4th Asia Pacific Conference of the Prognostics and Health Management,
Tokyo, Japan, September 11 – 14, 2023
R06-03

Study on the intermittent fault mechanism of electromagnetic relay under complex environmental stress

Ye Jingzhong[1], Lyu Kehong[2], Liu Guanjun[3], Qiu Jing[4*]

[1,2,3,4]*Science and Technology on Integrated Logistics Support Laboratory, College of Intelligence Science and Technology, National University of Defense Technology, Changsha, 410073，P. R. China*
673724684@qq.com
fhrlkh@163.com
gjliu342@qq.com
qiujing16@sina.com

ABSTRACT

When the relay experiences intermittent failures, its faults are difficult to reproduce, making it difficult to repair, and bringing daunting challenges to equipment reliability and mission success. Domestic and international studies have shown that environmental stresses, especially vibration stress and temperature stress, are important causes of intermittent failures of relays, but their mechanisms are not yet clear. Therefore, an in-depth analysis of the mechanism of relay intermittent failure under complex environmental stresses has become a critical challenge that needs to be accomplished. To address this issue, this paper takes a model of electromagnetic relay as the research object and conducts an in-depth study of the intermittent failure mechanism of the relay under vibration stress and temperature stress after salt spray corrosion using the technical approach of theoretical analysis, simulation analysis and experimental verification.

1. INTRODUCTION

Relay is an important automatic control device, when the input (electric, magnetic, acoustic, optical, thermal and other signals) reaches a certain value, the output will be step change, widely used in aviation, aerospace, missiles and other fields with high reliability requirements, mainly in the control system to undertake important tasks, such as power conversion, equipment start-up and equipment protection, alarm, indication, etc.(Ren & Zhai, 2015). With the improvement of electronics, information technology and automation, the role of relay is also more and more important, with the use increasing and the scope of use expanding. For example, a large military transport aircraft needs more than 200 general-purpose relays, a high-performance fighter aircraft on the use of relays can reach thousands, a large satellite needs to use relays up to about 1500. Due to the important role of relays, sometimes a relay failure will cause millions or even hundreds of millions dollars of system failure, especially the important parts of the relay, its reliability is directly related to the success or failure of a aerospace system engineering (Zhu & Wu, 2005).For example, the original intention of establishing China Aerospace Quality Day was that on March 22, 1992, the launch of the Long March II F rocket, which was responsible for carrying out the Australian B1 communication satellite launch mission, failed due to an internal excess material in the relay, which caused a short circuit in the contact group, resulting in significant losses (Yan, 2020).

In order to cope with the various types of relay failures, the overhaul method has evolved from emergency troubleshooting to regular preventive maintenance. However, most of the relay failures are difficult to follow, and incidental failures are common. Poor product consistency and consequent drifting of the suction time parameter, contact bonding due to arcing, contact sticking due to excess accumulation, and contact bouncing due to unreasonable suction-reverse force coordination are also quite common in trouble spots (Fu, 2017). However, occasional failure is not as expected by the regular maintenance to eliminate, which will cause great potential for the safety of the entire electrical system. This phenomenon of occasional faults that occur during use and are not necessarily reproduced by stopping and checking is defined as intermittent faults. The main difference between intermittent faults and permanent faults is that intermittent faults can occur in a very short period of time and disappear again without taking any measures (Liu et al., 2019). During the testing process, it was found that the frequency of no faults found and retesting qualified due to intermittent faults is increasing, the appearance of intermittent faults greatly shortens the average failure cycle of relays, and nearly 1/3 of the relay faults could not be detected when the relay was removed for off-line testing and repair at the base level maintenance process, and the configuration of powerful automated test systems could not help. Current traditional relay test equipment is not designed to detect intermittent failures, but only to test the normal operation of relays, thus hiding any short-term abnormal events, or misdiagnosing intermittent failures as permanent failures leading to unnecessary downtime and excessive maintenance problems, resulting in a waste of maintenance assurance resources, which in turn affects the efficiency of equipment use, resulting in ineffective maintenance activities and threatening the safety of equipment use .

