Towards reducing acoustical high-frequency noise of a direct current relay via contact structure

직류 계전기의 접촉구조에 의한 고주파수 소음저감

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ABSTRACT: In this work, a straightforward component design of a direct current (DC) relay equipped in electric vehicles is discussed. The work aims to provide and evaluate effective measures for reducing high-frequency sound from the DC relay carrying electric power. From the operation experiments for the relay, it is observed that noise is caused by the resonance from the forced vibration by the electromagnetic repulsive force originating at the area of electric contacts with a resonance frequency of around 710 Hz ~ 730 Hz. A finite element model for the relay was established to conduct vibration mode analysis, consisting of stationary and movable contacts and a contact spring. Vibration mode analysis indicates that in the resonance frequency, the movable contact with two-point contacts experiences rotational vibration mode. For the proposed relay with a three-point contact, vibration mode analyses give reasonable results of reducing noise at that frequency. Furthermore, for the fabricated relays with the three-point contact, similar results have been obtained. In conclusion, one can see that the proposed measures provide one of the feasible solutions to the reduction of relay noise.

Keywords: Acoustic noise, DC relay, High frequency noise, Noise reduction

PACS numbers: 43.20.Ks, 43.40Kd

초   록: 직류 계전기는 전기자동차의 하나의 부품으로 간헐적으로 고주파수 소음이 710 Hz ~ 730 Hz의 주파수 범위에서 전기적 부하에 의해 발생한다. 고정접점과 가동접점 사이에서 발생하는 전자 반발력이 가동접점과 접압 스프링을 진동시키고, 그 진동으로 가동접점과 접압 스프링에 공진이 발생하여 고주파수 소음이 발생한다. 본 논문에서는 수치해석 및 실험을 통하여 고주파수 소음의 원인을 규명하고, 소음을 제거하는 방안을 제시하였다. 710 Hz ~ 730 Hz의 주파수 범위에서 가동접점은 고정접점과의 2개의 접촉점을 기준으로 회전하는 공진모드가 발생한다. 따라서 해당 여기서 제안한 방법은 공진모드를 제거하기 위해 가동접점의 구조를 2점 접촉구조 방식에서 3점 접촉구조 방식으로 변경하는 것이다. 3점 접촉구조를 적용함에 따라 공진모드가 제거되는 것을 수치해석으로 확인하였고, 실험적으로도 고주파수 소음이 발생하지 않는 것을 확인하였다.

핵심용어: 음향소음, 직류 계전기, 고주파수 소음, 소음저감

I. Introduction

Electric Vehicles (EVs) are one of the primary candidates for the next generation of transportation to combat climate change, mainly because they have the advantage of overall energy efficiency and zero emissions compared to the conventional Internal Combustion (IC) engine vehicles.[1,2] Since EVs are powered by high voltage DC power, safety and reliability of the electrical system are required, and as a component of the power system, high voltage DC

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relays that cut off power from the battery play essential roles. In terms of the operation of electrical systems, the reduction of acoustical noise of electrical components is a challenging issue, and much research work has been done.[3-8] This work focuses on the mechanical noise of a DC relay utilized in EVs to control high voltage load and proposes a method to mitigate the noise.

Noises from DC relays can be classified into at least three categories: (1) Impulse noise produced from internal contacts during the switching operation, (2) Noise from structural vibration of relay's components due to the impact (shock), and (3) High-frequency noise caused by the resonance phenomenon of mechanical components of the relay due to excitation of electromagnetic repulsive force generated around the contact points. The first two types of noises are resolved in various ways, and a few representative research works are introduced. The patent[9] in proposes a way to reduce impact noise by controlling the current of the relay coil to slow the movement of contact points when opening and closing relays. Ko *et al.*[10] performed a study to improve the impact noise and bounce characteristics between contact points of relays applied to Hybrid Electric Vehicles (HEVs). A study[11] proposes a double-junction spring structure to reduce noise generated when the DC relay is closed. An experimental study[12] has been carried out on noise reduction in relay modules for HEVs, suggesting sealing relay components and insulating vibration to battery packs. However, much research has not been reported for the vibration and noise reduction issues on the third type of noise listed above. Given these circumstances, this work analyzes the causes of high-frequency noise generated by the contacts' vibration and proposes a contact structure to reduce this noise. In the following, the detail of the analysis and the proposed method is illustrated. In order to proceed, this paper is organized as follows. In Section 2, the structure of the DC relay at hand is given. The overall noise level of the DC relay equipped in EVs is introduced with and without acceleration operation of the vehicle. In Section 3, noise characteristics of the DC relay are identified through

reappearance tests and vibration mode analysis. A noise reduction method is proposed, and its performance evaluation is discussed in Section 4. Finally, Section 5 concludes the paper with a summary of the work.

