Challenge Journal of Structural Mechanics

Reliability design of the hinge kit system subjected to repetitive loading in a commercial refrigerator

Seong-woo Woo [a,*], Dennis L. O'Neal [b]

[a] Reliability Association of Korea, 146-102 Sunyoo-ro, Yeongdeungpo-gu, Seoul 150-103, Korea
[b] School of Engineering and Computer Science, Baylor University, Waco, TX 76798-7356, USA

ABSTRACT

A newly designed hinge kit system (HKS) of a commercial refrigerator was subjected to a robust reliability methodology during the design phase of the system. This methodology included setting the overall parametric accelerated life test (ALT) plan of product and identifying failure mechanisms and modes in field. The ALT included a sample size equation to improve several of the HKS design parameters. Reliability of the new HKS was targeted to be 10 years over B1. Failure sites in the HKS were identified through returned products from the field. The first ALT confirmed a failure that occurred at the housing of HKS. The missing design parameters of HKS housing for the refrigerator were that it had no support ribs in the original design. The supporting structure of HKS in the refrigerator was modified based on the action plan. Cracks were identified in a second ALT that was generated in the torsional shaft. Due to it having squared off corners, the HKS torsional shaft did not have not enough strength to withstand repetitive stresses. The shaft was modified as a consequence of the ALTs. The reliability of redesigned HKS is now guaranteed as B1 10 years. The design methods - load analysis and three ALTs were very effective in identifying the missing design parameters during the design phase. The robust design method presented in this paper might be applicable to the other mechanical systems.

ARTICLE INFO

Article history:
Received 29 March 2016
Accepted 13 May 2016

Keywords:
Robustness
Parameter design
Load analysis
Accelerated life testing

1. Introduction

When a consumer opens and closes a refrigerator door, they should be able to accomplish this with minimal effort. The hinges of a door are a component of the door that is subjected to repetitive use over the life of the refrigerator. A new hinge kit system (HKS) was designed for the refrigerator (see Fig. 1(a)) to improve the ease of opening and closing the door for the consumer. The HKS is shown in Fig. 1(b) consists of a kit cover, shaft, spring, and oil damper, etc.

The functional loss of the original HKS had been reported often by owners of the refrigerator. Thus, exact data analysis was required to find out the root cause of the defective HKS and what parameter in the HKS needed to be redesigned.

Fig. 2 shows a damaged HKS which has two cracks that appeared after a period of use. It was not known under what usage conditions the failure occurred. When comprehensive data from the field were reviewed, it was concluded that the root cause of the HKS failure was a structural design flaw–no round of torsional shaft. Moreover, due to the repetitive loading of the opening and closing of the door, this design defect eventually led to creating the cracks of HKS.

Robust design techniques, including statistical design of experiments (SDE) and Taguchi methods (1978), were developed by statisticians many years ago. Taguchi's robust design method uses parameter design to place the design in a position where random ''noise'' does not cause failure and is used to determine the proper design parameters and their levels

* *Corresponding author*. Tel.: +82-42-936-1026 ; Fax: +82-42-936-2052 ; E-mail address: twinwoo@yahoo.com (S. Woo)
ISSN: 2149-8024 / DOI: http://dx.doi.org/10.20528/cjsmec.2016.05.010

(Taguchi and Shih-Chung, 1992; Ashley, 1992; Wilkins, 2000; Phadke, 1989; Byrne and Taguchi, 1987). The basic idea of parameter design is to identify, through exploiting interactions between control factors and noise factors, appropriate settings for the control factors that make the system's performance robust in relation to changes in the noise factors. Thus, the control factors are assigned to an inner array in an orthogonal array, and the noise factors are assigned to an outer array. However, a large number of experimental trials in the Taguchi product array may be required because the noise array is repeated for every row in the control array. However, for a simple mechanical structure, a lot of design parameters should be considered in the Taguchi method's robust design process. Those products with the missing or improper minor design parameters may result in recalls and loss of brand name value.

Fig. 1. Commercial refrigerator and its HKS: (a) Commercial refrigerator; (b) HKS.

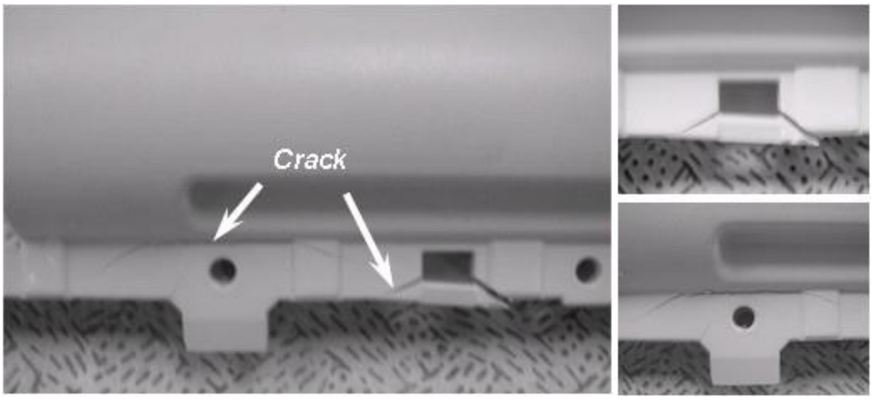


Fig. 2. A view of damaged HKS after a period of use.

The purpose of this study was to present a robust reliability evaluation methodology to the HKS as mechanical system subjective to repetitive loading in the commercial refrigerator. The method includes

- setting overall parametric ALT plan for the product,
- analyzing the failure modes of the returned product from the field, and
- improving the designs of the HKS using a tailored of ALTs with a sample size equation.

