

Development of Spring Life Test Apparatus and Life-Cycle Assessment of Extension Springs



Gregory Mathew, Santosh B. Rane, Yogesh Patil, and Sanjay V. Mohan

Abstract Life-cycle test of moulded case circuit breakers (MCCB) on mechanical endurance test apparatus exhibited springs as the weak links. Therefore, improvement in the reliability of the circuit breaker mechanism was possible only with an improvement in the life of the springs. To evaluate spring life, a life-cycle test apparatus was developed which subjected springs to actual load conditions as experienced in MCCB. This paper describes the development and working of the test apparatus. The paper also explains how reliability of springs can be estimated using life data provided by the apparatus.

Keywords Reliability · Fatigue failure · Hook failure · Weibull plot

1 Introduction

Circuit breakers are complex engineering systems used for protection of distribution feeder systems, transformers, etc. Mechanical springs are the heart of a circuit breaker operating mechanism. They provide the driving force necessary for the instant opening of the contacts of a circuit breaker and also play a vital role by ensuring adequate contact pressure between the fixed and the moving contacts. Therefore, failure of the extension springs must be avoided. Their reliability is crucial for the safety and the overall reliability of the breaker.

The best engineering practice is to build reliability into a product at the earliest in the design and development phase [1]. One of the ways to determine the inherent reliability is to test under controlled environments based on the product usage and development requirements [2]. Fatigue tests are increasingly being performed to

G. Mathew (✉)

Dwarkadas J. Sanghvi College of Engineering, Vile Parle, Mumbai, Maharashtra 400056, India
e-mail: greg_12@ymail.com

S. B. Rane

Sardar Patel College of Engineering, Andheri, Mumbai, India

Y. Patil · S. V. Mohan

L&T EAIC, Mumbai, India

© Springer Nature Singapore Pte Ltd. 2020

H. Vasudevan et al. (eds.), *Proceedings of International Conference on Intelligent Manufacturing and Automation*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-4485-9_51

simulate and investigate real-world failures of springs in various applications [3–10]. The circuit breaker selected for the study had a designed mechanical life of 30,000 cycles. But mechanical endurance tests on the circuit breakers terminated before 30,000 cycles because of premature failures of the extension springs of the breaker. A need was therefore felt to estimate and improve the life of springs to improve the life of the circuit breaker. Reliability assessment of a mechanical spring is required to evaluate different spring designs for various spring deflection applications [11]. In the conventional process of evaluating the life of helical extension springs, the circuit breaker with extension springs was mounted on a mechanical endurance test apparatus. A pneumatic actuator then operates the circuit breaker (switches on and switches off) at the standard frequency cycle. The test cycle at which the endurance test terminates is noted, and the circuit breaker is analysed to identify the root cause for the premature termination of the test. During the investigation, if the spring is found to be failed, then the value of the cycle at which the test terminated denotes the life of the springs. The conventional process of testing spring life is time-consuming and expensive. Hence, a need was felt to establish a life-cycle test apparatus to eliminate the time constraints (i.e. it should test multiple springs at the same time) and to provide adequate and reliable data for plotting reliability of the operating life of springs.

2 The Life-Cycle Test Apparatus

The life-cycle test apparatus consists of two stacks of mounting space for springs, i.e. the lower stack between the bottom plate and the mid-plate (nos 6 and 3, respectively) and the upper stack between the top plate and the mid-plate (nos 2 and 3, respectively). The top and the bottom plates are stationary while a double-acting pneumatic cylinder actuates the mid-plate (provides vertically up/down motion to the mid-plate) in order to flex the springs between their 1st and 2nd operating limit.

Grooved spring rods (no. 5) are used to support the springs. Grooves on the spring rod support the spring hooks and prevent their tilting when the springs are flexed between their two operating lengths. Support blocks (no. 7) hold the spring rods as indicated in the diagram. To prevent the spring rods from sliding away during operation (because of vibrations), stopper blocks (no. 10) are provided which restrict the translational movement of the rods. Support block screws (no. 12) and support block nuts (no. 13) fix the support blocks and stopper blocks to the respective top plate, mid-plate and base plate. The apparatus is bolted to the test bench through holes provided in the base plate. Guide pillars (no. 4) welded to the base of the base plate guides the longitudinal traverse of the mid-plate. The distance adjusting bolts (no. 1) are used to maintain the required gap between the top plate and the base plate. Roller guide bushes (no. 8) fixed to the mid-plate reduce the friction between the mid-plate and guide pillar. Stopper pins (no. 9) which prevent the travel of the mid-plate beyond the set limits are fixed to the mid-plate using stopper nuts (11).

