IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 19, 2019, accepted August 27, 2019, date of publication September 4, 2019, date of current version September 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2939377

Numerical and Experimental Analysis of Potential Causes Degrading Contact Resistances and Forces of Sensor Connectors for Vehicles

JANGMUK LIM[1], HANSU KIM[1], JAE KYUN KIM[2], SUNG JOON PARK[2], TAE HEE LEE[1], (Member, IEEE), AND SANG WON YOON[1], (Senior Member, IEEE)
[1]Automotive Engineering Department, Hanyang University, Seoul 04763, South Korea
[2]Electronics Convenience Control Test Team, Hyundai-Kia Global Research and Development Center, Seoul 445-706, South Korea

Corresponding author: Sang Won Yoon (swyoon@hanyang.ac.kr)

This work was supported in part by the Electronics Convenience Control Test Team, Hyundai-Kia Research and Development Center, South Korea.

ABSTRACT Faults in vehicle sensor connectors are crucial to the safety of a vehicle. Once the connector is loosened according to the reduction of its contact forces, its electrical contact resistance may be increased, causing unexpected errors in sensor systems. However, such error mechanisms have enormously diverse causes that have not yet been identified. This study proposes a process to analyze the causes influencing the connector contact force and resistance by employing a combination of numerical and experimental methods. Specifically, the causes of variation of contact force are numerically analyzed and their influence on the electrical contact resistance is experimentally studied. Precise 3D models of a commercial vehicle sensor connector are developed based on a 3D tomography, and a 3D finite element (FE) simulation is employed to estimate the connector contact force, considering plastic deformation. After classifying potential causes into three categories, two major factors are selected: manufacturing tolerance occurring during the connector manufacturing process and plastic deformation occurring during the vehicle maintenance process. The factors are observed to substantially reduce the contact force (by $\sim$14.6 or 19%). The impact of the reduced contact force is validated in sequential experiments, and exhibits a nonlinear relationship between the contact force and corresponding contact resistance. In addition, the experiments also consider simulated manufacturing and maintenance factors, and demonstrate an increased contact resistance by the functions of the decreased contact force with minor measurement errors ($<$7.5%).

INDEX TERMS Electrical contact resistance, contact force, vehicle sensor connector, electrical signal, signal fault.

I. INTRODUCTION

Vehicle sensors are becoming increasingly important in the performance and reliability of automobiles. Vehicle sensors measure, calibrate, monitor, and transmit feedback information needed in vehicle systems. Diverse sensors have been already installed in vehicles and applications demanding new sensors continue to develop. As the number and diversity of vehicle sensors increase, their reliability has been thoroughly reviewed and methodologies to prevent possible faults or failures have been studied [1]. As a result, fault tolerant control and diagnosis are drawing attention [2].

The reliability of sensor signal is determined not only by the sensors themselves but also by the components comprising the sensor system. Figure 1 depicts an example of a vehicle sensor systems including measurement and signal processing sections. This sensor system configuration is typical in many automotive systems, especially engine management systems [3], [4]. In addition, this configuration is common in on-board diagnostics (OBD), exhaust gas control, HVAC (heating, ventilation, & air conditioning) system, etc. [5]–[9]. The sensor connector links the measurement and signal processing sections, and delivers the sensor output signals that are either raw or processed data. Obviously, if any interferences occur at the sensor connector, sensor signals are distorted, leading to fatal problems in the control system.

The associate editor coordinating the review of this article and approving it for publication was Xiaosong Hu.

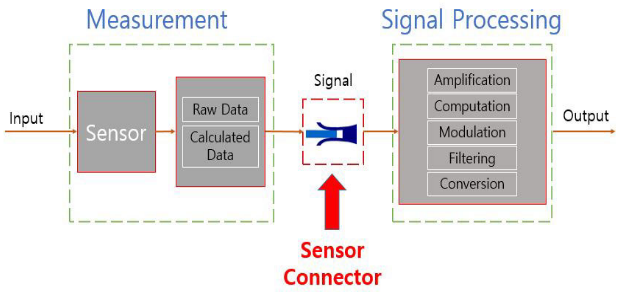


FIGURE 1. An example configuration of vehicle sensing systems.

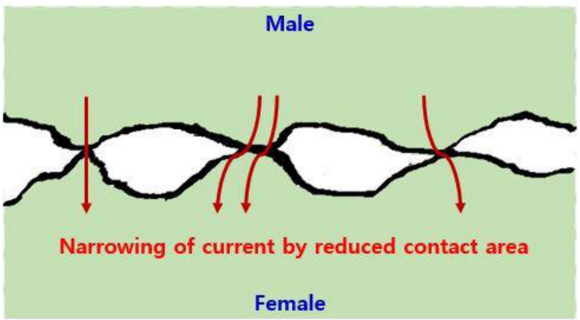
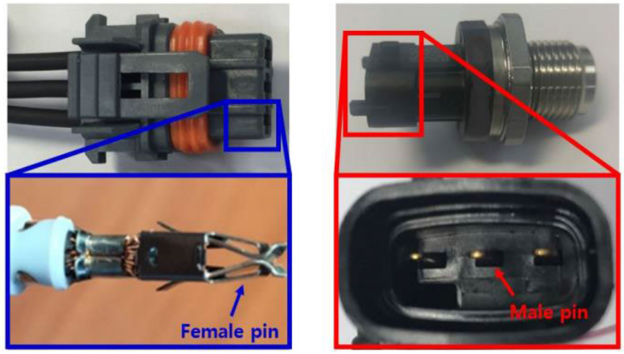


FIGURE 2. Narrowed current path by the reduced contact area.

In that respect, the reliability of sensor connectors must be carefully examined. Thus, mechanisms inducing failures or faults in vehicle-sensor connectors must be specifically identified.

Many studies were conducted to identify the causes of failure/fault in connectors or to examine the influence of the causes, but most of them handled general electrical connectors and did not specify their applications. Popularly reported causes are physical failures represented by corrosion and wear, because most connector contacts are made of metals. Corrosion is accelerated in environments exhibiting high temperature or severe vibration [10]–[12]. Wear appears at the metal of the contact part when the connectors are repeatedly disconnected and reconnected during usage [13]–[15]. Such repeated processes may also flatten or roughen the contact surface. These physical failures are hardly predictable damages.