II. Backgrounds

2.1 Overview

The DC relay considered in this work is employed in EVs, consisting of a stationary contact, a movable contact, a shaft, contact and return springs, and electrical actuators that can operate on control signals (see Fig. 1). Refer to Gurevich's book for electric relays for more details.[13] The stationary and movable contacts of the DC relay act as the bridge through which the electric power from the battery is supplied to electric components. The current flow at the contacts is directly related to EVs' acceleration performance characteristics, which affect the motor's output torque, so does the change of the battery's voltage. In this work, although the first two types of noise introduced above are also an important consideration, it is intended to address high-frequency sound associated with vibration caused by electromagnetic forces due to current flowing when the relay is working.
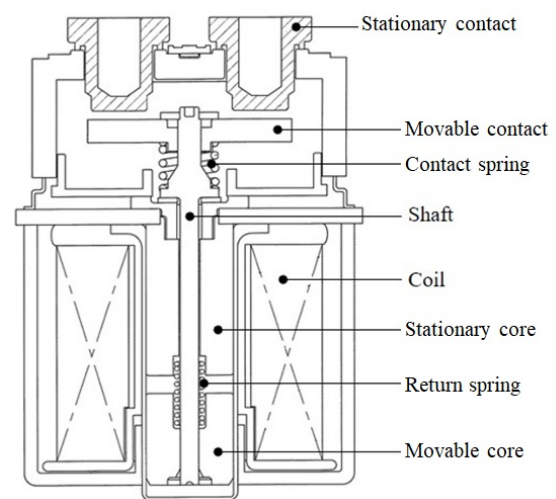

Fig. 1. Schematic of the DC relay under consideration.

2.2 Main feature of relay noise

Fig. 2 indicates the measurement of sound produced by a DC relay mounted on the vehicle under development
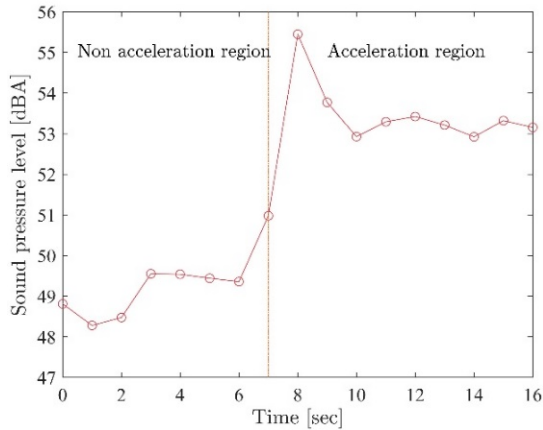

Fig. 2. (Color available online) Overall noise level of the DC relay under normal operation.
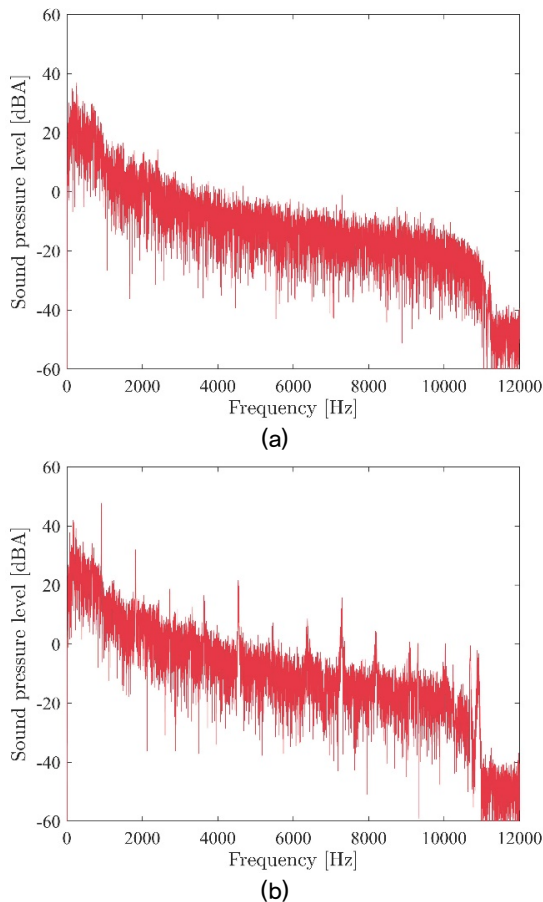

