Experimental Study of the Vibration-induced Fretting of Silver-plated High Power Automotive Connectors

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Abstract—Relatively little is known about the fretting mechanism of high power connectors used in hybrid vehicles, even though the vehicles are widely being introduced to the market. This work experimentally investigates the fretting mechanisms of silver-plated high power connectors caused by vibrations. In order to emulate operational and environmental effects, a test stand was designed that is capable of measuring ECR, relative displacement and connector temperature. The experimental results show that the variation of electrical contact resistance (ECR) of connectors subject to vibration is primarily due to the effect of periodic changes of contact area caused by relative motion between the contact interfaces, rather than other fretting mechanisms. This finding is reinforced by observing a good correlation between relative motion and the increase of ECR under vibration. When a vibration stopped, the ECR decreased to a value that is slightly larger than the original value. A surface analysis showed no obvious corrosion until the coating was worn away.

Keywords —high power automotive connectors, fretting, silver coating, vibrations, dynamic response.

I. INTRODUCTION

Hybrid and electrical vehicles (HEV) are the next evolutionary step of the automobile, but there are a few limiting technologies that delay widespread HEV success, which includes the battery, power electronics and connectors. Automotive connectors are very important and critical to any vehicle containing electrical components. A well designed and fabricated connector will be durable and easily disconnected so that electrical components can be easily replaced or repaired.

Automotive connectors experience a harsh environment comprised of vibrations induced by the engine, thermal cycling as the vehicle starts up and shuts down, and a corrosive environment which can cause the formation of undesired oxides [1]-[2]. These conditions are very demanding on the reliability of connectors and often lead to their degradation and failure. A vehicle may have more than 400 connectors with 3000 individual terminals but field data has shown that connector degradations and failures contribute to 30–60% of the electrical problems [3]-[4]. This requires investigations on connector behavior under vehicle conditions and studies on its degradation mechanisms so that connectors perform on an acceptable level.

For connectors subject to vibration, a main degradation mechanism is considered to be fretting, which is a relative cyclic motion with small amplitude that occurs between two oscillating surfaces, defined by Waterhouse [5]. Varenberg et al. provide a method for characterizing fretting in terms of the local relative motion [6]. In another paper, fretting is shown to cause intermittent electrical contact, wear and corrosion on contact materials and in turn results in variations of electrical contact resistance (ECR) such as an increase, fluctuation or intermittence [7]. Therefore, connector temperature will increase due to the increase in ECR based on the process of Joule heating. These mechanisms could accelerate connector degradation.

Tin-plated connectors have been widely used in motor vehicles for their low cost and the relative low ECR due to its softness. However, tin plating is often criticized for its high failure rate [8]. Its degradation mechanism, generally considered to be fretting corrosion, has been extensively investigated by many researchers. During fretting corrosion, fretting wear repeatedly exposes fresh metal to the atmosphere which causes oxidation and the accumulation of debris on the contact interface. This continuously reduces the electrical conducting area and conductivity [9]-[11]. Consequently, when vibration is applied to tin-plated connectors the ECR will continue to increase nominally and gradually with time [8]-[9], [11]-[16]. This gradual increase of ECR under fretting has been found for other contact materials, such as copper-tin alloys [13] and gold [15]. Many works report that the degradation of the contact interface will cause the ECR to increase greatly with sudden failure after a certain number of vibration cycles [9], [13]-[15].

