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Vibration Analysis and Electrical Contact Resistance Assessment for Automotive Relays

Thanigaivelraja Mohandoss and Femi Robert*

Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamil Nadu – 603203, India

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Abstract

Automotive relays are used in vehicles, subject to various mechanical vibration levels during regular operation. Vibration analysis helps ensure that the relay can withstand these vibrations without malfunctioning. It is essential for the relay's durability and long-term dependability. In this work, vibration analysis is carried out for the relay using an electrodynamic shaker, and the electrical contact resistance (ECR) is obtained. Relays used in vehicles undergo vibration because of the environmental and on-road conditions. Hence, vibration analysis is mandatory for automotive relays. ECR is obtained under DC and AC static environments with a frequency of 10 Hz to 70 Hz. Vibration analysis is carried out using an electrodynamic shaker experimental setup. Finite Element Analysis (FEA) using COMSOL Multiphysics is carried out to obtain the electrical and mechanical parameters of relay electrical contact. The highest current density occurs at the contact surface edges that have been visualized. Vibration analysis examines the dynamic behavior of electrical contacts in relays. This study also delves into prescribed displacement, Von Mises stress, and total displacement performance under dynamic conditions.

Keywords: Relay, Electrical Contact, Vibration, Electric Vehicle, Electrical Contact Resistance, Voltage Drop, Displacement, Stress, Frequency, Electrodynamic Shaker.

1. Introduction

Electric Vehicles (EVs) are the future of transportation. In the next few decades, EVs will be more mainstream than Internal Combustion Engine (ICE) vehicles. However, EVs, Hybrid EVs (HEVs), and ICE vehicles are currently in use. The electrical network of ICE vehicles operates on Low Voltage (LV) ranges between 12V and 24V. This voltage is now upgraded to 60V because of increased electrical circuit complexities and sophistication [1]. High Voltage (HV) range from 60 V to 1000 V is required for EVs. Vehicles such as cars, scooters, and auto rickshaws operate with a voltage range from 60 V to 300 V. The HV range of 300V to 800V is required for commercial EVs such as busses, military vehicles, earthmovers, agriculture vehicles, etc., [2]. Electric components are required to be designed and tested differently for vehicles because of the vibrating environment, on-road conditions, and safety requirements. The components used in the automotive sector follow a higher safety grade than the industrial grade. Electrical components in automotive vehicles undergo harsh environments, which comprises mechanical shock and vibrations induced by on-road conditions and motor. The effect of vibration, shock, temperature, and humidity on electrical components are potential causes of failure [3]. These parameters affect the reliability and lifetime of EV components such as connectors, relays, switches, circuit breakers, junction boxes, wiring assembly, and electric centers. These components are used to allow and interrupt electric current in various parts of the electrical network. Shock and vibration lead to loss of electrical continuity and structural failure in electrical contact. An EV has more than 400 electrical contacts, which causes 30 – 60% of electrical problems. This leads to electrical hazards and safety issues [4]. The important reason for contact failure includes contact welding, oxidation, wear, fretting, and arc. Among these, arc and contact welding are more influencing parameters. Also, the possibility of contact welding and arc significantly increases due to shock and vibration [5]. The voltage rating of electromechanical and electronic relays is 12 V to 600 V. The current rating ranges from 100 mA to 300 A [6].

Electrical contacts are the main components in electrical systems that are used to allow and interrupt electric current between the battery, motor, and other parts of the electrical system. The durability of electrical contacts in vehicles is of great concern because of the power appearing across the contact and vibrating on-road conditions. The number of electrical contacts increases due to the rise in requirement for more comfort, sophistication, and safety [7]. An increased number of electrical contacts reduces the electrical system's reliability. Arc and contact welding are influenced mainly by contact structure and material. As contact materials, a variety of metals and alloys have been employed. The ideal contact material will be highly conductive both electrically and thermally, have high melting and evaporation points, and exhibit stable resistance to oxidation, corrosion, deformation, arcing, and contact welding. Among these, the lifespan mainly depends on electric arc, an inevitable and detrimental phenomenon [8]. Moreover, an increase in voltage level exacerbates electric arc and its effects on connections. The pace at which the moving and immovable parts, tension, and material composition are the factors that control the electric arc. The three main mechanisms that cause failure are contact welding, high contact resistance, and severe contact erosion caused by switching arc [9]. Although it is well

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known that precious metals like gold and silver make good electrical contact materials, their application has been restricted due to their high cost. Despite reasonably good performance, copper alloys and copper with tin coatings are frequently utilized as substitute materials for electrical contacts [10].

