

# Improve the design of mechanical system by using parametric accelerated life testing

Seong-woo Woo, Dereje Engida Woldemichael, Samson Mekbib At naw, Muluneh Mekonnen Tulu

**Abstract** — To enhance the design of mechanical system, parametric Accelerated Life Testing (ALT) as systematic reliability method suggests to evaluate the design of mechanical systems subjected to repeated stresses. It involves: (1) a parametric ALT plan formed on system BX lifetime, (2) a load examination, (3) a customized parametric ALTs with the design changes, and (4) an assessment of whether the design(s) of product attains the objective BX lifetime. We suggest a general life-stress model and sample size equation. As a test case, based on market data and a customized ALT, the redesign of hinge kit system (HKS) in a refrigerator was investigated. To carry out parametric ALTs, utilizing a force and moment balance analysis, the mechanical impact loading of HKS were computed in operating the refrigerator door. At the first ALT, the HKS failure occurred in the fracture of the kit housing, and oil damper leaked when the HKS broke. The failure modes and mechanisms found in the 1<sup>st</sup> ALT were alike to those of the failed samples obtained from the marketplace. The missing design parameters of the HKS included the stress raisers such as corner rounding and rib of the housing in HKS, the oil seal in the oil damper, and the material of the cover housing. In the second ALT, the cover housing fractured. The missing design parameter of the cover housing in the HKS was the plastics material. As a corrective action plan, we modified the cover housing from plastic to aluminum. After ALTs, the lifetime of the redesigned HKS was reassured to be a B1 life 10 years with a yearly failure rate of 0.1%.

**Keywords**—Lifetime Design, Hinge Kit System, Fracture, Parametric ALT, Missing Design Parameter,

## I. Introduction

The mechanical products such as automobile, airplane, and refrigerator [1] manage power, which produce mechanical advantages by adapting product mechanisms. Most mechanical products are comprised of multi-module structures. If the modules are assembled, mechanical product can work properly and perform their own intended functions. For example, to stock food raw, refrigerator is designed to supply chilled air from the evaporator to the freezer (or refrigerator) section. It consists of some dissimilar 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. Whole parts have roughly 2,000 pieces.

The reliability of mechanical product could be explained as the multiplication of lifetime,  $L_B$ , and failure rate,  $\lambda$ . That is, the total failure rate of mechanical product such as refrigerator over its lifetime is the sum total of the failure rate of each module. If there were no early failures in a product, we know that the product lifetime is determined by problematic designed module #3 such as new HKS that will be discussed as case-study. The refrigerator lifetime is anticipated to beat a B20 life 10 years. Because refrigerator consists of 20 units if each unit has 100 components, lifetime of each unit is strictly targeted to be B1 life 10 years. We can carry out parametric ALT for newly designed mechanical system to search out the design problems (Figs. 1&2).

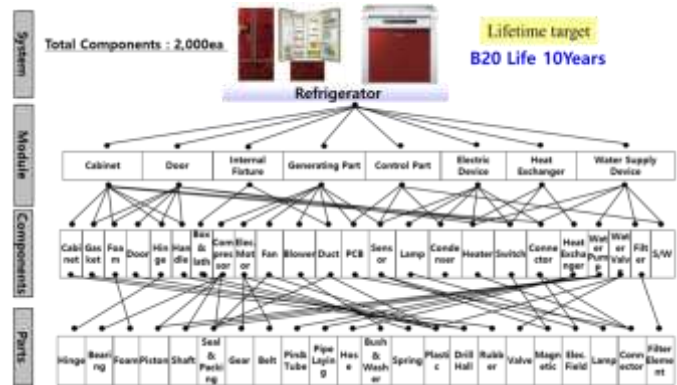


Figure 1 Breakdown of refrigerator with multi-modules

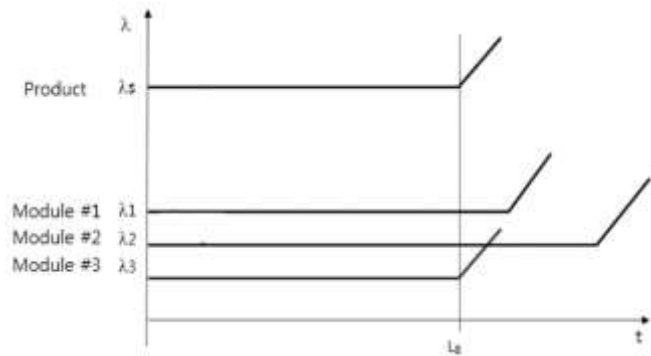


Figure 2 Lifetime  $L_B$  and failure rate  $\lambda_s$  of multi-modules product

To avoid the failure of mechanical system in the field, it must be designed to robustly endure the working conditions exposed by the customers who buy and use. Any design faults therefore should be recognized and modified through statistical methodology [2] or reliability testing [3] before a

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product is released. However, they requires huge computations for optimum solution but have no results because of not figuring out failure mechanics. That is, if there are design faults that causes an inadequacy of strength (or stiffness) when a product is subjected to repeated loads, the product will fail before its expected lifetime due to fatigue.