In the current work, the results do not agree with the results of connectors with tin and other conventional coatings, whose ECRs gradually and significantly increase along with vibration [8]-[9], [11]-[16]. Examination of worn surfaces demonstrates that wear exists on silver-plated connectors, but no obvious fretting corrosion and oxidation build-up is found. It is the relatively stable property of silver that makes the test results so different compared with other coating materials. The test results from Hubner-Obenland and J. Minuth also supported the benefits of silver contacts [15]. Their work showed that the silver-to-silver contact has the lowest ECR increase after 31 hours of vibration, compared to other combinations of male and female contact materials, including tin, silver, and gold.
In recent years, the demands on high power automotive connectors have increased because of a need to conduct much more current for electrical propulsion in HEVs. Fretting can also occur in high power connectors and their reliability problems are more susceptible to severe conditions. The temporary fluctuation of ECR is another major problem for power connectors subject to vibration, where observations show that the contact voltage fluctuates periodically around a mean value higher than the constriction voltage [17]-[18]. Carvou and Jemaa explained that the contact surface moves along the track formed by oxide particles and consequently ECR varies periodically under vibration [17]. The reliability of high power connectors under vibration are also threatened by the electrical arc which leads to great increases of contact voltage and surface damage [18]. The fluctuation of ECR may also be caused by the previously described intermittence of contact due to connector motion [7].

In summary the increased demands for connectors to handle higher powers, the main motivation of the current study is to investigate the performance of high power connectors. As described above, tin coatings are often not adequate for high power connectors and so a noble metal such as silver is used. Relatively few papers have studied the performance of silver plated power connectors under vibration.

Since the investigations of the connector performance are mostly realized by accelerated simulated tests, a precise measurement can help to better characterize connector fretting and degradation mechanisms. It is recommended to use high sampling rate of measuring ECR under vibration to characterize a complete waveform of the ECR [18]-[19]. Proper instruments are also inevitable for obtaining fretting mechanisms in experimental tests. In 2003, Flowers et al. used non-contacting laser vibrometer to measure relative displacement of contact interface to predict the fretting corrosion of tin-plated connectors [20]. They found that the relative motion of contact interface is proportional to the increase rate of ECR. The current work also measures relative displacement of silver-plated high power connectors, and the results reveal that the relative motion is a good predictor of the temporary increases of ECR under vibration, which will be discussed in the following section.

II. CONNECTORS AND EXPERIMENTAL SETUP

A. Test Object

The connectors to be tested are high power automotive connectors manufactured by LS Cable™. The connector system is designed to work under current as high as 220A. The connector surface is plated with silver and the bulk connector material is copper. The geometrical structure is cylindrical, as shown in Fig. 1. A ring-shape spring punched from sheet metal is mounted inside the female connector. The spring has 22 pieces of tabs which contacts with the male connectors and each of them compresses radially.

![Diagram](a) (b) (c) (d)

Figure 1. Geometrical structures of (a) connector mate, (b) female part with contact spring inside, (c) contact spring and (d) male part.

B. Test Stand Design

In order to study the effects of vibration and temperature on the connectors, we used a custom designed test stand, an electrodynamic shaker and an environmental chamber. The designed test stand facilitates the supply of a high current; the measurement of ECR, relative displacement, temperature; and the associated data processing and display. A schematic diagram of the test stand is depicted in Fig. 2.

Multiple power supplies were wired in parallel which were able to provide DC current as high as 375A. The power supplies were able to be remotely controlled by PC to output the desired current. The accelerated tests were performed using an electrodynamic shaker and environmental chamber, which enclosed the connector to be tested. The LDS™ V850 electrodynamic shaker is able to output a vibration with a certain amplitude and frequency. The CSZ™ environmental chamber was used to control the ambient temperature and was
placed above the shaker so that the connector can be enclosed. A fixture was specially designed to secure the connector on the shaker, as shown in Fig. 3 (a). Compared to Fig. 1, a connector in testing was equipped with a housing and supplied cable. The jig secured the connector housing and the clamp fixed the supplied cable to the shaker. The direction of vibration was Y, as shown in Fig. 3 (a), which is perpendicular to the plate. This configuration ensured that the two changed locations of the connector system follow the motion of the shaker: One is the terminal of the female connector and the other one is the end of supplied cable, as shown in Fig. 3 (b).