Springs are mounted on spring rods between the base plate and mid-plate and between the mid-plate and top plate. The distance between the base and top plates is calculated and then adjusted using distance adjusting bolts such that when the mid-plate traverses upwards (towards the top plate) on being actuated by a pneumatic cylinder, the springs in the lower stack will be flexed to the 2nd operating length, while the springs in the upper stack will be relieved to the 1st operating length. The upward motion of the mid-plate beyond the calculated limit is prevented by stopper pins which stop against the top plate and restrict the further upwards motion of the mid-plate. The advantage of the apparatus is that the relaxing force exerted by the springs in the upper stack (when the springs in the upper stack relax from its 2nd operating limit to its 1st operating limit during the upwards movement of the mid-plate) will aid the pneumatic force in flexing (stretching) the springs in the lower stack to their 2nd operating limit (they were initially at 1st operating limit). The process is reversed during the downward moment of the mid-plate. Figures 1 and 2 indicate various components of the apparatus.

Figure 3 shows the 3D CAD model of the apparatus.

Springs with operating lengths and diameters can be easily tested for life on the apparatus. Before testing, the length between the top and base plates should be readjusted such that when the mid-plate traverses upwards, the springs in the lower stack will be flexed to the 2nd operating length, while the springs in the upper stack will be relieved to the 1st operating length, and vice versa. The length can be adjusted by rotating the distance adjusting bolts, clockwise or anticlockwise, depending on whether the distance needs to be increased or decreased. Spring rods need to be changed to suit the hook diameter of the selected spring. Stopper pins need to be redesigned to maintain the 1st operating length of the new springs in both the stacks.

