportion of historical mechanical quality problems is leakage at 35%. The second highest failure mode is stuck (including not able to open, close and unlock), accounting for approximately 29% of failures. Current and insulation resistance exceeding design criteria (electromechanics such as solenoid valves and servo motors) and fatigue fracture failure mode rank third, accounting for approximately 12% of failures. The lowest proportions of causes of failure are debonding and abnormal starting, as shown in Figure 5.

b) Further analysis of inappropriate manufacturing processes causing product failure is shown in Figure 6. The proportion of superfluous materials being introduced during production and processing is as high as 57%, indicating that the control of superfluous materials should be strengthened in manufacturing. For example, the mating surface of moving parts with sharp edges and burrs should be sufficiently cleaned, and designing blunt or rounded corners is ideal to avoid potential risks. The second and third highest proportions of processing defects are screened by the temperature cycle, and pressure cycle and surface roughness at 15 and 14%, respectively.

c) Further analysis of the design resulting in product failure is shown in Figure 7. The highest, second, and third highest proportion of design defects screened by the life test of moving parts, temperature cycle, and random vibration was 37, 27, and 18%, respectively. Further, the design defects screened by pressure cycle and failures caused by lack of protection against superfluous materials were both accounted for the fourth highest proportion of 9% respectively.

d) Mechanical product quality problems generally result from stuck and leakage caused by superfluous materials such as debonding of the sealing pair, uneven force, excessive gap of the mating surface, and motion wear, locking due to excessive friction caused by rough surface processing, and fatigue problems caused by continuous action, etc. Sensitive stresses that cause failure modes in these mechanics are analyzed, as shown in Figure 8. Failures screened by superfluous materials (can be eliminated by improving checking methods) and temperature cycle accounted for the highest proportion at 23% each. Failures screened by pressure, vibration, operation (life span), and processing problems accounted for the second highest proportion with 12%, each. The lowest proportion of failures was screened by impact at 6%. Thus, sensitive stresses resulting in the failure of mechanics such as valves and servo motors are typically temperature cycles, random vibrations, and the number of actions. Therefore, based on the identified sensitive stress, numerical simulation can be used to analyze the weakness preferentially, which is the first step in designing corresponding load application methods, clarifying the enhancement test plan, rapidly stimulating the design and process defects of the product, and effectively improving product reliability.

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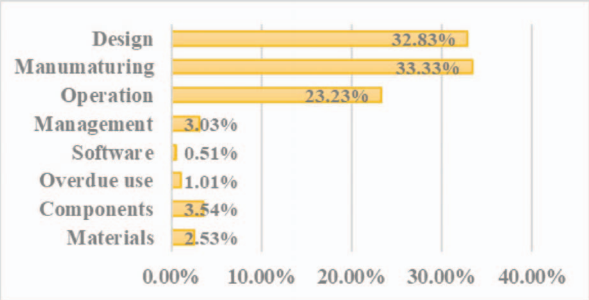

