engineering proceedings

MDPI

Proceeding Paper

Study on Intensifying the Fatigue of Mechanical Products: Examination of Household Refrigerator †

Seongwoo Woo [1,*], Dennis L. O'Neal [2], Yimer Mohammed Hassen [1] and Gezae Mebrahtu [1]

1 Mechanical Technology Faculty, Ethiopian Technical University, Addis Ababa P.O. Box 190310, Ethiopia; imoha@ymail.com (Y.M.H.); gezaemebrahtu@gmail.com (G.M.)
2 Department of Mechanical Engineering, Dean of Engineering and Computer Science, Baylor University, Waco, TX 76798-7356, USA; dennis_oneal@baylor.edu
* Correspondence: twinwoo@yahoo.com; Tel.: +251-90-047-6711

† Presented at the 4th International Electronic Conference on Applied Sciences, 27 October–10 November 2023; Available online: https://asec2023.sciforum.net/.

Abstract: To refine the fatigue lifespan of products such as automobiles, refrigerators, etc., parametric accelerated life testing (ALT), as a new method for ensuring structured reliability, put forward to assess designs by subjecting them to repeated loads. This method is based on identifying the failure mechanism and redesigning the product. It involves: (1) a parametric ALT procedure based on BX lifespan, (2) load evaluation for elevated life experiments, (3) a tailored sample of parametric ALTs with changes, and (4) a calculation of whether the product reaches the BX lifespan objective. As such, life-stress failure type are suggested along with effort idea, accelerated factor, and sample size. This method of structured reliability, such as parametric ALT, might help designers to discover the product flaws influencing reliability, as indicated by enhancement in life, L_B, and lower failure rate, λ, seen during the design phase. As a result, manufacturers may avoid recall due to market failure. As a test investigation, we redesigned a hinge kit system (HKS) in a household refrigerator. After tailoring the ALT parameters, HKSs with modifications were predicted to fulfil the life objective—B1 life of ten years.

Keywords: fatigue; design defects; mechanical product; parametric ALT; HKS

Citation: Woo, S.; O'Neal, D.L.; Hassen, Y.M.; Mebrahtu, G. Study on Intensifying the Fatigue of Mechanical Products: Examination of Household Refrigerator. *Eng. Proc.* **2023**, *56*, 107. https://doi.org/10.3390/ASEC2023-15371

Academic Editor: Ana Paula Betencourt Martins Amaro

Published: 26 October 2023

1. Introduction

To be competitive in the open space market, even conventional devices, such as domestic refrigerators, may need to be refined with novel technologies and attributes to satisfy the requests of end-users. If a new system is rushed to the marketplace with insufficient testing to mimic customers' usage of these attributes, there is the possibility for the untimely failure of the product. This can undesirably influence the perception of the quality of the product manufactured by the company. Since 1970s, it also has been recognized that there exists a considerable gap between the reliability thesis and its implementation to business areas. To circumvent anticipated design defects in the market, the novel attributes of a newly designed product should be appraised in the development phases before its delivery into the field. Developing a system operated by machine thus necessitates a structured design method that incorporates reliability quantitative (RQ) statements [1].

To terminate the market recall of products that have design flaws, companies might devised products to outlive the normal working circumstances applied by end-users who purchase and utilize them. The Boeing 737 MAX airplane was prohibited from flying after 346 passengers were killed. This was a passenger aircraft that possessed CFM International LEAP-1B engines utilizing the greatest favorable 68-inch fan design. They had 12% less power consumption and were 7% lighter than other engines [2]. Inspectors, including the Ethiopian Civil Aviation Authority, suspected that the accident was produced by the airplane's engines.

