Methodology to Enhance the Lifetime of Mechanical System by Utilizing Parametric Accelerated Life Testing

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Abstract. To enhance the design of mechanical systems, parametric Accelerated Life Testing (ALT) as a systematic reliability method is proposed as a way to evaluate the design of mechanical systems subjected to repeated impact stresses. It requires: (1) a parametric ALT scheme shaped on system BX lifetime, (2) a load inspection, (3) parametric ALTs with the associated design modifications, and (4) an assessment of whether the revised product design(s) reach the targeted BX lifetime. We propose using a general life-stress model and sample size equation. A test example using both market data and parametric ALT was the redesign of a hinge kit system (HKS) in a refrigerator. To conduct parametric ALTs, a force and moment balance analysis was utilized. The mechanical impact loadings of the HKS were evaluated for an working refrigerator door. For the first ALT, the HKS failure happened in the crack/fracture of the kit housing and oil spilled from the damper when the HKS was disassembled. The failure modes and mechanisms constructed in the 1st ALT were similar to those of the unsuccessful samples found from the marketplace. The missing design parameters of the HKS included stress raisers such as corner roundings and the rib of the housing in HKS, the seal in the oil damper, and the material of the cover housing. In the second ALT, the cover housing fractured. The design defect of the cover housing in the HKS was the plastic material. As a corrective action plan, the cover housing was modified from plastic to aluminum. After the second ALT, the lifetime of the modified HKS was reassured to be B1 life 10 years with a yearly failure rate of 0.1%.

Keywords: Lifetime design · Hinge kit system · Fracture · Parametric ALT · Design defects

1 Introduction

Mechanical products such as automobiles, airplanes, and refrigerators convert some form of power into a mechanical advantages utilizing various mechanisms. Most mechanical products are multi-module structures. If the modules are assembled, the mechanical

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product can satisfactorily function and perform its own planned purposes. For instance, a refrigerator is designed to provide chilled air from the evaporator to the freezer (or refrigerator). It includes various modules – cabinet, door, internal fixture (shelves and drawers), generating parts (motor or compressor), controls and instruments, heat exchanger, water supply device, and other various parts. A refrigerator may have as many as 2,000 parts.

The reliability of a mechanical product might be described as the multiplication of its lifetime, L_B, and failure rate, λ. The entire failure rate of mechanical product such as refrigerator over its lifetime is the grand total of the failure rate of each module. If there were no premature failures in a product, the product lifetime could be decided by problematic designed module #3 in Fig. 2 such as a newly designed HKS examined in case-study in this paper. The refrigerator lifetime is anticipated to beat a B20 life 10 years, That is, the time period that accumulated failure rate becomes 20% is ten years. If a refrigerator consists of 20 units and each unit has 100 components, the lifetime of each unit is targeted to be a B1 life 10 years. In other word, the time period that accumulated failure rate becomes 1% is ten years. We can conduct a parametric ALT for the newly designed mechanical system to potentially identify the design issues (Figs. 1 and 2).

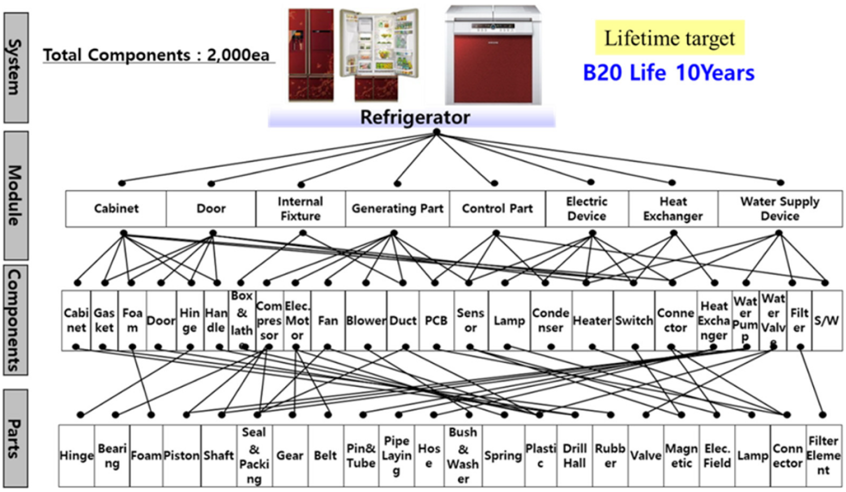


Fig. 1. Classification of refrigerator with multi-modules.

