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Study on Intensifying the Fatigue of Mechanical Product Such as Household Refrigerator †

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Abstract: To refine the fatigue lifespan of product such as automobile, refrigerator, etc., parametric Accelerated Life Testing (ALT) as a new reliability structured manner puts forward to determine its design subjected to repeated loads, based on failure mechanism and design. It holds: (1) parametric ALT procedure established on BX lifespan, (2) load evaluation for elevated life experiment, (3) a tailored sample of parametric ALTs with changes, and (4) a calculation of whether the product reaches the objective BX lifespan. So, life-stress failure type with effort idea, accelerated factor, and sample size are suggested. This structured reliability way such as parametric ALT might help designer to discover the product flaws influencing reliability as calculated by the enhancement in life, L_B, and the lowering in failure rate, λ, during the design phase. As a result, manufacturers may avoid recalls from the market failure. As a test investigation, hinge kit system (HKS) in a household refrigerator was redesigned. After a tailored of parameter ALT, the HKS with modifications were predicted to fulfil the life objective–B1 life ten years.

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

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1. Introduction

To be competitive in the open space where a market is, even conventional devices, such as domestic refrigerator, may be refined with novel technologies and attributes to satisfy the request of end-users. If a new system is hurried to the marketplace with insufficient testing which mimics customers' usage of these attributes, there is the possibilities for untimely failure of the product. It can undesirably influence the perception of the product quality manufactured by the producer. Since 1970's, it also has been recognized that there exists considerable gap between reliability thesis and its implementation to business areas. To circumvent having anticipated design defects in the market, the noble attributes of a newly designed product should be appraised in the developing phases before delivering 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 product recalls from the market that have design flaws, it might be devised to outlive the normal working circumstances applied by end-users who purchase and utilize it. The Boeing 737 MAX airplane was prohibited from flying after 346 passengers were dead. The passenger aircrafts mounted in the CFM International LEAP-1B motors utilizing the greatest favorable 68-inch fan design. They had 12% less power consumption and were less 7% weight, compared with other engines [2]. Inspectors, involving the Ethiopian Civil Aviation Authority, conjectured that the accident was produced by the airplane's motor.

Fatigue is the major origin of failure in parts, detailing 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. It is the withering of a substance produced by regularly repeated loads under the end-user utilization. It may produce catastrophic consequences in a system so that the product failure could be in wound or death of end-users. Notable study concentrates on the fatigue of superalloys, especially in the area of turbine–motors (nickel-found polycrystalline). It has 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, obvious in parametric ALT, can help point out the design faults in the product operated by machine.

Engineers frequently pinpoint design imperfections and secure them utilizing Taguchi's method [5] or design of experiments (DOE) [6]. DOE is an arranged manner to identify the link between factors determining the process and its manufacturing. The DOE's aim is to secure that the elements are devised optimally for the operating conditions (or surrounding). DOE is carried out for some design factors that influence it. Their effectiveness is proved by analysis of variance. Taguchi's way also manifests it for product and its assessment. It sets to find the most favorable design where the ''noise'' element does not have any result on. However, because DOE incorporating Taguchi's method cannot recognize which factors are critical due to fatigue in the process to be followed in calculations, these perspectives request huge mathematical calculations. However, they cannot supply for most favorable design.

