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Characteristics of Linear Actuator Type Vehicle Horn Considering Magnetic Saturation and Eddy Current Loss

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Electrical characteristics of a typical vehicle horn are determined by its resistance and inductance. The inductance is affected by factors such as the magnetic circuit, current magnitude, eddy currents and material properties. The mechanical characteristics of the vehicle horn are also affected by its material properties, the horn structure and its natural frequency. Mechanical and electrical parameters change during the operation of a vehicle horn. Therefore, it is difficult to predict the vehicle horn performance and hence, its design. In this study, firstly, the electrical and mechanical system of a vehicle horn are mathematically modeled. Secondly, the electrical and mechanical parameters are calculated using the finite element analysis method. Thirdly, to predict the operating characteristics of the vehicle horn, the electrical/mechanical system equations are solved by applying the parameters obtained from the finite element analysis. Finally, the simulation results and experimental results are compared and verified.

Keywords : eddy current, finite element analysis, linear actuator, inductance

1. Introduction

A vehicle horn, also known as 'klaxon', is a kind of linear actuator. It is made of solid steel and requires rapid mechanical action. The internal system of a vehicle horn moves quickly in response to its magnetic field and generates a significantly high eddy current. The eddy current causes heat to be generated in the internal system and reduces its inductance. Therefore, it is important to predict the effect of the eddy current.

In order to analyze the behavior of a vehicle horn, it is necessary to know the diaphragm and shaft mass, the spring constant, damping coefficient, resistance, and inductance. These constants are interrelated and are not independent. Therefore, when the value of a certain constant changes, other values also correspondingly change. Hence, it is challenging to analyze the operating characteristics of a vehicle horn at the initial design stage.

Therefore, a method for analyzing the coupling between the electromagnetic FEA and structural FEA has been studied in order to predict the electro-mechanical operational characteristics. Although this was a suitable way to increase the accuracy, it did not reflect the eddy current effect [1, 2].

Another method is to predict the performance using an equivalent magnetic circuit. In this study, the eddy current effect and magnetic saturation characteristics were investigated using an equivalent magnetic circuit. The results of the method using the equivalent magnetic circuit can be predicted quickly, thus rendering the method suitable for the initial design stage [3].

In this paper, the effect of the eddy current on the vehicle horn characteristics was investigated. Experiments and the FEA were used to solve the mathematical modeling equations of the vehicle horn. Finally, the experimental results and the analytical results were compared and verified.

2. Modeling and Operating Principle of the Vehicle Horn

2.1. Operating principle of the vehicle horn

The structure of the vehicle horn is shown in Fig. 1. The vehicle horn is covered with a diaphragm in a cylindrical structure. When a current flows through the coil,

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the generated magnetic flux passes through the fixed core, air gap, shaft, diaphragm, and body. The magnetic flux creates a force between the shaft and fixed core, thereby closing the circuit. When the voltage is turned off, the force between the fixed core and shaft disappears and the shaft returns to its original position due to the restorative force of the diaphragm. This action is repeated to produce sound in the vehicle horn. Generally, the vehicle horn is driven by voltage PWM.

2.2. Modeling of the vehicle horn

The resistor of the coil is ideally considered to be in series with the inductor. The voltage equation for the vehicle horn can be expressed by Eq. (1). The rate of change of the linkage flux $\psi(I, z)$ is expressed by Eq. (2) [4].

$$V = RI + \dot{\psi}(I,z) \tag{1}$$

$$\dot{\psi}(I,z) = \frac{\partial\psi(I,z)}{\partial I}\frac{\partial I}{\partial t} + \frac{\partial\psi(I,z)}{\partial z}\frac{\partial z}{\partial t} \tag{2}$$

The linkage flux $\psi(I, z)$ changes nonlinearly with the current I and shaft position z. The first term on the right side of Eq. (2) is the induced voltage due to the current change, and the second term is the induced voltage due to the shaft speed. This formula needs to be modified to reflect the eddy current effect. The magnetic flux due to eddy currents reduces the main flux, thereby reducing the inductance. The second term on the right-hand side of Eq. (2) is difficult to obtain experimentally or numerically; therefore, equation (3) is modified to reflect the first term.

$$V = RI + L(I,z)\frac{dI}{dt} \tag{3}$$

In order to numerically obtain the inductance that reflects the eddy current effect, modeling is performed as shown in Fig. 1, and the material data (BH-curve, conductivity) is reflected.