Electrical performances are decisive characteristics of vehicle sensor connectors that provide electrical connection and disconnection, basically, by assembly and disassembly. One common measure of the electrical performances is the electrical contact resistance of the connector. The electrical contact resistance largely depends on the contact area. As shown in Fig. 2, the reduced contact area at the contact interface results in a narrowed current path passing through the connector and increases the electrical contact resistance. The amount of the resistance increment is influenced by various factors and difficult to validate. Among the factors influencing the electrical contact resistance for structural reasons, the reduced contact force, which sometimes referred as contact pressure, is the most popularly observed cause once physical failures like corrosion or wear are excluded. The relationship of the contact force and electrical contact resistance is mainly investigated in semiconductor fabrication foundries (e.g., pressed probe tips in mechanical probe station, cantilever tips of contact-type atomic force microscopes) [16], [17].



(a) (b)

FIGURE 3. (a) Female part of the connector and its female pin after decapsulation of the housing plastic mold, (b) male part of the connector and its front view showing four male pins.

However, there are few reports focusing on the possible fault mechanisms in vehicle sensor connectors, and no serious attempts to define their contact force-electrical contact resistance relationship, even though vehicle connectors have shapes/performances different from general electrical connectors and require extremely high reliability. Therefore, this study numerically analyzes a target vehicle-sensor connector by focusing on a change in the contact force, and, to determine their relationship, characterizes the electrical contact resistance. In addition, the causes of possible faults in vehicle operation are categorized and tested in our simulations and experiments.

II. SENSOR CONNECTOR

A. TYPICAL STRUCTURE OF VEHICLE SENSOR CONNECTORS

A typical vehicle sensor connector consists of male and female parts. One example connector is shown in Fig. 3. The female part contains multiple female pins while the male part includes corresponding male pins. Some pins are used to provide power to the vehicle sensor while another pins deliver sensor signals to the signal processing section.

Electrical connection is established by inserting the male pins into the female pins. This insertion deforms the female pin by widening the gap between the two facing areas and generates a reaction force maintaining the contact. The reaction force contributes to the contact force of the connector that decides its electrical contact resistance. Generally, a larger contact force decreases the contact resistance. For the purpose, the male pin is designed to be thicker than the facing gap of the female pin.

The increased contact force may induce an elastic-plastic deformation at the contact area combining male and female pins, which modifies the asperity of the surface like roughness and ruggedness. Diverse studies have presented elastic-plastic contact models through the asperity geometry of contact surfaces [18]–[20]. In addition, other factors such as dynamic conditions are under consideration [21], [22]. This elastic-plastic deformation of the contact will influence its electrical characteristics. However, this study focuses on potential causes reducing the contact force by analyzing connector structures. Thus, the contact surface is assumed to be elastic because we consider the changes on the contact surface asperity are physical contact failures.

B. THEORETICAL BACKGROUND OF RELATIONSHIP BETWEEN CONTACT FORCE AND ELECTRICAL CONTACT RESISTANCE

Many previous studies calculated the electrical contact resistance using the resistivity and the contact area, assuming that the contact surface does not change. The contact area and resistance of a single-spot contact is popularly modeled either by Sharvin or diffuse scattering mechanism, depending on the radius of the contact spot and the length of an electron mean-free-path [23], [24]. Equation (1) is an interpolation equation considering both of the two mechanism [25].

$$R_c = \frac{4\rho l_e}{3\pi r^2} + \upsilon(l_e/r)\frac{\rho}{2r} \tag{1}$$

where R_c is the electrical contact resistance, and ρ is the resistivity, and l_e is the length of electron mean-free-path. r is the radius of the contact spot and υ refers to Poisson's ratio. The first term on the right hand side represents Sharvin mechanism, while the second term represents the diffuse scattering mechanism.

For multiple contact spots, Greenwood's formula in equation (2) may be one of the most recognized statistical model [26], [27].

$$R_G = \frac{\rho}{2\sum a_i} + \frac{\rho}{\pi}\left(\sum_{i\neq j}\sum \frac{a_i a_j}{d_{ij}}\right) / \left(\sum a_i\right)^2 \tag{2}$$

where a_i is the radius of the spot i and d_{ij} is the distance between the centers of the spots i and j. The first term on the right hand side is the resistance of all spots in parallel, while the second term represents the resistance from the interaction between all spots. Of course, there are substantial efforts to incorporate various shapes of the contact spots [28], [29].

However, recent studies have begun to consider the influence of contact structures in calculating electrical contact resistance, recognizing that the contact structure may deform and that the amount of the deformation may largely vary by contact situations and materials.

Representative results are provided in equation (3), where the contact structure is expressed by the contact force and its influence on the contact resistance is described [30].

$$R_c = \left(\frac{\rho^2 \pi H}{4F}\right)^{\frac{1}{2}} \tag{3}$$

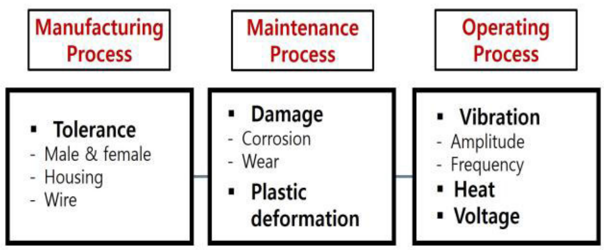


FIGURE 4. Main factors reducing the contact force, classified into three process steps.

Here, the contact force and material hardness are symbolized by F and H. If the applied force is reduced, the contact area is also reduced and the current passing through the contact is disturbed, increasing the electrical contact resistance. This relationship demonstrates that the relationship between the contact force and electrical contact resistance is nonlinear, and, that there is a sharp increment of the electrical contact resistance at a contact force lower than a certain threshold.