Nomenclature

AF	Acceleration factor
BX	Durability index
C1	Housing design of HKS
C2	Roundness of torsional shaft
F(t)	Unreliability
F	Force (kN)
F1	Impact force under accelerated stress conditions
F0	Impact force under normal conditions
h	Testing cycles (or cycles)
h^*	Non-dimensional testing cycles
KCP	Key Control Parameter
KNP	Key Noise Parameter
L_B	Target B_X life (x = 0.01X, on the condition that $x \leq 0.2$)
M	Moment around the hinge kit system (kN·m)
M_1	Moment under accelerated stress conditions
M_0	Moment under normal conditions
M_A	Moment due to the accelerated weight (kN·m)
M_{door}	Moment due to the door weight (kN·m)
n	Number of test samples
N1	Consumer door open/close force (kN)
r	Failed numbers
S	Stress
S_1	Mechanical stress under accelerated stress conditions
S_0	Mechanical stress under normal conditions

t_i	Test time for each sample (h)
TF	Time to failure (h)
x	$x = 0.01 \cdot X$ (on condition that $x \leq 0.2$)
Greek symbols	
η	Characteristic life
Superscripts	
β	Shape parameter in a Weibull distribution
n	Stress dependence ($n = -\left[\frac{\partial \ln(T_f)}{\partial \ln(S)}\right]_T$)
Subscripts	
0	Normal stress conditions
1	Accelerated stress conditions

2. Load Analysis and Bx Life

In the field, HKS parts of a refrigerator were failing due to cracking and fracturing (Fig. 2) under unknown consumer usage conditions. Field data indicated that the damaged products might have had structural design flaws, including sharp corner angles and not enough enforced ribs resulting in stress risers in high stress areas. These design flaws combined with the repetitive impact loads on the HKS could cause a crack to occur, and thus cause failure consumer usage conditions, HKS were subjected to different loads during the opening and closing of the refrigerator door.

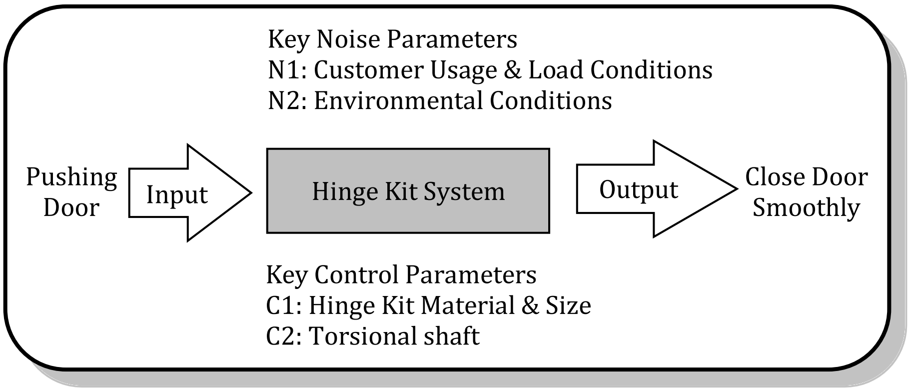


Fig. 3. Robust design schematic of HKS.

Fig. 3 shows the robust design schematic overview of the HKS. Depending on the consumer usage conditions, HKS were subjected to different loads during the opening and closing of the refrigerator door.

Because the HKS is a relatively simple structure, it can be modeled with a simple force-moment equation (see Fig. 4). As the consumer opens or closes the refrigerator door, the stress due to the weight momentum of the door is concentrated on HKS.

The number of door closing cycles will be influenced by specific consumer usage conditions. The door system of the refrigerator were required to be opened and closed between three and ten times a day in the Korean domestic market.

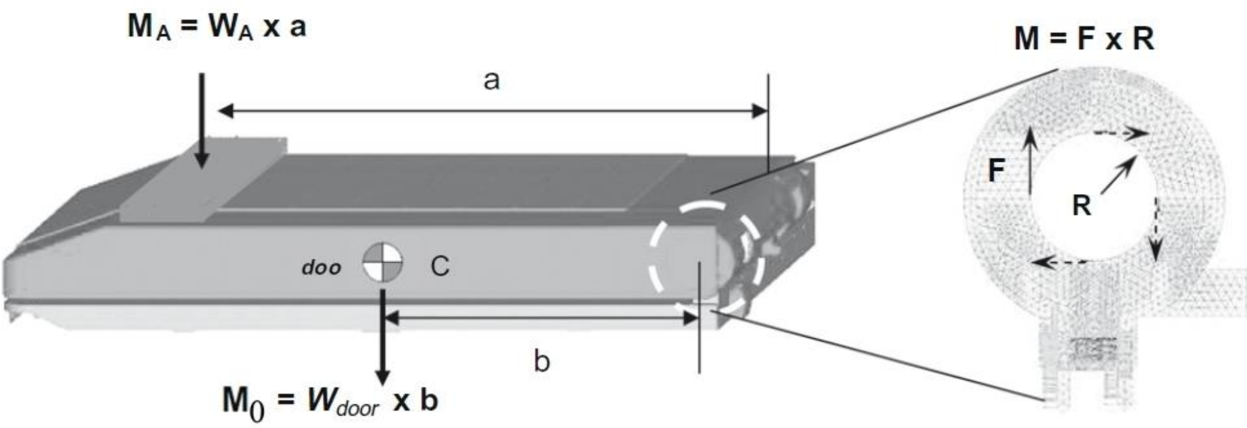


Fig. 4. Design concept of HKS.