(a)

(b)

Fig. 3. (Color available online) Frequency spectrum for (a) non-acceleration and (b) acceleration region.

during operation. Noise in the acceleration region is more extensive than in the non-acceleration region, mainly due to increased electric motor input. It can be seen from Fig. 3 that the noise characteristics of the acceleration region not only have a specific high-frequency band but also occur in the form of harmonics, unlike the non-acceleration region.

III. Identification of noise attribute

3.1 Reappearance experiments

A set of reappearance experiments have been conducted to investigate the characteristics of relay's sound at the laboratory level. Since the DC relay equipped in the vehicle at a developmental stage shows a high-frequency sound when the current flows in the normally closed state, 150 amps of current from DC and AC power sources each was allowed to flow for 20 seconds through the contact points of the relay and measured the sound pressure level using a microphone. For the AC power application, the current with different frequencies was applied to prevent harmonics from overlapping as much as possible, as shown in Table 1. Fig. 4 is the result from the reappearance experiments.

It is observed from the figure that sound with a specific frequency range (710 Hz ~ 730 Hz) occurs in common regardless of the types of power. In particular, in the AC power application, the sound with the multiple frequency components of the fundamental frequency of currents each is generated. Furthermore, it is observed that the sound of a particular frequency, which is not related to the multiple frequency components of each fundamental frequency of current applied, is commonly produced. It is speculated that this frequency is related to the resonant frequency of

Table 1. Electric current sources for reappearance tests.

Source	Frequency (Hz)
DC 150A	--
AC 150A	120
	140
	150

certain parts within the DC relay. The resonance is caused by the presence of external forces with a component of the resonance frequencies. The external force exerted on the DC relay can be originated from the electric current going through the contact spots. The generation of electromagnetic force at the contacts can be illustrated by the
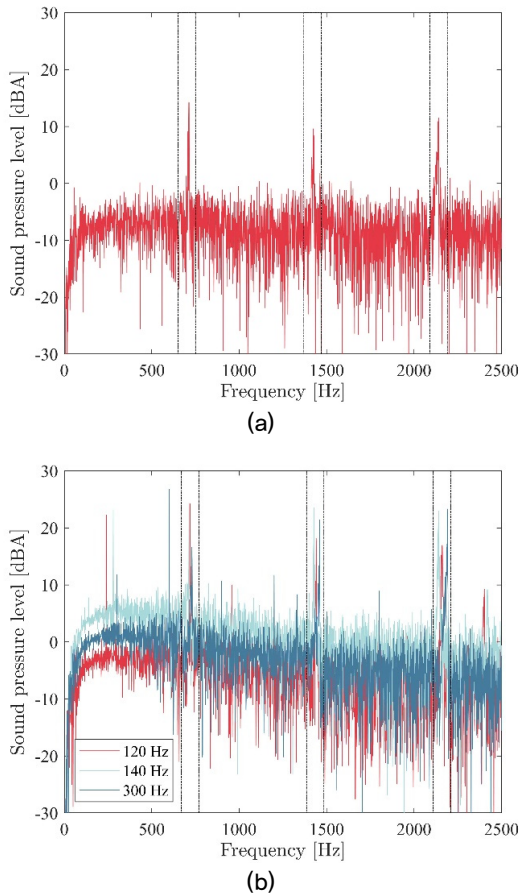

(a)

(b)

Fig. 4. (Color available online) Comparison of frequency spectra of sound emitted when (a) DC and (b) AC power is supplied through the relay.