To reduce the failure rate of a mechanical system in the marketplace, it should be designed to robustly endure the working conditions for the consumers who purchase and use it. Any design defects should be identified and altered through statistical methodology or reliability testing [1] before a product is released. However, this approach demands enormous computations for an optimum answer but may not identify the most likely failure. If there are design faults that create an insufficiency of strength (or stiffness) when a product is subjected to repeated loads, the product will fail before its anticipated lifetime due to fatigue.

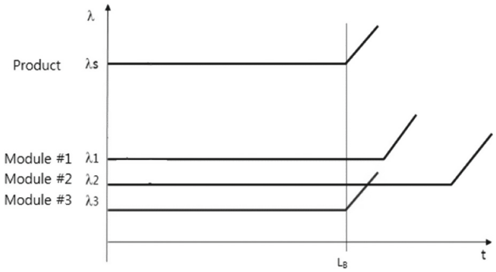


Fig. 2. Lifetime L_B and failure rate λ_S of multi-modules product.

The typical methodologies for identifying failures in a product are stress–strength interference analysis, failure modes, effects, and criticality analysis (FMEA/FMECA), and fault tree analysis (FTA). In the product development process, these analyses are executed and documented by a company's technical specialists. Because the crucial designs of a new product is often missed in reviewing designs, the product can undergo field failures and then have to be recalled. Stress/strength interference models predict why mechanical products fail during a gradual wearout process. It also explains product failure if the stress is larger than the strength. However, because product failure may occur rapidly from fragile parts of a product, it necessitates using complementing design concepts such as fracture mechanics and life-stress model [2].

To execute the optimal design of a mechanical structure, engineers have investigated conventional design perspectives such as strength of materials. A new fracture mechanics study on the crucial components should be include fracture toughness instead of strength as a relevant material attribute. With quantum mechanics advances applied in electronic technology, engineers have identified system failures from micro-void coalescence (MVC), that may appear in metallic alloys or numerous engineered plastics. To determine the failure phenomena of a mechanical product, a better life-stress model might be combined with the traditional design approaches and applicable to electronic parts indentifying a small crack or pre-existing defect that is impractical to model using FEM.

To understand why systems failure in the field, some engineers try to use the finite element method (FEM) to model the components in a system. Many engineers believe that infrequent product failures can be appraised by: (1) mathematical modeling utilizing Newtonian or Lagrangian methods, (2) after getting the system response for (dynamic) loads, the product stress/strain from it obtains, (3) employing the rain-flow counting method for von Mises stress, and (4) approximating thr system damage by the Palmgren–Miner's law. However, employing a systematic method that can produce a closed-form, specific answers would entail making countless assumptions that cannot identify multi-module product failures due to micro-void, contacts, design defects, etc. when subjected to loads.

This work presents a parametric ALT as a systematic reliability method that might be relevant to mechanical systems. It contains: (1) a parametric ALT scheme shaped on product BX lifetime, (2) a load inspection for ALT, (3) a parametric ALTs with the design changes, and (4) an assessment of whether the latest design(s) of the product gets the objective BX lifetime. As an case-study, we will examine the design of a HKS in a domestic refrigerator.

2 Parametric ALT for Mechanical System

2.1 Placing an Comprehensive Testing Plan

Reliability can be manifested as the system potential to run under stated conditions for a specified period of time. Product reliability can be illustrated by a diagram called the "bathtub curve" that is composed of three areas. At the beginning, there is a lessening failure rate in the early life of the product ($\beta < 1$). Then, there is a nearly constant failure rate ($\beta = 1$). Utimately, there is a growing failure rate at the end of the system's life ($\beta > 1$). If a product follows the bathtub curve, it may have difficulties being successful in the field because of the large failure rates and short lifetimes due to design defects. A manufacturer can update the product design by targeting reliability for new products to (1) minimizing premature failures, (2) reduce random failures during the product working period, and (3) enlarge product lifetime. As the design of a mechanical product improves, the failure rate of the product in the market decreases and its lifetime lengthens. For such states, the failure rate can become nearly a straight line (Fig. 3).