Owing to the structural reasons described above, vehicle sensor connectors may suffer abrupt changes in the electrical contact resistance. The abruptly increased resistance drifts vehicle-sensor signals, and imposes intermittent faults in vehicle sensor systems. These sensor-fault scenarios endanger vehicle safety, considering the high level of reliability required in vehicle electronics, and even worse, they may happen even if the sensor connector is not defective. Therefore, it is necessary to investigate possible factors influencing the contact force of vehicle sensor connectors, and to clarify their riskiness as described by the amount of variation of the electrical contact resistance.

III. FACTORS AFFECTING THE CONTACT FORCE

The contact force of a sensor connector can be decreased by various factors. The major factors are classified into three categories, as depicted in Fig. 4, based on the usage process of vehicle connectors. The categories are manufacturing, maintenance, and operating processes. This study does not include factors raised by the operating process, to exclude the excessive diversity of vehicle operating environments.

A. MANUFACTURING PROCESS

In engineering, tolerance generally refers to a permissible limit of variations in an object, and mainly occurs when manufacturing a sensor connector. The manufacturing tolerances can appear at both the male and female pins. As an example, a male pin happens to be made to be thinner than its nominal thickness (~0.8mm in the used connector). Note that typical male pin is designed to be thicker than the facing gap of the female pin, to secure a sufficient contact force. The thin male pin is inserted into the female pin, resulting in smaller contact force than a standard product. A similar phenomenon may occur when the facing gap of the female pin is accidently manufactured to be larger than a standard female gap. These manufacturing tolerances also exist in the housing or wire

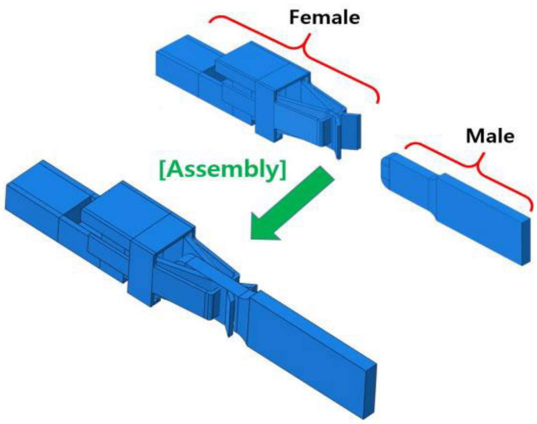


FIGURE 5. Modeled vehicle sensor connector before and after assembly.

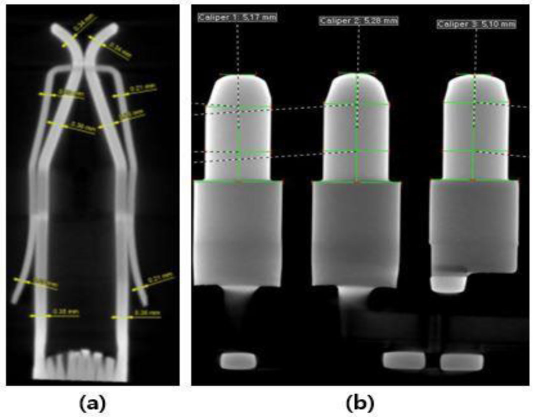


FIGURE 6. Images and measured dimensions of 3D tomography of (a) a female pin and (b) male pins of the vehicle sensor connector.

of the connector. But, they do not contribute as much to the contact force variation, because, as depicted in Fig. 3, they simply hold the male/female pins and do not apply a pressure to the contact.

B. MAINTENANCE PROCESS

Automobile maintenance is essential and must be periodically conducted. During maintenance, the sensor connectors are often disassembled for check-up or repair purposes, and then are assembled again. The repeated disassembly-assembly processes may induce plastic deformation in the female pins and reduce the contact force. The plastic deformation is actually observed in our finite element (FE) simulation in Section IV. Thus, the maintenance process also influences the contact force of the connector.

The maintenance process is reported to impose other damages on connector contacts, including fretting wear, corrosion, or peeling off of plated materials [15]–[20]. However, as mentioned in Section I, these physical damages are not considered in this study because the sensor connectors we are analyzing are assumed to be in acceptable conditions without any damages.

IV. SIMULATION

FE simulations are conducted to understand the effect of the factors reducing the contact force that are explained in Section III. For a reliable simulation, a precise 3D model is built and proper simulation conditions are applied.

A. MODELLING

The vehicle sensor connector shown in Fig. 3 is converted to a 3D model. Figure 5 illustrates the developed connector model, consisting of one female pin and one male pin. To focus on the contact force between the two pins, only one female-male pin pair is modeled and the plastic housing is not included. The male and female pins can be assembled in the simulation, as shown in the Fig. 5.

For the modeling, we utilize a design drawing provided by the connector manufacturer. However, the drawing does not provide all necessary dimensions, and it is worthwhile to investigate an actual product. Thus, a high precision 3D tomography of the sensor connector, depicted in Fig. 6, is used to build the connector model. By these 3D models, we can obtain a highly precise connector model having almost identical dimensions and shapes as actual products. For example, the thicknesses of male and female pins are 0.8 mm and 0.35 mm, respectively. Our FE simulations use hexahedral elements whose total number is about 210,000.

TABLE 1. Material properties of CuNi1Si.

Material	Young's modulus	Poisson's ratio	Density
CuNi1Si	130 GPa	0.35	8,880 kg/m^3

One FE simulation took about four to six hours depending on the vehicle sensor connectors. The material used for the FE modeling is CuNi1Si, which material properties are given in Table 1. The model also considers plastic material properties. In addition, except the contact surface of the male and female pins, an isotropic elasto-plasticity model is employed so that yield stresses increase or decrease to all stress directions, once a plastic straining occurs. Moreover, we use a temperature-independent model whose deformation is not significantly affected by temperature fluctuations.

The developed model is further validated by conducting insertion force tests using a universal testing machine (UTM, Instron Model 5969) as shown in Fig. 7(a). The sensor connector is fixed by two action grips in the UTM and pulled by a pre-defined control method. We characterize the insertion forces of the target connector by a displacement control method. The test condition is a constant pulling velocity of 0.5 mm/min for 10 minutes. Then, the UTM calibrates the insertion force of the connector, which is readily converted to the contact force. The experimental result is illustrated in Fig. 7(b). The measured force values (individually measured for three samples of the target connector) are consistent.