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

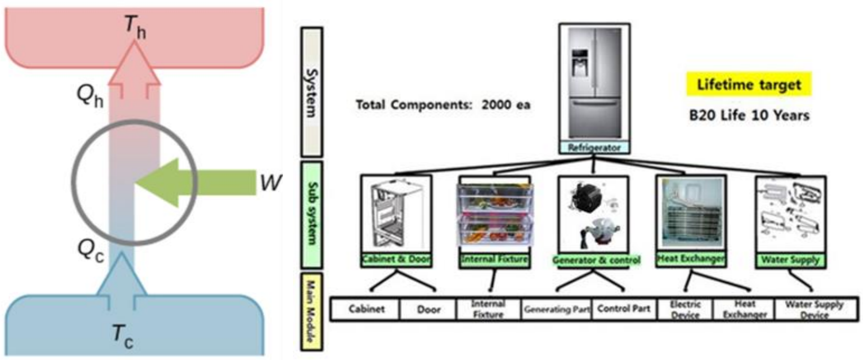
As other possibility way, engineers utilize the finite element analysis (FEA) [7]. They also think that failure can be recognized by (1) rigorously exact (Lagrangian or Newtonian) modeling; (2) assessing the response for load, creating the product stress/strain; (3) employing the accepted way such as rain-flow counts; and (4) judging product successfulness by 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 is to provide parametric ALT as a widespread way that produces reliability quantitative (RQ) statement, such as the mission cycles, which can identify the product defects and supply a way for enhancing the fatigue life of product. This confirmed procedure is suitable to the mechanical product such as airplane, automobile, appliance, etc. It involves: (1) an ALT program generated on BX lifespan, (2) load analysis, (3) tailored of ALTs with the changes, and (4) a judge of whether the product attains the targeted BX lifespan. To attain the usefulness for ALT, it is necessitated to evaluate the new system in the field to fulfil the 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. pass power to manage a job that has in need of forces and move, generating mechanical advantages by adopting their mechanisms. Most systems operated by machine thus are formed of subsystem structures. If the subsystem are properly constructed, system operated by machine can carry out its own planned tasks. As an instance, a refrigerator is devised of as approximately 2000 parts. The target of product life is set to have B20 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 B1 life ten years. The product life is managed by some design flaws in a module.



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

Figure 1. Mechanical product 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 (β < 1). Second, there is a continual failure rate (β = 1). Third, there is an enlarging failure rate to the termination of the lifespan in a substance manufactured (β > 1). If it goes behind bathtub, product will manage with difficulty to accomplish a desired aim in the market space due to the big failure rates and low life. Manufacturers will emphatically enhance its design by setting reliability aims 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 reduces and its life extends. For such circumstance, bathtub will be converted to a line with the shape parameter β that can be the advantageous form of a failure rate enveloping the whole lifespan of a system with good quality (Figure 2).

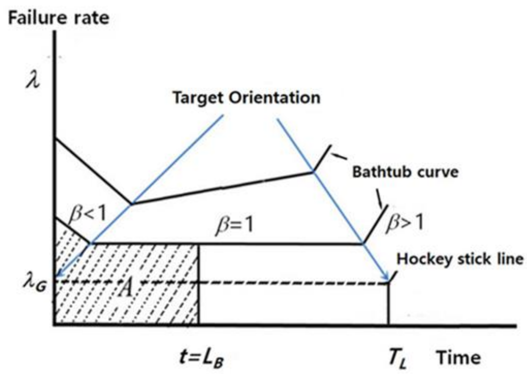


Figure 2. Bathtub and hockey stick line with slope β to the end of the product lifespan.

As product design is reinforced, the failure rate in the marketplace may decrease. On the other hands, the product life expands. For such situations, the product reliability can be indicated as the product between failure rate & its life and declared as follows:

$$F(L_B) = 1 - R(L_\mathrm{B}) = 1 - e^{-\lambda L_\mathrm{B}} \cong \lambda L_\mathrm{B} \quad (1)$$

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).

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

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 main matter for a reliability testing is how untimely the feasible failure may be discovered. 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 a product defects shaped on an atomic/microscopic size when repetitive subjected to load, the life-stress prototype from such viewpoint should be defined. That is, fatigue can originate from material flaws–electron/void–which are emerged on Nano, microscopic or macro range. From such perspective, it can be expressed as transport procedures–the diffusion of shallow level dopants–in silicon (semiconductor).

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

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

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

The boundary conditions are: (1) ψ_n restricted in the metal but decomposing 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:

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

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

Transport processes therefore are expressed as:

$$J = LX \quad (4)$$

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

For instance, the following processes are figured out to utilize for solid-state diffusion of impurities in silicon which is extensively utilized in semi-conduct as follow: (1) electromigration-induced voiding, (2) gradual accumulation of chloride ions, and (3) confinement of electrons or holes.