The moment balance around the HKS can be represented as

$$M_0 = W_{door} \times b = T_0 = F_0 \times R \ . \qquad (1)$$

The moment balance around the HKS with an accelerated weight can be represented as

$$M_1 = M_0 + M_A = W_{door} \times b + W_A \times a = T_1$$
$$= F_1 \times R \, . \qquad (2)$$

Because F_0 is impact force in normal conditions and F_1 is impact force in accelerated weight, the stress on the HKS depends on the applied impact. Under the same temperature and efforts concept proposed by Karnopp et al. (2000), the life-stress model (LS model) proposed by McPherson (1989) and can be modified as

$$TF = A(S)^{-n} = AT^{-n} = A(F \times R)^{-n} \, , \qquad (3)$$

The acceleration factor (AF) can be derived as

$$AF = \left(\frac{S_1}{S_0}\right)^n = \left(\frac{T_1}{T_0}\right)^n = \left(\frac{F_1 \times R}{F_0 \times R}\right)^n = \left(\frac{F_1}{F_0}\right)^n . \qquad (4)$$

The characteristic life η_{MLE} from the Maximum Likelihood Estimation (MLE) can be derived as:

$$\eta_{MLE}^{\beta} = \sum_{i=1}^{n} \frac{t_i^{\beta}}{r} . \qquad (5)$$

If the confidence level is 100(1 - α) and the number of failure is $r \geq 1$, the characteristic life, η_α, would be estimated from Eq. (5),

$$\eta_{\alpha}^{\beta} = \frac{2r}{\chi_{\alpha}^2(2r+2)} \eta_{MLE}^{\beta} = \frac{2r}{\chi_{\alpha}^2(2r+2)} = \sum_{i=1}^{n} t_i^{\beta} \, . \qquad (6)$$

Presuming there is no failures, p-value is α and ln$(1/\alpha)$ is mathematically equivalent to Chi-Squared value, $\frac{\chi_\alpha^2(2)}{2}$. The characteristic life η_α, would be represented as:

$$\eta_{\alpha}^{\beta} = \frac{2r}{\chi_{\alpha}^2(2)} \sum_{i=1}^{n} t_i^{\beta} = \frac{1}{ln\frac{1}{\alpha}} \sum_{i=1}^{n} t_i^{\beta} \, . \qquad (7)$$

Eq. (6) is established for all cases $r \geq 0$ and can be redefined as follows:

$$\eta_{\alpha}^{\beta} = \frac{2r}{\chi_{\alpha}^2(2r+2)} \sum_{i=1}^{n} t_i^{\beta} \qquad for \geq 0 \, . \qquad (8)$$

To evaluate the Weibull reliability function, the characteristic life can be converted into L_B life as follows:

$$R(t) = e^{-\left(\frac{L_{BX}}{\eta}\right)^{\beta}} = 1 - x \, . \qquad (9)$$

After logarithmic transformation, Eq. (9) can be expressed as:

$$L_{BX}^{\beta} \left(ln\frac{1}{1-x}\right) \eta^{\beta} \, . \qquad (10)$$

If the estimated characteristic life of p-value α, η_α, in Eq. (8), is substituted into Eq. (10), the B_X life equation can be obtained:

$$L_{BX}^{\beta} = \frac{2}{\chi_{\alpha}^2(2r+2)} \left(ln\frac{1}{1-x}\right) \sum_{i=1}^{n} t_i^{\beta} \, . \qquad (11)$$

If the sample size is large enough, the planned testing time will proceed as:

$$\sum_{i=1}^{n} t_i^{\beta} \, . \qquad (12)$$

The estimated lifetime (L_{BX}) in test should be longer than the targeted lifetime (L^*_{BX}) :

$$L_{BX}^{\beta} \cong \frac{2}{\chi_{\alpha}^2(2r+2)} \left(ln\frac{1}{1-x}\right) nh^{\beta} \geq L_{BX}^{*\beta} \, . \qquad (13)$$

Then, sample size equation is expressed as follows:

$$n \geq \frac{\chi_{\alpha}^2(2r+2)}{2} \frac{1}{\left(ln\frac{1}{1-x}\right)} \left(\frac{L_{BX}^{*\beta}}{h}\right)^{\beta} . \qquad (14)$$

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

$$\sum_{i=1}^{n} t_i^{\beta} = \sum_{i=1}^{n} t_i^{\beta} + (n-r)h^{\beta} \geq (n-r)h^{\beta} \, . \qquad (15)$$

If Eq. (15) is substituted into Eq. (13), the B_X life equation can be modified as follows:

$$L_{BX}^{\beta} \geq \frac{2}{\chi_{\alpha}^2(2r+2)} \left(ln\frac{1}{1-x}\right) (n-r)h^{\beta} \geq L_{BX}^{*\beta} \, . \qquad (16)$$

Then, sample size equation with the number of failure can also be modified as:

$$n \geq \frac{\chi_{\alpha}^2(2r+2)}{2} \frac{1}{\left(ln\frac{1}{1-x}\right)} \left(\frac{L_{BX}^{*}}{h}\right)^{\beta} + r \, . \qquad (17)$$

From the generalized sample size Eq. (17), we can proceed lifetime testing (or parametric ALT testing) under any failure conditions ($r \geq 0$). Consequently it also confirm whether the failure mechanism and the test method are proper.