The movable portion of an electrical contact is activated by dynamic forces in vibratory settings, which increase the initial static load. Unwanted vibration causes electrical connections to fail momentarily. The vibration of the contact causes an increase in operating current of 4- 25% [11]. Vibrations induced by road irregularities range in frequency from 20 Hz to 200 Hz for the electric wheel system. High-frequency electromagnetic excitation is vibration caused by in-wheel motor systems that range in frequency from 2 kHz to 8 kHz. Most recent studies on electric wheel systems concentrate on issues with low-frequency vibration [12]. Electric arc caused by contact vibration is analyzed extensively. The switching speed of the contact must be quick enough to decrease the arcing time of pre-breakdown arc phenomena. Excessive closing speed of electrical contact also causes contact vibration. To improve the reliability and lifetime of electrical contact present in relays, electrical contact resistance at vibrating, shock environments, and on-road conditions needs to be analyzed [13]. The lifetime of relays and circuit breakers can be predicted based on vibration analysis [14].

An examination of the wear caused by fretting was conducted on a dry Ti-6Al-4V cylinder/plane contact. The study examined the effects of sliding frequency, contact size, and cycle normal force[15]. The breakdown, arcing, contact touch, melting, and solidification of the contact material are among the sequential steps of the welding dynamics at contact closure that are extensively studied [16]. Research has been done on fretting corrosion's effect on an automotive connector's contact surface [17]. The deterioration of automotive connectors tested on the road has been the subject of extensive research. Studying tin-plated terminals with sealed and unsealed connectors, contact failures resulting from temperature, vibration, humidity, and corrosive gas assault were observed [18]. The influence of cable vibrations on connectors used in automotive applications is presented [19]. Exploration is done on the electrical behavior of golden automotive connectors under vibration tests [20] and also examined nickel coatings' fretting wear behavior for use in dry and lubricated electrical contact applications [21]. A break arc study is performed on electrical contact for the 42 V in Automotive Applications. In this, the anode is flat, and the cathode is convex with a curvature radius of 10mm and the analysis has been carried out for materials Ag, AgCu, AgNi, $AgSnO_2$, and AgZnO [22]. The investigation is carried out on the contact behavior of the electrical vehicle-battery junction box under high shorting and breaking currents at 200V and 200A [23].

When contact pairs of surfaces shift as a result of external mechanical vibrations, fretting corrosion damage happens. With a 3D laser vibrometer, the study examines global relative movement in 11-part, 1-way automotive connectors. The study identifies relative motions on housing, the terminals, and the wire to examine induced movement through connector components. In order to detect damaged frequency domains and assess the possibility of fretting corrosion, the findings are checked against the frequency response using the method of modal analysis modeling. The results show that frequency peak was observed only for the higher frequency domain, and it was smaller for the lesser frequency domain. Two-mode forms were found comparing the FEA simulation results with the experimental test. A small discrepancy was found between the natural frequency data from the experiment and the simulation. Therefore, it's essential to remember that fretting corrosion can occur in both the high- and low-frequency domains [24]. Wear particles cannot raise contact resistivity in the silver coating, which is resistive to oxidation in the air, and vibration will not cause the resistance of the electrical contact to rise progressively [25]. The G value due to mechanical shock and on-road conditions would be obtained from the literature. These G values and frequency would be provided on electrical contact by using an electrodynamic shaker. The change in contact resistance, voltage drop, current carrying capability, and temperature would be obtained. The effect of the vibration, shock, and on-road conditions on the arc will also be analyzed. The reliability of the micro-electrical contact will also be examined. The mechanical characteristics of railway signal relays under vibration have been explored in which contact clearance, initial pressure, and contact force play a significant role [26]. Lifetime is the most significant feature that decides the reliability of electrical connectors. ECR is the analysis of the prediction of reliability [27].