To search out the failure, its modes and effects of a product, the typical methodologies are stress–strength interference analysis [4], failure modes, effects, and criticality analysis (FMEA/FMECA) [5,6], and fault tree analysis (FTA) [7,8]. In the product developing process, these representative analyses are performed by a company's specialists for documentation. Because the crucial design parameters of a new product is frequently missed in reviewing them, the product would experience field failures and then have to be recalled. Especially, stress/strength interference model figures out why mechanical products fail in the gradual wearout process. It also explains product failure as the chance that stress is over strength. However, because product failure occurs suddenly from the fragile parts of a product, it requires the complementing design ideas such as fracture mechanics [9,10] and life-stress model [11].

To implement the optimal design of a mechanical structures, engineer has studied on traditional design approaches such as strength of materials [12,13]. On the other hand, a new fracture mechanics study [14] proposed the crucial elements should be fracture toughness instead of strength as a pertinent material attribute. As quantum mechanics advances in electronic technology, engineers have identified system failures from micro-void coalescence (MVC), noticed in the predominance of metallic alloys or numerous engineering plastics [15]. To figure out the failure phenomena of mechanical product, a better life-stress model might be combined with the traditional design approaches and applicable to electronic parts and a small crack or pre-existing defect that is clearly unfeasible to model using FEM [16].

To obtain the solution of system failures from the marketplace, there is an alternative engineering perspective that incorporates the finite element method (FEM) [17,18]. Many engineers believe rare product failures can be evaluated by: (1) mathematical modeling utilizing Newtonian or Lagrangian methods, (2) after obtaining the time response of the system for (dynamic) loads, obtaining the product stress/strain from it, (3) utilizing the rain-flow counting method for von Mises stress [19,20], and (4) approximating system damage by the Palmgren–Miner's law [21]. However, utilizing a systematic method that can yield a closed-form, precise answers would involve inducing numerous presumptions that cannot recognize multi-module product failures due to micro-void, contacts, design defects, etc. when subjected to loads.

This study introduces a parametric ALT as systematic reliability method that can be applicable to mechanical systems. It incorporates: (1) a parametric ALT plan formed on product BX lifetime, (2) a load examination for ALT, (3) a customized parametric ALTs with the design changes, and (4) an assessment of whether the last design(s) of the product attains the objective BX lifetime. As an experiment instance,

we will discuss as following: the redesign of HKS in a refrigerator.

## II. ALT for Mechanical System

### A. Putting an overall testing plan for parametric ALT

Reliability can be expressed as the system capacity to operate under stated conditions for a specified period of time. Product reliability can be clarified by a diagram named a “bathtub curve” that is made up to three areas. Initially, there is a lessening failure rate in the premature life of the product ( $\beta < 1$ ). Then, there is a continual failure rate ( $\beta = 1$ ). Lastly, there is a growing failure rate to the ending of the system's life ( $\beta > 1$ ). If a product pursuits the bathtub curve, it may have difficulties prospering in the field because of the lofty failure rates and short lifetime due to design faults. Manufacturers can emphatically upgrade the product design by targeting reliability for newly designed products to (1) lessen premature failures, (2) reduce random failures during the product working time, and (3) extend product lifetime. As the design of a mechanical product makes better, the failure rate of the product from the marketplace decreases and its lifetime increases. For such conditions, the conventional bathtub curve can be modified to a linear line (Fig. 3).

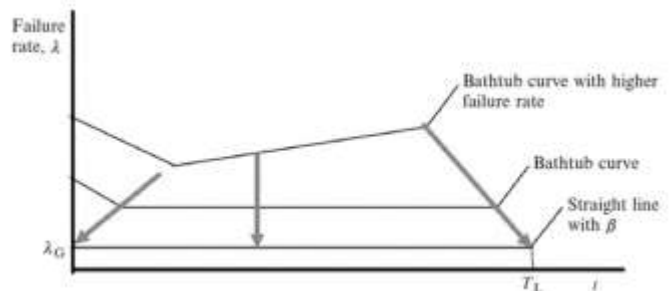


Figure 3 Bathtub curve and straight line with slope  $\beta$  to the ending of the life of the product

As the linear line with a low failure rate pursuits an exponential distribution, the cumulative failure function of a mechanical product might be computed from the product lifetime  $L_B$  and failure rate  $\lambda$  as follows:

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

where  $R(\cdot)$  is reliability function,  $F(\cdot)$  is unreliability function.

Equation (1) is relevant to  $\leq 20\%$  of cumulative failures,  $F(\cdot)$  [22]. After targeting the product lifetime  $L_B$ , designer should recognize any design faults and alter them through parametric ALT (Fig. 4 and Table I).