The derived values are similar regardless of the control methods, and thus, we consider that the conducted insertion

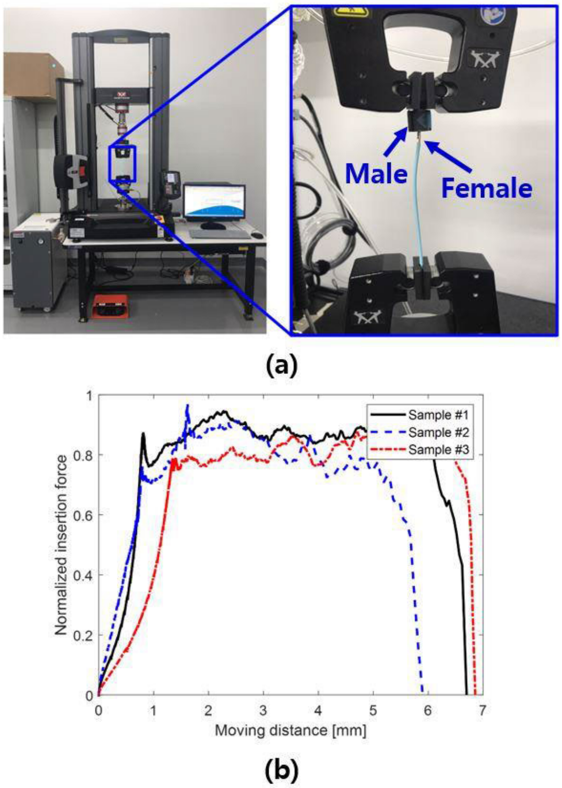


FIGURE 7. Insertion force test of the sensor connector using a universal test machine (UTM). (a) A connector under test and the UTM, (b) experiment results of three test samples.

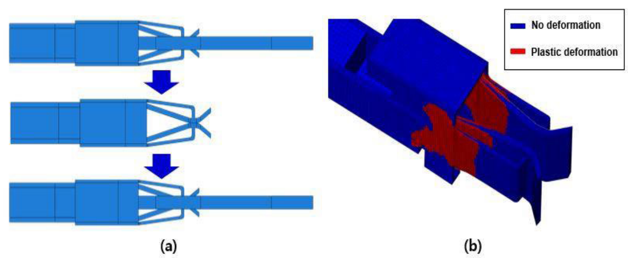


FIGURE 8. FEM simulation representing the plastic deformation during the repeated assembly and disassembly of the sensor connector. (a) Simulation process, (b) red-colored areas suffering the plastic deformation.

force experiments are reliably operated. The experimented insertion force is converted to a contact force by a simple calculation. The insertion force is first multiplied by the coefficient of sliding friction of the contact. The converted contact force values are within the ranges of the simulated force values in Section IV-B, the developed modeling is considered to be trustworthy.

B. SIMULATION CONDITIONS

FE simulations are conducted using an ABAQUS/CAE software [31]. Boundary conditions are differently applied to the male and female pins. As shown in Figs. 3 and 8, one end of the male side has a screw end to be tightly fixed on a solid surface mounted on an engine. Thus, the screwed end of the male pin is defined to be completely constrained in the simulation. For the female part, as one end is connected to the cables, it is not easy to simplify its boundary condition. We built two female models. The first model includes the cables, which is not included in the second model having a simplified partially-fixed boundary condition. The boundary condition is adjusted until the 1st and 2nd natural frequencies of the two models become similar. Afterward, the found partially-fixed condition is used to expedite FE simulations.

Our simulations are conducted for not only standard products but also for sensor connectors weakened by a manufacturing tolerance or maintenance process. To consider the effect by a manufacturing tolerance, we select two design parameters of the sensor connector that majorly affect the contact force. One is the changed thickness of male pins that is directly related to physical contact, and easily occurs in the manufacturing process.

The other is the Young's modulus of female pins, which is largely deterministic in plastic deformation. Note that the weakened connectors used in this study are not defective products but commercially allowable ones. Thus, we need to determine acceptable ranges of the manufacturing tolerance. The three-sigma rule is employed, and, as a result, the male pin allows a 95% variation in pin thickness and an 85% variation is considered in the Young's modulus of the female pin [32].

To understand the effect by a maintenance process, the sensor connector is repetitively assembled and disassembled. Figure 8 depicts the simulation results. First, the male pin is inserted into the female pin, and, afterward, it is disassembled and assembled again. During the assembly-disassembly sequence, plastic deformation is observed at various regions of the female pin, as shown by the red-colored areas in Fig. 8(b). The repeating plastic deformation continuously weakens the clamping force of the female pin, leading to notable reduction in the contact force of the sensor connector.

C. SIMULATION RESULTS AND DISCUSSION

Figure 9 compares the contact force of the sensor connector derived either by the UTM test or FE simulation, after repeatedly conducting assembly and disassembly. The UTM test was performed for three connector samples, and their mean value is depicted by the blue dashed line. Because FE models generally tend to be stiffer than real models, the normalized contact force of the FE simulation is higher. Nonetheless, as the connector is assembled and disassembled, a notable reduction of the normalized contact force is observed in both the UTM test and FE simulation results. Therefore, the FE model we developed reliably analyzes the tendency of contact force degradation.

The contact force-reduction factors induced by the manufacturing and maintenance processes are numerically simulated. The worst simulation results are summarized in Fig. 10. Considering only the manufacturing tolerance,

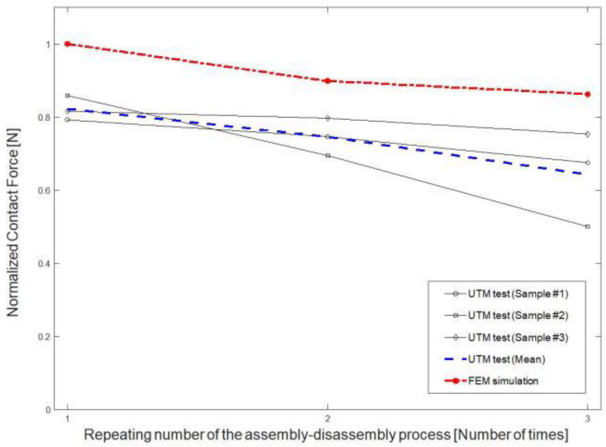


FIGURE 9. Result comparison of UTM test and FEM simulation for repeated sensor-connector assembly and disassembly process.