C. Measurement of ECR and Temperature

The principle of measuring the ECR is based on Ohm’s law. The voltage drop across the connector could be directly measured and the current flow was measured by a current transmitter. The minimum resolution of the ECR was 0.3µΩ. The temperature of a connector was measured by a K-type thermocouple that was calibrated on ice point reference. The accuracy is ±0.1°C. All of the signals are collected by analog signal conditioning modules conducted to a PC data acquisition aboard. In order to acquire the complete waveforms of the ECR variation under vibration, the sampling rate was set as high as 3000Hz, which was much larger than the excitation frequencies to avoid the aliasing effect.

D. Measurement of Relative Displacement

The measurement of the relative displacement of the connector was carried out using two non-contacting laser vibrometers, whose setup is depicted in Fig. 4. Fig 5 illustrates the two measuring locations of the male and female connector near the contact interface. The functions of the motions of the two spots are defined as $U_1$ and $U_2$. We assume that the directions of $U_1$ and $U_2$ are vertical to the connector.

When a connector was subject to vibrations, the relative motion represented a rocking mode, as depicted in Fig. 6. Flowers et al. mathematically described the relative motion to quantify relative displacement and the associated effects on the fretting and ECR [20]. When a connector was excited by a sinusoidal vibration, the female and male parts of the connector tended to follow the vibration. The motions of the two parts can be approximated as sinusoidal functions and expressed as two complex numbers in polar forms

$$U_1 = M_1 \sin(\omega t + \varphi) = M_1 \angle \varphi_1$$

and
where \( M_1 \) and \( M_2 \) are the magnitudes and \( \phi_1 \) and \( \phi_2 \) are the phase shifts. The maximum relative displacement \( |U| \) is defined as the modulus of the difference of \( U_1 \) and \( U_2 \), which can be expressed as follows:

\[
|U| = |U_2 - U_1| = M_1 \sqrt{(1 - M \cos(\phi))^2 + (M \sin(\phi))^2}
\]

where \( M \) is the magnitude ratio, \( M_2/M_1 \), and \( \phi \) is the phase difference \( \phi_2 - \phi_1 \). Please note that \( |U| \) is a scalar that represents the magnitude of relative displacement. The magnitude ratio \( M \) and phase difference of displacements \( \phi \) can be directly measured by laser vibrometers, and then the relative displacement \( |U| \) can be calculated using equation (3). Since the female part was directly fixed on the shaker, the amplitude of its motion, \( M_1 \), approximately equals the excitation amplitude.

III. RESULTS AND ANALYSIS

Since the fretting mechanism by vibration is difficult to predict and characterize, we then mainly focused on the effects of vibration on connectors by analyzing ECR and relative displacement. In addition, surface analysis of the material was conducted to confirm the level of corrosion.

A. Effects of Vibration with Fixed Amplitude and Frequency

The vibration in this test had constant amplitude of 0.64mm (peak-to-peak) and constant frequency of 100Hz. The duration was approximately 37s with 3700 vibration cycles. The ambient temperature was controlled at 25°C and the connector temperature before vibration started was around 40°C since the connector is heated by 220A current. The supplied current was controlled as constant and was never affected by vibrations in all of our tests.

The result of ECR in Fig. 7 shows that as vibration started, the ECR increased suddenly, oscillating with a maximum and a minimum amplitude during the vibration. When the vibration stopped, the ECR decreased to a value that is slightly larger than the original value and remained. The ECR for a duration of 50ms starting at 15s is plotted in Fig. 8(a) and the spectrum of ECR was analyzed using discrete Fourier transform in Fig. 8(b). It is important to recognize that ECR varied periodically, but was distorted from a harmonic signal. The period of the variation had a component of 10ms which is the same as that of the excitation. In addition, the waveform has two peaks in every vibration cycle and the spectrum shown in Fig. 8(b) reveals that the ECR has the highest magnitude at 200Hz, which is twice as the excitation frequency.