Fig. 4. Statistical analysis of reasons causing mechanics failure

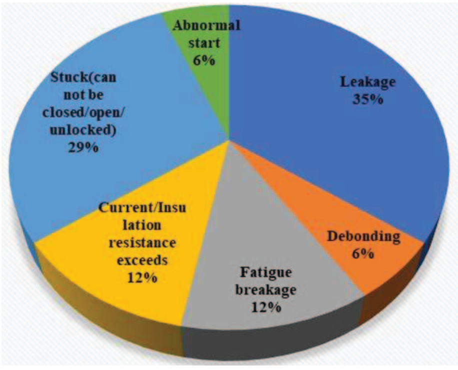

Fig. 5. Failure modes analysis of mechanics such as valve and servo motors

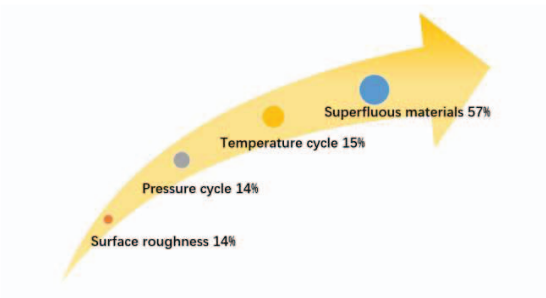

Fig. 6. Further analysis of manufacturing process

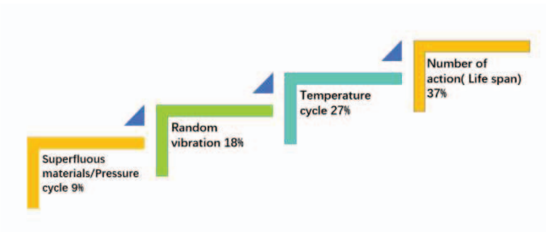

Fig. 7. Further analysis of design reasons

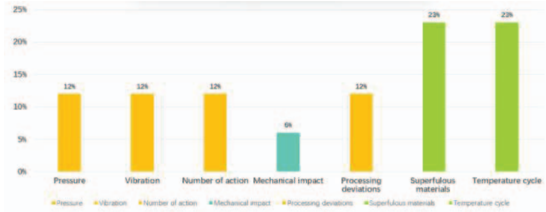

Fig. 8. Further analysis of sensitive stress

TABLE II. SENSITIVE STRESS ANALYSIS BASED ON TYPICAL QUALITY PROBLEM OF MECHANICS

Product	Failure mode	Reasons	Sensitive stress	Problem properties
Valve	Open abnormally	Threads are not adaptable to environmental vibration resulting in untightened loosing and torque degrading	Random vibration	design
	unclosed	Stuck caused by superfluous materials resulting from impact fatigue breakage	Number of actions	design
	leakage	Fluoroplastic shrinkage or debonding of assembly components in valve caused by temperature changes	Temperature cycling	process
	leakage	Leakage resulting from interface alignment neutrality	Number of actions	Design
	leakage	Seal failure caused by superfluous materials	Superfluous	process
	leakage	Wear of the guide surface caused by valve spool failing to go back to where it is	Number of actions (lifespan).	Design
	Leakage	Debonding of components assembly in valve caused by deformation of nonmetallic materials under high-pressure condition	Pressure	process
Servo motors	leakage (seal failure).	Cracks in the diaphragm resulting from poor heat resistance and mechanical properties of the raw material	Temperature/pressure cycling	materials
	Abnormal start	Friction torque increased by surface roughness out of control	Surface roughness exceeds standard	process
Lock spring	fracture	Insufficient fatigue strength caused by improper structural design	Random vibration	design
Other mechanics	locked/stuck	Increased transmission resistance caused by superfluous material	Superfluous	process
	locked	Frictional force increased by damaged coating of friction pair under cryogenic environment	Temperature	design
	Shedding of rubber pad	Solidification time of the adhesive is short and is not adaptable to the cryogenic environment	Temperature cycling	design
	Locked	Pressure relief port blocked by superfluous materials	Superfluous	design

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V. DESIGN PROCESS OF RET

Before implementing RETs, sensitive stresses that stimulate potential defects should be analyzed first. By incorporating appropriate test methods based on sensitive stresses identified in the first step, design defects are stimulated effectively. The RET implementation process is detailed in Figure 9, and it generally follows the following principles:

a) Failure mode and effect analysis (FMEA) should be carried out effectively during product design and process control. Sensitive stresses or associated failure mechanisms resulting in product failure should be identified by analyzing historical problems of similar products to determine the type of stresses applied and its implementation level, analyze its possible consequences in advance, and formulate corresponding prevention or improvements.

b) Due to the characteristics of aerospace mechanics such as complex structural design, long development cycle, difficult processing, small batches, and high cost, finite element simulation analysis should be carried out before test implementation to predict test results in advance under one identified sensitive stress or comprehensive stresses. This could guide actual tests, save costs, and simplify processes.

c) Monitoring parameters should be reasonably set during the test to identify the failure modes of the product and facilitate their detection. Surface temperature, stress, and strain of important parts of the product should be accurately detected and recorded. The primary performance parameters and functional modes of the tested product should be monitored as a priority. Accordingly, the test process and results can be effectively monitored, and effective data support can be provided for subsequent analysis.

d) If the test fails during implementation, it should be stopped on time, and the abnormal state of the product should be recorded to identify the defect part. By carrying out FEMA on the product, the failure mechanism should be identified and improvements should be implemented. Subsequently, necessary verification tests should be performed to improve product reliability.

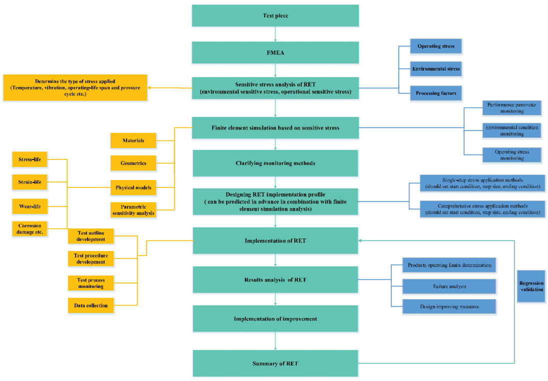

Fig. 9. Further analysis of sensitive stress

VI. CONCLUSION

Considering the design ideas of electronical RETs, sensitive stresses of non-electrics RETs were analyzed in this paper, which are used to efficiently stimulate the weakness in product design or process control. Additionally, they play an important role in developing stress implementation methods for the RET to suggest improvements in mechanical design. Data analysis necessitates enhancement tests for the failure modes of valve and servo motors such as leakage, stuck, and fatigue in addition to traditional development tests. By applying temperature cycle, vibration cycle, life test with action, and impact tests, design weaknesses in products can be stimulated accurately, and operational or damage margin of products can be identified. By incorporating design changes to the products, their reliability can be improved, thereby improving the adaptability of the product when performing different task profiles considering the current trend constantly shortening equipment development cycles.

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