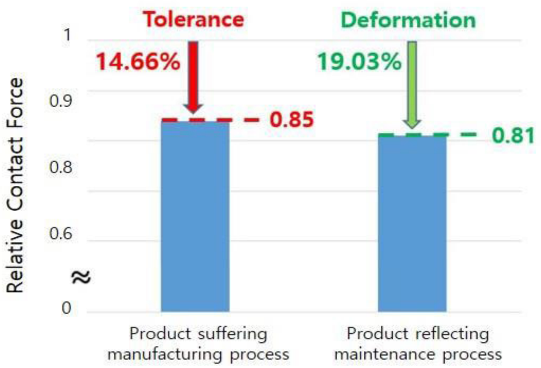


FIGURE 10. Summary of FE simulation results revealing the reduced contact forces by manufacturing and a repeated assembly-disassembly maintenance sequence.

a sensor connector having the thinnest male pin and smallest Young's modulus exhibits the least contact force. The effect of the pin thickness is expected, and the small Young's modulus decreases the contact force by reducing the reaction force generated from the deformed female pin. Within the allowance of the three-sigma rule, the connector contact force is decreased by approximately 14.7% by the manufacturing tolerance, as revealed in the figure 10. While, the plastic deformation by the repeated maintenance becomes more influential in thicker male pins that more widely open the female pin. Such sensor connectors demonstrate approximately 19.0% contact-force reduction after the one-time assembly-disassembly-assembly sequence shown in Fig. 8(a).

These observations suggest that the contact-force reduction is significant and potentially occurs even in typical products by diverse causes. As an example, connectors having either thin or thick male pins undergo contact force reduction by different reasons and at distinct processes. To investigate the contact force-resistance relation that is not provided by the explained FE simulations, follow-up experiments are conducted.

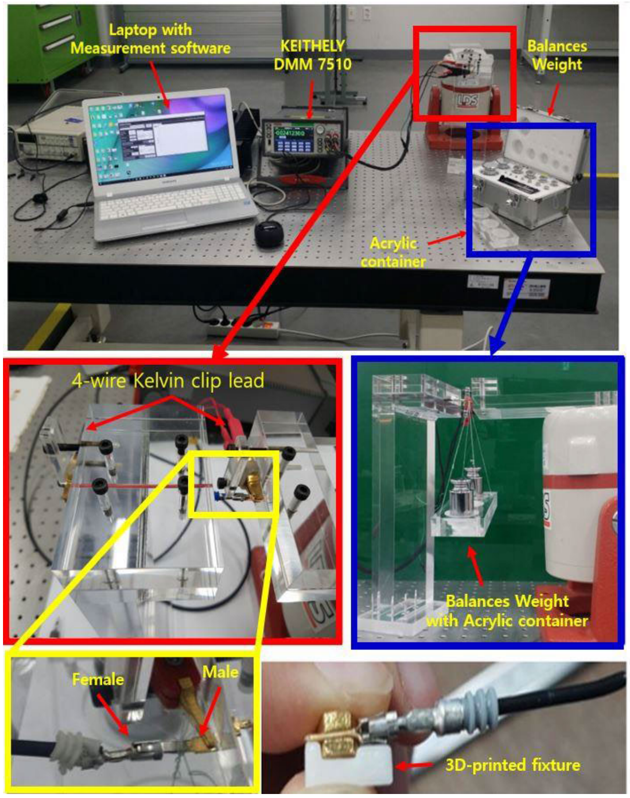


FIGURE 11. Experiment setup to measure the contact resistance of the vehicle sensor connector. The contact force is applied by the balance weights mounted on the acrylic container. By adding the weights, the contact force is increased.

V. EXPERIMENT

Experiments are conducted using a custom contact resistance measurement setup. Two experiments are conducted. The first one aims to define the contact force-resistance relationship in the analyzed vehicle sensor connector. The second experiment is designed to investigate the variation of electrical contact resistance by the manufacturing tolerance and plastic deformation enforced to the connector.

A. EXPERIMENTS TO DEFINE THE CONTACT FORCE-RESISTANCE RELATION

Figure 11 depicts an overview of our test setup. To calibrate the contact force-resistance of the vehicle sensor connector, there are several challenges. First, we need to incrementally change the contact force applied to the connector pins. This is, however, difficult in the sensor connector shown in Fig. 3, because of the housing plastic and parallel-placed male/female pins. In addition, in such configuration, it is almost impractical to measure the contact force in real time. Thus, we removed the housing plastics of the male and female parts, and use only one male pin and one female pin, similar to the simulation model in Fig. 5. To apply a varying contact force, one edge of the female pin is removed and the male pin is placed on top of the remaining female edge. On top of the two pins, an acrylic container is hanged. By adding balance weights in the container, we can easily modify the

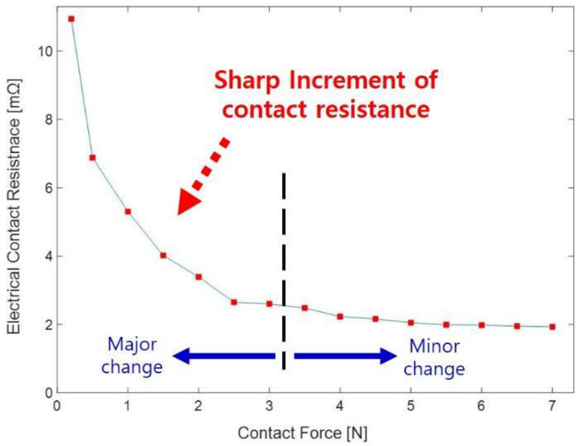


FIGURE 12. Experiment result showing the contact force-resistance relationship of the vehicle sensor connector (error rate < 7.5%).