For a 60% confidence level, the first term $\chi_{\alpha}^2(2r+2)/2$ in Eq. (17) can be approximated to (r + 1) proposed by Ryu and Chang (2005). And if the cumulative failure rate, x, is below about 20 percent, the denominator of the second term $\ln(1/(1-x))$ approximates to x by Taylor expansion. Then the general sample size equation can be approximated as follows:

$$n \geq (r+1) \frac{1}{x} \left(\frac{L_{BX}^{*}}{h}\right)^{\beta} + r \, . \qquad (18)$$

If the acceleration factors in Eq. (4) are added into the planned testing time, Eq. (18) will be modified as:

$$n \geq (r+1)\frac{1}{x}\left(\frac{L_{BX}^{*}}{h}\right)^{\beta} + r \, . \quad (19)$$

The reliability of the new HKS was targeted to be 10 years over B1. Based on the customer usage conditions, the normal range of operating conditions and cycles of the product (or parts) were investigated. Under the worst case, the objective number of cycles and the number of required test cycles can be obtained from Eq. (19).

ALT equipment can then be conducted on the basis of load analysis. In ALT testing, the missing parameters in the design phase can be identified.

3. Laboratory Experiments

Generally, the operating conditions for the HKS in a refrigerator were approximately 0–43 °C with a relative humidity ranging from 0% to 95%, and 0.2–0.24g's of acceleration. The closing of the door occurred an estimated average of 3 to 10 times per day. With a life cycle design point for 10 years, HKS incurs about 36,500 usage cycles (Table 1).

Table 1. Operating cycles of the HKS.

Item	Number of operations (times)			
	1 day		10 years	
	Normal	Worst	Normal	Worst
HKS	1–3	10	10,950	36,500

For the worst case, the impact force around the HKS was 1.10 kN which was the maximum force applied by the typical consumer. The impact force for the ALT with accelerated weight was 2.76 kN. Using a stress dependence of 2.0, the acceleration factor was found to be approximately 6.3 in Eq. (4). The test cycles and the numbers of samples used in the ALT were calculated from Eq. (19).

For the B1 life, the required target *x* was 0.01. The test cycles and test sample numbers calculated in Eq. (8) were 34,000 cycles and six units without failure, respectively. ALT was designed to ensure a B1 of 10 years life with about a 60% level of confidence that it would fail less than once during 34,000 cycles. Fig. 5 shows the experimental setup of the ALT with labelled equipment for the robust design of HKS. Repetitive stress can be expressed as the duty effect that carries the on/off cycles and shortens part life (Ajiki et al., 1979). Fig. 6 shows the duty cycles for the impact force *F*.

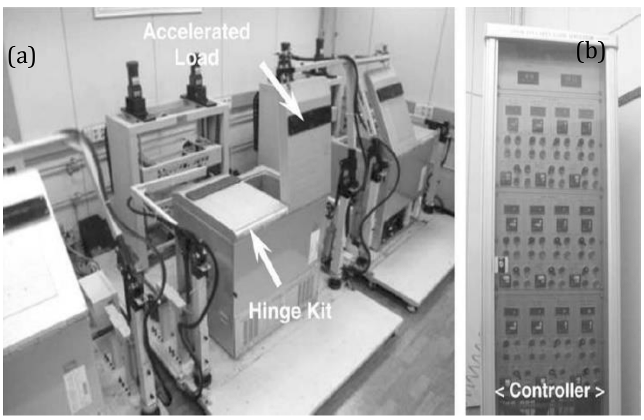


Fig. 5. Equipment used in accelerated life testing and controller: (a) ALT Equipment; (b) Controller.

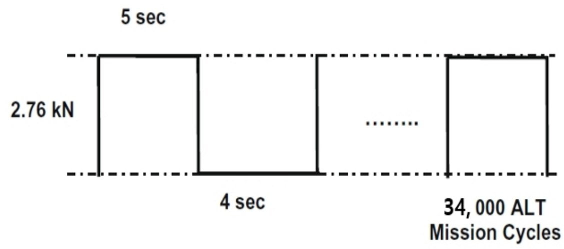


Fig. 6. Duty cycles of the repetitive impact load *F* on HKS.

The control panel was used to operate the testing equipment - the number of test time, starting or stopping the equipment, and the other. When the start button in the controller panel gave the start signal, the simple hand-shaped arms held and lifted the refrigerator door. As the door was closing, it was applied to the HKS with the maximum mechanical impact force due to the accelerated load (2.76 kN).

Fig. 7 shows a photograph comparing the failed product from the field and from 1st accelerated life testing, respectively. As shown in the picture, the shape and location of the failure in the ALT were similar to those seen in the field. Fig. 8 represented the graphical analysis of the ALT results and field data on a Weibull plot. The shape parameter in the first ALT was estimated at 2.0. From the Weibull plot, the shape parameter was confirmed to be 2.1.

The defective shape of the ALT was very similar to that of the field. From the Weibull plot, the shape parameters of the ALT and market data were found to be similar. As supported by two findings in the data, these methodologies were valid in pinpointing the weak designs responsible for failures in the field, which determined the lifetime.

Fig. 7. Failed products in field and crack after 1st ALT: (a) Failed products in field; (b) crack after 1st ALT.

