Theoretical Study and Experimental Test on Solenoid Actuator of Active Control Mount

Fang-Hua Yao, Rang-Lin Fan, and Song-Qiang Qi

Abstract Solenoid active control mount is excellent in vibration isolation, but the complex nonlinear relationship between electromagnetic force and exciting voltage/current makes it difficult to be controlled. The nonlinearity in solenoid actuator was studied by combining methods of theory, simulation, and experiment. Two theoretical equations for electromagnetic suction on voltage/current were obtained, then the equation with voltage was modified through electromagnetic simulation, and the test data were used to get the fitted parameters in equation with current. The results of simulation and theoretical calculation are consistent, and the fitted curve is close to the test, indicating the two equations are reliable. This reveals the nonlinear relationship between solenoid actuator and excitation and promotes follow-up control research.

Keywords Active control mount · Nonlinearity · Electromagnetic suction · Modeling · FEM · Automotive

1 Introduction

One of the main sources of vehicle vibration is the simple harmonic excitation of different harmonic orders and amplitudes generated by automobile engine [1]. The mounting between the powertrain and the frame can greatly reduce the vibration transmitted from the engine to the frame. Due to immature production technology and high price, active mount only appears in a few high-end cars. With the continuous improvement of new material technology and control level, active mount will be more

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and more popular [2, 3], so the research on active mount has practical engineering value.

The solenoid-type active mount is composed of a solenoid actuator on the basis of the traditional hydraulic engine mount (HEM). The actuator converts the electric energy into mechanical energy by using the unidirectional alternating suction produced by the electromagnet when alternating voltage/current being applied to the coil. These advantages of no permanent magnet, compact structure, wide frequency band, and large displacement make solenoid actuator widely used in active vibration control [4]. The principle of solenoid actuator is similar to electromagnet. Xiang et al. [5] using finite element method to obtain accurate magnetic field calculation results. The static and dynamic performance test of force and displacement type proportional electromagnet can be completed automatically by computer, and the corresponding performance index can be obtained [6]. In addition, according to the typical structure of the toroidal electromagnet, Mei et al. [7] have derived the calculation equation of the electromagnetic attraction of the circular ring electromagnet, which lays a foundation for the research of solenoid actuator. This paper focus on the nonlinearity of solenoid actuator in active force and input voltage/current.

2 The Structure of Solenoid Actuator

The structure of solenoid actuator is shown in Fig. 1. The actuator is formed by the coil, armature (mover), upper yoke, lower yoke, coil cover, and conical air gap, which can reduce the magnetic resistance, so that the magnetic flux generated by the energized coil is less leaked, the suction force is enhanced, and the power efficiency is improved.

The solenoid actuator is installed in the mount bottom case and incorporated with the decoupling membrane. When the coil is electrified, a magnetic field is generated, which produces a unidirectional suction on the mover; when the suction decreases, the mover moves upward by the elastic restoring force of the decoupling membrane.

When engine is running, unbalanced reciprocating inertia force and unbalanced overturning torque are transmitted to the frame end through the primary channel of the active mount [8, 9]. The working principle of solenoid actuator is that the coil generates alternating magnetic field through alternating current, which produces

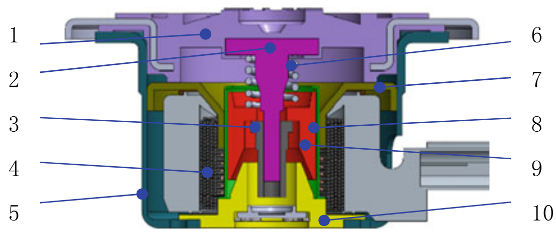


Fig. 1 Solenoid actuator 3D model: 1. Decoupling membrane, 2. Ejector rod, 3. Ejector rod nut, 4. Coil, 5. Mount bottom case, 6. Positioning spring, 7. Upper yoke, 8. Sleeve, 9. Armature (mover), 10. Lower yoke

suction to the mover fixed on the decoupling membrane. The reaction force generated by the movement of the actuator counteracts the force transmitted by the engine to the frame end to reduce the vibration of the frame. Meanwhile, the dynamic characteristics of the HEM are also changed by the electromagnetic force. The active attenuating mechanism could be comprehended from the perspective of directly reducing the force transmitted from the engine to the frame end by the actuator, or from the perspective of changing the dynamic characteristics of HEM to harvest good vibration isolation.