However, the working environment of relays is an important factor leading to their intermittent failures, among which corrosion, vibration, and temperature are the most common stressors, with their resulting degradation effects being the most significant. Therefore, this paper takes a model of electromagnetic relay that has undergone artificially accelerated simulated salt spray environment test as the research object, carries out the relay intermittent failure mechanism analysis, designs the degradation experiment of electromagnetic relay under different stresses, and initially explores the influence mechanism of vibration stress and temperature stress on the intermittent failure of electromagnetic relay under corrosion degradation state. This is of great theoretical and practical significance for identifying relay degradation mechanisms, enhancing relay intermittent fault detection capability, improving equipment integrity, avoiding ineffective flow of spare parts and equipment operation with faults.

2. FAILURE ANALYSIS

The common failure modes and failure mechanisms of electromagnetic relays are sorted out, and the details are shown in Table 1. It can be seen that the points of contact are the most likely part of the relay to fail, mainly in the form of points contacting failure, and poor contact is one of the main forms of contact failure. Poor contact of the points means that the contact resistance between the points is too large when the points are in contact. Intermittent failures of electromagnetic relays are often the result of poor contact of the points. Therefore, the contact resistance between the points of electromagnetic relays as a characterization parameter of the performance of electromagnetic relays, according to the "General Specification for Electromagnetic Relays", 50mΩ as a nominal value, contact resistance more than 50mΩ after a rapid fall back to the normal range, is the occurrence of an intermittent failure (Liu et al. 2011, Ma 2013, Wang et al. 2011, Yang 2006 and Wang 2015).

Table 1. Main failure modes of the electromagnetic relay

Failure mode Mode	Phenomenon	Failure mechanism
Poor contact	Large contact resistance ; Contact break	(1) contact surface contamination, organic adsorption film, carbonized film, etc. (2) dust and other excess material entrapped in the contact surface (3) magnetic pole surface clamping excess, so that the armature movement is not in place (4) contact pressure drop due to electrical wear of the contact (5) contact reed stress relaxation leads to contact drop (6) push rod crack or push rod creep (7) generation of friction polymer
Contact bonding	Normally open contact bonding; Normally closed contact bonding	(1) contact fusion welding caused by sparks and electric arcs (2) Van der Waals force cold welding (3) contact fusion welding caused by contact Joule heat (4) sealed relay leakage, stored at a low temperature below 0 ℃, the internal ice, contact condensation
Contact jitter break	Normally open contact jitter closed; Normally closed contacts jitter off	(1) contact reed resonance (2) structural parts, armature resonance (3) stress loose Hong, contact pressure drop; electromagnetic holding force is not enough (4) relay shaft hole with too loose (5) mounting ears are not flat, the product is subject to twisting stress after clamping relay mounting parts vibration magnitude amplification
Coil short circuit	Coil resistance	(1) the inner lead wire is not well insulated, and the winding turns layer, the

	value is reduced, or even zero	outer lead wire short circuit (2) damage to the enameled wire varnish (3) enameled wire and lead wire welding is not smooth, burrs, piercing the lead wire wrapping insulation film
Coil breakage	Coil inaccessible	(1) the enameled wire and the lead wire welding at the false welding (2) the enameled wire to the paint skin when damaged (3) the lead wire welded to the lead rod, taut, in the role of tension lead wire welding broken (4) mechanical stress vibration break (5) coil short circuit burned (6) due to coil over-voltage caused by the coil overheating aging
Sensitivity is poor	Suction voltage, release voltage is poor; do not convert	(1) contact pressure drop (2) return spring, permanent magnet force changes (3) magnetic gap change (4) armature shaft hole friction force increases, or armature movement is blocked (5) coil resistance change or break (6) relay air leakage, ice below 0 °C, contact condensation (7) relay installation parts have magnetic leakage or magnetic interference (8) undervoltage operation
Withstand voltage breakdown; insulation drop	Contact to ground; between contacts; coil to ground; coil to contact	(1) metal excess, welding spatter, fusion tumor connection (2) relay air leakage or baking degassing is not in place, so that there is water gas in it (3) glass insulators are contaminated (4) rupture of the coil lead wire sleeve (5) the coil skeleton (insulating film) is broken, the wire package and the core short circuit (6) silver ion migration
Seal air leakage	Sealed welding parts of air leakage; insulator air leakage	(1) moving the lead-in rod to crack the insulator (2) under the action of hot and cold stress to make the welding seam and insulator leakage (3) under the action of mechanical stress caused by sealing air leakage