The vibration with the surface displacement amplitude of 3 nm with the structural vibration of 100 Hz is explored to analyze the ECR. An increase in ECR can happen in automotive because of external shock and vibration [28]. The rise of electric vehicles and hybrid electric vehicle market increases the demand for light weight, reliable relays and circuit breakers which has electrical contact. Dynamic tests such as sine sweep, random variable, and mechanical shock are necessary for reliable testing [29]. Relays and connectors are placed in the chassis, electronics, power train, and multimedia connections. Finite element simulations can be used to predict the performance parameters such as ECR in the electrical contact of the relay [30]. Harsh mechanical vibration stress leads to the failure of electrical contacts in relays and circuit breakers. Vibration stress includes acceleration and stress. An electrodynamic shaker can be used to provide vibration [31]. Operation temperature and humidity also affect the electrical contact resistance and reliability [32].

2. Relay Electrical Contact

An automotive relay is an electromechanical switch used in automobiles to control electrical devices, such as lights, motors, fans, and various accessories. It is a critical component in an automotive electrical system, serving as a control device to manage the flow of electrical current. Automotive relays are used for various purposes, including switching high-current loads, enabling complex functions, and providing safety features. Electrical contact is a very important part of relay, which is responsible for conducting and interrupting electrical current in electrical circuits. These electrical contacts are made up of conducting metals such as Cu, Al, Au, Ag, Pt, etc. Cu and Al are commonly used contact metals. The ECR should be generally low so that the contact can allow maximum current with lower losses. These resistance values should be stable for a long time. The relays that are operated in pleasant working environments can easily maintain stability and low resistance for a long time. However, the relays that are used in unpleasant working environments, such as vibration and shock, experience an irregular increase in resistance, which causes higher losses and low current flow and leads to lower lifetime and reliability. These mechanical vibrations can cause electrical contact failure, hence leading to relay failure. The relative displacement of the contact pairs causes the rise in ECR.

The external mechanical vibrations influence the ECR by influencing the contact force, which decides the contact area. The failure of an electrical contact in the presence of mechanical vibration is explored. Mechanical vibrations also affect the surface tribology of electrical contacts.

In all these, automotive electrical contact is an important part that is used in connectors, switches, junction boards, battery terminals, circuit breakers, contractors, and relays. Each vehicle has more than 400 contacts. 30% to 60% of electrical problems are due to the degradation and failure of these electrical contacts. This is due to the vehicle's mechanical vibrations. The main sources of mechanical vibrations are engines, sudden starting and stopping, shock, and on-road conditions. Because of these vibrations, the ECR can fluctuate or increase or intermittence. The increase in resistance further increases the joule heating, which causes degradation of contact. This can cause sudden failure after a definite number of vibrations. Under vibration, the formation of an electric arc between the contact surfaces also increases, which causes surface change, which leads to an increase in resistance.

Vibration analysis allows manufacturers to assess how relays perform under different vibrational conditions. This includes evaluating whether the relay maintains its functionality, stability, and contact resistance in the presence of vibrations. In automotive applications, relays are often responsible for controlling critical functions like engine management, airbags, and braking systems. Any malfunction due to vibrations can lead to safety risks. Vibration analysis helps identify potential issues and ensures the relay's safe operation.

The relay considered for this analysis is shown in Fig. 1. Electrical contact is made up of copper. These automotive relays operate on the principle of electromagnetic attraction. They consist of a coil of wire and one or more movable contacts. When an electrical current is applied to the coil, it generates a magnetic field, which attracts the movable contact(s) to close the electrical circuit. The electrical contact is shown in Fig. 2. The contact surfaces of the electrical contact with dimensions are given in Fig. 3. The measurement setup used for the measurement of the dimensions of the electrical contact is shown in Fig. 4. OLM 3020 Vision Measuring system is a non-contact measurement system that uses optical and imaging technology to capture and analyze the features and dimensions of objects. It is equipped with high-resolution cameras and optics to capture detailed images of the component under inspection. The observed diameter of the contact surface is 2.787 mm, and the depth of the rectangular-shaped terminal, which holds the contact part, is 3.931 mm.