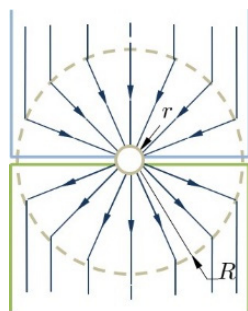

Fig. 5. (Color available online) Schematic of Holm's a-spot model.[14]

Holm's a-spot model given in Fig. 5.[14-17]

In terms of the direction of an electric current around the contact, the current is directed toward the center of the contact in the upper side of contact (i.e., stationary contact) and vice versa at the lower side of contact (i.e., movable contact). Current passing across a contact interface is constricted to flow through a-spots.[18]

The electromagnetic repulsive force F can be represented from Holm's equation shown in the below[14,18]

$$F = \mu \, I^2/4\pi \ln(R/r) \quad [N], \tag{1}$$

where μ is the permeability ($4\pi \times 10^{-7}$ [N/A^2] for air), I represents the electric current [A], R the equivalent radius of the area of contact and r the radius of contact spot [mm].

3.2 Vibration modal analysis

Since it is expected that the resonance phenomenon of specific parts inside the DC relay cause noise generation, vibration mode analyses on the relay have been performed by constructing FE models of the relay.

A commercial 3D designing program was used, and its FE model was established. The FE model consists of the stationary and movable contacts and the contact spring shown in Fig. 6. The 10-node tetrahedron with mid-node was used as a finite element. In the two (three)-point contact model, the total number of nodes and finite elements is shown in the Table 2. The boundary conditions of the contact points in the FE model have been set as a "bonded condition" so that the lower nodes of the movable contact and the upper ones of the contact spring are not separated. Table 3 lists the material properties used in the
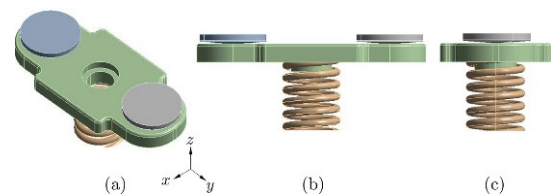

Fig. 6. (Color available online) Two-point contact FE model for mode analysis. (a) An over-head view, (b) yz- and (c) xz-plane view.

Table 2. The number of nodes and finite elements in FE models. Note. SC/MC, Stationary/Movable contact; CS, Contact spring.

Model	Part	Number of nodes	Number of elements
Two-point contact	SC	5364	2968
	MC	22919	14504
	CS	4399	1679
Three-point contact	SC	5434	3030
	MC	22024	14006
	CS	4347	1657

Table 3. Material properties assigned in FE models.

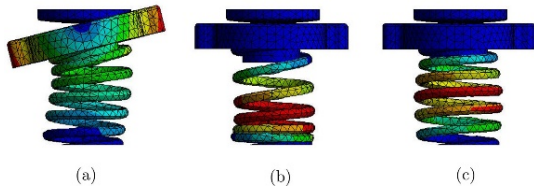| Part	Material	Density (kg/mm^3)	Young's Modulus (MPa)	Poisson's Ratio (-)
SC	Copper Alloy	8.30e-6	110,000	0.34
MC	Copper Alloy	8.30e-6	110,000	0.34
CS	Steel	7.85e-6	200,000	0.30

Fig. 7. (Color available online) Mode analysis result for two-point contact model. (a) First mode, 722 Hz, (b) second mode, 2203 Hz and (c) third mode, 2527 Hz.

relay model.

With the FE model established, a vibration mode analysis was conducted up to the third mode, and its natural frequency and mode shape per mode are given in Fig. 7. The first mode showed that at the frequency of 722 Hz, the movable contact rotates about the y-axis (see Fig. 6 for the axis of direction), while the movable contact is in contact with the stationary contact by the elastic force of the contact spring. The second and third modes exist above the frequency of 2,000 Hz and represent the rotational and translational motion modes of the contact spring itself. It can be seen that the frequency of the first mode is similar to the frequency of the noise identified in the experiment.