Figure 4 Parameter diagram of mechanical system – HKS (example)

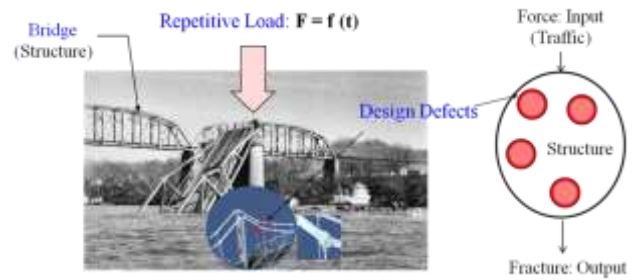


Figure 5 Failure mechanics on the structure generated by repeated load and design flaws

TABLE I. WHOLE PARAMETRIC ALT PLAN FOR A MECHANICAL SYSTEM – REFRIGERATOR (EXAMPLE)

No	Module Name	Market Data, $F$ (RN=1.8)		Design	Compression	Expected, $F$ (RN=1.8)		Targeted, $F$ (RN=1.8)	
		Yearly Failure Rate, %/year	$L_{50}$ Life, year			Yearly Failure Rate, %/year	$L_{50}$ Life, year	Yearly Failure Rate, %/year	$L_{50}$ 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 (RN=1.5)
6	Others	0.50	12.0	Given	x1	0.50	12.0	0.45	10 (RN=4.5)
Total	Product (R-Set)	1.79	5.1	-	-	3.60	3.6	1.00	10 (RN=10)

In putting the BX lifetime target of a mechanical system for parametric ALT, there are (1) a newly designed module, (2) an altered module, and (3) alike module where there is no change to the previous design. A HKS that will be case-studied can be considered as a new module attached because consumers would close the door gently. Like module A itemized in Table 1, HKS from the marketplace had yearly failure rates of 0.34% per year and a lifetime of B1.8 life 5.3 years. To answer to customer requests, a lifetime for the HKS was targeted to B1 life 10 years.

### B. Failure mechanics and ALT for design

Mechanical system moves (generated) power from one place to another by adopting its mechanisms. A HKS as one of mechanical system gently closes the refrigerator door by adapting mechanism. Thus, HKS are subjected to repeated stress due to impact loads. If there is design fault in the structure that causes an inadequacy strength (or stiffness) when the loads are exerted, HKS may suddenly fail over its anticipated lifetime. After pinpointing the product failure by parametric ALT, an engineer can most favorably design the HKS configuration and choose a proper material. The HKS sustains repeated loads in its lifetime so that it can achieve the targeted reliability (Fig. 5).

The most important issue for a reliability test is how premature the potential failure mode can be established. To fulfill this purpose, it is required to express a failure model and determine the associated coefficients. That is, we can configure the life-stress (LS) model, which involve stresses and reaction parameters. This equation can explain several failures such as fatigue in the mechanical system. Fatigue failure appears, not due to conceptual stresses in an ideal part, but rather due to the existence of a tiny crack or existed defect at an earlier time on the exterior of a part that become plastic by the implied stress. To better understand it, engineer recognizes how small crack or pre-existed material defects in material generate. That is, because system failure starts from the presence of a material defects formed on a microscopic when repeatedly subjected to a variable tensile and compression load, we might define the life-stress model from such a standpoint. For example, we can figure out the following processes utilized for solid-state diffusion of impurities in silicon that is popularly 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,  $\xi$ , is applied, we know that the impurities such as void in material formed by electronic movement is easily 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 defined as [23,24] (Fig. 6):

$$\begin{aligned}
 J &= [aC(x-a)] \cdot \exp\left[-\frac{q}{kT}\left[w - \frac{1}{2}a\xi\right]\right] \cdot v \\
 &= -[a^2ve^{-qw/kT}] \cosh\frac{qa\xi}{2kT} \frac{\partial C}{\partial x} + [2ave^{-qw/kT}]C \sinh\frac{qa\xi}{2kT} \\
 &\cong \Phi(x,t,T) \sinh(a\xi) \exp\left(-\frac{Q}{kT}\right) \\
 &= B \sinh(a\xi) \exp\left(-\frac{Q}{kT}\right) \quad (2)
 \end{aligned}$$

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

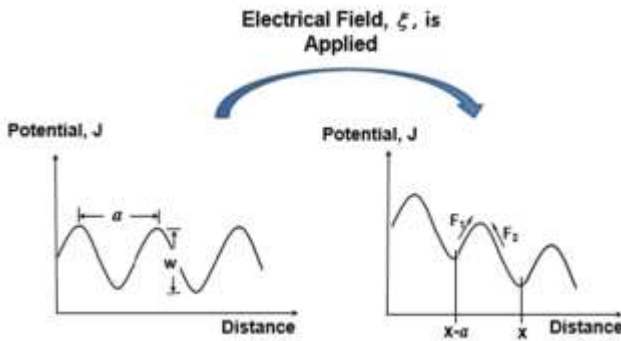


Figure 6 Potential change in material such as silicon after electrical field (or stress) is applied

Contrastingly, a reaction process that is relied on speed could be defined as:

$$K = K^+ - K^- = a \frac{kT}{h} e^{-\frac{\Delta E - \alpha S}{kT}} - a \frac{kT}{h} e^{-\frac{\Delta E + \alpha S}{kT}} \quad (3)$$

$$= 2 \frac{kT}{h} e^{-\frac{\Delta E}{kT}} \cdot \sinh\left(\frac{\alpha S}{kT}\right)$$

So the reaction rate, K, from Equations (2) and (3) can be abridged as:

$$K = B \sinh(\alpha S) \exp\left(-\frac{E_a}{kT}\right) \quad (4)$$

If Equation (4) takes an inverse function, the generalized life-stress model might be expressed as

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

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)  $(e^{\alpha S})^{-1}$  in high stress effect. Because ALT will be performed in the medium stress range, Equation (5) is expressed as follows (Fig. 7):