Fig. 1. Electrical Relay

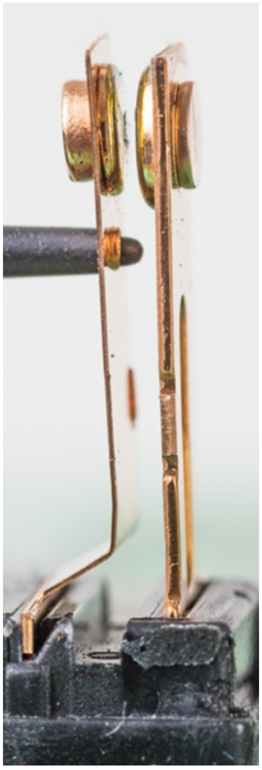
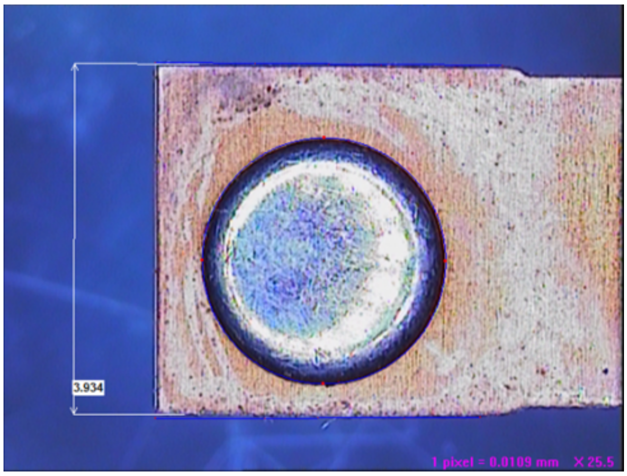


Fig. 2. Electrical Contact



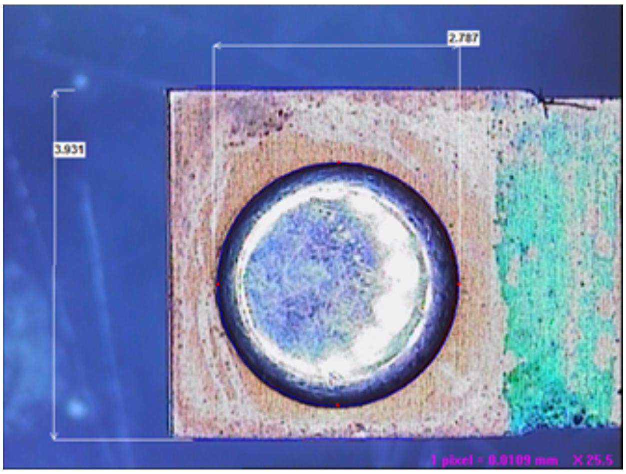


Fig. 3. Contact Surfaces of two sides in mm

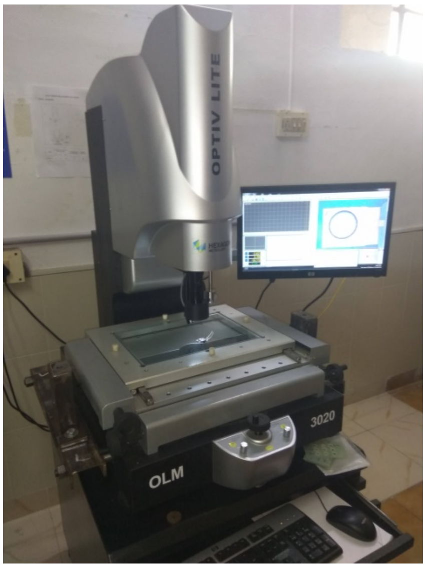


Fig. 4. Measurement of contact dimensions

3. Electrical Contact Resistance Under Static Environment

In a static environment, the ECR is measured for DC and AC circuit conditions. The relay has an electromagnetic coil that operates the electrical contact based on electromagnetic induction. Voltage sources are used to provide the power supply. The resistive lamp load is connected to the circuit. A voltmeter, ammeter, and ohmmeter are used to measure the parameters.