3 Modeling of Solenoid Actuator

According to the structure of the actuator in Fig. 1, the mechanical model is shown in Fig. 2. The mathematical model of solenoid actuator is as follows:

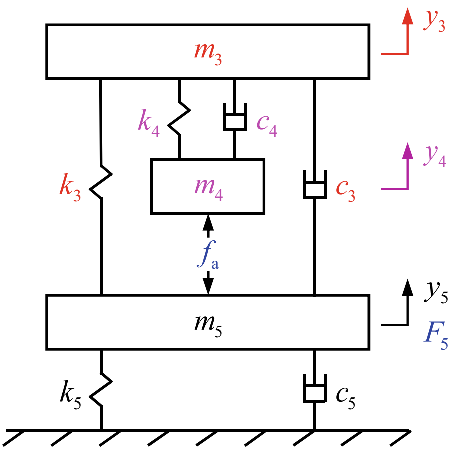
$$m_3\ddot{y}_3 + c_4(\dot{y}_3 - \dot{y}_4) + k_4(y_3 - y_4) + c_3(\dot{y}_3 - \dot{y}_5) + k_3(y_3 - y_5) = 0 \quad (1)$$

$$m_4\ddot{y}_4 + c_4(\dot{y}_4 - \dot{y}_3) + k_4(y_4 - y_3) - f_a = 0 \quad (2)$$

$$m_5\ddot{y}_5 + c_5\dot{y}_5 + k_5 y_5 + c_3(\dot{y}_5 - \dot{y}_3) + k_3(y_5 - y_3) + f_a = 0 \quad (3)$$

When the actuator works, in addition to the reaction force of electromagnetic force, the elastic force and damping force of decoupling membrane are transferred to the stator. Therefore, the net output force (positive upward) harvested on the stator is as follows:

Fig. 2 Solenoid actuator physical model



$$F_5 = -f_a + c_3(\dot{y}_3 - \dot{y}_5) + k_3(y_3 - y_5) = -(m_3\ddot{y}_3 + m_4\ddot{y}_4) \tag{4}$$

The equation shows that the force on the body end caused by the action of the actuator is essentially the sum of the inertia force of the mass m_4 of the mover, and the mass $m_3$of the ejector bar, the decoupling membrane, and the attached liquid. The sum of the inertia forces is used to counteract the force transferred from the primary channel to the body end, so as to achieve the effect of vibration and noise reduction.

According to the mathematical model, the frequency response function (FRF) of net output force F_5 to electromagnetic force f_a can be obtained, and the FRF curve is obtained after the actual parameters of actuator in Table 1 are brought in, as shown in Fig. 3.

Table 1 Solenoid actuator parameters

Parameter	Name	Value
m_3	Mass of decoupling membrane/kg	0.266
m_4	Mass of mover/kg	7.100×10^{-2}
m_5	Mass of stator/kg	0.4
k_3	Dynamic stiffness of decoupling membrane/N·m^{-1}	8.641×10^4
k_4	Stiffness of mover/N·m^{-1}	1.547×10^6
k_5	Stiffness of stator/N·m^{-1}	2.855×10^6
c_3	Damping of decoupling membrane/N·s·m^{-1}	19.5
c_4	Damping of the mover/N·s·m^{-1}	16
c_5	Damping of the stator/N·m·s^{-1}	5.000×10^2