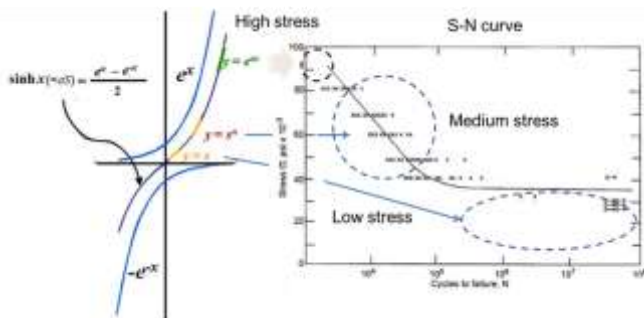


Figure 7 Hyperbolic sine stress term versus S-N curve

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

Because the stress of mechanical system is hard to measure in testing, we need to redefine Equation (6). When the power is expressed as the multiplication of effort and flows, stresses may come from effort in a multi-port system [25].

So Equation (6) can be redefined as the more general term:

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

Design flaws in products can be obtained by exerting larger effort under the accelerated conditions. From the time-to-failure in Equation (7), an acceleration factor (AF) can be explained as the proportion between the appropriate accelerated condition levels and common condition levels. AF can be expressed to incorporate the effort ideas:

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

$$= \left(\frac{e_1}{e_0}\right)^\lambda \left[\frac{E_a}{k} \left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] \quad (8)$$

### C. Parametric ALT of mechanical systems

To formulate the sample size equation and perform a parametric ALT, the characteristic life  $\eta$  should be approximated from the Weibull distribution. First, the characteristic life  $\eta_{MLE}$  from the Maximum Likelihood Estimation (MLE) was obtained as:

$$\eta_{MLE}^\beta = \sum_{i=1}^n \frac{t_i^\beta}{r} \quad (9)$$

If the confidence level was  $100(1 - \alpha)$  and the number of failures was  $r \geq 1$ , the characteristic life,  $\eta_\alpha$ , could be approximated from equation (9),

$$\eta_\alpha^\beta = \frac{2r}{\chi_\alpha^2(2r+2)} \cdot \eta_{MLE}^\beta = \frac{2}{\chi_\alpha^2(2r+2)} \cdot \sum_{i=1}^n t_i^\beta \quad (10)$$



If there was no failures and the p-value has  $\alpha$ ,  $\ln(1/\alpha)$  was mathematically identical to the Chi-square value,  $\frac{\chi_\alpha^2(2)}{2}$ . The characteristic life,  $\eta_\alpha$ , could be obtained as:

$$\eta_\alpha^\beta = \frac{2}{\chi_\alpha^2(2)} \cdot \sum_{i=1}^n t_i^\beta = \frac{1}{\ln \frac{1}{\alpha}} \cdot \sum_{i=1}^n t_i^\beta \quad (11)$$

Because equation (10) was accepted for all cases  $r \geq 0$ , it can be restated as:

$$\eta_\alpha^\beta = \frac{2}{\chi_\alpha^2(2r+2)} \cdot \sum_{i=1}^n t_i^\beta \quad (12)$$

The Cumulative Distribution Function (CDF) in the Weibull distribution function can be defined as

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (13)$$

To assess the Weibull reliability function, the characteristic life can be transformed into  $L_B$  life as follows:

$$R(t) \Big|_{t=L_B} = e^{-\left(\frac{L_B}{\eta}\right)^\beta} = 1 - x \quad (14)$$

After logarithmic transformation, equation (14) can be obtained as:

$$L_B^\beta = \left(\ln \frac{1}{1-x}\right) \cdot \eta^\beta \quad (15)$$

If the approximated characteristic life of p-value  $\alpha$ ,  $\eta_\alpha$ , in equation (12), was replaced with equation (15), we obtain the BX life equation:

$$L_B^\beta = \frac{2}{\chi_\alpha^2(2r+2)} \cdot \left(\ln \frac{1}{1-x}\right) \cdot \sum_{i=1}^n t_i^\beta \quad (16)$$

If the sample size was big enough, the planned testing time should carry out as:

$$\sum_{i=1}^n t_i^\beta \cong n \cdot h^\beta \quad (17)$$

The approximated lifetime ( $L_B$ ) in test should be lengthier than the targeted lifetime ( $L_B^*$ )

$$L_B^\beta \cong \frac{2}{\chi_\alpha^2(2r+2)} \cdot \left(\ln \frac{1}{1-x}\right) \cdot n h^\beta \geq L_B^{*\beta} \quad (18)$$

If equation (28) is rearranged, sample size equation is defined as follows:

$$n \geq \frac{\chi_\alpha^2(2r+2)}{2} \cdot \frac{1}{\left(\ln \frac{1}{1-x}\right)} \cdot \left(\frac{L_{BX}^*}{h}\right)^\beta \quad (19)$$

However, most of the lifetime testing had inadequate samples. The allowed number of failures would not have as much as that of the sample size.

$$\sum_{i=1}^n t_i^\beta = \sum_{i=1}^r t_i^\beta + (n-r)h^\beta \geq (n-r)h^\beta \quad (20)$$

If equation (20) was replaced with equation (16), BX life equation can be expressed as follows:

$$L_{BX}^\beta \geq \frac{2}{\chi_\alpha^2(2r+2)} \cdot \left(\ln \frac{1}{1-x}\right) \cdot (n-r)h^\beta \geq L_{BX}^{*\beta} \quad (21)$$

If equation is rearranged, the sample size equation with the number of failure can also be expressed as:

$$n \geq \frac{\chi_\alpha^2(2r+2)}{2} \cdot \frac{1}{\left(\ln \frac{1}{1-x}\right)} \cdot \left(\frac{L_{BX}^*}{h}\right)^\beta + r \quad (22)$$

From the sample size equation (22), we can begin with parametric ALT under any failure cases ( $r \geq 0$ ). Thus, it also affirms whether the failure mechanism and the test method were appropriate.