3.1 DC analysis

The relay is connected to the regulated power supply, which provides DC voltage. The DC supply voltage is varied from 5 V to 25 V. The voltage, current, and resistance, which are measured, are shown in Tab. 1. This shows that the resistance values are similar and maintained at almost constant values throughout the analysis.

Table 1. Under Static Conditions for DC Supply

Supply Voltage (V)	Voltage across Relay (mV)	Current Through Relay (mA)	Electrical Contact Resistance (Ohm)
5	1	7	1.428571
10	12	31	0.387097
15	13	36	0.361111
20	14	40	0.35
25	15	42	0.357143

3.2 AC Analysis

The relay is connected to the signal generator, which supplies AC voltage of various amplitude, frequency, and shape. The sinusoidal waveform with a peak voltage of 12 V is applied. The average and rms values of voltage and current are measured using a multimeter. The frequency is varied between 10 Hz to 70 Hz, and the rms voltage, rms current, and resistance are obtained which are given in Tab. 2. This shows that as frequency increases, the resistance also increases because the tendency of alternating frequency causes currents to crowd toward the surface of a conducting material.

Table 2. Under Static Conditions for AC Supply

Supply Frequency (Hz)	Voltage across Relay (mV)	Current Through Relay (mA)	Electrical Contact Resistance (Ohm)
10	48.2	134.96	0.36
20	48.5	138.57	0.35
30	52.1	144.28	0.36
40	52.3	135.11	0.39
50	55.4	40.74	1.36
60	60.2	42.14	1.43
70	77.4	51.6	1.50

4. Experimental Setup for Electrical Contact Resistance at Dynamic Condition

Electrodynamic Shaker provides a testing platform for vibration, mechanical shock, and on-road conditions. Electrodynamic shakers are dynamic and have improved performance in acceleration, displacement, velocity, and force to imitate a variety of circumstances properly. The electrodynamic shaker is equivalent to an electric vehicle, which can provide a wide range of frequencies, and displacement would be provided across the electric contact, and performance would be analyzed. Experiments will be carried out, and contact resistance will be measured for various currents with and without vibration. The vibration in experiments would be more severe than in the real condition. The performance of the electrical contact will be analyzed for more vibration cycles. Temperature rise on contact would be monitored using a thermocouple. The experiment may be carried out to obtain the effect of vibration on electrical contact performance for various amplitude and frequencies. The electrodynamic shaker is used to provide vibration, as shown in Fig. 5, in which the relay is mounted. The periodic sine vibrations are provided. The shaker has an operating frequency range of 1 Hz to 3500 Hz. The vibration table is powered by three power supply and a digital switching power amplifier. Spark dynamic controller is used to provide the vibration signal which is capable of providing sine cosine and triangular signals. The complete experimental setup is shown in Fig. 6. Measuring modules used are the ohm meter, voltmeter, ammeter, fluke, and Digital Signal Oscilloscope (DSO). Regulated Power Supply (RPS) is used to provide DC voltage. The sine wave is provided using a spark controller with software. The experimental setup with lamp load during vibration analysis is shown in Fig. 7. The frequency of 10 Hz and amplitude of 5 mm sinusoidal waveform is provided for 10 seconds. The initial value of ECR is 0.35 ohm. Then vibration started.

After 10 seconds of vibration, the relay started forming an arc and then got damaged. The resistance values measured for each second are provided in Tab. 3. The electrical contact resistance fluctuates between 0.35 ohms and 0.38 ohms.

Fig. 5. Electro dynamic shaker with relay mounted

Fig. 6. Experiment setup for Relay Vibration Analysis

Fig. 7. Experimental Setup with lamp load during vibration analysis

Table 3. Under Vibration Conditions for DC Supply

Time (s)	Voltage across Relay (mV)	Current Through Relay (mA)	Electrical Contact Resistance (ohm)
1	12	31.5	0.38
2	14	40	0.35
3	12	31.5	0.38
4	14	40	0.35
5	12	31.5	0.38
6	14	40	0.35
7	12	31.5	0.38
8	14	40	0.35
9	12	31.5	0.38
10	14	40	0.35

5. Finite Element Analysis at Static Conditions

To understand the mechanical and electrical aspects of electrical contact of relays, FEA software COMSOL Multiphysics. The 3D model geometry of the relay's electrical contact is created, shown in Fig. 8(a) and its zoomed view in 8(b). The dimensions of the terminal, which holds the electrical contact part in terms of width x depth x height, is 1 x 3 x 20 mm, and the electrical contact part in terms of base radius x height x top radius is 1 x 0.5 x 1.5 mm. The material properties of copper define the electrical contact. The electrical conductivity of 59 MS/m, the relative permittivity of 1, the density of 8940 kg/m^3, Young's modulus of 126 GPa, and Poisson's ratio of 0.34 were assigned.