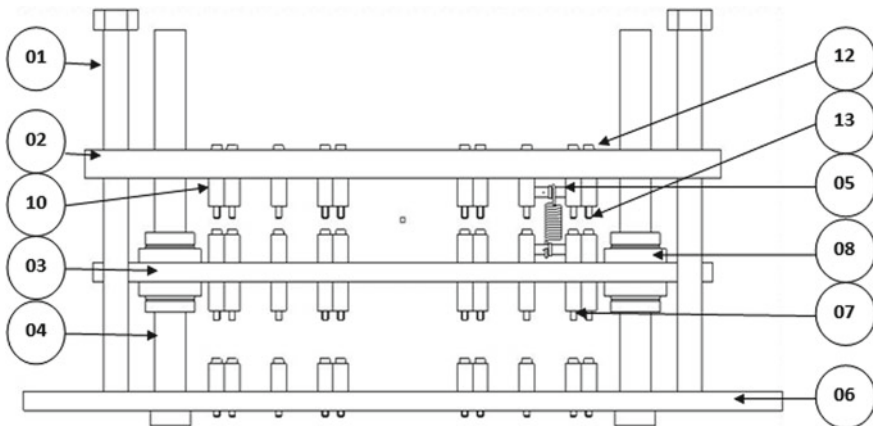


Fig. 1 New experimental apparatus

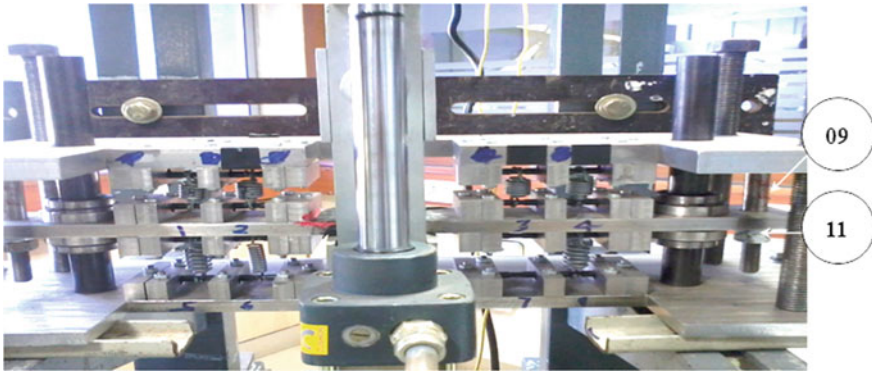


Fig. 2 Actual apparatus

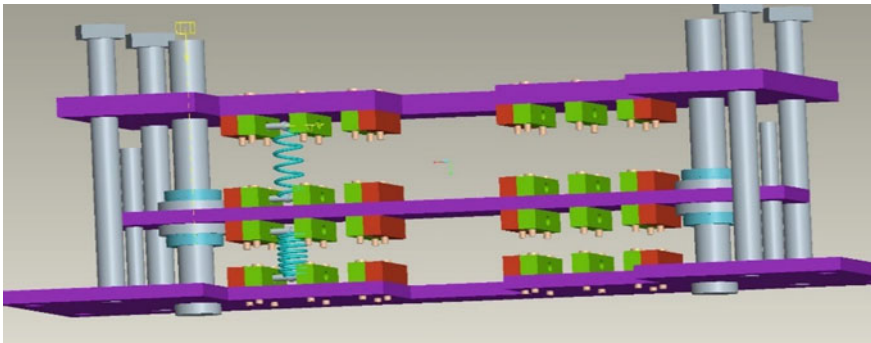


Fig. 3 3D model of the apparatus

3 Testing and Improvement

For the purpose of the study, 8 circuit breaker springs (of initial design), accepted by the quality control department of the company, were selected. The springs mounted on the apparatus were flexed between its 1st and 2nd operating limits (38.3 mm and 48.5 mm, respectively) with a standard test frequency of 240 cycles/hr. Times to failures of these springs as provided by the test apparatus are tabulated in Table 2.

Examination of the failed spring specimens clearly indicated failure at the hooks. The hooks were redesigned to reduce the stress. The physical properties of the springs with improved hooks are tabulated in Table 1 under the column 'Design 2'. Figures 4a and 4b show the condition of the spring (from initial design category) after testing.

To further improve the life of the springs, springs of initial design parameters but with a different material (changed from grade 3 to grade 4) were manufactured and tested. Their physical characteristics are tabulated in Table 1 under the column 'Design 3'.

Table 1 Spring properties through different phases of improvement

S No.	Parameter	Initial	Design 2	Design 3
1	Wire dia in mm	1.7	1.7	1.7
2	Mean dia in mm	9.7	9.7	9.7
3	Active no. of turns	10.5	10.5	10.5
4	Free length in mm	30.2	30.2	30.2
5	Material as per IS 4454: (Part I): 2001: patented and cold drawn unalloyed steel wire	Grade III	Grade III	Grade IV
6	Permissible shear stress Kgf/mm ²	92.49	92.49	98.89
7	Permissible bending stress Kgf/mm ²	176.49	176.49	189.16

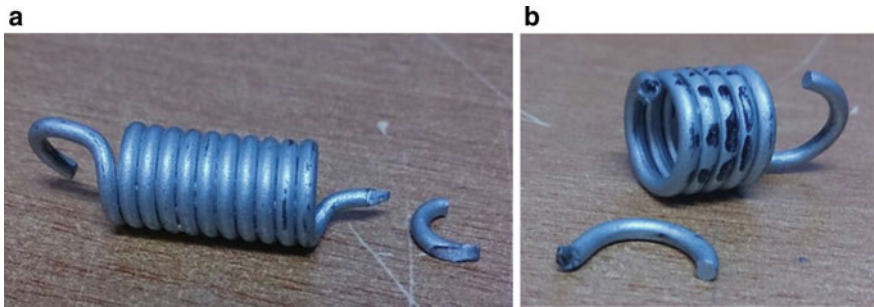


Fig. 4 a Failed spring (initial design). b Failed spring (initial design)

4 Observations

The life-cycle test for each design phase was run for a maximum duration of 30,000 cycles, and the springs surviving the test were suspended. The interval censored life data of the springs obtained from the life-cycle test apparatus are tabulated in Table 2. The ‘initial design’ column tabulates the observations on the life-cycle test apparatus for the springs with the initial design. ‘Design 2’ and ‘Design 3’ columns tabulate the observations on the life-cycle test apparatus for the springs from the first and the second design modification phases, respectively. The ‘from cycle’ and ‘to cycle’ columns define the interval in which a spring failure was reported. For example, three spring failures were observed between 28,000 and 29,250 cycles for springs from Design 3 phase.