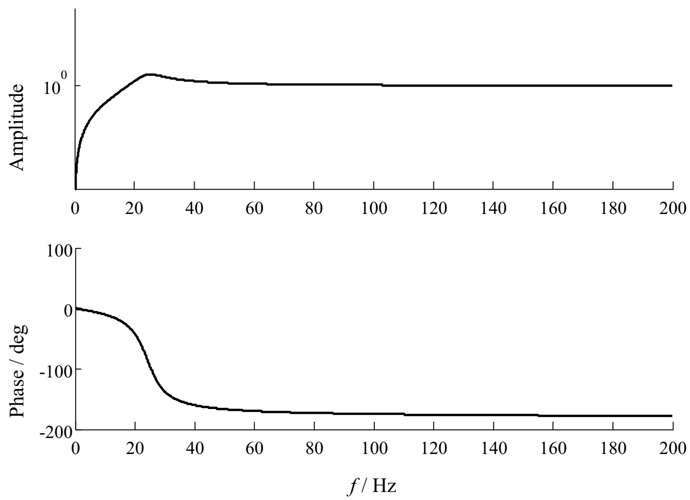


Fig. 3 Frequency response curve of actuator net output force to electromagnetic force

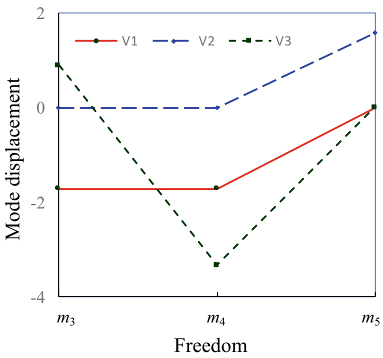


Fig. 4 Actuator mode curve

$$G(s) = \frac{F_5}{f_a} = \frac{-M_3M_4M_5 + M_3M_4C_3 + M_5C_3C_4 + M_5C_4^2 - C_3^2C_4 - C_3C_4^2}{M_3M_4M_5 - M_4C_3^2 - M_5C_4^2} \tag{5}$$

where $M_3 = m_3s^2 + (c_3 + c_4)s + (k_3 + k_4);\ M_4 = m_4s^2 + c_4s + k_4$

$$M_5 = m_5s^2 + (c_3 + c_5)s + (k_3 + k_5);\ C_3 = c_3s + k_3; C_4 = c_4s + k_4$$

It can be seen from Fig. 3 that the ratio of net output force to electromagnetic force is 1 in the frequency band of 25–200 Hz, that is, the net output force and electromagnetic force of the actuator are equal. Therefore, electromagnetic force can be used to replace the active force. Thus, the required electromagnetic force can be directly obtained by controlling the voltage or current to eliminate the vibration of the engine. The frequency band meets the requirements of active engine mount.

In fact, the modal analysis was shown in Fig. 4, which shows that the low-frequency peak value of the FRF in Fig. 3 is induced by the modal of the ejector rod, the decoupling membrane and its attached liquid mass m_3, and the mass m_4 of the mover on the elastic k_3 of the decoupling membrane. The modal frequency of this order is low, m_3 and m_4 vibrate in the same amplitude simultaneously, which was shown in the first mode shape in Fig. 4; the other two orders, the modal of the stator mass m_5 on the foundation elasticity k_5 and the modal of the mover mass m_4 on the ejector elasticity k_4, are higher than 400 Hz, which is far away from the working frequency band of the actuator.

4 Theoretical and Experimental Study on Solenoid Actuator

The results of the previous sections show that, in the working frequency band of the actuator, the active electromagnetic force f_a acts on the frame end with equal reverse force F_5, so as to attenuate the force transmitted from the passive channel to the frame end, achieving the purpose of vibration reduction. The following contents will study the relationship between the exciting current/voltage of solenoid actuator and active electromagnetic force.

4.1 Study on the Relationship Between Electromagnetic Attraction and Voltage/Current

The simplified structure of solenoid actuator is shown in Fig. 5. For the electromagnet with conical surface [10], the air gap magnetoresistance is:

$$R_\delta = \frac{1}{\mu_0 \times 10^{-2}\left(\frac{100\pi d_c^2}{4\delta \sin^2\alpha} - \frac{15.7 d_c}{\sin^2\alpha} + 75 d_c\right)} = \frac{10^8}{\left(\frac{0.139}{\delta} + 1.452\right)} \tag{6}$$

where α is cone angle, 45°; d_c is outer diameter of mover, 26.5 mm; A_0 is cross-sectional area of air gap, 379.5 mm^2; μ_0 is air permeability, $4\pi \times 10^{-7}$ H/m; R_δ is air gap magnetoresistance, H^{-1}; δ is air gap length, m.