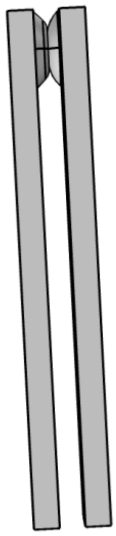


Fig. 8 (a). Electrical contact of relay in COMSOL

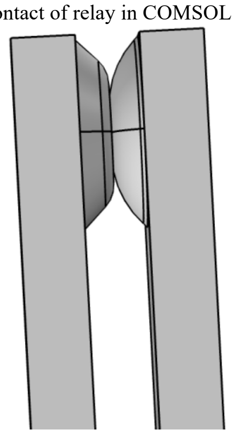


Fig. 8 (b). Zoomed view - Electrical contact of relay in COMSOL

5.1 Current Density

The physics interface and electric current are set up to perform mechanical and electrical analysis. Appropriate boundary conditions have been provided for electrical analysis by specifying the applied current of 1 A and ground terminals. The electrical performance parameters such as current density, electrical contact resistance, and voltage drop have been obtained. The current density is visualized in the surface plot shown in Fig. 9. This indicates that the maximum current density is 3.5E-6 A/m^2, which appears at the edges of the contact surface.

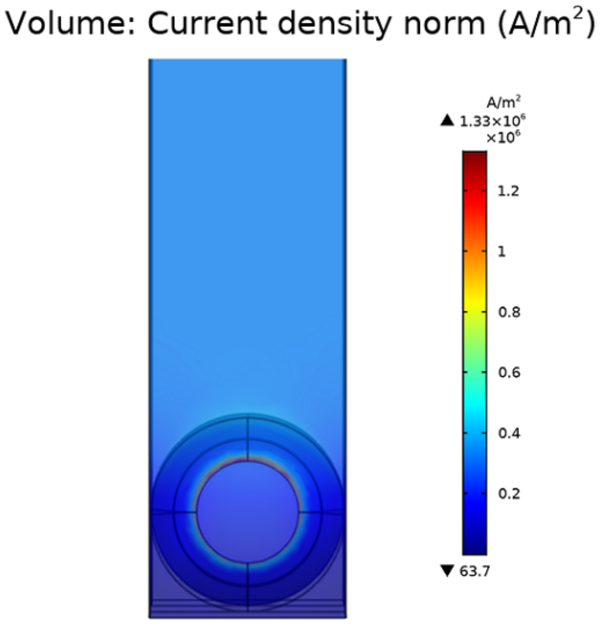


Fig. 9. Current density of contact surface

5.2 Voltage Drop and Resistance

The voltage drop across the relay electrical contact is obtained, which is 1.16E-4 V, shown in Fig. 10. Hence, the Electrical contact Resistance (ECR) is calculated as 0.116 milliohms.