Fatigue is the major origin of failure in parts, causing more or less 80–90% of all constructional unsuccessfulness [3]. It manifests itself in cracks that start from stress areas, such as channels, hollow places in a surface, narrow exteriors, etc., in systems operated by machine. This failure is the result of the degradation of a material produced by regularly repeated loads under the end-user utilization. This may produce catastrophic consequences in a system so that product failure results in the injury or death of end-users. A notable study concentrated on the fatigue of superalloys, especially in the area of turbine–motors (nickel-found polycrystalline). This study had kinds of index, such as the stress portion, R ($=\sigma_{min}/\sigma_{max}$), expressed as the connection of the greatest cyclic load to the minimal cyclic load [4]. Utilizing this parameter, which is obvious in parametric ALT, can help point out the design faults in the product operated by machine.

Engineers frequently pinpoint design imperfections and fix them utilizing Taguchi's method [5] or the design of experiments (DOE) [6]. DOE is an arranged procedure used to identify the link between factors determining a process and its manufacturing. The DOE's aim is to ensure that elements are devised optimally for the operating conditions (or those surrounding). DOE is carried out for some design factors that influence it. Their effectiveness is shown via analysis of variance. Taguchi's method can also be used for products and their assessment. The method attempts sets to find the most favorable design where the "noise" element does not have any impact on the design. However, because DOE incorporating Taguchi's method cannot recognize which factors are critical due to fatigue in the process followed in calculations, these perspectives require significant mathematical calculations. However, the method may not identify the most favorable design.

Engineers can design a mechanical system utilized on the basis of the strength of its materials as an established design method. A recent investigation also indicated that an important element in fracture mechanics might be fracture toughness, interpreted as a quality of the strength of materials. With the achievement of quantum mechanics, designers realize that failure in a product happens due to nanoscale/microscale voids found in relation to metal alloys and/or plastics that have better mechanical and/or thermal properties. However, as restricted samples and test time are employed, this method may not replicate the design defects of components due to the fatigue inflicted by end-users in the marketplace. To correct for this, a current life-stress type should be merged with a (quantum) mechanical technique to pinpoint a current imperfection or cracks because failure stochastically happens in the regions of stress concentrations.

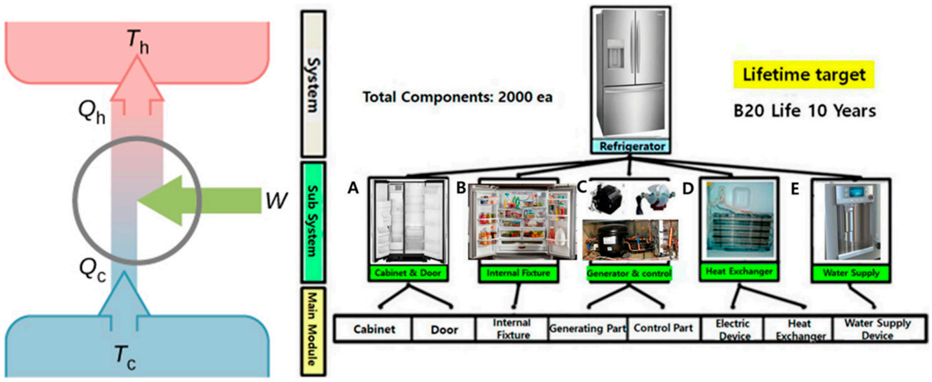
As another possibility way, engineers can utilize finite element analysis (FEA) [7]. This method attempts to identify failure via (1) rigorously exact (Lagrangian or Newtonian) modeling; (2) assessing the response to loads, thus creating the product stress/strain; (3) employing accepted methods, such as rainflow counts; and (4) judging product successfulness using Palmgren–Miner's assumption. Implementing these organized approaches can provide some closed formations. However, this way also cannot reproduce fatigue failure that is created by material defects such as micro-voids, narrow surfaces, channels, etc.

This paper proposes using parametric ALT as a widespread way to produce reliability quantitative (RQ) statements. An example would be the mission cycles, which can identify the product defects and supply a way of enhancing the fatigue life of products. This procedure is suitable for mechanical products such as airplanes, automobiles, appliances, etc. It involves: (1) an ALT program generated on BX lifespan, (2) load analysis, (3) tailoring ALTs with changes, and (4) a judgement of whether the product attains the targeted BX lifespan. To assess the usefulness for ALT, it is necessary to evaluate the new system in the field to see whether the designed objects fulfil object life. A quantum-transported life stress type and sample size also are suggested. As an instance investigation, the redesign of HKS in a household refrigerator was investigated.