5 Results

Life data distribution plots were used to estimate the reliability of springs. The relationship of a distribution plot with failure data differs from plot to plot and

Table 2 Time to failure for springs

Failure No.	Initial design		Design 2		Design 3	
	From cycle	To cycle	From cycle	To cycle	From cycle	To cycle
1	20,800	21,770	18,000	18,770	25,050	26,000
1	24,005	25,065	18,770	19,500	28,000	29,250
1	26,400	27,240	18,770	19,500	28,000	29,250
1	26,400	27,240	19,500	20,000	28,000	29,250
1	26,400	27,240	19,500	20,000	29,250	29,680
1	28,110	29,820	19,500	20,000	29,250	29,680
1	28,110	29,820	20,500	21,000	29,250	29,680
1	28,110	29,820	22,500	24,000	30,000	Suspended

depends on the nature of the data collected. To estimate reliability correctly, it is essential to select the distribution plot that fits the data closely. To select the most appropriate distribution, failure data were analysed using Minitab, and the goodness-of-fit plots for various distribution plots with failure data were compared. Some of these plots are shown in Fig. 5.

As it is difficult to identify the distribution plot which fits the data best, values of Anderson–Darling coefficient and correlation coefficient calculated for various

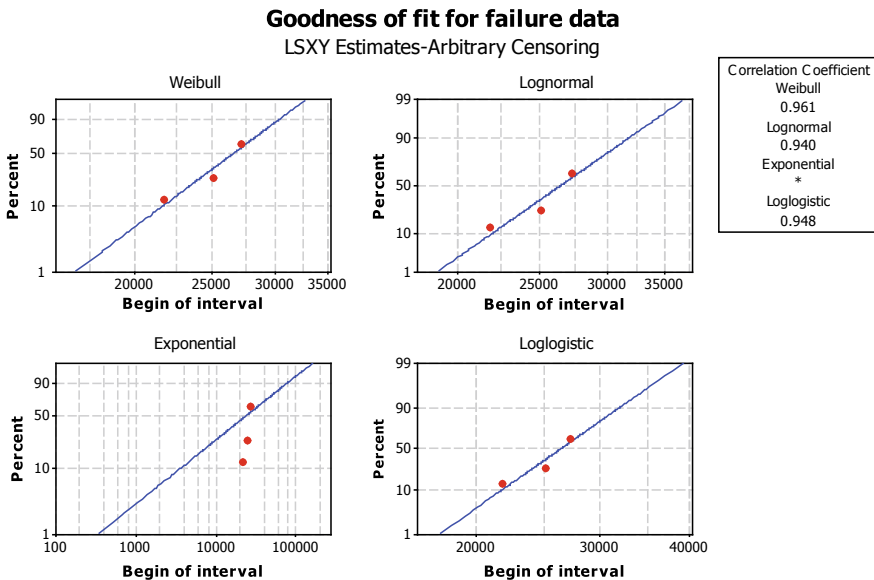


Fig. 5 Goodness of fit for failure data (Weibull, lognormal, exponential and loglogistic distribution plots)

Table 3 Estimated correlation coefficient for springs with initial design

S. No.	Distribution	Anderson–Darling coefficient	Correlation coefficient
1.	Lognormal	10.892	0.940
2.	3-parameter Weibull	10.875	0.969
3.	3-parameter lognormal	10.892	0.950
4.	3-parameter loglogistic	10.890	0.957

plots were compared with each other. The values of these coefficients for some distributions are summarized in Table 3.

The distribution with correlation coefficient close to 1 and Anderson–Darling value close to zero will give the most appropriate results. By analyzing the values summarized in Table 3 for initial spring design, it can be concluded that 3-parameter Weibull plot fits the life/failure data of the springs closely.

The reliability graphs for the spring through its various design phases are plotted in Fig. 6. The reliability plot of springs in the initial design phase shows a gradual decrease in reliability which indicates that the fatigue properties of the springs are inconsistent (even though they are from the same lot). If the properties of the springs were identical, the failures would have been clustered around a single time interval and there would be a sudden decrease in the slope of the graph. Defects in the material or inconsistencies in the manufacturing techniques lead to above-said inconsistencies in fatigue properties of springs.