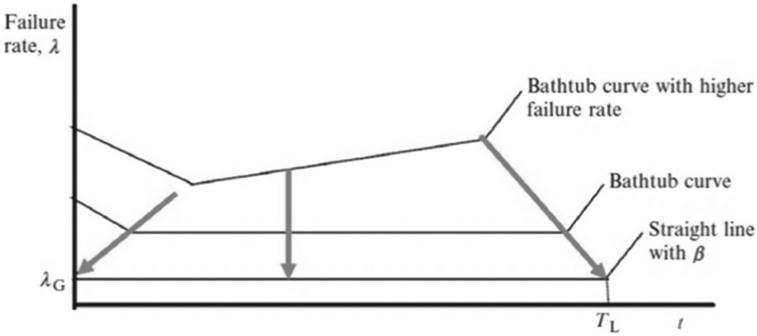


Fig. 3. Bathtub curve and straight line with slope β to the ending of the life of the product

For a constant failure rate, the cumulative failure function of a mechanical product might be evaluated from the product lifetime L_B and failure rate λ as follows:

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

where R(·) is reliability function, F(·) is unreliability function.

Equation (1) is relevant to ≤20% of cumulative failures, F(·). After targeting the product lifetime L_B, designer should recognize any design defects and alter them through parametric ALT (Fig. 4 and Table 1).

In targetting the BX lifetime of a mechanical system for a parametric ALT, there is (1) a newly designed module, (2) an revised module, and (3) identical module where there is no change to the preceding design. A HKS can be considered as a new module

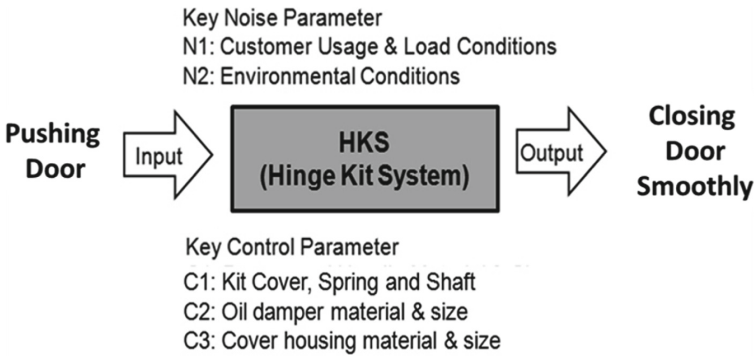


Fig. 4. Robust design schematic of a mechanical system such as HKS

Table 1. Whole parametric ALT plan for a mechanical system – refrigerator (example).

No	Module Name	Market Data, *F* (BX=1.8)		Design	Conversion	Expected, *F* (BX=1.8)		Targeted, *F* (BX=1.0)	
		Yearly Failure Rate, %/year	L_{BX} Life year			Yearly Failure Rate, %/year	L_{BX} Life year	Yearly Failure Rate, λ_G, %/year	L_{BX} Life year
1	Module A	0.34	5.3	New	x5	1.70	1.1	0.10	10
2	Module B	0.35	5.1	Given	x1	0.35	5.1	0.10	10
3	Module C	0.25	7.2	Modified	x2	0.50	3.6	0.10	10
4	Module D	0.20	9.0	Modified	x2	0.40	4.5	0.10	10
5	Module E	0.15	12.0	Given	x1	0.15	12.0	0.15	10 (BX=1.5)
6	Others	0.50	12.0	Given	x1	0.50	12.0	0.45	10 (BX=4.5)
Total	Product (R-Set)	1.79	5.1	-	-	3.60	3.6	1.00	10 (BX=10)

for the refrigerator because consumers desire to close the door softly. Like module A analysed in Table 1, HKSs from the marketplace had yearly failure rates of 0.34% per year and a lifetime of B1.8 life 5.3 years. To respond to customer complaints, a lifetime for the HKS was targeted to be B1 life 10 years.

2.2 Failure Mechanism and Accelerating Testing

Mechanical systems move (generated) power from one place to another by adapting its mechanisms. A HKS is a mechanical system that allows the refrigerator door to be gently closed by using a proper mechanism. A HKS is subjected to repeated stress due to impact loads. If there is a design defect in the structure that creates an inadequate strength (or stiffness) when the loads are applied, the HKS may quickly fail before its anticipated lifetime. After identifying the product failure by a parametric ALT, an engineer can redesign the HKS configuration with a proper material. The HKS can then endure repeated loads over its lifetime so that it can reach the targeted reliability (Fig. 5).