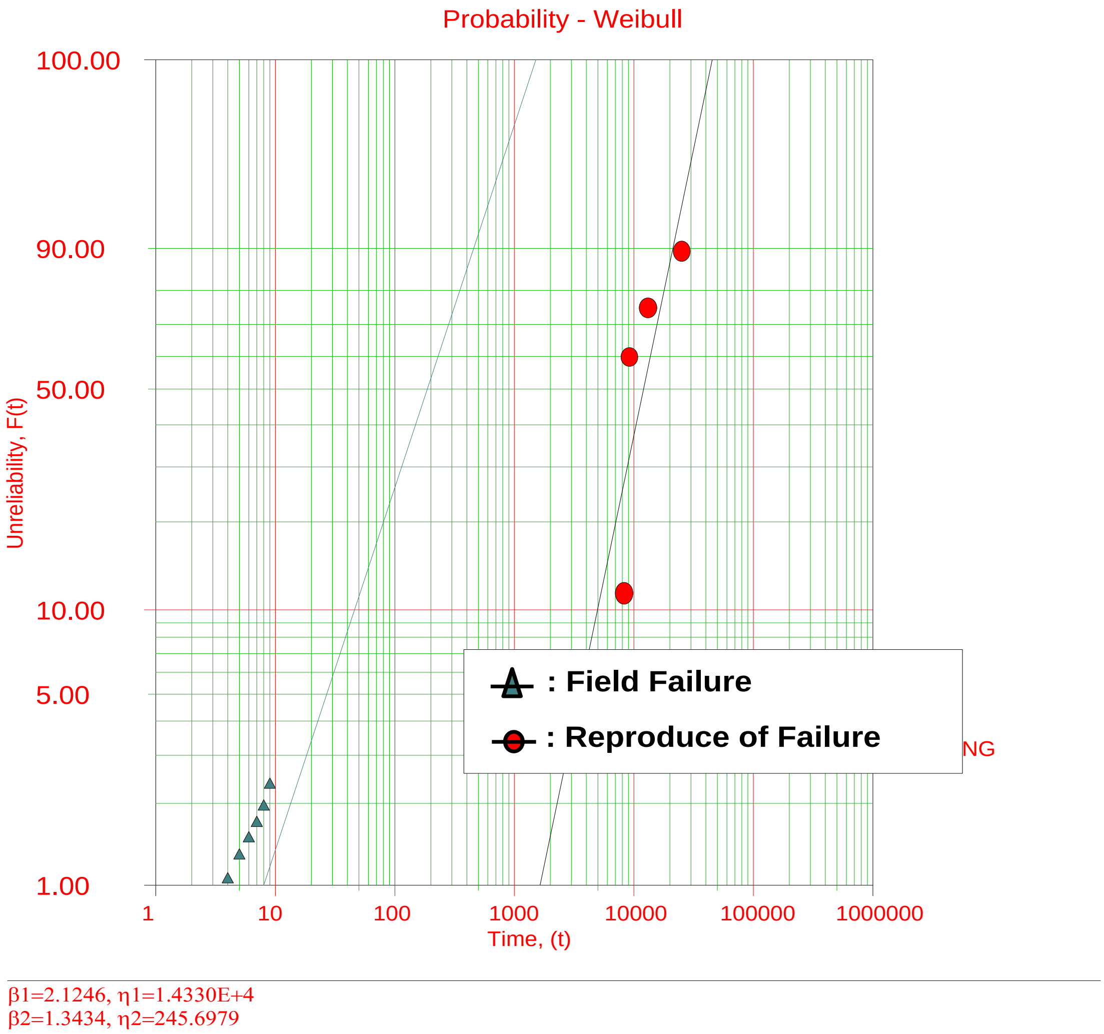


Fig. 8. Field data and 1st ALT on Weibull chart.

The fracture of the HKS in both the field products and the ALT test specimens occurred in the housing and support of the HKS (Fig. 9). The missing design variables of the HKS in the design phase came from no support structure. The repetitive applied force in combination with the structural flaws may have caused the fracturing of the HKS. The concentrated stresses of the HKS were approximately 21.2 MPa, based on finite element analysis. The stress risers in high stress areas resulted from the structural design flaws of not having any supporting ribs.

The corrective action plans was to add the support ribs (Fig. 10). Applying the new design parameters to the finite element analysis, the stress concentrations of the HKS decreased from 21.2 MPa to 18.9 MPa. Therefore, the corrective action plan had to be made at the design stage before production.

The design target of the newly designed samples were more than the target life of a B1 of 10 years. The confirmed values of AF and b in Fig. 8 were 6.3 and 2.1, respectively. The recalculated test cycles and sample size in Eq. (19) for reliability target of B1 of 10 years were 41,000 and six units, respectively. Based on the BX and sample size, three ALTs were performed to obtain the design parameters and their proper levels. In the second ALTs the crack of torsional shaft occurred due to its sharp rounding and repetitive impact stresses (Fig. 11). The torsional shaft of the HKS was modified by giving it more roundness from R0.5mm to R2.0mm at the corner of torsional shaft (see Fig. 12). Finally, the redesigned HKS could withstand the high impact force during closure of the door. With this design change, the refrigerator could also be opened and closed more comfortably.