The measurement of relative displacement was then applied
to this vibration test. Two representing characteristics of relative displacement are magnitude ratio \(M\) and phase difference \(\phi\) of the motions of male and female part, which were measured by the laser vibrometer. Their values were measured as 1.17 and -30.8° respectively, and were used to calculate the waveforms of the two motions for the female and male parts. The absolute value of their difference is regard as the waveform of relative displacement. The waveform of relative displacement and the ECR are shown in Fig. 9. When the waveform of relative displacement is compared with the variation of ECR, it shows that the frequency of the relative displacement is the same as that of the ECR. Therefore they are twice as high as the excitation frequency. In addition, ECR tended to follow the magnitude of the relative displacement. When the instantaneous magnitude of the relative displacement gets high, it is suggested that the contact area becomes lower so the value of ECR increases rapidly.

B. Effects of Vibration with Varying Amplitudes and Fixed Frequency

In this test, the vibration frequency was fixed at 100Hz and the ambient temperature was controlled at 25°C. The vibration amplitude was increased from 0.04mm to 0.64mm (peak-to-peak) with an incremental step of 0.04mm at every 30s and then held for 30s without vibration. The measured ECR is shown in Fig. 10. It is observed that the ECR tends to follow the increase of the vibration amplitude.

In order to investigate the effect of the relative displacement on the increase of ECR, the magnitude of relative displacement, \(|U|\), is calculated by equation (3) based on the measured magnitude ratio \(M\) and phase difference \(\phi\). Because of the oscillating ECR under vibrations, \(\Delta R\) is introduced as its mean value under vibration subtracted by the baseline of ECR (the value before vibration starts). Both \(|U|\) and \(\Delta R\) are plotted as a function of the vibration amplitudes, shown in Fig. 11. When the vibration amplitude increased, the relative displacement increases. Accordingly, the ECR tended to follow it. This relationship can be approximated by

\[
\Delta R = k_1 |U|
\]

where \(k_1\) is a constant that can be determined based on the experimental data.

C. Effects of Vibration with Fixed Amplitudes and Varying Frequencies

In this experiment, the vibration amplitude was constant at 0.15 mm (peak-to-peak) and the ambient temperature was set at 25°C. The vibration frequency was varied from 40Hz to 260Hz with an incremental step of 20Hz every 30s. The relative displacement, \(|U|\), is obtained in the same manner as the previous sections. \(\Delta R\) and \(|U|\) are also plotted as a function of vibration frequency in Fig. 12. For the frequency range that is less than 180Hz, the ECR followed the amplitude of the relative displacement \(|U|\), but it started to deviate significantly when the frequency is larger than 180Hz. As a result, equation (4) does not represent the ECR over all ranges of the frequency. The ECR should be dependent upon not only the relative displacement \(|U|\), but also the vibration frequency.
This relationship can be approximated by

$$\Delta R = k_2 |U|^2 f^2$$  \hspace{1cm} (5)$$

as depicted in Fig. 12, where $k_2$ is a constant obtained from experiment data. It shows that the variation of ECR tended to follow the product of relative displacement and the square of frequency, $|U|^2 f^2$. In the previous section, since the vibration frequency was a constant, equation (5) is also valid and the trend of $|U|$ and $|U|^2 f^2$ overlap to each other, shown in Fig. 11.

D. Effects of Vibration with Varying Amplitudes and Frequencies

Like the previous experiments, the ambient temperature was set at 25°C. The vibration frequency was varied from 30Hz to 600Hz with an incremental step of 30Hz, and the corresponding vibration amplitude decreased accordingly under the fixed g-value of 10. Based on equation (5), $\Delta R$ and $|U|^2 f^2$ are plotted in Fig. 13, where $k_2$ is an experimentally obtained constant. It should be noted that the overall trends of $\Delta R$ and $|U|^2 f^2$ are identical. Their peak values are located around the frequency of 150Hz and 450Hz. In addition, $k_1 |U|$ is also plotted in Fig. 13 for comparison. However, the prediction of equation (4) deviates from the variation of ECR.