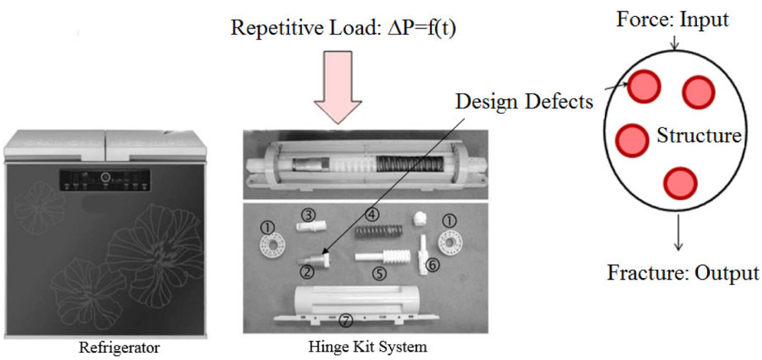


Fig. 5. Failure mechanics on the structure generated by repeated load and design flaws

The most important matter for a reliability test is how a potential premature failure mode can be identified. A life-stress (LS) model of the HKS can be developed which involve stresses and reaction parameters. This model can describe some failures such as fatigue in the mechanical system. Fatigue failure appears, not due to conceptual stresses in a flawless part, but rather due to the existing of a tiny crack or a defect on the exterior of a part that can become plastic by the implied stress. It is important to understand how a small crack or pre-existing material defects may be generated. Because system failures start from the existence of a material defect shaped on a microscopic level, we might eavaluate the life-stress model from such a standpoint. For example, we could adopt processes utilized for solid-state diffusion of impurities in silicon that is widely used as semi-conduct material: 1) electro-migration-induced voiding; 2) build-up of chloride ions; and 3) trapping of electrons or holes.

When electric magneto-motive force, ξ, is exerted, we know that the impurities such as void in a material shaped by electronic movement is effortlessly migrated because the barrier of junction energy is lowered and distorted/phase-shifted. For solid-state diffusion of impurities in silicon, the junction equation J can be expressed as (Fig. 6) [3]:

$$J = B \sinh(a\xi) \exp\left(-\frac{Q}{kT}\right) \tag{2}$$

where B is constant, a is the interval between (silicon) atoms, ξ is the exerted field, k is Boltzmann's constant, Q is energy, and T is absolute temperature.

In contrast, a reaction process that is relied on speed could be stated as [4]:

$$\begin{aligned} K = K^{+} - K^{-} &= a\frac{kT}{h}e^{-\frac{\Delta E - \alpha S}{kT}} - a\frac{kT}{h}e^{-\frac{\Delta E + \alpha S}{kT}} \\ &= 2\frac{kT}{h}e^{-\frac{\Delta E}{kT}} \cdot \sinh\frac{\alpha S}{kT} \end{aligned} \tag{3}$$

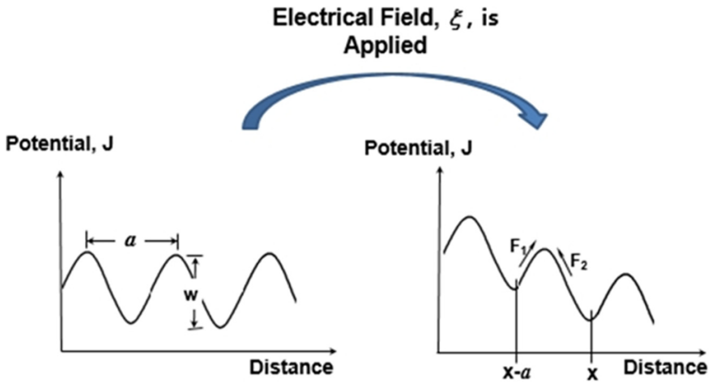


Fig. 6. A potential (barrier) change in material for electron/void migration after electric magneto-motive force is applied.

So the reaction rate, K, from Eqs. (2) and (3) can be simplified as:

$$K = B \sinh(aS) \exp\left(\frac{E_a}{kT}\right) \tag{4}$$

If Eq. (4) takes an inverse function, the generalized life-stress model might be stated as

$$TF = A[\sinh(aS)]^{-1} \exp\left(\frac{E_a}{kT}\right) \tag{5}$$

The hyperbolic sine stress term grows the stress as follows: (1) initially $(S)^{-1}$ in low stress effect, (2) $(S)^{-n}$ in medium stress effect, and (3) $\left(e^{aS}\right)^{-1}$ in high stress effect. Because ALT will be executed in the medium stress range, Eq. (5) is stated as follows (Fig. 7):