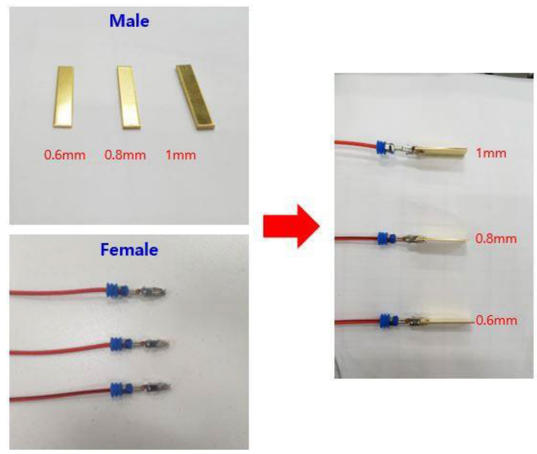


FIGURE 13. Female pin after removing the plastic mold and male pins with different thicknesses.

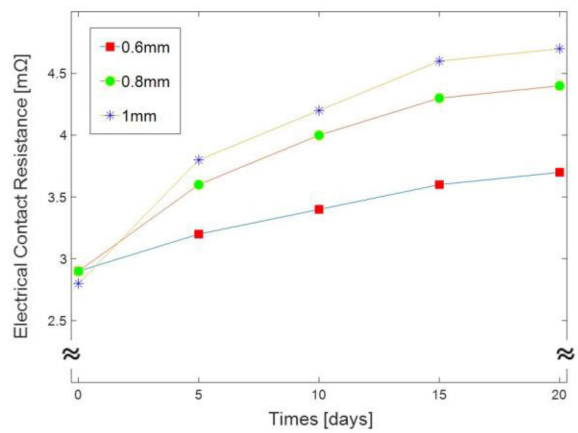


FIGURE 14. The increased contact resistance by the functions of assembled time.

contact force of the male-female contact and calculate the force value. The male and female pins are supported by a 3D-printed fixture, to prevent any bending or damages of the pins.

The electrical contact resistance is accurately characterized. A high precision 71/2 digital multimeter (DMM 7510 manufactured by Keithley Instruments) is used with a custom computer interface and signal processing software. The multimeter is connected to the test sample by four-wire Kelvin clip leads, enabling a four-wire Kelvin resistance sensing method.

Figure 12 depicts the measured contact resistance by the functions of the contact force (from 0.2 to 7 N) defined by the balance weights. Note that the graph reveals a typical contact force-resistance relationship explained in Section II-B. The vehicle sensor connector demonstrates almost constant resistance at contact force values larger than approximately 2.5N. The resistance begins to elevate when the contact force becomes smaller than 2.5N, and considerably increases at forces smaller than a threshold value (herein, approximately 2N). This resistance measurement is consistent (with ignorable measurement variations of $<$7.5%), even we conduct the same experiment five different instances for the same connector. Eventually, the contact resistance becomes 5.5 times larger than the normal value. This increased resistance will deteriorate the vehicle sensor system performance.

B. EXPERIMENTS TO INVESTIGATE THE CONTACT RESISTANCE CHANGES

In this experiment, the edges of the female pins are not removed, but their housing plastics are removed. Male pins (made of nickel-coated brass) having different thickness are prepared to represent the different male thicknesses occurred owing to the manufacturing tolerance (described in Section III-A and Fig. 10) and to impose a plastic deformation to the female pin (explained in Section III-B and Figs. 9 and 11). Figure 13 shows the female pins without housing and the prepared male pins having different thicknesses. The male pins are inserted into the female pins. The thickness of male pins is selected as 0.6, 0.8, and 1.0 mm, acknowledging that the 0.8 mm thickness is the standard product. Note that, as explained in Fig. 10, connectors having thin male pins have a relatively large impact on the contact force decrement during the manufacturing process, while thick male pins are anticipated to enforce increased chances of plastic deformations during the maintenance process.

The changes of the contact resistance are characterized by two approaches. In the first approach, the male and female pins are assembled, and their electrical contact resistance is measured after a certain time interval. The results are shown in Fig. 14. Here, the contact-time interval is set to be five days, because a notable resistance increment is not observed at shorter time intervals. The electrical contact resistances apparently increase as time elapses in all three cases. Initially, the electrical contact resistance is the smallest in the sample having 1.0 mm thickness, but the variation is minor and not meaningful, because it stems from the manufacturing tolerance. However, the resistance variation becomes prominent as the contact time increases, and obviously differs by

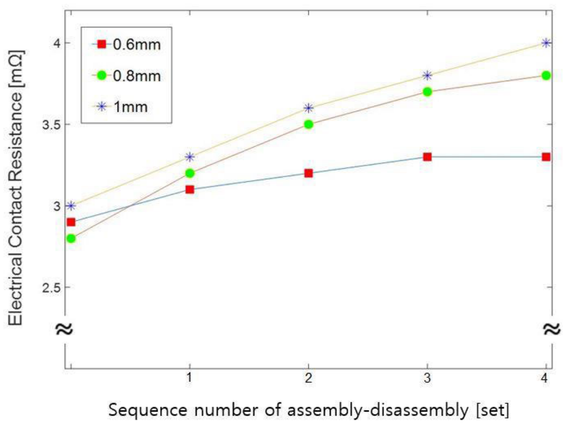


FIGURE 15. The increased contact resistance by the repeating assembly-disassembly sequence of the sensor connector.

male-pin thickness. After 20 days, the amounts of increased electrical contact resistance are 27%, 51%, and 67% in the samples having male thicknesses of 0.6, 0.8, and 1.0 mm, respectively.

Meanwhile, in the second approach depicted in Fig. 15, the male pin is repeatedly assembled and disassembled from the female pin, mimicking the maintenance process. In all test cases, the electrical contact resistance increases as the sequence undergoes. The amount of the resistance increment becomes larger in samples having thicker male pins. This result matches well with the simulation in Fig. 10, which explains reduction of contact force by the enlarged plastic deformation with thick male pins.

In all experiments, we observe the changes of the electrical contact resistance. Note that not only the increment but also fluctuation of the electrical contact resistance is feasible, because the contact force may fluctuate for various reasons. When the sensor signal is rapidly transmitted, the changed electrical contact resistance readily leads to the fault of sensor signals and distorts the reliability of vehicle sensor system [33], [34]. In addition, these faults can be accumulated and reliability problem will be more severe [35].