2. Accelerated Testing for System Worked by Machine

2.1. New Concepts of Reliability for ALT

The products operated by machine such as refrigerator, car, aeroplane, etc., transfer power to manage a job that requires forces and movement, generating mechanical advantages by adopting their mechanisms. Most systems operated by machine thus are formed of subsystem structures. If subsystems are properly constructed, a system operated by machine can carry out its own planned tasks. As an instance, a refrigerator comprises approximately 2000 parts. The target of product life is set to have a B20 of life ten years. A household refrigerator is composed of twenty units (or 8~10 modules), with every unit possessing 100 components (See Figure 1). Thus, the lifespan objective of every unit could be targeted to have a B1 life of ten years. The product life is managed using some design flaws in a module.



(**a**) Refrigerator (**b**) Breakdown of refrigerator

Figure 1. Mechanical products such as refrigerator.

2.2. Positioning a Unabridged Parametric ALT Program

Product reliability is expressed as the potential of a product to properly run under declared circumstances for a defined period of time. It is represented by a picture labelled as "bathtub curve" with three sections. First, there is a declining failure rate in the premature lifespan of the substance manufactured ($\beta < 1$). Second, there is a continual failure rate ($\beta = 1$). Third, there is a growing failure rate up until the termination of the lifespan in a manufactured product ($\beta > 1$). If a new product follows the bathtub curve, the product will have difficulties succeeding in the market due to high failure rates and low life rates. A manufacturer will have to enhance the design by setting reliability goals as follows: (1) minimize untimely unsuccessfulness, (2) lower random unsuccessfulness for the operating time, and (3) enhance product life. As the design of a product worked by machinery enhances, its failure rate is reduced and its life extends. For such circumstance, the bathtub curve will be converted into a line with the shape parameter β, representing the advantageous form of a failure rate that envelops the whole lifespan of a good-quality system (Figure 2).

As product design is improved, the failure rate in the marketplace should decrease and the product life should increase. For such situations, product reliability can be indicated as the product of the failure rate and its life and declared as follows:

$$F(L_B) = 1 - R(L_B) = 1 - e^{-\lambda L_B} \cong \lambda L_B \tag{1}$$

where Equation (1) is pertinent to less than 20% of accumulative failure rates, F(·).

As putting the objective for system lifespan, L_B, designer pinpoints the defect and alter it by parametric ALT (Table 1).

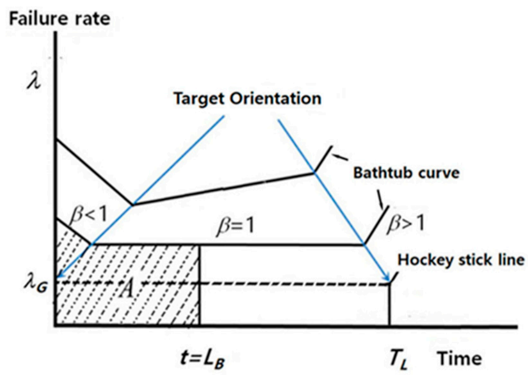


Figure 2. Bathtub and hockey stick line with slope β to the end of the product lifespan.

Table 1. Unreduced elevated testing strategy of product operated by machine such as refrigerator modules [1,8,9].