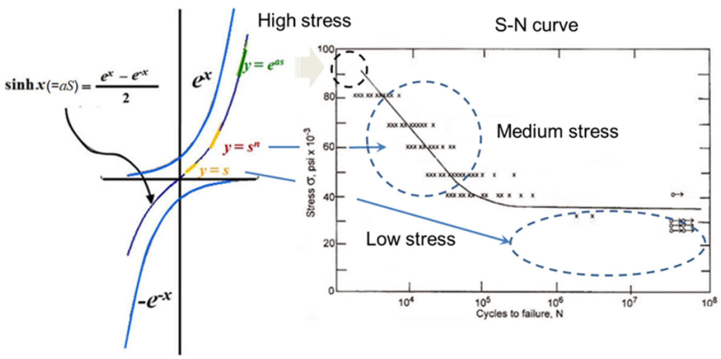


Fig. 7. Hyperbolic sine stress term versus S-N curve.

$$TF = A(S)^{-n} \exp\left(\frac{E_a}{kT}\right) \tag{6}$$

Because the stress of a mechanical system is hard to measure in testing, we need to redefine Eq. (6). When the power is expressed as the multiplication of effort and flows, stresses may come from effort in a multi-port system. Equation (6) can then be ststed as the more general form:

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

Design defects in products can be attained by exerting larger forces under elevated conditions. From the time-to-failure in Eq. (7), an acceleration factor (AF) can be stated as the proportion between the proper elevated condition levels and common condition levels. AF can be stated to integrate the effort ideas:

$$AF = \left(\frac{S_1}{S_0}\right)^n \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] = \left(\frac{e_1}{e_0}\right)^\lambda \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] \tag{8}$$

2.3 Parametric ALT for Mechanical Systems

Sample size equation with the AF in Eq. (8) would be stated as [5]:

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L_{BX}^*}{AF \cdot h_a}\right)^\beta + r \tag{9}$$

The lifetime of the new HKS was targeted to be B1 life 10 years. Based on the customer usage conditions, the mission cycles of the product were studied. Under the worst case, the number of required test cycles could be estimated from Eq. (9) for the assigned samples. ALT equipment could then be performed on the basis of the observed loads on the product. In parametric ALTs, the missing design defects of HKS could be identified to attain the lifetime target – B1 life 10 years.

2.4 Case Study: Improving the Lifetime of the HKS

When a consumer uses the door in commercially produced refrigerator, they usually want the door to close comfortably. For this (intended) function, the HKS should be designed to endure the working conditions subjected to it by the consumers who purchase and use the refrigerator. The principal parts in a HKS consists of a kit cover, shaft, spring, and oil damper, etc. (Fig. 8).

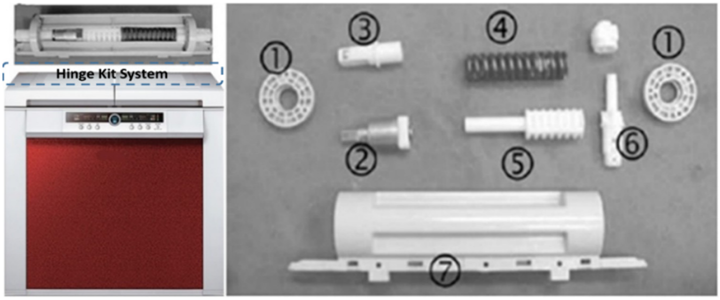


Fig. 8. Domestic refrigerator and HKS parts: kit cover ①, oil damper ②, fixed cam ③, spring ④, cam ⑤, shaft ⑥, and HKS housing ⑦

In the marketplace, the HKS parts in refrigerators were failing due to repeated loading under unidentified consumer operation conditions. When data from the marketplace were examined, it appeared that the HKS in the refrigerators had structural design defects, including sharp corner angles and not enough enforced ribs resulting in high stress concentrations. These design flaws, integrated with the repeated impact loads on the HKS, could create a crack in the part and produce a failure in the system (Fig. 9).

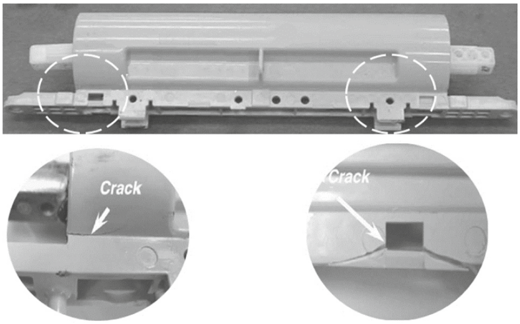


Fig. 9. Products damaged from the marketplace

The closing function of the HKS included several mechanical structural parts. The HKS was often subjected to repeated mechanical impact loads when the consumer closed the door. Door closings required straightforward mechanical procedures: (1) the customers opened the door to take out or store food, and (2) they then closed the door by force.