In order to better simulate the harmful industrial gases (e.g., H2S, SO2, etc.) in the working environment of relays, which rapidly degrade to the mid- to late-life stage where intermittent failures are frequent, this paper uses a salt spray test to accelerate the corrosion degradation of the relay contact surfaces and bring the degradation state closer to the real situation. The main material of the relay contacts is silver tin oxide (Ag-SnO2), whose electrochemical corrosion process is shown in the following reaction equation (Graedel 1992, Cheng & Du 1995).

$$4Ag + 2H_2S + O_2 = 2Ag_2S + 2H_2O \quad (1)$$

$$2Ag + SO_2 + 2H_2 = Ag_2S + 2H_2O \quad (2)$$

$$4Ag + O_2 = 2Ag_2O \quad (3)$$

The sulfide reaction and oxidation reaction on the contact surface will be accelerated under the long-term effect of environmental stresses such as vibration and temperature, and the thickness of the compound film generated by the reaction will increase and spread, and the corrosion situation is shown in Figure 1. When the small signal weak current, low voltage is not able to break through the film or contact pressure is small enough to squeeze through the film, the contact resistance will increase, causing poor contact, resulting in intermittent failure (Wang 2015, Pan 2002).

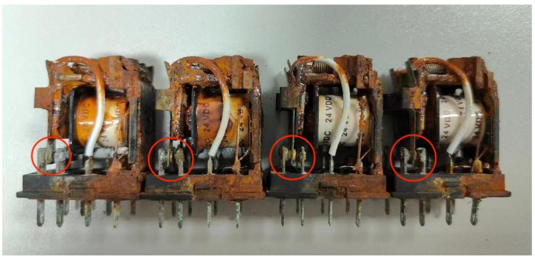


Figure 1. The corrosion situation of relays

3. EFFECT OF VIBRATIONAL STRESS

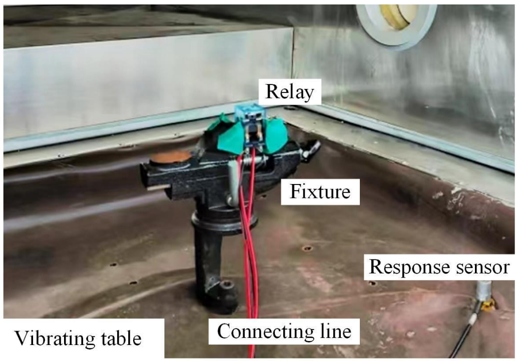


Figure 2. Field installation diagram of the vibration experiment

After salt spray corrosion of the electromagnetic relay contact surface will produce oxides and corrosive materials, vibration environment there is a short period of high stress (that is, the stress parameters in a very short period of time more than the vibration limit, is not enough to make the permanent failure of the electromagnetic relay), easy to make the contacts of the electromagnetic relay micro-motion wear, wear generated debris is also oxidation, hard abrasive particles formed, they interact to cause the plow effect, the contact surface is further damaged, the contact resistance increases, resulting in the performance of the electrical contact over time to reduce or even failure.

The experiments were designed to study the change law of contact resistance of electromagnetic relay under vibration stress. The field installation is shown in Figure 2, the contact resistance measurement curve is shown in Figure 3, and the intermittent fault signal is shown in Figure 4.