IV. Measures and evaluation for relay's noise reduction

4.1 Alteration of Movable Contact Structure

The previous section observed that the movable contact rotates while contacting the stationary contact in the first resonance mode. As shown in Fig. 8(a), the contacts take place at two points, and the movable contact rotates around the virtual line connecting these points. This aspect appears in the first vibration mode. Therefore, it is necessary to constrain the degree of freedom of rotation of the movable contact to remove the first rotational vibration mode. One way to constrain the rotational motion is to create not a line but a plane when contact points are connected to each other. The minimum number of contact points required to make a plane is three. Based on the discussion above, a structural and straightforward design is proposed to prevent the rotation of the movable contacts (and to reduce high-frequency relay's noise finally), which changes the movable contact's shape so that one end of the movable contact comes into contact with the stationary contact at two points, as shown in Fig. 8(b).

4.2 Evaluation of proposed design

Fig. 9 shows an FE model for the relay with the proposed structure in Fig. 8(b). Like the existing two-point contact structure, the FE model consists of the stationary contact, the movable contact, and the contact spring. With the FE model established, a vibration mode analysis has been conducted up to the third mode, and its natural frequency and mode shape per mode is given in Fig. 10.
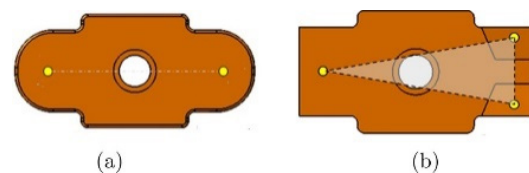

Fig. 8. (Color available online) Movable contact structures with (a) two-point contact and (b) three-point contact, respectively. Note: Yellow circles represent points of contact.
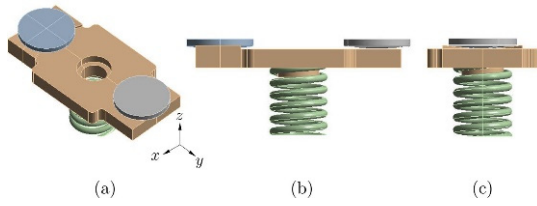
Fig. 9. (Color available online) Three−point contact FE model for mode analysis. (a) An overhead view, (b) yz− and (c) xz−plane view.
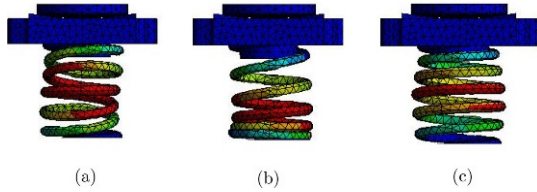

Fig. 10. (Color available online) Mode analysis result for three−point contact model. (a) First mode, 3850 Hz, (b) second mode, 3884 Hz and (c) third mode, 4423 Hz.
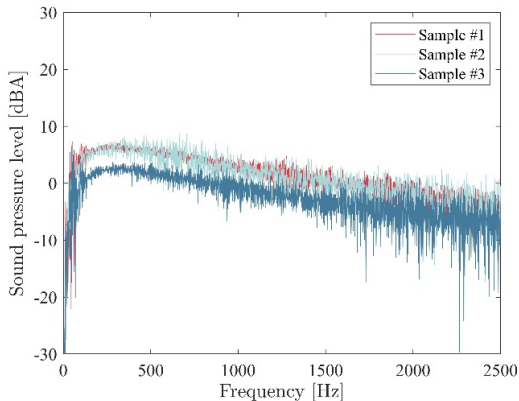

Fig. 11. (Color available online) Noise frequency spectrums for samples applied with the design of three−point contact.

According to the modal analysis results of the structure shown in Fig. 9, unlike the conventional two-point contact structure, the rotation mode shown in the two-point contact structure disappears. Furthermore, the second and third modes in the two-point contact structure again appear in order. Twenty DC relays applied with the proposed design were fabricated, and a set of tests were conducted to verify its applicability using a DC power source (discussed in Section 3). Fig. 11 shows the noise frequency spectrum resulting from the tests. As shown in the figure, for the

three samples randomly selected among 20, we observe that high-frequency noise disappears compared with the existing two-point contact structure.