For a 60% confidence level, the first term  $\frac{\chi^2_{\alpha}(2r+2)}{2}$  in equation (22) can be estimated as  $(r + 1)$ . If the cumulative failure rate was below about 20 percent, the denominator of the second term  $\ln \frac{1}{1-x}$  could be estimated to  $x$  by a Taylor expansion. Then the general sample size equation (22) can be estimated as follows:

$$n \geq (r + 1) \cdot \frac{1}{x} \cdot \left( \frac{L_{BX}^*}{h} \right)^{\beta} + r \quad (23)$$

If the AF in equation (8) were put into the planned testing time, equation (23) would be expressed as:

$$n \geq (r + 1) \cdot \frac{1}{x} \cdot \left( \frac{L_{BX}^*}{AF \cdot h_a} \right)^{\beta} + r \quad (24)$$

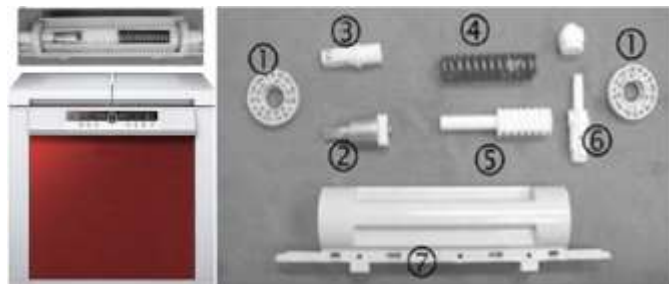
The lifetime target of the new HKS was reassured to be B1 life 10 years. Based on the anticipated customer usage conditions, the mission cycles of the product were studied. Under the worst case, the number of needed test cycles could be attained from equation (24) for assigned sample pieces. ALT equipment can then be performed on the basis of load examination. In parametric ALTs, the missing parameters of HKS in the design phase could be recognized to fulfill the lifetime target – B1 life 10 years.

### III. Case study: reliability design of the HKS

When a consumer utilizes 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 buy and use the refrigerator. The primary components in a HKS consists of a kit cover, shaft, spring, and oil damper, etc (Fig. 8).

The functional loss of the original HKS had been described often by owners of the refrigerator. The data of the returned products in the field were critical for understanding and determining the usage patterns of consumers and helping to identify design changes that needed to be implemented in the product. Based on market data, failure analysis was required to search out the root cause(s) of the problematic HKS and what

part(s) in the HKS needed to be reshaped to enhance reliability.



(a) Domestic refrigerator and HKS (b) Mechanical parts of HKS: kit cover ①, oil damper ②, fixed cam ③, spring ④, cam ⑤, shaft ⑥, and HKS housing ⑦

Figure 8 Commercial Refrigerator and its HKS

From the marketplace, the HKS parts in refrigerator were failing due to repeated loading under unidentified consumer operation conditions. When comprehensive data from the field were reviewed, the returned products might have had structural design defects, including sharp corner angles and not enough enforced ribs resulting in high stress concentrations. These design defects, integrated with the repeated impact loads on the HKS, could cause a crack to happen, and so fail (Fig.9).

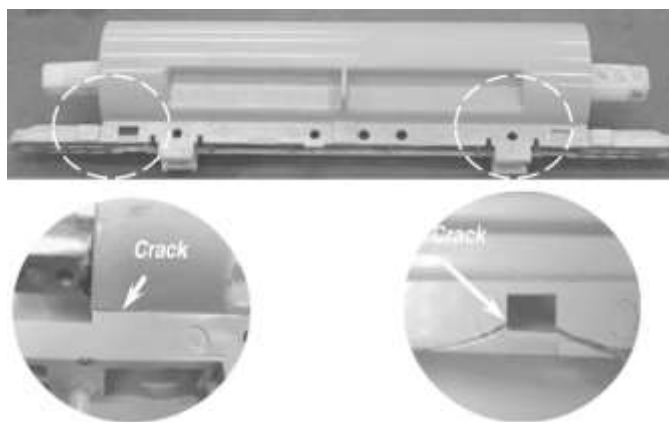


Figure 9 Products damaged from the marketplace

The closing function of the HKS included some mechanical structural parts. Relying on the consumer usage conditions, the HKS was often subjected to repeated mechanical impact loads when the consumer closed the door. Door closing involved the simple mechanical procedures: (1) the consumer opened the door to take out or store food, and (2) they then closed the door by force.

In the process, the HKSs were subjected to dissimilar loads during the operation of the refrigerator door. To search out the required AF, it was crucial to figure out the forces on the HKS

during operating the door. Because the HKS was a comparatively straightforward mechanical structure, the forces impacting the HKS could be modeled with a force-moment equation. As the consumer opened or closed the refrigerator door, the stress due to the door weight was concentrated on the HKS (Fig. 10).