Modeling of the mechanical systems can be done with the help of Newton's second law [5].

$$F(I,z) = M\frac{d^2z}{dt^2} + D\frac{dz}{dt} + Kz \tag{4}$$

$F(I, z)$ is the force of the magnetic field generated between the shaft and the fixed core, M is the mass of the shaft and the diaphragm, D is the damping coefficient, and K is the spring constant.

3. Experimental and Simulation Verification

3.1. Inductance

The experimental setup for measuring the inductance to be applied in the simulation of the vehicle horn is shown in Fig. 2. The inductance was calculated using reactive power.

The current amplitude was applied as input, while being gradually increased, up to $7A_{rms}$ at intervals of 1 A_{rms}, and the current frequency was applied as input, while being gradually increased, up to 500 Hz at intervals of 100 Hz. When applying the current as the input, a non-magnetic paper was inserted between the shaft and fixed core in order to maintain the air gap length constant. In addition, to suppress the vibration, the vehicle horn was held in place using a vise.

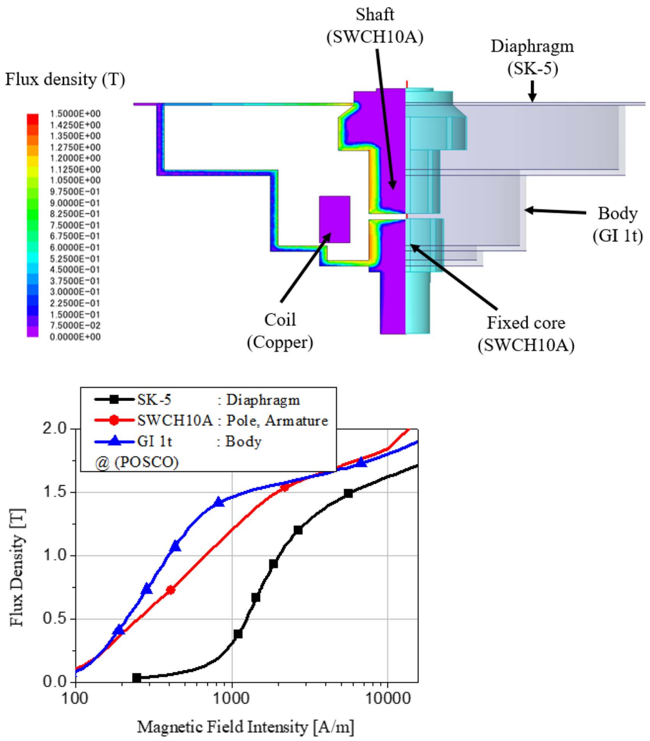


Fig. 1. (Color online) Vehicle horn structure and B-H curve.

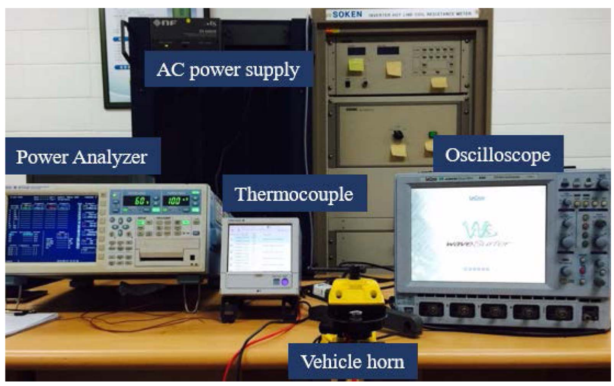


Fig. 2. (Color online) Experimental setup for parameter measurement.

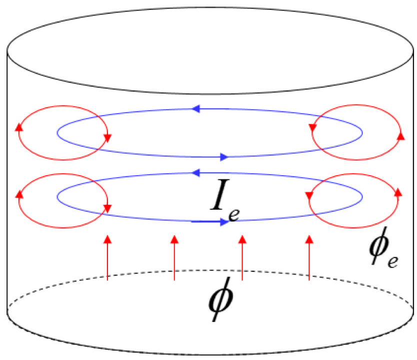


Fig. 3. (Color online) Comparison of inductance by frequency.