V. Conclusions

In this work, a structural and straightforward design is proposed to reduce the high-frequency sound emitted from a DC relay during operation. The characteristics of high-frequency sound were investigated via the actual driving and laboratory level tests. It is found from the investigation that the noise is caused by the forced vibration of the relay's components, which are exerted by the electromagnetic repulsive force. The repulsive force at hand is one generated at the electric contacts through which electric power is flowing. FE models, including electric contacts (the stationary and movable contacts) and the contact spring, are established to conduct vibration mode analyses. Through vibration mode analyses, an alteration of the movable contact structure is proposed, and its prototype relays applied with the proposed design are fabricated. Vibration reduction capability was evaluated for the relays with the proposed design through transmitting DC power to the relay and measuring its sound pressure level. Evaluation results say that the vibration at 722 Hz generated from the existing relay with the two-point contact structure disappears. From the observation, one can conclude that the proposed design gives one of the simple but viable solutions to reduce the relay's high-frequency noise.

References

1. J. Y. Yong, V. K. Ramachandaramurthy, K. M. Tan, and N. Mithulananthan, "A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects," Renewable Sustainable Energy Rev. **49**, 365-385 (2015).

2. F. Un-Noor, S. Padmanaban, L. Mihet-Popa, M. N. Mollah, and E. Hossain, "A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of develop-

ment," Energies, **10**, 1217 (2017).

3. P. Vijayraghavan and R. Krishnan, "Noise in electric machines: a review," IEEE Trans. Ind. Appl. **35**, 1007-1013 (1999).

4. D. Hubbard, "Reducing noise on the output of a switching regulator," TI, ADJ, Rep., 2018.

5. J. Hua, "Output Noise Filtering for DC/DC Power Modules," TI, ADJ, Rep., 2019.

6. T. Ito and K. "Akatsu, Electromagnetic force acquisition distributed in electric motor to reduce vibration," Proc. 18th ICEMS, 1329-1333 (2015).

7. V. Umesh, S. Mishra, S. Simon, A. K. Singh, and P. Moses, "Universal electrical motor acoustic noise reduction based on rotor surface modification," Proc. IconDSC, 1-5 (2019).

8. C. Ma and S. Zuo, "Black-box method of identification and diagnosis of abnormal noise sources of permanent magnet synchronous machines for electric vehicles," IEEE Trans. Ind. Electron. **61**, 5538-5549 (2014).

9. D. Tousignant and J. Bylinski, "Relay acoustical noise reduction system," Ademco Inc, 2014.

10. Y. K. Ko, S. S. Cho, H. Huh, S. Y. Lee, H. T. Park, and I. S. Oh, "Design of HEV-relay using response surface method to improve bounce characteristics," Proc. IEEE ISIE, 169-174 (2009).

11. G. H. Lee, Y. B. Kim, H. T. Park, and J. W. Son, "Study on the noise reduction of the high voltage DC relay" (in Korean), Proc Trans. Korean Soc. Noise Vib. Eng. 788-792 (2007).

12. J. Y. Seo and W. J. Kim, "An experimental study on the noise reduction method of HEV-relay module" (in Korean), Journal of KSPE, **27**, 77-83 (2010).

13. V. Gurevich, *Electric Relays, Principles and Applications* (CRC Press, Boca Raton, 2005), pp. 79-82.

14. R. Holm, *Electric Contacts: Theory and Application* (Springer-Verlag, Berlin, 1967), pp. 1-484.

15. J. A. Greenwood, "Constriction resistance and the real area of contact," Br. J. Appl. Phys. **17**, 1621-1632 (1966).

16. P. Zhang, *Effects of surface roughness on electrical contact, RF heating and field enhancement*, (Ph.D. dissertation, The University of Michigan, 2012).

17. Y.M. Kim, S. H. Cho, K. J. Lim, K. S. Kim, and B. Y. Jang, "Analysis on electromagnetic repulsion force in molded case circuit breaker," Proc. 1st ICEPE-ST, 379-382 (2011).

18. M. Braunovic, V. V. Konchits, and N. K. Myshkin, *Electrical Contacts - Fundamentals, Applications and Technology* (CRC Press, Boca Raton, 2006), pp.6-9.

Profile

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