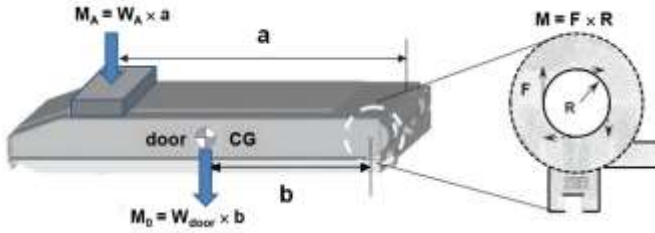


Figure 10 Design concept of HKS

The moment balance around the HKS might be defined as

$$M_0 = W_{door} \times b = T_0 = F_0 \times R \quad (25)$$

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

$$\begin{aligned} M_1 &= M_0 + M_A = W_{door} \times b + W_A \times a \\ &= T_1 = F_1 \times R \end{aligned} \quad (26)$$

Because  $F_0$  is the impact force in normal conditions and  $F_1$  is the impact force in the ALT, we knew that the stress on the HKS depended on the exerted impact due to the accelerated weight. Under the same working conditions, the life-stress model (LS model) in equation (8) could be modified as

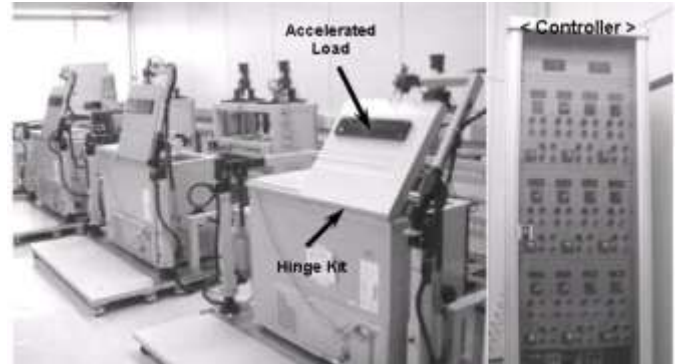
$$TF = A(S)^{-n} = AT^{-\lambda} = A(F \times R)^{-\lambda} \quad (27)$$

The AF can be defined as

$$AF = \left( \frac{S_1}{S_0} \right)^n = \left( \frac{T_1}{T_0} \right)^\lambda = \left( \frac{F_1 \times R}{F_0 \times R} \right)^\lambda = \left( \frac{F_1}{F_0} \right)^\lambda \quad (28)$$

The operating conditions for the HKS in a refrigerator were roughly 0–43 °C with a relative humidity varying from 0% to 95%, and 0.2–0.24g's of acceleration. The opening and closing of the door happened an approximated average of 3 to 10 times per day. With a life design cycle for 10 years, the lifetime of HKS experienced about 36,500 usage cycles for the worst case.

For this scenario, the impact force around the HKS was 1.10 kN which was the anticipated greatest force exerted by the consumer. For the ALT with an accelerated weight, the impact force on the HKS was 2.76 kN. Using a cumulative damage exponent,  $\lambda$ , of 2.0, the AF was established to be roughly 6.3 in equation (28).



(a) ALT Equipment (b) Controller

Figure 11 Equipment utilized in the ALT and the controller

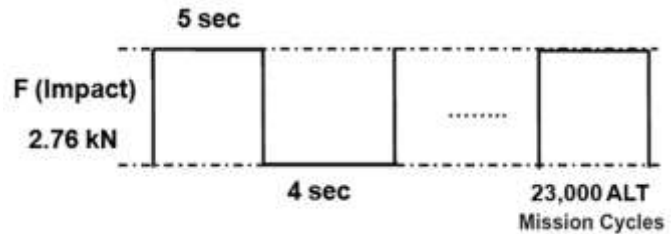
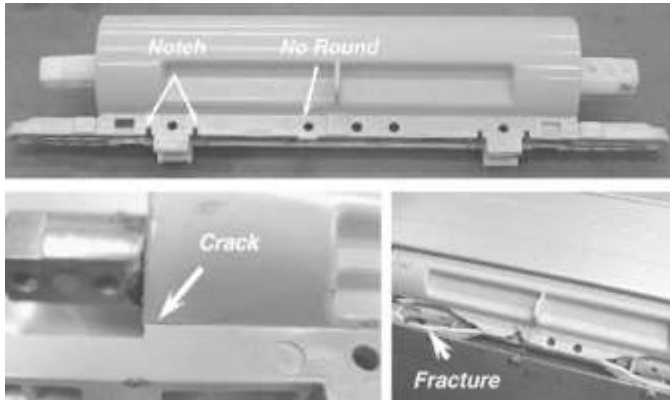


Figure 12 Duty cycles of the repeated impact load F on the HKS

For the lifetime target – B1 life 10 years, the test cycles for sample six pieces computed in equation (24) were 23,000 cycles if the shape parameter was presumed to be 2.0. This parametric ALT was designed to assure a B1 life 10 years with roughly a 60% level of confidence that it would fail less than once during 23,000 cycles. Fig. 11 represents the test facility of the ALT with labeled equipment for the durable design of HKS. As seen in Fig. 12, repeated stress can be demonstrated as the duty effect due to the on/off cycles and HKS shortens part life.