The results obtained from three experimental cases have shown that the variation of ECR of the connectors subject to vibration was affected by both relative displacement and vibration frequency. Equation (5) is derived to describe this relationship, where the variation of ECR was based on a product of the relative displacement and the square of frequency, $|U|^2 f^2$, which can be regarded as the maximum value of relative acceleration of contact interfaces under vibration.

E. Effects of Vibrations on Wear and Corrosion

Other than relative motions, the wear and fretting corrosion at the contact interface may also have effects on ECR when vibrations are applied to the connectors. In order to study the existence of wear and fretting corrosion, a vibration with more severe conditions was applied to a connector with 1mm vibration amplitude and 100Hz frequency for half an hour, where the ambient temperature during the vibration was set at 80°C. After vibration, a snapshot of a worn surface on the male part of a connector taken from a scanning electron microscopy (SEM) is shown in Fig. 14. The SEM was operated in backscattered electron mode in order to highlight the different surface morphologies observed on the connectors. Position 1 is the wear pit caused by friction during vibrations. Position 2 refers to non-contact area. By observation, the pit in position 1 was just a hole or valley with a lower altitude compared to position 2. Very little material build-up was found.

The results of electron spectroscopy (AES) for position 2 and position 1 are shown in Fig. 15. AES is a true surface technique, allowing for the detection of all elements of the periodic table (except H) located within the first 50Å of the surface to a sensitivity of ~ 0.01 atom %. In Fig. 15(a), silver is the only element detected in non-worn position. As for Fig.
15(b), the bulk material (copper) and its impurity (nickel) were mainly detected in the worn position where the silver coating appeared to be almost worn out. In addition, a little oxygen element was detected which suggested the existence of a small quantity of copper oxide.

The results show that the defect area on the surface is best referred as a worn pit rather than corrosion because the main finding is indentation and removal of coating material. If fretting corrosion occurred, there would be material accumulation and a more random appearance in the SEM image. For example, metallic fretting debris [21] and thick oxide films [15] can be found after tin-plated fretting corrosion.

The results in Fig. 14 and Fig. 15 show that vibrations have caused some wear and little fretting corrosion. However, vibration induced wear still changed the surface roughness and formed indentation so there were some permanent changes of the ECR after vibration, as shown in section III-B. Since silver is resistant to oxidation in the air, the wear particles could not increase the contact resistivity and then ECR will not gradually increase under vibration.

IV. CONCLUSION AND FUTURE WORK

This work studied the performance and fretting mechanism of silver-plated high power connectors for hybrid vehicles subject to different vibrations. The ECR of the connectors was measured to assess the effects of the conditions on performance. The connectors were tested under different operational conditions and analyzed using the ECR. The main findings are as follows:

1) As vibration started, ECR suddenly increased and then oscillated with the vibration. When the vibration stopped, the ECR decreased to a value that is slightly higher than that before the vibration. The variation of ECR during vibration was periodic, whose frequency was the same as that of the relative displacement and twice as high as the excitation frequency.

2) The variation of ECR under vibration, $\Delta R$, is approximated with an equation that is proportional to the product of relative displacement and frequency squared, $|U|^2$. It can be regarded as relative acceleration of the contact interfaces and is likely to cause periodic changes of contact area and then resulted in ECR variation and increase under vibration.

3) According to analysis by SEM and AES, fretting corrosion of the high power connector is negligible until the silver coating was worn out. The results show indentation and removal of the coating material on the worn connector, and no accumulation of debris and few oxides were found. Therefore, wear and fretting corrosion have less effect on the variation of ECR under vibrations compared to the relative motion.

Future work will include theoretical analysis of the obtained experimental data using a multi-physics model and a vibration model, which are being developed in our research laboratory. In addition, the experiments of degradation and failure mechanism of the connectors over long operating time are planned.

REFERENCES