When the coil is energized, a certain amount of magnetic flux is generated on the magnetic circuit formed by the mover, upper yoke, lower yoke, and actuator shell. According to the theory of electromagnetism, electromagnet suction is $f = 10^7 B_0^2 A_0 / (8\pi)$, the premise that the core is not saturated, the magnetic field in the AC electromagnet is also AC. if the AC magnetic field $B_0 = B_m \sin\omega t$, the instantaneous value of electromagnetic attraction f, the maximum value F_m and the average value F_0 are, respectively:

$$f = \frac{1}{2}F_m - \frac{1}{2}F_m \cos 2\omega t \tag{7}$$

$$F_m = \frac{10^7}{8\pi} B_m^2 A_0 \tag{8}$$

$$F_0 = \frac{1}{2}F_m \tag{9}$$

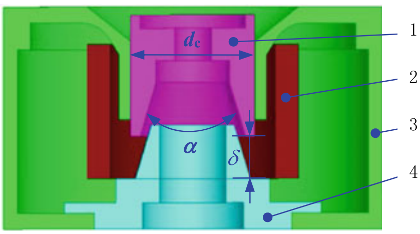


Fig. 5 Simplified model of solenoid actuator: 1. Armature (mover), 2. Coil, 3. Outer shell, 4. Lower yoke

Based on the relationship $\Phi_{\mathrm{m}} = B_{\mathrm{m}}A_0$, and Ohm's law of magnetic circuit $\Phi_{\mathrm{m}}R_\delta = NI_{\mathrm{m}}$, the relationship between the maximum suction force F_m and the maximum current I_m is:

$$F_{\mathrm{m}} = \frac{10^7}{8\pi}\frac{N^2}{A_0}\left(\frac{1}{R_\delta}\right)^2 I_{\mathrm{m}}^2 = \left(\frac{0.00639}{\delta} + 0.06697\right)^2 I_{\mathrm{m}}^2 \tag{10}$$

where N is the number of coil turns, with a value of 150.

For AC iron core-coil circuit, the relationship between the effective value of voltage U and the maximum magnetic flux Φ_{m} is $U = 4.44fN\Phi_m$, combined with $\Phi_{\mathrm{m}} = B_{\mathrm{m}}A_0$, the relationship between the maximum suction force F_{m} and the effective voltage U is as follows:

$$F_{\mathrm{m}} = \frac{10^7}{8\pi}\frac{1}{A_0}\left(\frac{1}{4.44N}\right)^2\left(\frac{U}{f}\right)^2 = 2132.1\left(\frac{U}{f}\right)^2 \tag{11}$$

Accordingly, the relationship between the amplitude of electromagnetic suction F_{a} and the maximum current I_{m} and the effective voltage U is as follows:

$$F_{\mathrm{a}} = \frac{1}{2}F_{\mathrm{m}} = \left(\frac{0.001598}{\delta} + 0.01674\right)^2 I_{\mathrm{m}}^2 \tag{12}$$

$$F_{\mathrm{a}} = \frac{1}{2}F_{\mathrm{m}} = 1066.05\left(\frac{U}{f}\right)^2 \tag{13}$$

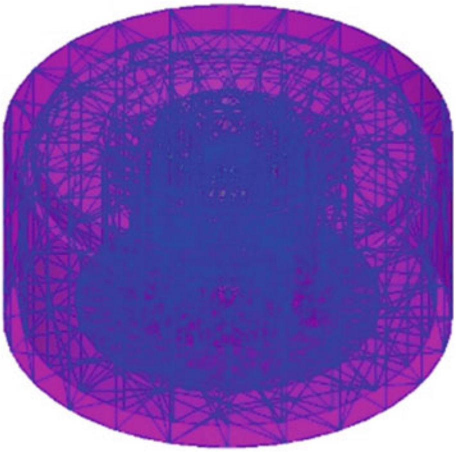
4.2 Simulation Analysis Based on Ansoft Maxwell

This paper mainly simulates the transient magnetic field of solenoid actuator. Based on the actual structure and working principle of solenoid actuator, the simulation model is established and analyzed by Ansoft Maxwell. The finite element model (FEM) is shown in Fig. 6.