Compared to initial spring designs, ‘Design 2’ phase shows a decrease in reliability of springs. Analysis of the springs revealed that the material quality was inconsistent with that described in design which led to a decrease in reliability (even though

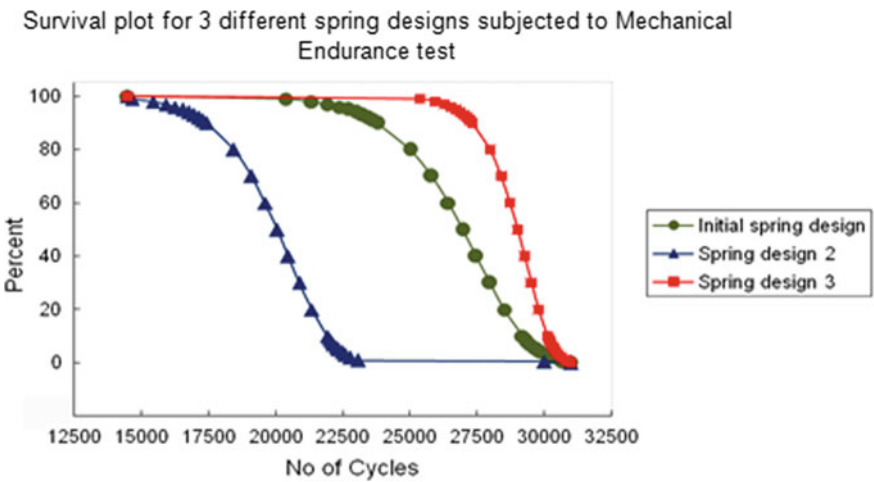


Fig. 6 Survival plot for three different spring designs

theoretical design calculations suggest an improvement in design). Tool marks at the hook bends induced during the spring production process resulted in increased stress and led to decreased spring life. Springs of Design 3 phases were manufactured from grade IV material which has better mechanical strength. Critical zone in the plot of Design 3 phase (between 28,000 and 29,680 cycles) shows 75% springs failures and hence suggested that these springs had consistent fatigue properties. The reliability plot also indicates an increase in reliability of the springs as compared to springs from initial design and Design 2 phases.

6 Conclusion

The fatigue life-cycle test apparatus provides for a quicker and an economical process to evaluate the fatigue life and reliability of springs. The modular construction of the test apparatus makes it versatile enough to permit easy assembly/disassembly of the springs and test helical extension springs of varied lengths (20 mm to 190 mm). Improvements can be incorporated into the springs by changing design parameters such as coil diameter and wire diameter. The improved springs can be tested on the apparatus to estimate the improved life/reliability.

Acknowledgements We express our special appreciation and thanks to Larsen and Toubro, EAIC, Mumbai, for encouraging this research and for providing the necessary resources, support and the motivation for carrying out this study.

References

1. Cui Y, Khan AW (2007) A case study—reliability based product development and improvement model. *Qual Reliab Eng Int* 24:361–373
2. Zanoft J, Ekwaro-Osire S (2009) An Approach that can quickly assess product reliability. *Qual Reliab Eng Int* 26:571–578
3. Chen J, Xia Z (2014) Fatigue behaviour of coke drum materials under thermal-mechanical cyclic loading. *Theor Appl Mech Lett* 4(4):041006
4. Pyttel B, Brunner I, Kaiser B, Berger C, Mahendran M (2013) Fatigue behaviour of helical compression springs at a very high number of cycles—investigation of various influences. *Int J Fatigue* 60:101–109
5. Ravi Kumar B, Das Swapan K, Bhattacharya DK (2003) Fatigue failure of helical compression spring in coke oven batteries. *Eng Fail Anal* 10(3):291–296
6. Schulz BA, Moran AL (2001) Fatigue failure of an F/A-18 fin retainer spring. *Eng Fail Anal* 8(2):167–172
7. Berger C, Kaiser B (2006) Results of very high cycle fatigue tests on helical compression springs. *Int J Fatigue* 28(11):1658–1663
8. Rivera R, Chiminelli A, Gómez C, Núñez JL (2010) Fatigue failure analysis of a spring for elevator doors. *Eng Fail Anal* 17(4):731–738
9. Nohut S, Schneider GA (2009) Failure probability of ceramic coil springs. *J Eur Ceram Soc* 29(6):1013–1019

10. Das SK, Mukhopadhyay NK, Ravi Kumar B, Bhattacharya DK (2006) Failure analysis of a passenger car coil spring. *Eng Fail Anal* 14:158–163
11. Cheng JX, Yan WC (2004) Mechanical spring reliability assessments based on FEA generated fatigue stress and monte carlo simulated stress/ strength distributions. In: International compressor engineering conference (Paper no: 1693)