As electro-magnetic force, ξ, is employed, the impurities such as material void set up by electronic motion is simply drifted because the energy obstacle of junction is less high in position, phase-shifted, distorted, etc. For solid-state diffusion of impurities in silicon, the junction function J could be manifested as [8]:

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

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

$$= -[a^2 ve^{-qw/kT}]\, cosh\frac{qa\xi}{2kT}\frac{\partial C}{\partial x} + [2ave^{-qw/kT}]C\, sinh\frac{qa\xi}{2kT}$$

$$\cong \Phi(x,t,T)\, sinh(a\xi)\, exp\left(-\frac{Q}{kT}\right)$$

$$= B\, sinh(a\xi)\, exp\left(-\frac{Q}{kT}\right) \quad (5)$$

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 inversed function, stress prototype is attained as

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

The hyperbolic sine term can be manifested as: (1) at first $(S)^{-1}$ in little effect, (2) $(S)^{-n}$ in middle effect, and (3) $(e^{aS})^{-1}$ in tall effect. As elevated test is accomplished in the medium-sized effect, Equation (6) is restated as:

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

Because the system stress is complicated to express the testing quantity, Equation (14) need to be modified. As the power is manifested as the product of effort and flows, stresses in a system will originate from effort such as force.

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

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

Product defects can be discovered by exercising greater effort under the 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 build in the effort views:

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

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]:

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

2.4. Case Investigation: Reliability Design of the HKS

To comfortably operate the door of household refrigerator, HKS with a spring-damper mechanism is conceived. As 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, shaft ④, and spring ⑤. as seen in Figure 3.

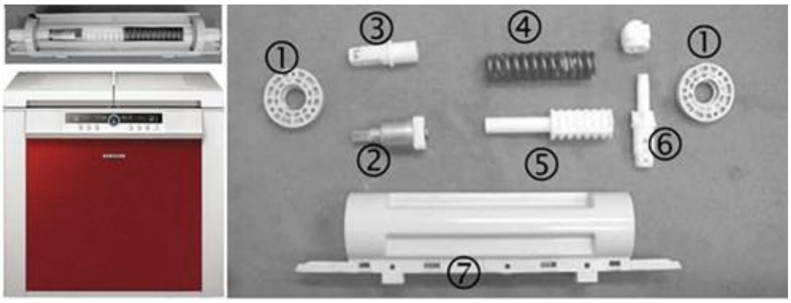


Figure 3. Household refrigerator and HKS parts.

In the marketplace, the cracking and fracturing of HKS elements in a household refrigerator were occurred due to fatigue and some design flaws. To replicate the real customer use and load states, engineers does not recognize which reliability tests are required. A manufacturer should optimally and robustly design a mechanical system to retain the product working for its expected life. If there are the design defects, the system may fail to accomplish a desired result before its anticipated life. 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 if lifetime target is attained.

Established on the end-user usage situations in the field, HKS is exposed to various loading 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).

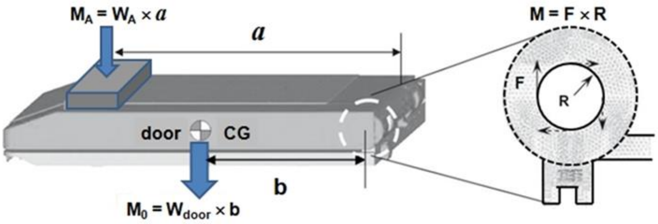


Figure 4. Model with a simple force and moment of HKS.

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 was appended to increase 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 the similar environmental circumstances, Equation (8) is redefined as:

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

where A is constant and B is constant.

Equation (9) may be redefined as:

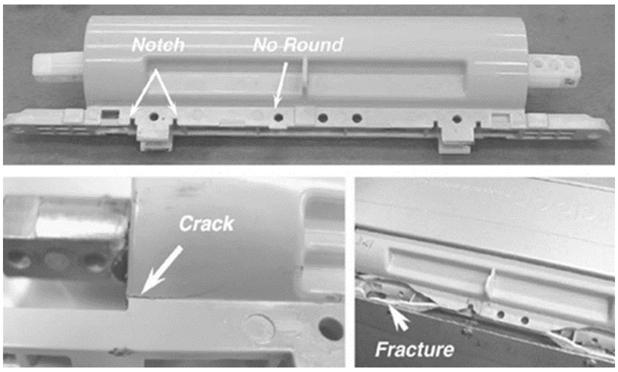
$$AF = \left(\frac{S_1}{S_0}\right)^n = \left(\frac{T_1}{T_0}\right)^\lambda = \left(\frac{F_1 \times R}{F_0 \times R}\right)^\lambda = \left(\frac{F_1}{F_0}\right)^\lambda \tag{13}$$

3. Results and Discussion

The surrounding circumstances of HKS in a domestic refrigerator ranges from 0 to 43 °C with a humidity varying from 0% to 95%. The HKS is exposed between 0.2 and 0.24g's of acceleration. The door operating times is determined by specified end-user utilization. Consumer statistics manifests that the refrigerator door is usually operated between three and ten cycles per day in the marketplace. With the life cycles for ten years, the HKS experiences about 36,500 usages for the worst-instance. The impact around the HKS is 1.10kN that was the predicted greatest force deployed by the end-user. For the ALT with a raised weight, the HKS impact is 2.76kN. Employing a damage constant, λ, of 2.0, AF was found to be 6.3 in Equation (21).