The relative permeability of the silicon steel sheet is 8000–10,000, the mover is pure iron, and the coil turns are 150. The size of the air gap is adjusted by the position of the actuator. When the air gap is 0, 2.5 and 5 mm, a voltage with effective value of 5 V and frequency of 50 and 100 Hz, respectively, are applied to simulate the magnetic induction strength, the magnetic flux generated at the air gap, the current in the coil, and the amplitude suction force of the actuator are extracted.

The simulation results and theoretical calculation results show that the current, magnetic flux, magnetic resistance, and electromagnetic force obtained by simulation have large errors compared with the theoretical calculation results. The causes of large error are analyzed as follows:

Fig. 6 Actuator FEM



(1) When the magnetic resistance equation in electromagnet design manual is applied to solenoid actuator, the actual structure between them is different, so the theoretical calculated reluctance is smaller than the simulated reluctance, and the simulation current is greater than the theoretical calculation current.

(2) There is magnetic flux leakage in the simulation process, which leads to the simulated magnetic flux less than the theoretical calculation, so the simulated electromagnetic force is less than the theoretical calculation.

In view of the fact that the electromagnetic force of theoretical calculation is increased by 30% compared with the electromagnetic force of FEM simulation, to sum up the error analysis and simulation results, Eq. (13) is modified as follows:

$$F_{\mathrm{a,m}} = \frac{F_{\mathrm{a}}}{1.3} = 820.04\left(\frac{U}{f}\right)^2 \tag{14}$$

The comparison between the calculation results by using the modified Eq. (14) and the simulation results is given in Table 2. The modified results agree well with the simulation ones, indicating that the calculation Eq. (14) of electromagnetic force on voltage is reliable.

4.3 Experimental Test on Solenoid Actuator

The experimental test is carried out. When the actuator being activated, the force sensor picks up the force transmitted to the frame end, and the current sensor picks up the loading current.

The first group of tests: the current is used as the excitation, the effective current remains unchanged, and the excitation frequency varies from 10 to 70 Hz. The test

Table 2 Comparison of simulation and theoretical calculation after voltage equation correction

	U/V	f/Hz	Φ_m/Wb	F_a/N
0 mm				
Theoretical results	5	50	1.502×10^{-4}	8.204
Simulation result	5	50	1.529×10^{-4}	8.195
Theoretical results	5	100	7.510×10^{-5}	2.050
Simulation result	5	100	7.430×10^{-5}	2.045
2.5 mm				
Theoretical results	5	50	1.502×10^{-4}	8.491
Simulation result	5	50	1.490×10^{-4}	8.861
Theoretical results	5	100	7.510×10^{-5}	2.123
Simulation result	5	100	7.780×10^{-5}	2.212
5.0 mm				
Theoretical results	5	50	1.502×10^{-4}	8.323
Simulation result	5	50	1.589×10^{-4}	8.841
Theoretical results	5	100	7.510×10^{-5}	2.081
Simulation result	5	100	7.350×10^{-5}	2.429

results of the maximum force and frequency under different current are shown in Fig. 7. The maximum force is basically not affected by the frequency, which is consistent with the theoretical result without frequency variable in Eq. (12), and is also consistent with the simulation results of the frequency response curve in Fig. 3 reaching horizontal straight line after 25 Hz.