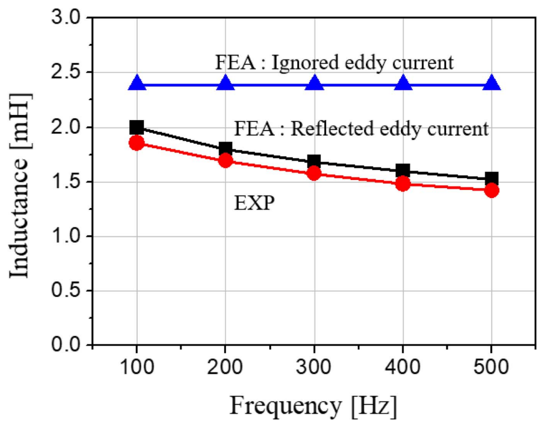


Fig. 4. (Color online) Effect of eddy current on core.

A comparison of the numerical analysis and experimental results of the inductance is shown in Fig. 4. Material data (B-H curve) in Fig. 1 was used for the FEA. Core conductivity is 6.25×10^6 [S/m]. The conductivity may be somewhat different for each material but has been ignored in this study.

The magnetic flux generated by the input current is ϕ. The magnetic flux is alternated and the eddy current is generated in the core (ϕ_e), which is opposite to ϕ. As shown in Fig. 3, the magnetic flux that flows in the core is the difference between ϕ and ϕ_e. The inductance is analyzed and measured by changing the frequency, with the input current fixed at $7A_{rms}$. As shown in Fig. 4, if the eddy current effect is neglected, the inductance is constant regardless of the frequency. However, when the eddy current effect is considered, the eddy current increases and the inductance tends to decrease, with an increase in frequency.

3.2. Mechanical parameters

To solve Eq. (4), *M*, *D*, and *K* values should be known. *M* was easily measured using a scale. *D* and *K* were measured using a modal test. The spring constant *K* was calculated using Eq. (5) and the damping coefficient D was calculated by Eq. (6) [6].

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \tag{5}$$

$$D = \frac{1}{\sqrt{1+\left(\frac{2f_n}{f_{delta}}\right)^2}} \tag{6}$$

f_n is the natural frequency, and f_{delta} is defined as the difference in the frequency which is 3 dB smaller than the

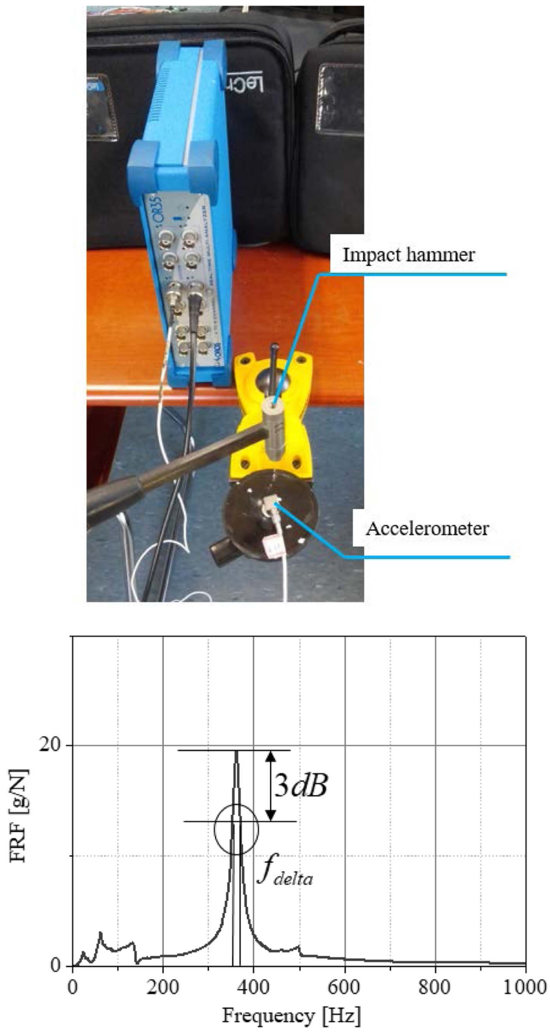


Fig. 5. (Color online) Modal test.

Table 1. Mechanical parameters.