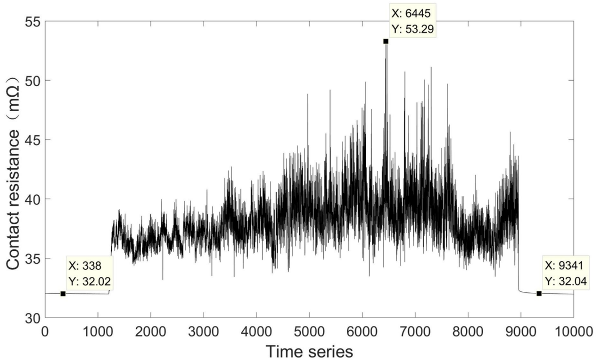


Figure 3. Contact resistance measurement curve

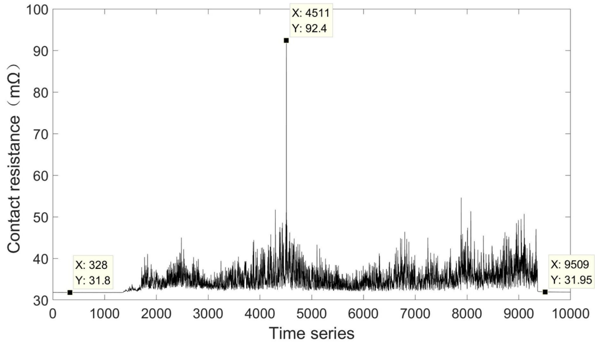


Figure 4. Intermittent fault signal

After comparing several groups of experiments, the following general rules can be derived for the signal characteristics of intermittent failures of corrosion-degraded electromagnetic relays under vibration stress.

1. The occurrence of intermittent failure of a corroded and degraded electromagnetic relay under vibration stress is indeed random, but not without warning, and the intermittent failure is preceded by a sudden and rapid increase in the contact resistance value.
2. The intermittent failure of a corroded and degraded electromagnetic relay under vibration stress is mainly characterized by the resistance value exceeding the threshold in a very short period of time and falling back to the normal resistance range quickly.
3. After the vibration test, the post-vibration contact resistance value of the corrosion degradation electromagnetic relay is almost same as the pre-vibration contact resistance value.

4. EFFECT OF TEMPERATURE STRESS

Since the contacts of electromagnetic relays are subjected to external ambient temperature stresses while generating Joule heat themselves, these temperature stresses are balanced in the material by continuous heat transfer, heat convection, and heat radiation, and eventually the temperature stress distribution inside the entire electromagnetic relay, especially the temperature stress situation inside the contacts, is difficult to monitor with instrumentation. Therefore, finite element simulation is used to analyze the temperature stress distribution inside the electromagnetic relay under external temperature stress, and then analyze the effect of temperature stress on the contact resistance of the electromagnetic relay. Based on the simulation analysis, experimental monitoring of the change in contact resistance of the electromagnetic relay under temperature stress and excitation capture of the intermittent failure are performed for the actual situation, and then the data analysis is used to verify the mechanism of the intermittent failure of the electromagnetic relay under temperature stress. The mechanism of intermittent failure of electromagnetic relays under temperature stress is verified by data analysis.

The simulation model of the contact spring system is established by the modeling function that comes with COMSOL. The structure dimensions are shown in Table 2, the material properties are shown in Table 3, and the mesh division and temperature profile is shown in Figure 5.

Table 2. Contact model structure size parameters(mm)

Static/Dynamic Reed Length	Reed Width	Static/Dynamic R Thickness
16/5	5	0.25/0.5
Contact thickness	Contact diameter	Dynamic contact radius of curvatu
1	4.4	12

Table 3. List of material properties

Material	Beryllium bronze	Silver tin oxide
Reference resistivity（Ω • m）	4.02×10^{-8}	2.4×10^{-8}
Resistivity temperature coefficient（1/K）	.00039	.00031
Density（kg/m^3）	8960	9800
Modulus of elasticity（GPa）	26.8	79
Poisson's ratio	0.35	0.37
Constant pressure heat capacity（J/（kg·K））	385	272
Thermal conductivity（W/（m·K））	195	325
Melting point（K）	1356	1233