Modules	Field Data		Anticipated Reliability					Objective Reliability	
	Failure Rate Per Year, %/Year	BX Life, Year	Failure Rate Per Year, %/Year				BX Life, Year	Failure Rate Per Year, %/Year	BX Life, Year
A	0.35	2.9	Alike	×1	0.35		2.9	0.10	10 (BX = 1.0)
B	0.24	4.2	New	×5	1.20		0.83	0.10	10 (BX = 1.0)
C	0.30	3.3	Alike	×1	0.30		3.33	0.10	10 (BX = 1.0)
D	0.31	3.2	Changed	×2	0.62		1.61	0.10	10 (BX = 1.0)
E	0.15	6.7	Changed	×2	0.30		3.33	0.10	10 (BX = 1.0)
Others	0.50	10.0	Alike	×1	0.50		10.0	0.50	10 (BX = 5.0)
System	1.9	2.9	-	-	3.27		0.83	1.00	10 (BX = 10)

2.3. Failure Mechanisms and Accelerated Testing

The most important matter in reliability testing is how to discover untimely and feasible failure. To achieve this, it is indispensable to show a failure type and resolve the associated coefficients. First, the life-stress prototype that embraces stresses and reaction parameters is configured. It formulates many failures, such as fatigue in the system. Because product failure originates from the existence of product defects shaped to an atomic/microscopic size when repeatedly subjected to loads, the life-stress prototype should be defined from such a viewpoint. That is, fatigue can originate from material flaws—electrons/voids—that have emerged in nano-, micro- or macroscopic ranges. From such a perspective, it can be expressed as transport procedures—the diffusion of shallow-level dopants—in silicon (semiconductor).

First, reflect about a (electric) particle prevented from going in x direction from $x = 0$ to $x = a$. That is, Schrodinger wave differential formulation is defined as:

$$-\frac{h^2}{8\pi^2 m}\frac{d^2\psi_n(x)}{dx^2} = E_n\psi_n \tag{2}$$

where m is electron mass, h is Planck constant, V is potential energy, ψ_n is the wave function, and E_n is the energy.

The boundary conditions are: (1) ψ_n restricted in the metal but decompose more and more rapidly. That is, $\psi_n \to 0\ as\ x\ \to \infty$, (2) $\psi_n = 0$ at barriers. The Equation (2) is solved as follows:

$$\psi(x) = \sqrt{\frac{2}{a}}sin\left(\frac{n\pi}{a}\right)x;\ E_n = \frac{n^2h^2}{8ma^2}\ n > 0 \tag{3}$$

where $\psi(x+a) = \psi(x)$, a is interval, and n is quantum number.

Transport processes therefore are expressed as:

$$J = LX \tag{4}$$

where J is a (flux) vector, X is stated as a (driving) force, and L is a transport numerical quantity.

For instance, the following processes can be utilized for solid-state diffusion of impurities in silicon, which is extensively utilized in semi-conductors as follows: (1) electro-migration-induced voiding, (2) gradual accumulation of chloride ions, and (3) confinement of electrons or holes.

As an electro-magnetic force, ξ, is employed, impurities such as material voids, set up via electronic motion, are simply drifted because the energy obstacle of junction is less high in position, phase-shifted, distorted, etc. For the solid-state diffusion of impurities in silicon, the junction function J could be manifested as [10]:

$$J = [aC(x-a)] \cdot exp\left[-\frac{q}{kT}\left[w - \frac{1}{2}a\xi\right]\right] \cdot v$$

[Density/Area]·[Jump Probability]·[Jump Frequency]

$$= -[a^2ve^{-qw/kT}]cosh\tfrac{qa\xi}{2kT}\tfrac{\partial C}{\partial x} + [2ave^{-qw/kT}]Csinh\tfrac{qa\xi}{2kT}$$
$$\cong \Phi(x,t,T)sinh(a\xi)exp\left(-\tfrac{Q}{kT}\right)$$
$$= Bsinh(a\xi)exp\left(-\frac{Q}{kT}\right) \tag{5}$$

where B is constant, a is the interim between atoms, ξ is the field, k is Boltzmann's quantity, Q is energy, and T is temperature.