The control console was utilized to work the testing apparatus. It ran the number of tests, the testing time, and the starting or stopping of the equipment. As the start button on the controller console was pressed, the straightforward hand-shaped arms could clasp and raise the refrigerator door. As the door was closing, it could apply to the greatest mechanical impact force required to reproduce the accelerated load in the HKS (2.76 kN).

## IV. Results and discussion



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

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

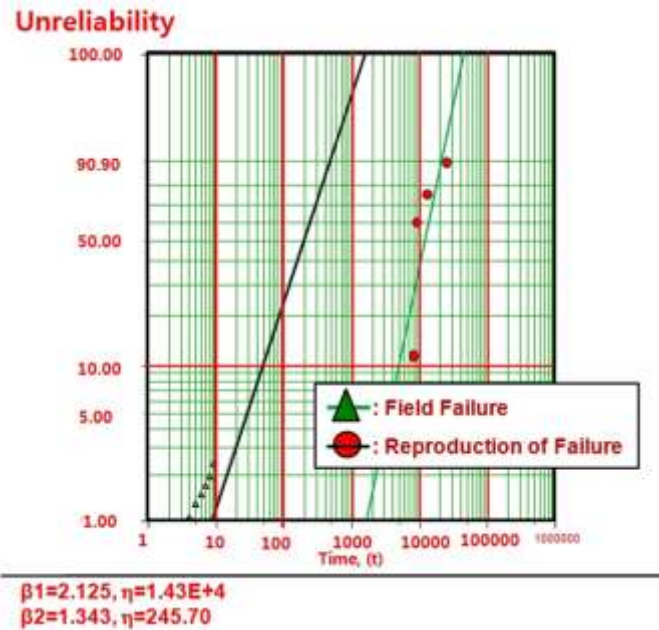


Figure 14 Field data and results of ALT on Weibull chart.

Fig. 13 shows a picture contrasting the failed product from the marketplace and that from the 1st ALT, separately. In the 1st ALT, the housing of the HKS failed at 3,000 cycles and 15,000 cycles. As shown in the picture, the tests confirmed that the HKS housing had a weak structure near the notch because there were no rounded edges. The flawed shape of the 1st ALT was very alike to that of the returned product from the marketplace. Figure 14 showed the graphical examination of the ALT results and market data on a Weibull plot. That is, under the similar repetitive stress, we recognized the failure patterns shown in 1<sup>st</sup> ALT and field were close. 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.

Based on test results and Weibull plot, parametric ALT was well-founded because it pinpointed the design frailties that were account for the failures from the marketplace. As substantiated by two results, these systematic method were well-founded in identifying the problematic designs accountable for failures from the marketplace, which decided the lifetime.

When disassembling the HKS, we found that the oil damper in the HKS leaked into at 15,000 cycles (Fig. 15). Because of the repeated impacts of the working of the HKS in combination with its structural design defects, the HKS housing fractured and the oil damper spilled. Based on finite element analysis, the concentrated stresses of the housing HKS was about 21.2 MPa. The stress raisers in high stress areas originated from the design defects like sharp corners/angles, poorly enforced ribs, and housing notches.

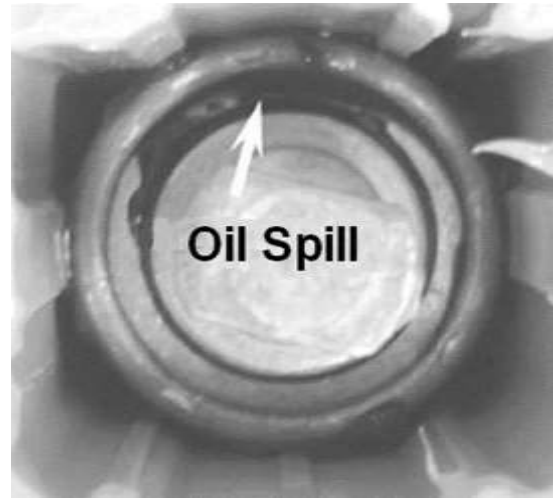


Figure 15 Spilled products after 1st ALT

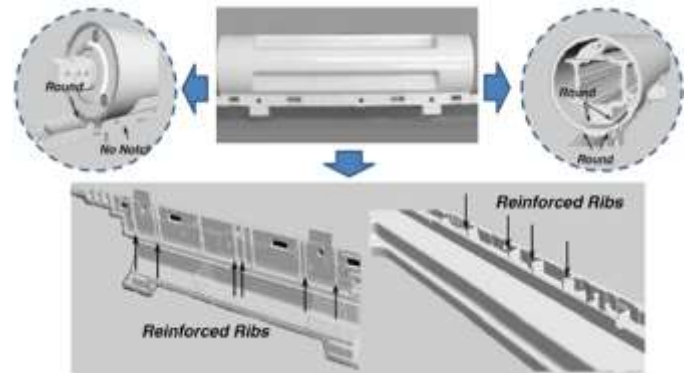


Figure 16 Redesigned HKS housing structure

The corrective action plans for the weak HKS housing were to make fillets, add the enforced ribs, and round the notching on the housing of HKS (Figure 16). Implementing the new design parameters, the stress concentrations in the housing of HKS lessened 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 leaking oil damper was examined, 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, we knew that this sealing structure with the gap leaked effortlessly for first ALT. With the corrective action plan, the sealing structure of the reshaped oil damper had been changed to no gap with the Teflon/O-ring/Teflon (Fig. 17).