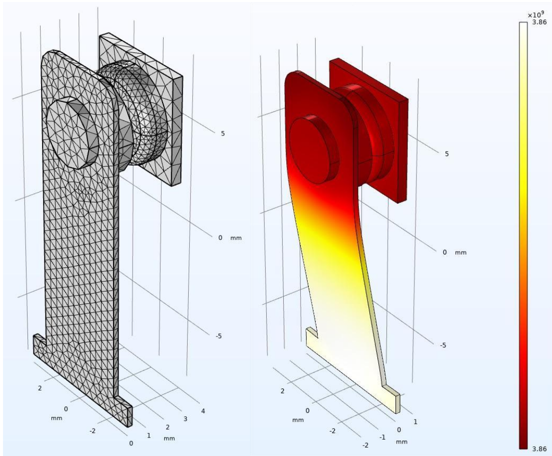


Figure 5. Finite element meshing of contact model and temperature profile

To stimulate the failure of a relay, or to accelerate the contact contact resistance change, generally in high temperature, low temperature or temperature shock environment. The high and low temperature environment stress retention test is suitable to excite the contact resistance trend change and resistance fluctuation caused by high and low temperature induced resistivity change, and the temperature shock test is suitable to excite the sudden resistance change phenomenon caused by temperature stress induced contact surface micro-movement. The overall scheme of the experimental platform is shown in Figure 6.

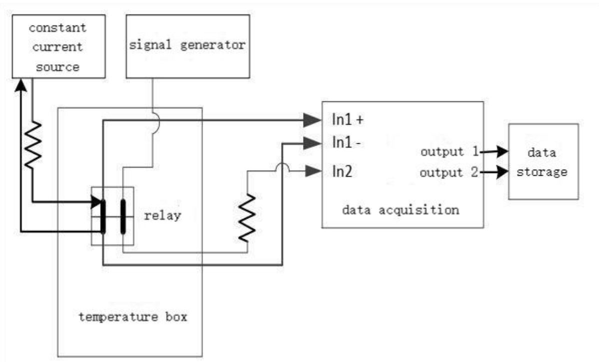


Figure 6. Temperature test platform scheme diagram

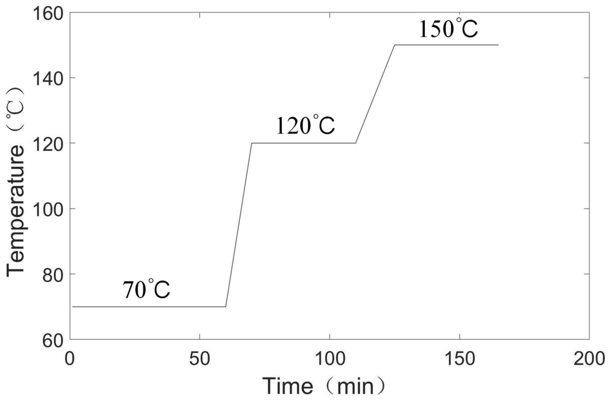


Figure 7. High-temperature stress diagram

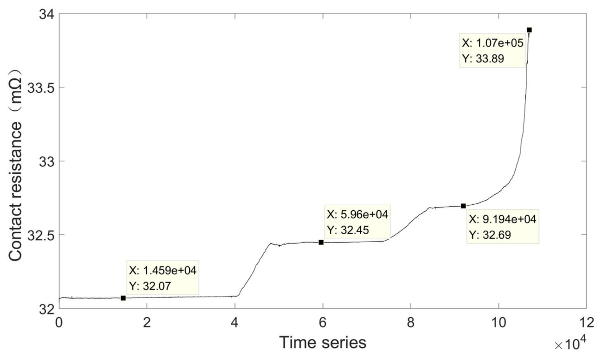


Figure 8. Contact resistance curve under high temperature stress

Through experimental analysis, the following main laws can be derived.

1. Under the stress of a constant external temperature value, the contact resistance of an electromagnetic relay will vary with temperature, the higher the ambient temperature, the greater the contact resistance.
2. Under the stress of external temperature, the contact resistance of an electromagnetic relay will have unavoidable, small fluctuations in resistance and sudden changes in resistance.
3. When the high temperature stress exceeds the safety threshold that the relay can withstand, the contact resistance will continue to rise sharply, leading to the permanent failure of the relay.

5. CONCLUSION

In this paper, we analyze the intermittent failure mode and induced mechanism of electromagnetic relays in degraded state under vibration and temperature environment, and find the weak link of intermittent failure of electromagnetic relays frequently. A complex stress environment such as corrosion, vibration and temperature is built to experimentally analyze the intermittent failure mechanism of electromagnetic relays in a vibration and temperature environment under corrosion degradation state, and the influence law of key parameters of environmental stress on intermittent failure of electromagnetic relays is obtained. The occurrence of intermittent failures is indeed random and difficult to predict, but it is closely related to the excitation of environmental stresses, and the stronger the stress, the higher the frequency of intermittent failures.