If Equation (5) puts the inverted function, stress prototype is attained as

$$TF = A[sinh(aS)]^{-1}exp\left(\frac{E_a}{kT}\right) \tag{6}$$

The hyperbolic sine term can be manifested as: (1) $(S)^{-1}$ with small effect, (2) $(S)^{-n}$ with medium effect, and (3) $\left(e^{aS}\right)^{-1}$ with a large effect. Because elevated testing is accomplished in the medium-sized effect, Equation (6) is restated as:

$$TF = A(S)^{-n}exp\left(\frac{E_a}{kT}\right) \tag{7}$$

Because the system stress is complicated to express the testing quantity, Equation (7) need to be modified. As the power is manifested as the product of effort and flows, stresses in a system will originate from elements such as force.

So, Equation (7) may be replaced as the generic formation:

$$TF = A(S)^{-n}exp\left(\frac{E_a}{kT}\right) = A(e)^{-\lambda}exp\left(\frac{E_a}{kT}\right) \tag{8}$$

Product defects can be discovered by exercising greater effort under elevated situations. In Equation (8), acceleration factor (AF) is stated as the amount between the elevated situations and regular situations. That is, AF may be changed to factor in the effort views:

$$AF = \left(\frac{S_1}{S_0}\right)^n\left[\frac{E_a}{k}\left(\frac{1}{T_0}-\frac{1}{T_1}\right)\right] = \left(\frac{e_1}{e_0}\right)^\lambda\left[\frac{E_a}{k}\left(\frac{1}{T_0}-\frac{1}{T_1}\right)\right] \tag{9}$$

To achieve the mission time (or cycle) for ALT from the objective BX lifespan on the test policy, the sample size linked with the AF is stated as [9]:

$$n \geq (r+1)\cdot\frac{1}{x}\cdot\left(\frac{L_B^*}{AF\cdot h_a}\right)^\beta + r \tag{10}$$

2.4. Case Investigation: Reliability Design of the HKS

HKS with a spring-damper mechanism was conceived of to comfortably operate the door of a household refrigerator. As we are releasing the new HKS, it is essential to locate potential design inadequacies and assess its reliability. The principal elements of HKS consist of HKS cover ①, oil damper ②, cam ③, spring ④, shaft ⑤, cam ⑥, and HKS housing ⑦ as seen in Figure 3.

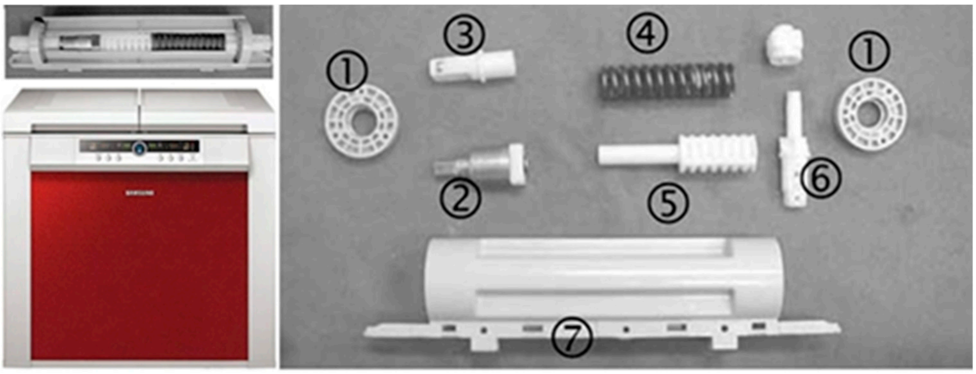


Figure 3. Household refrigerator and HKS parts.

In the marketplace, the cracking and fracturing of HKS elements in a household refrigerator occurred due to fatigue and some design flaws. To replicate the real customer use and load states, engineers do not recognize which reliability tests are required. A manufacturer should optimally and robustly design a mechanical system to keep the product working for its expected life. If there are design defects, the system may fail to accomplish the desired result before its anticipated lifespan. Thus, HKS's life depends on the troublesome components. To reproduce the failing parts in the system design and modify them, an engineer requires a structured reliability method. It consists of (1) a load examination failed from the market, (2) carrying out ALTs with changes, and (3) confirming whether a lifetime target is attained.