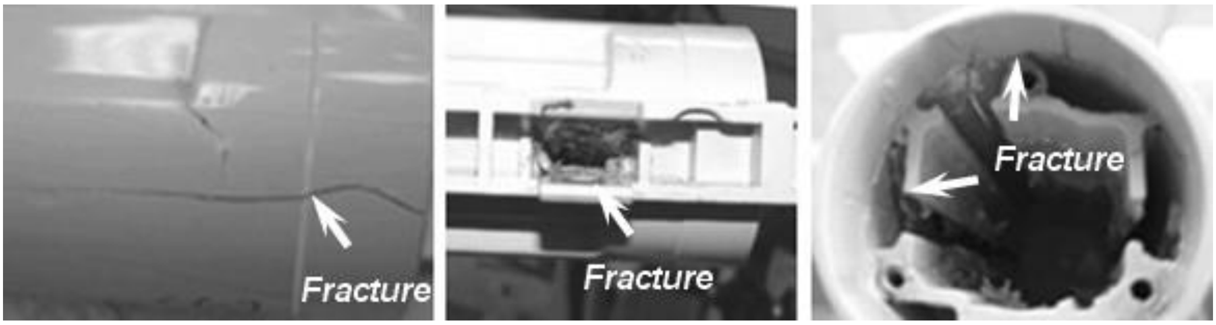


Fig. 9. Structure of failing HKS in 1st ALT Results of ALT plotted in Weibull chart.

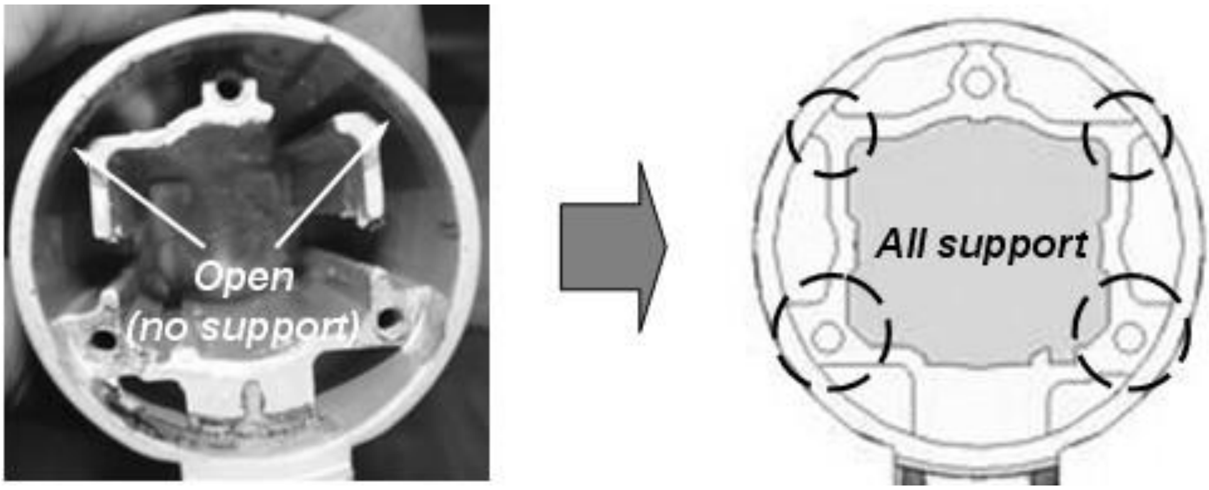


Fig. 10. Redesigned HKS structure.

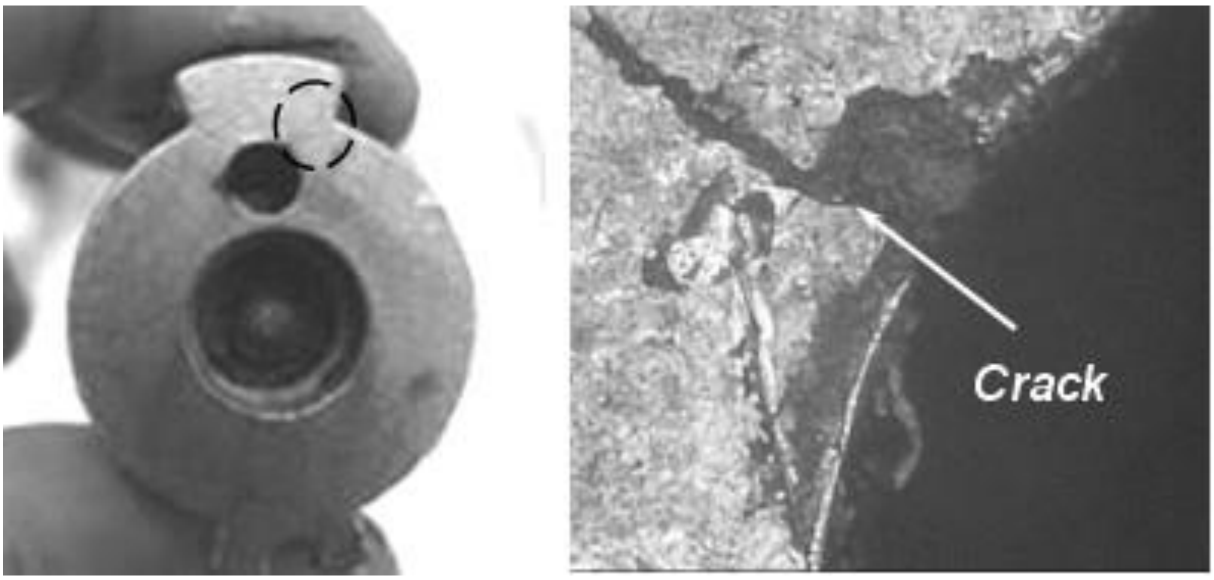


Fig. 11. Cracked torsional shaft of HKS.