Thus, the HKS were subjected to various loads during the functioning of the refrigerator door. To identify the required AF, it was crucial to determine the forces on the HKS during the operation of the door. Because the HKS was a comparatively simple mechanical structure, the forces impacting the HKS could be modeled with a force-moment equation. As the customer opened or closed the refrigerator door, the stress due to the door weight was concentrated on the HKS (Fig. 10).

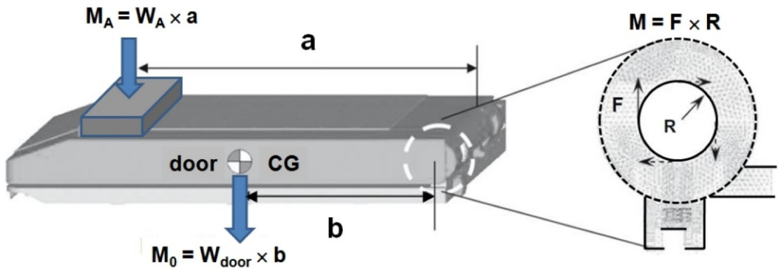


Fig. 10. Design concept of HKS

The moment balance around the HKS can be defined as

$$M_0 = W_{door} \times b = T_0 = F_0 \times R \tag{10}$$

The moment balance around the HKS under ALT condition can be defined as

$$\begin{aligned} M_1 &= M_0 + M_A = W_{door} \times b + M_1 \times a \\ &= T_1 = F_1 \times R \end{aligned} \tag{11}$$

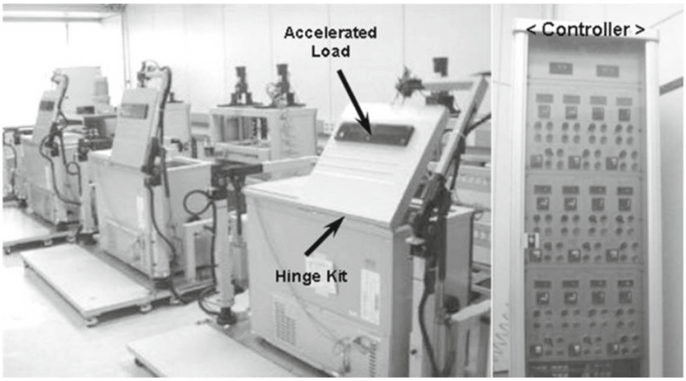
F_0 is the impact force in usual conditions and F_1 is the impact force in the ALT. The stress on the HKS relied on the applied impact due to the elevated weight. The life-stress model (LS model) in Eq. (8) can be restated as

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

The AF can be stated as

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

The working conditions for the HKS in a refrigerator were a temperature between 0 °C and 43 °C, relative humidity varying from 0% to 95%, and 0.2–0.24 g's of acceleration. The opening and closing of the door ocurred approximately 3 to 10 times per day. With a life design cycle for 10 years, the lifetime of HKS was about 36,500 usage cycles for the worst case.



(a) ALT Equipment (b) Controller

Fig. 11. Design concept of HKS

For this scenario, the impact force around the HKS was 1.10 kN which was the anticipated greatest force exerted on the HKS by a user. For the ALT with an accelerated weight, the impact force on the HKS was 2.76 kN. Using a cumulative damage exponent, λ, of 2.0, the AF was established to be roughly 6.3 in Eq. (13).

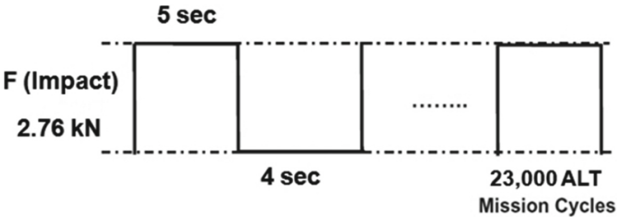
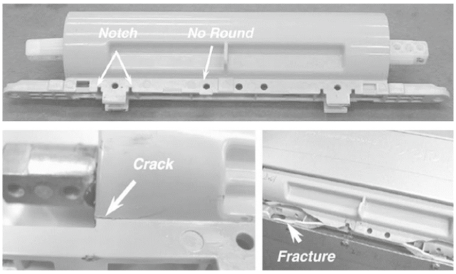


Fig. 12. Duty cycles of the repeated impact load F on the HKS.