Established on basis of end-user usage situations in the field, HKS is exposed to various loadings due to the door operation. Because the HKS including door module is a comparatively uncomplicated structure, it is modeled with a force and moment balance (Figure 4).

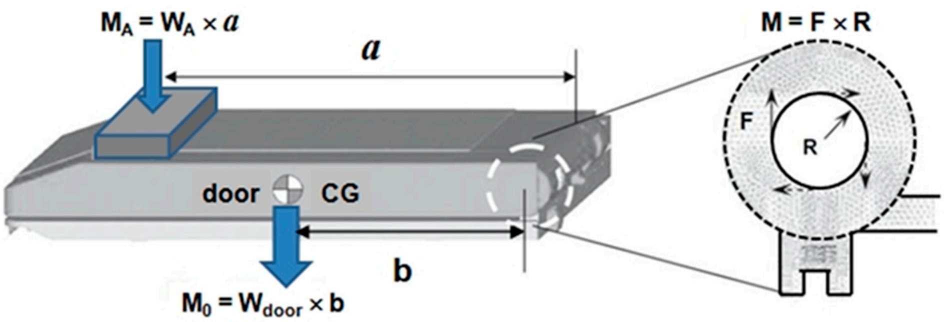


Figure 4. Model with a simple force and moment of HKS.

When the end-user operates the door in a refrigerator, the stress because of the weight impact is focused on HKS. Because the raised weight on the door end has been appended as increasing the impact of HKS, the moment equation around HKS is stated as

$$\sum M = W_{door} \times b + W_A \times a = T_1 = F_1 \times R \tag{11}$$

Under similar environmental circumstances, Equation (8) is redefined as:

$$TF = A(S)^{-n} = AT^{-\lambda} = A(F \times R)^{-\lambda} = B(F)^{-\lambda} \quad (12)$$

where A is constant and B is constant.

Equation (9) may be redefined as:

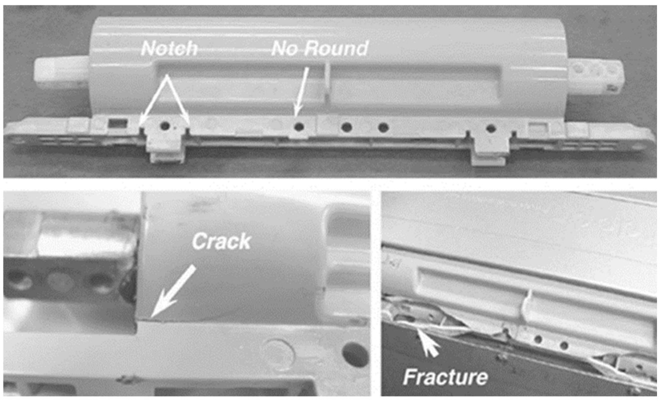
$$AF = \left(\frac{S_1}{S_0}\right)^n = \left(\frac{T_1}{T_0}\right)^\lambda = \left(\frac{F_1 \times R}{F_0 \times R}\right)^\lambda = \left(\frac{F_1}{F_0}\right)^\lambda \quad (13)$$

3. Results and Discussion

The surrounding circumstances of HKS in a domestic refrigerator range from 0 to 43 °C, with a humidity varying from 0% to 95%. The HKS is exposed to between 0.2 and 0.24 g of acceleration. Door operating times are determined via specified end-user utilization. Consumer statistics express that the refrigerator door is usually operated for between three and ten cycles per day in the marketplace. With life cycles of ten years, the HKS experiences about 36,500 usages for the worst instance. The impact around the HKS is 1.10 kN, the greatest predicted force deployed by the end-user. For the ALT with a raised weight, the HKS impact is 2.76 kN. Employing a damage constant, λ, of 2.0, AF was found to be 6.3 in Equation (13).