M: Mass [g]	*D*: Damping coefficient [Ns/m]	*K*: Spring constant [kN/m]
40	3.17	328

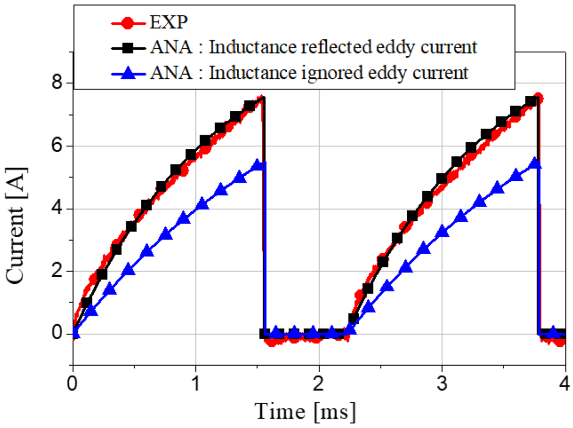
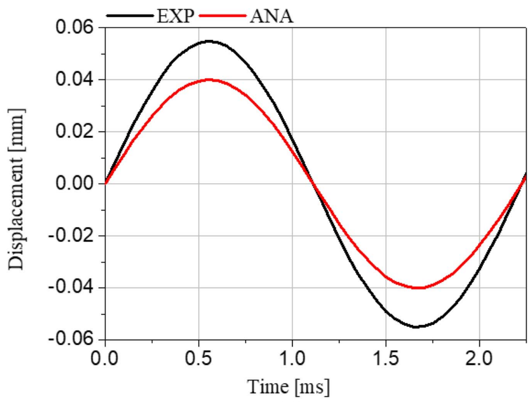


Fig. 6. (Color online) Current waveforms under operating conditions.

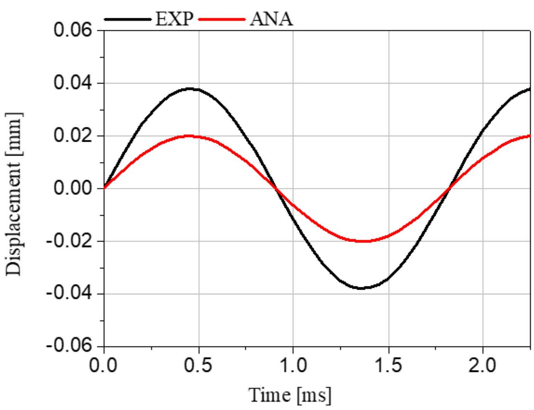
maximum value of the FRF (frequency response function). The experimental setup and experimental results for modal testing are shown in Fig. 5. The mechanical parameters were measured as presented in Table 1.

3.3. Dynamic characteristics

To analyze the dynamic characteristics of the vehicle horn, Eq. (3) and (4) were solved simultaneously. The experimental results and the results of the analysis of the dynamic characteristics were compared under a 12 V DC voltage, a PWM frequency of 450 Hz and 550 Hz, and a PWM duty ratio of 70 %. If the dynamic characteristics are analyzed by investigating the inductance considering the eddy current effect, the experimental value and the analytical value match well, as presented in Fig. 6. However, by investigating the inductance which does not consider the eddy current effect, the result of the analysis of the dynamic characteristics has an error.



(a)



(b)

Fig. 7. (Color online) Displacement comparison EXP and ANA at (a) 450 Hz (b) 550 Hz.

For the PWM operation, the measured displacement of the diaphragm is presented in Fig. 7(a) and the analysis value in Fig. 7(b). As the frequency decreases, the diaphragm displacement magnitude tends to increase. This is because the magnitude of the displacement increases as the PWM frequency approaches the natural frequency (375 Hz). At the same frequency condition, an error occurs in the analytical displacement and experimental displacement. This is expected to be due to the measurement error in either the spring constant or the damping coefficient. In order to reduce the error during analysis of the dynamic characteristics, it is necessary to study the measurement method or estimation method of the mechanical parameters.

4. Conclusion

In this study, a method for the dynamic analysis of a vehicle horn is presented. The necessity of analyzing the dynamic characteristics using inductance considering the eddy current is explained. The results obtained from analysis and experiment were compared and verified. This study can be used to analyze the dynamic characteristics of solenoid-type electric devices during the initial design stage.

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