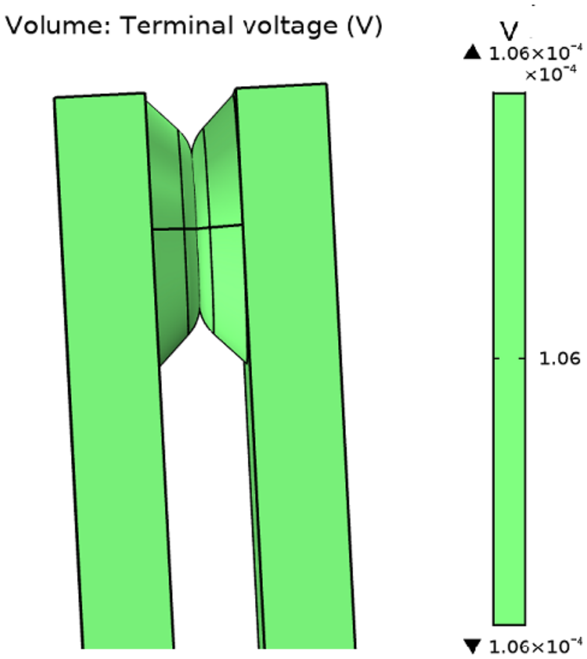


Fig. 10. Voltage drop

6 Finite Element analysis at Dynamic Conditions

Vibration analysis is a technique used to study the dynamic behavior of electrical contact of a relay. The important aspects of vibration analysis are prescribed displacement, von mises stress, and total displacement. Prescribed displacement is a boundary condition, which is the specific displacement or movement that is imposed at surfaces of the electrical contact. Prescribed displacement of the sinusoidal signal is used to simulate how a structure or component responds to external forces and excitations. For vibration analysis, a mechanical parameter, the prescribed displacement [0.00001*sin (wo*2*pi*t)] with wo is 66 Hz, and fixed constraints have been provided. Von mises stress is a stress measure used to represent the combined effect of multiple stress components in an electrical contact to assess the failure.

6.1 Von Mises Stress

Von mises stress helps determine whether electrical contact will fail due to a combination of stresses. The von mises stress appearing on the electrical contact is shown in Fig. 11. Time domain simulation is carried out for the time period of 0s to 0.015s. The von mises stress also appears as a sinusoidal structure with a maximum stress of 2800 MN/m^2.

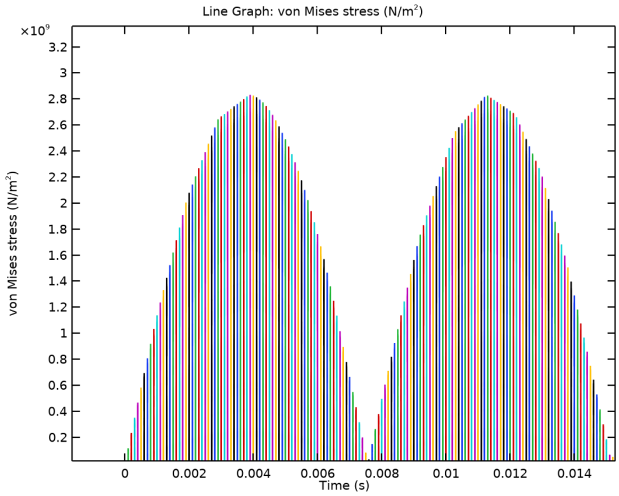


Fig. 11. Von Mises Stress Vs Time

6.2 Total displacement

Total displacement is the overall movement and deformation experienced by an electrical contact. In vibration analysis, understanding total displacement is essential to assess how a structure deforms over time due to external excitations. The total displacement of the electrical contact is shown in Fig. 12. Time domain simulation is carried out for the time period of 0s to 0.015s. The total displacement also appears as a sinusoidal structure with the maximum displacement of 11 μm.

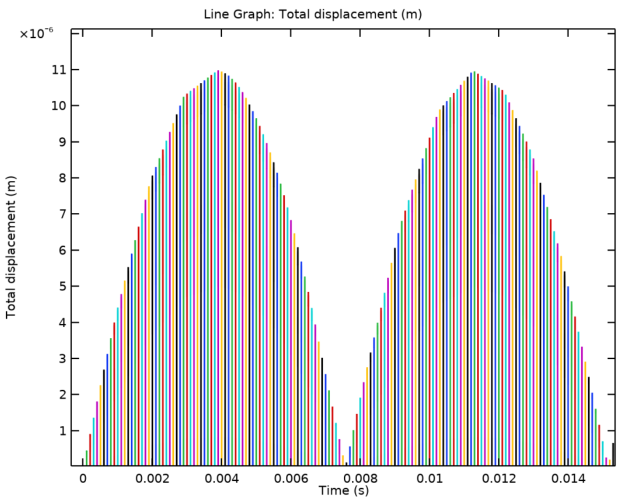


Fig. 12. Total displacement Vs time

7 Discussion

The device needs to undergo random vibration testing to analyze the failure of the real world applications. Vibrations in roadways are not repetitive and not predictable. Integrating the actual on-road data, practically like the non-uniform distribution of vibrations produced on the relays. The integration of these vibrations in terms of sudden rise and fall with respect to frequency requires utmost precise equipments for measurement of the resistance. In future, actual on road data will be integrated and experimental results will be measured and carried out as a future work.