The test cycles used in the ALT for the given sample size and lifetime target were calculated from Equation (10). That is, for six units and life aim—B1 of life ten years—the allotted mission time (or cycles) was 24,000 cycles. This ALT can be devised to acquire a B1 life of ten years, meaning that it should be unsuccessful less than once for 24,000 cycles.

In the first ALT, the fracturing of the HKS housing occurred at 3000 and 15,000 cycles. Figure 5 demonstrates a photograph contrasting the problematic system from the marketplace and that from the first ALT, separately. As shown in the photo, the formation and place of the unsuccessfulness in the first ALT were the same as those seen in the marketplace.



(**a**) (**b**)

Figure 5. Failed HKS in market and in the first ALT. (**a**) Unsuccessful products in market. (**b**) Fracture after the first ALT.

The fracturing of HKS housing in both the marketplace and 1st ALT arose in the HKS. The design flaws of the housing in the HKS originated from a lack of support structure as there were no ribs in the housing. As there were faults in the system where the impact loads were utilized, the fracturing of HKS occurred in its lifespan. In other words, the repeated exertion of force in combination with the system defects may have been the cause of the fracturing of the HKS. Therefore, in order to be adequately strong against impact loading, the weak HKS housing should be strengthened. That is, notches were removed, and corner rounding was performed outside and inside. Strengthened ribs also were fastened onto the housing and decks (Figure 6).

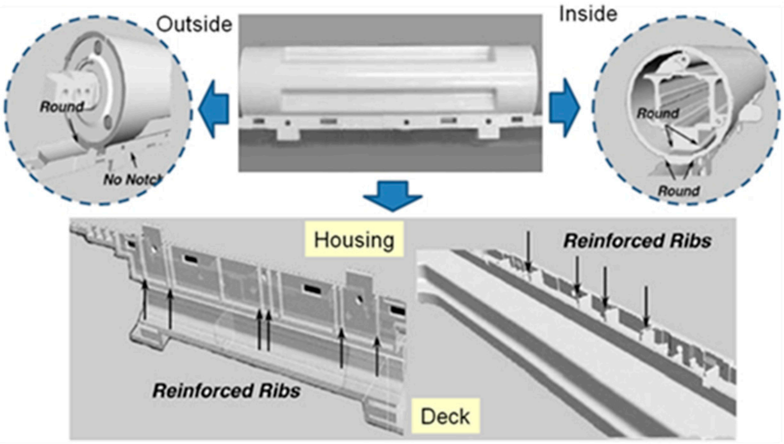


Figure 6. Reinforced HKS housing.

While separating problematic HKS samples into component parts, the spilled oil damper was found at 15,000 cycles. This unsuccessfulness started from the sealing structure that had attached an o-ring, Teflon, and o-ring with a space of 0.5 mm. It was conjectured that there could be intrusion between the Teflon and o-ring. To firmly have the o-ring grasped by the Teflon and have adequate strength against applied impact, the design in oil damper was modified as shown in Figure 7.

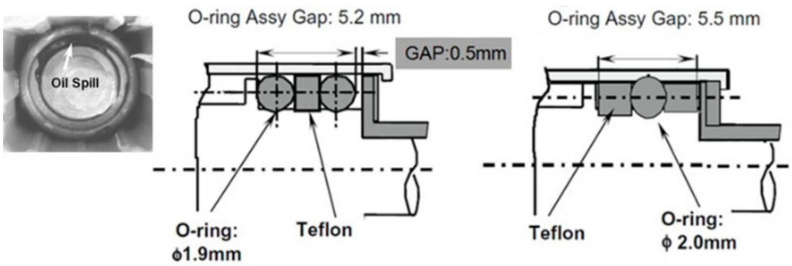


Figure 7. Redesigned oil damper.

In the second ALTs, the fracturing of HKS cover occurred at 8000, 9000, and 14,000 cycles. The HKS failure for the 2nd ALT started from the wrong material of cover in an HKS. When operating the HKS, the oil damper support was fabricated via aluminum stroke and the HKS cover was fabricated from plastic. Thus, the hinge kit cover began to crack and fracture at its end. As action plan, in order to ensure it had sufficient material strength for repeated impact loading, the HKS cover was amended from plastic to aluminum (Figure 8).