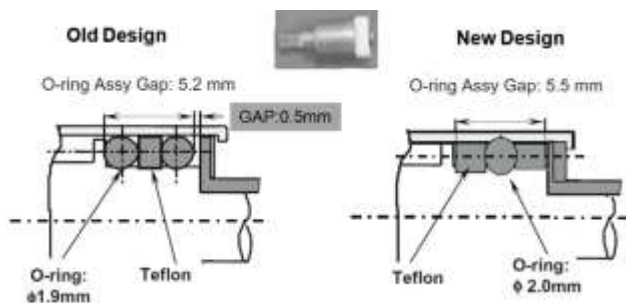


Figure 17 Redesigned oil damper

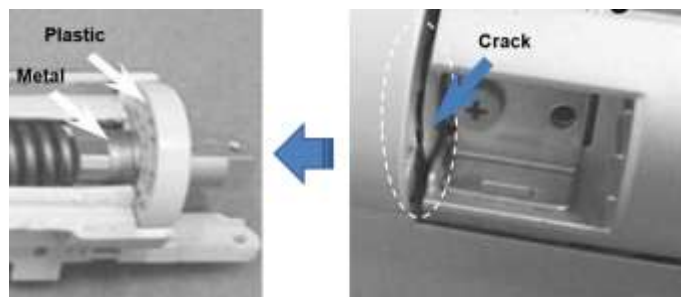


Figure 18 Structure of problematic products at 2<sup>nd</sup> ALT.

The modified HKS produced more than the lifetime target – B1 life of 10 years. The affirmed values of AF and  $\beta$  in Figure 14 were 6.3 and 2.1, separately. The recalculated test cycles in equation (24) were 24,000 for sample six pieces. To obtain the design flaws of the HKS, 2<sup>nd</sup> ALTs were performed. In the second ALTs the fracture of hinge kit cover happened 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 cover housing changed from the plastics to the Al die-casting. Lastly, the reshaped HKS could endure the high impact load during operation of the door.

To endure the repeated impact loads, the HKS system was reshaped as follows: (1) strengthening the housing design of HKS, C1; (2) modifying the sealing structure in the oil damper, C2; (3) altering cover housing material, C3, from plastics to the Al die-casting. With these design alterations, the HKS in refrigerator could also work properly over its product lifetime. In other words, the refrigerator door with these modified parameters could be gently closed for a longer time without failure. Over the course of three ALTs, the B1 life of

the samples was reassured to be 10.0 years. Table II shows the abridgement of the results of the ALTs.

TABLE II. RESULTS OF ALT

	1 <sup>st</sup> ALT	2 <sup>nd</sup> ALT	3 <sup>rd</sup> ALT
	Initial Design	Second Design	Final Design
	In 22,000 cycles, HKS has no crack	8,000 cycles: 1/6 Fracture 9,000 cycles: 3/6 Fracture 14,000 cycles: 1/6 Fracture 22,000 cycles: 1/6 Fracture	22,000 cycles: 0/6 OK 41,000 cycles: 0/6 OK 74,000 cycles: 0/6 OK
HKS Structure			
Action plans	C1: Reinforced housing of HKS C2: Modified sealing structure of oil damper		C3: Kit cover material (Plastic → Al die casting)

## v. Conclusions

To upgrade the lifetime of a newly designed mechanical system such as HKS, we have proposed a parametric ALT as systematic reliability method that incorporates: 1) a parametric ALT plan, 2) a load examination, 3) a customized 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 1<sup>st</sup> ALT, the failure of HKS happened in the fractured HKS housing and oil damper spilling. The design flaws 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 reshaped sealing structure in oil damper.
- (2) Based on the 2<sup>nd</sup> 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 satisfy 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 utilize this systematic method, engineers should comprehend why products fail. In other words, if there are design defects in mechanical product that causes inadequacy of strength (or stiffness) when subjected to repeated loads, the mechanical product will fail over its lifetime.

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Dr. Woo has a BS and MS in Mechanical Engineering, and he has obtained PhD in Mechanical Engineering from Texas A&M. He major in energy system such as HVAC and its heat transfer, optimal design and control of refrigerator, reliability design of mechanical components, and failure Analysis of thermal components in marketplace using the Non-destructive such as SEM & XRAY. Especially, he developed parametric accelerated life testing (ALT) as new reliability methodology. If there is design fault in the mechanical system that is subjected to repetitive stress, it will fail in its lifetime. Engineer should find the design faults by parametric ALT before product launches. In 1992–1997 he worked in Agency for Defense Development, Chinhae, South Korea, where he has researcher in charge of Development of Naval weapon System. In 2000-2010 he had been working as a Senior Reliability Engineer in Side-by-Side Refrigerator Division, Digital Appliance, SAMSUNG Electronics, where he focused on enhancing the life of refrigerator as using parametric the accelerating life testing. Now he is working as associate professor in mechanical department, Addis Ababa Science & Technology University.