Considering that the theoretical Eq. (12) of electromagnetic suction on current contains the air gap value δ between conical surfaces which is inconvenient to accurately measure. It can be seen from Table 2 when the air gap changes, the force almost

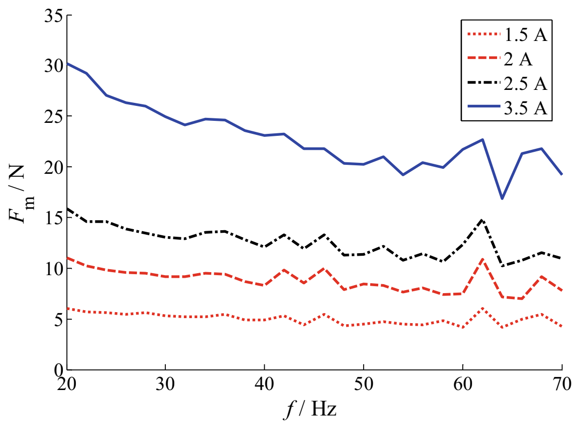


Fig. 7 Test curve of maximum force and frequency under different currents

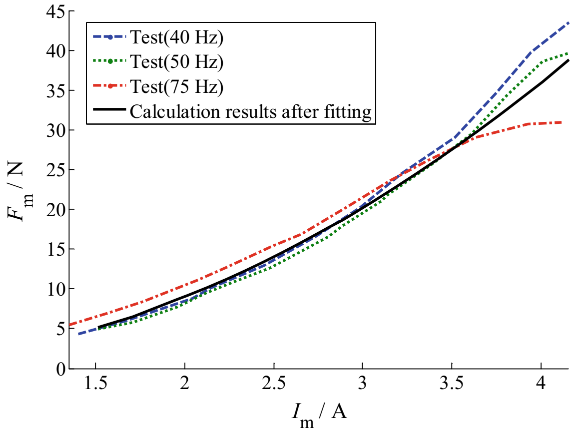


Fig. 8 Comparing calculation results with test results after fitting

remains unchanged at the same frequency. Therefore, the second group of tests can be designed to fit the parameter δ of Eq. (12).

The second group of tests: the current is used as the excitation to which frequency is fixed but the effective value is gradually increased from 0 to 5 A; the maximum attraction force at multiple frequencies of 40 Hz, 50 Hz, 75 Hz, etc., were measured, respectively.

Fitting the test data at multiple frequencies to obtain $\delta = 0.00460$, it can be substituted into Eq. (12) for calculation, and the maximum electromagnetic attraction at 40 Hz, 50 Hz and 75 Hz is compared with the test results as shown in Fig. 8. The test curve is basically consistent with the equation calculation curve obtained after fitting the parameters, indicating that the parameter fitting of δ is successful. Therefore, the fitting value of δ can be directly used in Eq. (12), and the accurate electromagnetic suction equation for current can be obtained as follows:

$$F_0 = \frac{1}{2}F_m = \frac{1}{2}\left(\frac{0.00639}{0.00460} + 0.06697\right)^2 I_m^2 = \frac{1}{2} \times 2.120 I_m^2 = 1.060 I_m^2 \qquad (15)$$

After obtaining Eq. (15), the problem that the required vibration isolation force cannot be calculated even when the air gap value could not be measured when the electromagnetic force is controlled by the current can be solved.

5 Conclusion

In this paper, the solenoid actuator is studied deeply, the frequency response curve of the net output of the actuator to the electromagnetic force is obtained through its mathematical and physical model. It is clear that the amplitude of electromagnetic suction and net output force are equal in the working range of the actuator, so the vibration transmitted from the engine to the body end can be offset by controlling electromagnetic suction.

Based on theoretical derivation, the electromagnetic attraction is studied. the calculation equations of electromagnetic suction with respect to voltage / current are obtained; electromagnetic simulation is carried out for the equation with voltage, and according to the error analysis between the theoretical calculation results and the simulation results, the equation is modified to make it close to the simulation results; In addition, the parameters in the electromagnetic suction equation about the excitation current are fitted through the test data. Finally, the simulation results are consistent with the modified theoretical calculation results, and the fitting calculation curve is basically consistent with the test curve, which shows that the calculation equation of electromagnetic suction of actuator about voltage / current obtained in this paper is accurate.

In conclusion, the research method of combining theory, simulation, and experimental test on solenoid actuator is effective and reveals the nonlinear relationship between solenoid actuator electromagnetic suction and excitation voltage / current, which lays a solid foundation for next research on the control strategy of solenoid active control mount.

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