For the lifetime target – B1 life 10 years, the test cycles for sample six pieces using Eq. (9) were 23,000 cycles for a shape parameter of 2.0. This parametric ALT was designed to ensure a B1 life 10 years with a 60% confidence level it would fail less than once during 23,000 cycles. Figure 11 shows the test facility of the ALT with equipment for evaluating the durability of the design of the HKS. As seen in Fig. 12, repeated stress caused by the on/off duty cycles allow for the evaluation of the impact on the HKS life. The control console was used to operate the testing apparatus. It ran the number of tests, the testing time, and the starting/stopping of the equipment. As the start button on the controller keypad was pressed, the simple hand-shaped arms could grasp and lift the refrigerator door. As the door was closing, it could apply to the greatest mechanical impact force necessary to reproduce the accelerated load in the HKS (2.76 kN).

3 Results and Discussion

Figure 13a and 13b show the failed product from the marketplace and the failed from the 1st ALT, respectively. In the 1st ALT, the housing of the HKS fractured at 3,000 cycles



(a) Failed products from the marketplace (b) Fracture after first ALT

Fig. 13. Failed products from the marketplace and fracture after 1st ALT.

and 15,000 cycles. As shown in the picture, the tests affirmed that the HKS housing had a fragile structure near the notch because there were high stresses produced at the sharp edges where it failed. The defective shape of the 1st ALT was very similar to that of the returned product from the marketplace. Figure 14 shows a graphical representation of the ALT consequences and market data on a Weibull plot. With similar repetitive stresses, the failure patterns manifested in 1st ALT and field were similar. When the shape parameter was originally approximated at 2.0, it was affirmed to be 2.1 from the Weibull plot of the first ALT.

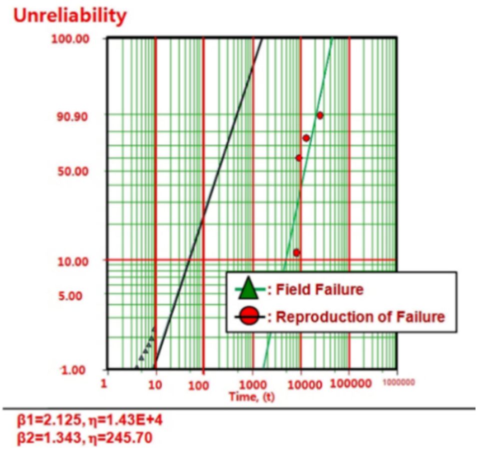


Fig. 14. Field data and results of ALT on Weibull chart.

Based on the test results and Weibull plot, the parametric ALT was justified because it identified the design defects that accounted for the failures in the marketplace. This systematic method helped in identifying the problematic designs found in failures from the marketplace. These failures determined the lifetime of the product.

When taking apart the HKS for examination, the oil damper in the HKS was found to leak at 15,000 cycles (Fig. 15). With the repeated impacts of the HKS in combination with its structural design defects, the HKS housing fractured and the oil damper leaked. Based on a finite element analysis, the concentrated stresses of the housing HKS was

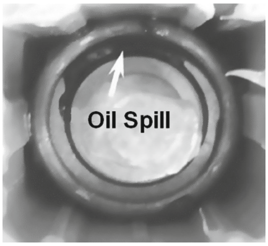


Fig. 15. Spilled products after 1st ALT.

about 21.2 MPa. The stress raisers in the high stress areas originated from design defects such as sharp corners/angles, poorly enforced ribs, and housing notches.

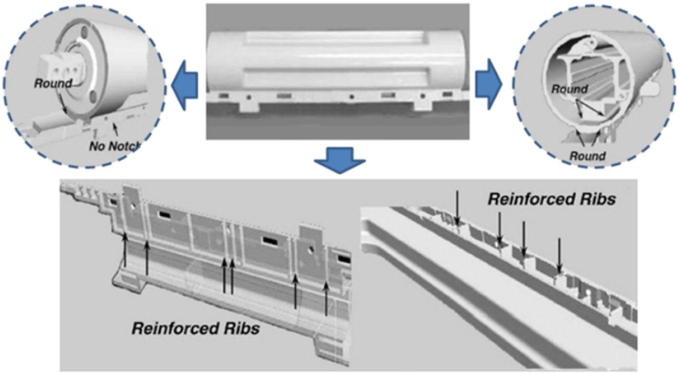


Fig. 16. Redesigned HKS housing structure.