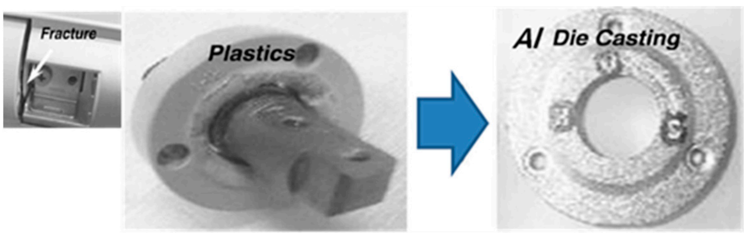


Figure 8. Redesigned kit cover.

4. Conclusions

To raise the fatigue tolerance of a new product operated by machine such as HKS, parametric ALT was suggested as a structured reliability method that covers: (1) ALT scheme, (2) load study, (3) a fitted ALTs with modifications, and (4) an analysis of the design requirements of the HKS needed to ensure realization. An HKS in a household refrigerator was utilized as an instance investigation.

In the first ALT, HKS failure occurred in the fracturing of the HKS housing and the leaked oil damper. In the 2nd ALT, the HKS cover fractured. After ALT testing with modifications, HKSs were resolved to achieve the lifespan aim—B1 life of 10 years.

Author Contributions: S.W. led the action of forming a concept, systematic method, examination, and testing and wrote this paper. D.L.O. and Y.M.H. examined the study and writing of the first draft. G.M. reviewed and edited the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data suggested in this investigation are accessible on formal asking from the corresponding author.

Conflicts of Interest: The authors state no conflict of interest.

References

1. Woo, S.; O'Neal, D.; Pecht, M. Improving the lifetime of mechanical systems during transit established on quantum/transport life-stress prototype and sample size. *Mech. Syst. Signal Process.* **2023**, *193*, 110222. [CrossRef]
2. WRDA 2020 Updates. The Final Report of the US House Committee on Transportation and Infrastructure on the Boeing 737 Max. Available online: https://transportation.house.gov/committee-activity/boeing-737-max-investigation (accessed on 1 September 2020).
3. Duga, J.J.; Fisher, W.H.; Buxaum, R.W.; Rosenfield, A.R.; Buhr, A.R.; Honton, E.J.; McMillan, S.C. *The Economic Effects of Fracture in the United States*; Final Report; A Report to NBS Special Publication 647-2; Battelle Laboratories: Columbus, OH, USA, 1982.
4. Fatigue. *Elements of Metallurgy and Engineering Alloys*; Campbell, F.C., Ed.; ASM International: Materials Park, Ohio, USA, 2008.
5. Taguchi, G. Off-line and on-line quality control systems. In Proceedings of the International Conference on Quality Control, Tokyo, Japan, 20–24 October 1978.
6. Allen, P. *Design of Experiments for 21st Century Engineers*, 1st ed.; Lulu Press: Morrisville, NC, USA, 2020.
7. Reddy, J.N. *An Introduction to the Finite Element Method*, 4th ed.; McGraw-Hill: New York, NY, USA, 2020.
8. Woo, S.; Pecht, M.; O'Neal, D. Reliability design and case study of the domestic compressor subjected to repetitive internal stresses. *Reliab. Eng. Syst. Saf.* **2019**, *193*, 106604. [CrossRef]
9. Woo, S.; O'Neal, D.L.; Atnaw, S.M.; Tulu, M.M. Reliability Design of Mechanical Systems Such as Compressor Subjected to Repetitive Stresses. *Mater. Proc.* **2021**, *3*, 14. [CrossRef]
10. Grove, A. *Physics and Technology of Semiconductor Device*, 1st ed.; Wiley International Edition: New York, NY, USA, 1967; p. 37.