In real time scenarios, the vibration frequeny generally ranges from 1 Hz to 2000 Hz. The frequency and amplitude range within which a relay can be used for vibration analysis can vary based on factors such as the particular application, industry requirements, and the relay's capabilities. The frequency range of interest in vibration analysis is contingent upon the specific machinery or system under observation. In vibration analysis, the amplitude range pertains to the spectrum of vibration intensities or magnitudes that the relay is capable of detecting or reacting to. The range is commonly quantified using units of acceleration, velocity, or displacement. Also vibrations with amplititude and frequency of realistic road profile conditions like smooth roads, potholes and rough surfaces also needs to be extensively analyzed. The precise extent is contingent upon the sensitivity and dynamic range of the relay, in addition to the demands of the application. It is crucial to acknowledge that various relays or vibration analysis systems may possess distinct frequency and amplitude ranges. Hence, it is important to refer to the specifications or technical documents provided by the manufacturer of the relay or vibration analysis equipment in order to ascertain the precise range for a certain item. In many conditions, shakers vibrate with vertical and horizontal orientations, but in practical conditions the shock pulse amplititude and vibrations are multidirectional.

The long-term performance of automotive relays under continual vibration is contingent upon various elements. Although engineered to endure such pressures, it is crucial to take into account the longevity and dependability. Durability refers to the ability to endure sustained vibration without sustaining harm. Relays that possess robust enclosures, secure installations, and terminals resistant to vibrations are likely to exhibit superior durability. However, it is important to realise that excessive vibration has the potential to gradually impact the performance of even very resilient relays. The reliability of automotive relays is determined by their ability to constantly perform their function without any failures caused by vibration. High-quality components, well-designed contacts, and effective dampening enhance reliability. Relays that have been tested for vibration and fulfil the required standards exhibit greater reliability. It is important to mention that the extended durability of automobile relays when subjected to constant vibratory stress can also be affected by additional elements, including temperature fluctuations, humidity, and electrical loads. Choose relays from reputed manufacturers known for their quality and reliability. To maximise durability under vibration stress, it is essential to adhere to the rules provided for installation, operating circumstances, and maintenance.

In Future, to further improve the relay's performance, it is advisable to use Nano-materials with increased surface resistance, enhanced conductivity, and greater hardness to serve as a protective layer over the relay contacts. This will enable the relay to endure higher levels of vibration. Vibration and impact tests will be conducted to assess the feasibility of implementing the technology in cars that are designed to operate under more intense vibrations.

8 Conclusion

The study presented in this work emphasizes the critical importance of conducting vibration analysis and assessing ECR for automotive relays. The automotive environment, characterized by diverse mechanical vibrations resulting from environmental conditions and on-road operations, stresses these essential components significantly. Through the use of an electrodynamic shaker, conducted rigorous vibration analysis to simulate real-world conditions. Our study revealed that the relay's ability to withstand mechanical vibrations is pivotal in ensuring its long-term reliability and durability in vehicle applications. The analysis conducted at a 5mm amplitude with a 10 Hz sine waveform demonstrated the importance of testing relays at varying frequencies, ranging from 10 Hz to 70 Hz, mirroring the dynamic nature of automotive operation. The assessment of ECR under both DC and AC static environments provided valuable insights into the relay's performance under different electrical conditions. This comprehensive evaluation approach aids in understanding the relay's behavior across a range of scenarios, leading to the development of more robust and reliable relay designs for automotive applications. In addition to this study, solid mechanics and electric current analyses using COMSOL Multiphysics FEA were established for examining mechanical and electrical aspects. The electrical performance parameters are evaluated, such as current density, voltage drop, and electrical contact resistance. Total displacement is explored to understand the relay electrical contact response to external excitations. Time domain simulations revealed a sinusoidal pattern, with sinusoidal stress and displacement demonstrating dynamic vibration behavior.

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