REFERENCES

Cheng, Y., & Du, Y. (1995). Atmospheric Corrosion of Electronic Devices. *Materials Protection*, 28(12), 16-19. doi:10.16577/j.cnki.42-1215/tb.1995.12.008

Fu, R., (2017). *Research on Simulation and Diagnosis of Degradation Failure for Electromagnetic Relay*. Master's dissertation. Harbin Institute of Technology, Harbin, China.

Graedel, T. E. (1992). Corrosion Mechanisms for Silver Exposed to the Atmosphere． *Journal of the Electrochemical Society*, 139(7), 1963 － 1970． doi:10.1149/1.2221162

Liu, G., Lyu, K., Li, H., Li, Q., & Qiu, J. (2019). No Fault Found and Intermittent Fault Diagnosis Technique for Equipment. *Measurement & Control Technology*, 38(01), 5-12, 18. doi.org/10.19708/j.ckjs.2019.01.002

Liu, G., Lu, J., & Wang, H. (2011). Failure Analysis of Contactor Relay. *Transactions of China Electrotechnical Society*, 26(01), 81-85.

Ma, Y., (2013). *Research on Failure Mechanism and Life Prediction Method for Aerospace Relays*. Master's dissertation. Harbin Institute of Technology, Harbin, China.

Pan, J., (2002). *Model and Estimate of Electrical Connectors under Vibration Stress*. Master's dissertation. Zhejiang University, Hangzhou, China.

Ren, W., Zhai, G. (2015). *Mechanical Environment Resistance Design Theory of Aerospace Electromagnetic Relay and its Application.* Harbin: Harbin Institute of Technology Press.

Wang, N., (2015). *Research on the Performance Degradation and Life Prediction of Railway Signal Relay under Vibration Condition.* Master's dissertation. Hebei University of Technology, Tianjin, China.

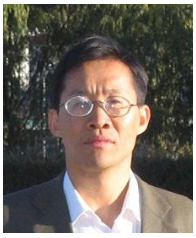
Wang, X., Gao, C. & Fu, G. (2011). Study on Electronic-test Failure Analysis Technology of Electromagnetic Relay. *Low Voltage Apparatus*, 02, 6-9, 18.

Yan, H., (2020). *Research on Recognition Technology of Reminders Material in Sealed*

Relay. Master's dissertation. Harbin Institute of Technology, Harbin, China.
Yang, C., (2006). *Failure Analysis and Reliability Research for JZ7 Intermediate Relay*. Master's dissertation. Hebei University of Technology, Tianjin, China.
Zhu, Y., & Wu, S. (2005). The development trend of military relays. *A Review of Electronic Science and Technology*. 01, 55-56.

Ye Jingzhong received his B.Sc.degree from National University of Defense Technology in 2013． He is currently a Master Degree Candidate at National University of Defense Technology． His main research interests include intermittent fault diagnosis and evaluation.

Lyu Kehong received his B.E. degree in Xi'an Jiao Tong University, in 2001 and received his M.S. and Ph.D. degrees in mechatronic engineering from NUDT, in 2003 and 2008. He worked as an associate professor in NUDT. His current research interests include prognostics and health management (PHM) technology, design for testability (DFT), mechanical signal processing, condition monitoring and fault diagnosis.



Liu Guanjun was born in Henan Province, China, in 1972. He received the B.S. degree in 1994 and the Ph.D. degree in 2000 from the NUDT, both in mechanics engineering. Since 2000, he has been carrying out teaching and research at NUDT. He is currently a Professor in 2011. His research interests include design for testability, testability demonstration, fault diagnosis, and fault prognostics.

Qiu Jing was born in Hubei Province, China, in 1964. He received the B.S. degree in solid mechanics from Beijing University of Aeronautics and Astronautics in 1985, M.S. degree in solid mechanics and Ph.D. degree in mechanics engineering from NUDT, in 1988 and 1998 respectively. Since 1988, he has been carrying out teaching and research at NUDT. He is a Professor in 1998. His research interests include design for testability, testability demonstration, fault diagnosis, and fault prognostics.