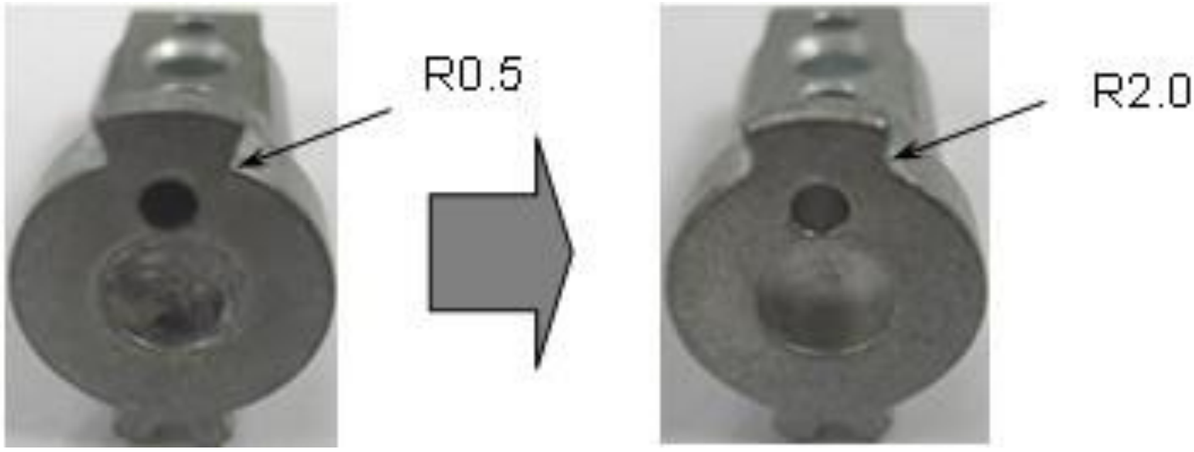


Fig. 12. Redesigned torsional shaft of HKS.

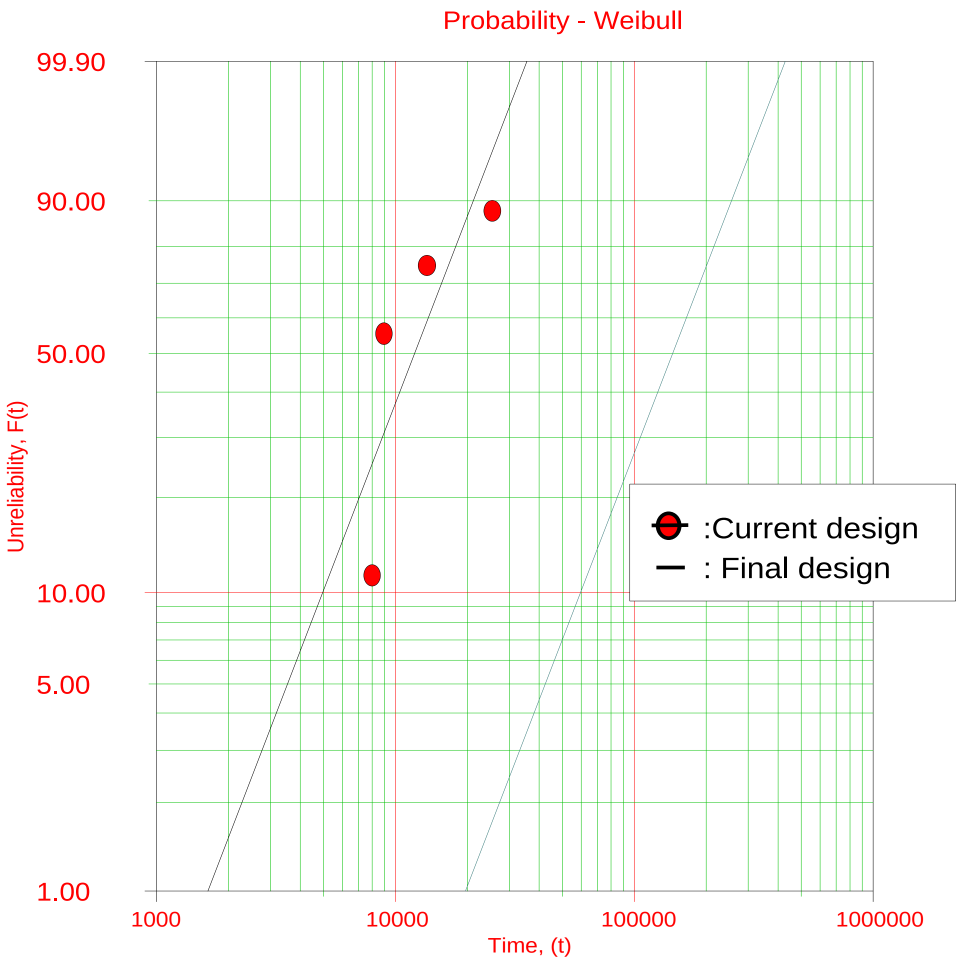
Table 4 and 5 show the design parameters confirmed from a tailored set of ALTs and the summary of the results of the ALTs, respectively. With these modified parameters, the refrigerator door could be smoothly closed for a longer period without failure. Fig. 13 shows the graphical results of the ALT plotted in a Weibull chart. Over the course of the three ALTs, the B1 life of the samples was guaranteed to be 10.0 years.

Table 4. Vital parameters based on ALTs.

CTQ		Parameters		Unit
Crack	KNP	N1	Impact force	MPa
	KCP	C1	Supporting structure	-
		C2	Corner roundness of torsional shaft	mm

Table 5. Results of ALT.