The test cycles used in the ALT for the given sample size and lifetime target were calculated from equation (17). That is, for six units and life aim–B1 life ten years, the allotted mission time (or cycles) were 24,000 cycles. This ALT can be devised to acquire a B1 life ten years 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 to 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 the HKS housing in both the marketplace and 1st ALT arose in the HKS. The design flaws of the housing in an HKS originated from no support structure in its housing there is no ribs. As there are faults in the system where the impact loads are utilized, the fracturing of HKS occurs in its lifespan. In other words, the exerted repeated force in combination with the system defects may have been the cause of the fracturing of the HKS. Therefore, to be adequate strength against impact loading, the weak HKS housing should be strengthened. That is, notches were removed and the corner rounding were given outside and inside. Strengthened ribs also were fastened on the housing and decks (Figure 6).

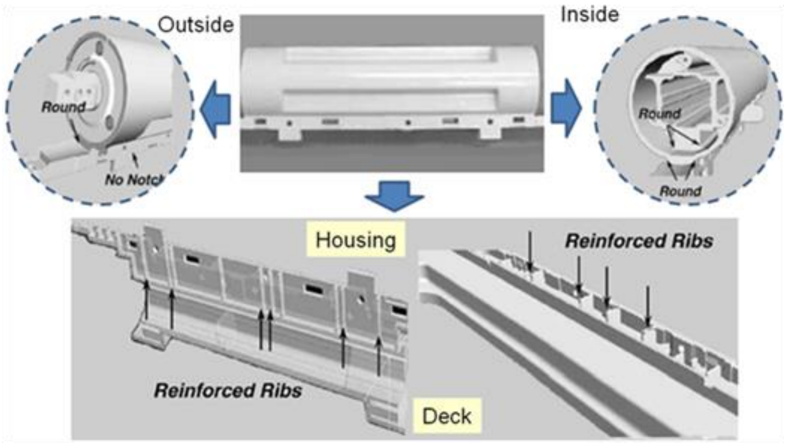


Figure 6. Reinforced HKS housing.

As separating problematic HKS samples into component parts, the spilled oil damper 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 0.5mm. 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.

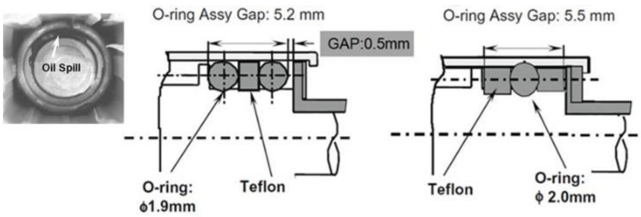


Figure 7. Redesigned oil damper.

In the second ALTs, the fracture 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 a HKS. As operating the HKS, the oil damper support fabricated by aluminum stroke the HKS cover fabricated by plastic. Thus, the hinge kit cover developed to crack and fracture at its end. As action plan, to be enough material strength for repeated impact loading, the HKS cover was ammended from plastic to aluminum (Figure 8).

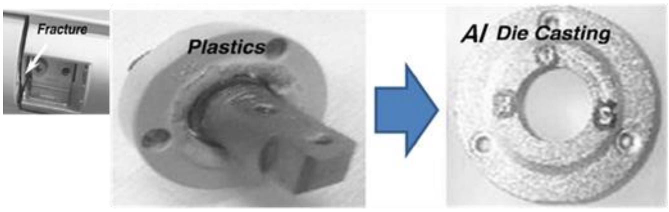


Figure 8. Redesigned kit cover.

4. Conclusions

To raise the fatigue of a new product operated by machine such as HKS, parametric ALT has been suggested as structured reliability way 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 to secure they were realized. An HKS in a household refrigerator was utilized as an instance investigation.

In first ALT, the unsuccessfulness of the HKS 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, HKS were resolved to be the lifespan aim–B1 life 10 year.

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