VI. CONCLUSION

This study proposes a process to identify causes affecting the contact resistance of sensor connectors used in vehicles, and focuses on the impact of reduced connector contact forces. The reduced contact-force sequentially changes the contact resistance but this mechanism is different from physical contact damages changing the resistance (e.g., corrosion, wear, removed coating, elastic-plastic deformation of contacts). Changes in contact resistance, induce potential errors in vehicle sensor systems that require an extremely high level of reliability. To numerically visualize the contact force reduction, a commercial vehicle sensor connector is precisely modeled and simulated using ABAQUS/CAE software. Simulation conditions (such as boundary conditions and plastic deformation) are customized to represent real operation conditions of vehicle sensors, and less influential components (such as housing plastics) are ignored. Simulation results clearly demonstrate that the contact force is obviously reduced in either manufacturing or maintenance processes of the sensor connector. Note that the two processes induce different degradation mechanisms. The reduced force sequentially increases the electrical contact resistance, as experimentally demonstrated. Four-wire resistance measurement validates a sharp increment of the contact resistance at contact force values smaller than a certain threshold, implicating substantial errors in vehicle sensor systems. In addition, the contact resistance of connector samples increases by the assembled time or by the number of repeated assembly-disassembly sequences. Therefore, our numerical and experimental results confirm that vehicle sensor connectors may be threatened by their manufacturing or maintenance, because of reduced contact force and increased contact resistance.

ACKNOWLEDGMENT

The authors would like to thank Min Ki Kim, Jihwan Seong, Jihoon Kim, Seungha Lee, and Taejoon Kwon in Hanyang University, Korea for their support in this paper.

REFERENCES

[1] P.-L. Hsu, K.-L. Lin, and L.-C. Shen, "Diagnosis of multiple sensor and actuator failures in automotive engines," *IEEE Trans. Veh. Technol.*, vol. 44, no. 4, pp. 779–789, Nov. 1995.

[2] H. Zhang and J. Wang, "Active steering actuator fault detection for an automatically-steered electric ground vehicle," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 3685–3702, May 2016.

[3] B. C. Mecrow, A. G. Jack, D. J. Atkinson, S. R. Green, G. J. Atkinson, A. King, and B. Green, "Design and testing of a four-phase fault-tolerant permanent-magnet machine for an engine fuel pump," *IEEE Trans. Energy Convers.*, vol. 19, no. 4, pp. 671–678, Dec. 2004.

[4] B. Ashok, S. D. Ashok, and C. R. Kumar, "A review on control system architecture of a SI engine management system," *Annu. Rev. Control*, vol. 41, pp. 94–118, Jan. 2016.

[5] S. Kumar, J. Paefgen, E. Wilhelm, and S. E. Sarma, "Integrating on-board diagnostics speed data with sparse GPS measurements for vehicle trajectory estimation," in *Proc. SICE Annu. Conf.*, Sep. 2013, pp. 2302–2308.

[6] A. Bieniek, "Adaptive control of exhaust gas recirculation at nonroad vehicle diesel engine," *J. KONES*, vol. 18, no. 4, pp. 11–18, 2011.

[7] B. S. K. K. Ibrahim, M. A. N. Aziah, S. Ahmad, R. Akmeliawati, H. M. I. Nizam, A. G. A. Muthalif, S. F. Toha, and M. K. Hassan, "Fuzzy-based temperature and humidity control for HV AC of electric vehicle," *Procedia Eng.*, vol. 41, pp. 904–910, Jan. 2012.

[8] H. Khayyam, J. Abawajy, and R. N. Jazar, "Intelligent energy management control of vehicle air conditioning system coupled with engine," *Appl. Therm. Eng.*, vol. 48, no. 15, pp. 211–224, Dec. 2012.

[9] H. Khayyam and A. Bab-Hadiashar, "Adaptive intelligent energy management system of plug-in hybrid electric vehicle," *Energy*, vol. 69, pp. 319–335, May 2014.

[10] M. Antler, "Survey of contact fretting in electrical connectors," *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, vol. 8, no. 1, pp. 87–104, Mar. 1985.

[11] M. D. Bryant, "Resistance buildup in electrical connectors due to fretting corrosion of rough surfaces," *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, vol. 17, no. 1, pp. 86–95, Mar. 1994.

[12] R. D. Malucci, "Impact of fretting parameters on contact degradation," in *Proc. 42nd IEEE Holm Conf. Elect. Contacts*, Sep. 1996, pp. 395–403.

[13] G. T. Flowers, F. Xie, M. Bozack, and R. D. Malucci, "Vibration thresholds for fretting corrosion in electrical connectors," in *Proc. 48th IEEE Holm Conf. Electr. Contacts*, Oct. 2002, pp. 133–139.

[14] M. Antler, "Electrical effects of fretting connector contact materials: A review," *Wear*, vol. 106, nos. 1–3, pp. 5–33, 1985.

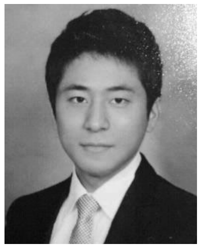
[15] H. Blanks, "Detection and accelerated testing of vibration-induced connector wear," *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, vol. 7, no. 1, pp. 3–10, Mar. 1984.