	1st ALT Initial Design	**2nd ALT** Second Design	**3rd ALT** Final Design
In 41,000 cycles, HKS has no crack	3,000 cycles: 2/6 Crack (HKS Housing)	12,000 cycles: 4/6 Crack (Torsional shaft)	41,000 cycles: 6/6 OK
HKS Structure			
Material and specification	Supporting rib C1: No → 2 supports	Roundness corner of torsional shaft C2: R0.5mm → R2.0mm	



β1=2.1246, η1=1.4330E+4
β2=2.1200, η2=1.7233E+5

Fig. 13. Results of ALT plotted in Weibull chart.

4. Conclusions

To improve the reliability of a newly designed hinge kit system in refrigerators, robust methodologies – setting overall parametric ALT plan of product have been utilized, identifying the failure modes and mechanism investigation of fractured HKS in field, conducting a series of accelerated life testing, and redesigning the HKS based on the ALT. Based on the products that failed both in the field and in the ALTs, the primary failure of the HKS occurred due to fracturing of the HKS housing.

The missing design parameters in the design phase of the refrigerator were the housing of HKS. The corrective action plans included adding supporting ribs to the HKS. Based on second set of ALTs, cracking occurred in the torsional shaft. The additional key design parameter of the failed torsional shaft was the corner roundness. After a sequence of ALTs, the proper values for the design parameters were determined to meet the life cycle requirements - B1 of 10 years, respectively. Inspection of the failed product, load analysis, and three rounds of ALTs, indicated that the newly designed mechanical HKS was greatly improved using the new robust design methodologies. Case studies on the design flaws also were suggested by Woo and Pecht (2008), Woo et al. (2009a; 2009b; 2009c; 2009d), Woo et al. (2010a; 2010b), Woo et al. (2011), Woo (2015), Woo and O'Neal D (2015), Woo and O'Neal D (2016).

References

Ajiki T, Sugimoto M, Higuchi H (1979). A new cyclic biased THB power dissipating ICs. *In: 17th Annual Proceedings Reliability Physics*, 118–126.

Ashley S (1992). Applying Taguchi's quality engineering to technology development. *Mechanical Engineering*, 114(7), 58.

Byrne D, Taguchi S (1987). The Taguchi approach to parameter design. *Quality Progress*, 20(12), 19–26.

Karnopp D, Margolis D, Rosenberg R (2000). System Dynamics: Modeling and Simulation of Mechatronic Systems. John Wiley & Sons, New York.

McPherson J (1989). Accelerated Testing, Packaging, Electronic Materials Handbook. *ASM International*, 1, 887-894.

Phadke M (1989). Quality Engineering using Robust Design. Prentice Hall, Englewood Cliffs, New Jersey.

Ryu D, Chang S (2005). Novel concept for reliability technology. *Microelectronics Reliability*, 45(3), 611-622.

Taguchi G (1978). Off-line and on-line quality control systems. *In: Proceedings of the International Conference on Quality Control*, Tokyo, Japan.

Taguchi G, Shih-Chung T (1992). Introduction to Quality Engineering: Bringing Quality Engineering Upstream. American Society of Mechanical Engineering, New York.

Wilkins J (2000). Putting Taguchi methods to work to solve design flaws. *Quality Progress*, 33(5), 55-59.

Woo S, Pecht M (2008). Failure analysis and redesign of a helix upper dispenser. *Engineering Failure Analysis*, 15(4), 642–653.

Woo S, O'Neal D, Pecht M (2009a). Improving the reliability of a water dispenser lever in a refrigerator subjected to repetitive stresses. *Engineering Failure Analysis*, 16(5), 1597–1606.

Woo S, O'Neal D, Pecht M (2009b). Design of a hinge kit system in a Kimchi refrigerator receiving repetitive stresses. *Engineering Failure Analysis*, 16(5), 1655–1665.

Woo S, Pecht M, O'Neal D (2009c). Reliability design and case study of a refrigerator compressor subjected to repetitive loads. *International Journal of Refrigeration*, 32(3), 478-486

Woo S, Ryu D, Pecht M (2009d). Design evaluation of a french refrigerator drawer system subjected to repeated food storage loads. *Engineering Failure Analysis*, 16(7), 2224–2234.

Woo S, O'Neal D, Pecht M (2010a). Failure analysis and redesign of the evaporator tubing in a Kimchi refrigerator. *Engineering Failure Analysis*, 17(2), 369-379.

Woo S, O'Neal D, Pecht M (2010b). Reliability design of a reciprocating compressor suction reed valve in a common refrigerator subjected to repetitive pressure loads. *Engineering Failure Analysis*, 2010, 17(4), 979-991.

Woo S, O'Neal D, Pecht M (2011). Reliability design of residential sized refrigerators subjected to repetitive random vibration loads during rail transport. *Engineering Failure Analysis*, 18(5), 1322–1332.

Woo S (2015). The reliability design of mechanical system and its Parametric ALT. Handbook of Materials Failure Analysis with Case Studies from the Chemicals, Concrete and Power Industries, Elsevier, 259-276.

Woo S, O'Neal D (2015). Reliability design of mechanical systems subject to repetitive stresses. *Recent Patents on Mechanical Engineering*, 8(4), 222-234.

Woo S, O'Neal D (2016). Improving the reliability of a domestic refrigerator compressor subjected to repetitive loading. *Engineering*, 8, 99-115.