The corrective action plans for the fragile HKS housing included making fillets, adding enforced ribs, and rounding the notches on the housing of HKS (Fig. 16). Upon executing the new designs, the stress concentrations in the housing of HKS were reduced from 20.0 MPa to 10.5 MPa. Thus, a corrective action plan had to be prepared at the design phase before manufacture.

When the spilled oil damper was investigated, the sealing structure in the oil damper had a 0.5 mm gap in the O-ring/Teflon/O-ring assembly. Due to the impact of the door closings, this sealing structure with the gap leaked for first ALT. With the corrective action plan, the sealing structure of the reformed oil damper was modified to have no gap between the Teflon/O-ring/Teflon (Fig. 17).

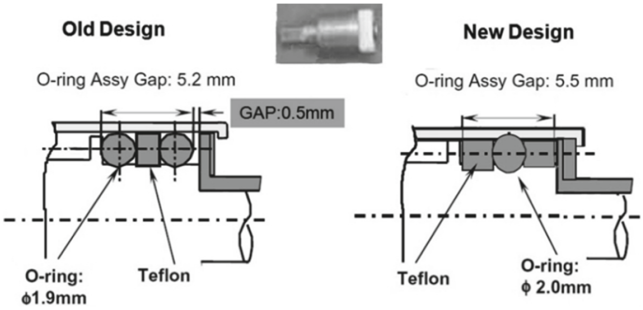


Fig. 17. Reshaped oil damper.

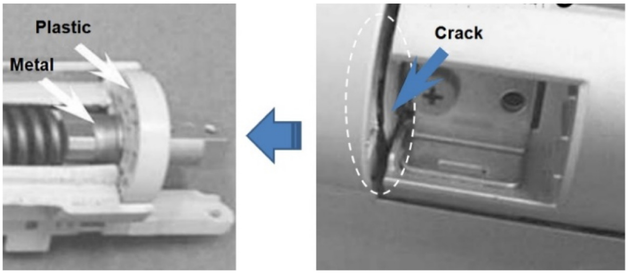


Fig. 18. Structure of problematic products at 2nd ALT.

The altered HKS produced more than the lifetime target – B1 life 10 years. The affirmed values of AF and β in Fig. 14 were 6.3 and 2.1, individually. The recomputed test cycles in Eq. (9) were 24,000 for sample six pieces. To evaluate the design flaws of the HKS, second ALTs were performed. In the second ALTs the fracture of the hinge kit cover ocurred at 8,000, 9,000, and 14,000 cycles (Fig. 18). The root cause of these fractures originated from striking the cover housing (plastic) by the support of oil damper (aluminum). As a corrective action plan, the material of the cover housing were changed from plastic to an Al die-casting. The final design of the HKS could endure the high impact load during operation of the door.

4 Conclusions

To enhance the lifetime of a newly designed mechanical system such as HKS, we have proposed a parametric ALT as a systematic reliability method that incorporates: 1) a parametric ALT plan, 2) a load examination, 3) a parametric ALTs with design alterations, and 4) an assessment of the last design needs of the HKS to assure they were fulfilled. A HKS in a refrigerator was investigated as a case study.

(1) Based on the products that failed both from the marketplace and in 1st ALT, the failure of HKS happened in the fractured HKS housing and oil damper spilling. The design defects of the HKS were the oil sealing structure and the HKS housing

that was caused from the concentrated stress due to inappropriate fillets, ribs, and notching. The corrective action plans were the alterations of the HKS housing and the redesigned sealing structure in oil damper.

(2) Based on the 2nd ALT, the fracturing of HKS happened in the cover housing. The design flaw of the HKS was the material of cover housing. As a corrective action plans, the cover housing from plastic to aluminum was altered. After ALTs, HKS with the correct values for the design parameters were decided to ensure the lifetime target – B1 life 10 years.

(3) As systematic reliability design method, we recognized that check of the returned product, load examination, and ALTs with design alternatives was much improved for the newly designed HKS in refrigerator. It also might be relevant to other mechanical systems such as airplane, automobiles, washing machines, and construction equipment. To employ this systematic method, engineers should understand why products fail. In other words, if there are design defects in mechanical product that creats inadequacy of strength (or stiffness) when subjected to repeated loads, the mechanical product will fail over its lifetime.

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