[16] N. Chiodarelli, "Measuring the electrical resistivity and contact resistance of vertical carbon nanotube bundles for application as interconnects," *Nanotechnology*, vol. 22, no. 8, pp. 085302-1–085302-7, 2011.
[17] K. Nagashio, T. Nishimura, K. Kita, and A. Toriumi, "Systematic investigation of the intrinsic channel properties and contact resistance of monolayer and multilayer graphene field-effect transistor," *Jpn. J. Appl. Phys.*, vol. 49, no. 5R, 2010, Art. no. 051304.
[18] G. Liu, J. Zhu, L. Yu, and Q. J. Wang, "Elasto-plastic contact of rough surfaces," *Tribol. Trans.*, vol. 44, no. 3, pp. 437–443, 2001.
[19] R. L. Jackson and L. Kogut, "A comparison of flattening and indentation approaches for contact mechanics modeling of single asperity contacts," *J. Tribol.*, vol. 128, no. 1, pp. 209–212, 2006.
[20] H. Ghaednia, X. Wang, S. Saha, Y. Xu, A. Sharma, and R. L. Jackson, "A review of elastic–plastic contact mechanics," *Appl. Mech. Rev.*, vol. 69, no. 6, 2017, Art. no. 060804.
[21] M. R. W. Brake, "An analytical elastic plastic contact model with strain hardening and frictional effects for normal and oblique impacts," *Int. J. Solids Struct.*, vol. 62, pp. 104–123, Jun. 2015.
[22] A. Lee and K. Komvopoulos, "Dynamic spherical indentation of elastic-plastic solids," *Int. J. Solids Struct.*, vol. 146, pp. 180–191, Aug. 2018.
[23] A. G. M. Jansen, A. P. van Gelder, and P. Wyder, "Point-contact spectroscopy in metals," *J. Phys. C, Solid State Phys.*, vol. 13, no. 33, p. 6073, 1980.
[24] R. Holm, *Electric Contacts: Theory and Applications*. Berlin, Germany: Springer-Verlag, 1967.
[25] G. Wexler, "The size effect and the non-local Boltzmann transport equation in orifice and disk geometry," *Proc. Phys. Soc.*, vol. 89, no. 4, pp. 927–941, 1966.
[26] J. A. Greenwood, "Constriction resistance and the real area of contact," *Brit. J. Appl. Phys.*, vol. 17, no. 12, pp. 1621–1632, Dec. 1966.
[27] L. Boyer, "Contact resistance calculations: Generalizations of Greenwood's formula including interface films," *IEEE Trans. Compon. Packag. Technol.*, vol. 24, no. 1, pp. 50–58, Mar. 2001.
[28] H. Ghaednia, X. Wang, S. Saha, Y. Xu, A. Sharma, and R. L. Jackson, "A review of elastic–plastic contact mechanics," *Appl. Mech. Rev.*, vol. 69, no. 6, 2017, Art. no. 060804.
[29] C. Zhai, D. Hanaor, G. Proust, L. Brassart, and Y. Gan, "Interfacial electro-mechanical behaviour at rough surfaces," *Extreme Mech. Lett.*, vol. 9, pp. 422–429, Dec. 2016.
[30] P. G. Slade, *Electrical Contacts: Principles and Applications*. New York, NY, USA: Marcel Dekker, 1999.
[31] M. Sartorato, R. de Medeiros, D. Vandepitte, and V. Tita, "Computational model for supporting SHM systems design: Damage identification via numerical analyses," *Mech. Syst. Signal Process.*, vol. 84, pp. 445–461, Feb. 2017.
[32] *Materials Data Book*, Dept. Eng., Cambridge Univ., Cambridge, U.K., 2003.
[33] Q. Shen, K. Lv, G. Liu, and J. Qiu, "Impact of electrical contact resistance on the high-speed transmission and on-line diagnosis of electrical connector intermittent faults," *IEEE Access*, vol. 5, pp. 4221–4232, 2017.
[34] A. F. Anderson, "Intermittent electrical contact resistance as a contributory factor in the loss of automobile speed control functional integrity," *IEEE Access*, vol. 2, pp. 258–289, 2014.
[35] K. Zhang, B. Jiang, X.-G. Yan, and J. Shen, "Interval sliding mode observer based incipient sensor fault detection with application to a traction device in China railway high-speed," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2585–2597, Mar. 2019.

JANGMUK LIM received the B.S. degree in automotive engineering from Hanyang University, Seoul, South Korea, in 2016, where he is currently pursuing the Ph.D. degree in automotive engineering.

His current research interests include analysis and design about power module for reliability improvement.

HANSU KIM received the B.S. degree from the Department of Automotive Engineering, Hanyang University, Seoul, South Korea, in 2015, where he is currently pursuing the Ph.D. degree. His main research interests include data-driven design and optimization, surrogate-model-based design optimization, design and analysis of computer experiments, and uncertainty-based design optimization.



JAE KYUN KIM received the B.S. degree from the Department of Electrical and Electronics Engineering, Yeonsei University, Seoul, South Korea, in 2012. He is currently a Research Engineer with the Electronics Convenience Control Test Team, Hyundai-Kia Global Research and Development Center, South Korea.

His research interests include powertrain control unit testing and high-speed network testing and start authentication and interlock algorithm development.

SUNG JOON PARK received the B.S. degree in mechanical and control engineering from Busan National University, in 2001. In 2001, he joined the Hyundai-Kia Global Research and Development Center, where he worked on testing vehicle electric control unit. He has over ten patents in the fields of electric control and test methods. His current research interests include the vehicle communication and electric test reliability.

TAE HEE LEE received the B.S. degree from Hanyang University, in 1981, the M.S. degree from KAIST, in 1984, and the Ph.D. degree from the University of Iowa, in 1991. He is currently a Professor with Hanyang University, where he is also the Director of the Automotive Research Center. His research interests include design optimization, design under uncertainty, surrogate model-based optimization, design and analysis of computer experiments, and data-driven design. He also serves as the Executive Vice President for the Korean Society for Computational Mechanics (KSCM), the General Council of the International Association for Computational Mechanics (IACM), and an Executive Committee Member of the Asian Society for Structural and Multidisciplinary Optimization (ASSMO). He was the President of the Korean Society for Design Optimization (KSDO) and the Division of CAE and Applied Mechanics of the Korean Society of Mechanical Engineers (KSME).

SANG WON YOON (SM'18) received the B.S. degree in electrical engineering from Seoul National University, Seoul, South Korea, in 2000, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Michigan, Ann Arbor, MI, USA, in 2003 and 2009, respectively. From 2009 to 2013, he was a Senior Scientist and a Staff Researcher with the Toyota Research Institute of North America, Ann Arbor, where he conducted research in the fields of power electronics and sensor systems for automobiles. Since 2013, he has been with the Department of Automotive Engineering, Hanyang University, Seoul, where he is currently an Associate Professor. His current research interests include power electronics, sensors and sensor systems, electronic reliability, and their applications in conventional and future vehicles.