Design of natural frequency adjustable electromagnetic actuator and active vibration control test

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ABSTRACT

An inertia electromagnetic actuator capable of adjusting natural frequency is designed in this paper. There are two procedures in the design of electromagnetic actuator: magnetic circuit design and stiffness conditioning design. ANSOFT software is used to simulate the magnetic circuit during the magnetic circuit design and optimize the design of the actuator. In order to adjust the natural frequency, the actuator spring is designed adjustable to meet the different need of the system stiffness. Using the X-LMS algorithm，a series of active vibration control test has been done on the test bench. Experiment results show that if fixing the adjustable spring, the actuator can be used as a normal actuator, and it can only get the best control effect at one natural frequency. But when using the adjustable spring, it can get the best control effect at four natural frequency. At different control frequency, that actuator can improve the control effect about 0.4~6.9dB.

Keywords: Adjustable Natural Frequency, Electromagnetic Actuator, Optimal Analysis, ANSOFT

1. INTRODUCTION

Electromagnetic actuator plays an important role in field of vibration control, but its output efficiency depends much on whether or not the resonance is reached.[1] Enhancing the output efficiency of electromagnetic actuator has received much attention in recent years. For example, Ref. [2] put forward a new-style and high powered electromagnetic actuator which increases the output force by using high-strength magnets and increasing the turns of coil reasonably. M.L Zhu deduces a theory of electromagnetic spring [3], describing the computing method between the annular electromagnet and ring permanent magnet, which can be used to investigate the distribution of magnetic field and enhance the output efficiency.

The present paper explores an alternative approach by considering the potential beneficial of the adjustable nature frequency. Several works have be done to explore the feasibility of this method. X.G Liu and M.G Zhu have designed an energy-saving resonance type electric actuator [4], which can output larger actuation force under the condition of low energy consumption and has compact structure and extensive engineering application prospect. The resonance type electromagnetic actuator [5] designed by Y Lu and Z.Q Gu can generate large loading control under the driving of smaller power supply, it can change its resonance by adjusting the electromagnetic actuator spring rate and movable mass quality.

The work of this paper is organized as follows. The next section introduces the structure of the nature frequency adjustable electromagnetic actuator. The third section describes the simulation and optimal analysis by using ANSOFT, and mechanical designing size of the NFAEA. The fourth section examines the main properties of NFAEA and explains some phenomena we met during experiments. The final section makes a conclusion of the whole work.

2. THE STRCTURE INTRODUCE OF THE NATURE FREQUENCY ADJUSTABLE ELECTROMAGNETIC ACTUATOR

The structure of natural frequency adjustable electromagnetic actuator is shown as Fig.1. Electromagnetic force would be generated when an alternating current passes through the coil of actuator. The lower half part of NFAEA includes four parallel springs, one main spring connected with center axle and three regulating springs distributed symmetrically. The overall stiffness of spring will be changed along with the adjustment of position of regulating springs.

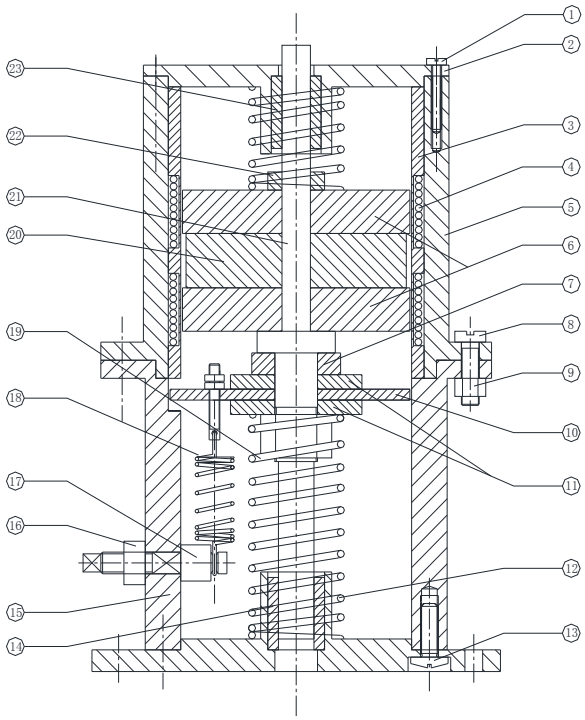


Fig 1 – Structure of natural frequency adjustable electromagnetic actuator
1-hex screw 2-upper cover 3-coil former 4-coil 5-upper outer cylinder 6-yoke 7-gasket 8-hex bolt 9-hex nut 10-adjustable plate 11-bottom plate 12-lower cover 13-slotted pan head tapping screw 14-lower cylinder 15-lower outer cylinder 16-butterfly nut 17-adjustable lever 18-regulating spring 19-main spring 20-permanent magnet 21-main axle 22- fixed collar 23-upper cylinder

The nature frequency of this actuator alters as the change of the overall stiffness of spring. When it is consistent with the electric current frequency, the actuator reaches resonance and output the maximum control force.

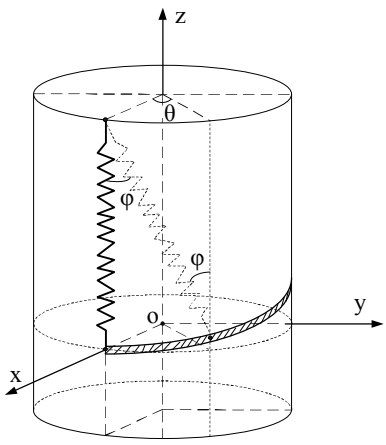


Fig 2 – Schematic diagram of stiffness adjustable mechanism

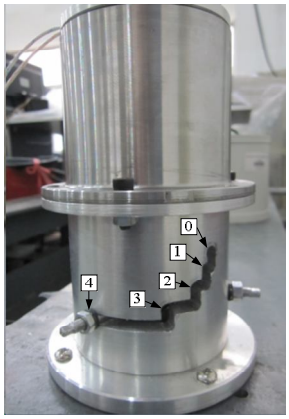


Fig 3 – Five positions of NFAEA

Fig.2 is the schematic diagram of stiffness adjustment mechanism. One end of the spring is fixed, and the other one moves along the path on the outer cylinder to ensure that the length of spring is invariable. If we define l the length of spring, the trajectory of the free end of the spring satisfies these equations below.

$$\begin{cases} x^2 + y^2 = r^2 \\ (x-r)^2 + y^2 + (z-l)^2 = l^2 \end{cases} \tag{1}$$

The effective stiffness of spring after the movement of the free end is a function of angle φ .

$$k' = k\cos\varphi \tag{2}$$

Where k is the effective stiffness when (the spring is parallel with center axle). From Fig.2, we can get $\cos\varphi = (l-z)/l$, so equation(2) can be rewritten as a function of displacement, z.

$$k' = k\cos\varphi = k\left(1 - \frac{z}{l}\right) \tag{3}$$

NFAEA has five status of springs, $k' = k$, $k' = 3k/4$, $k' = k/2$, $k' = k/4$, $k' = 0$, are represented by 4, 3, 2, 1, 0, respectively.

3. THE STRUCTURE OPTIMAL DESIGN OF THE NATURAL FREQUENCY ADJUSTABLE ELECTROMAGNETIC ACTUATER

This section describes the simulation of magnetic circuit and optimal parameters of various parts. We built simulation model according to the actual sizes of theoretical results by ANSOFT software, then we assigned actual material properties to the model.

3.1 Distributions of Magnetic Field and Magnetic Induction Intensity of the Actuator

Distributions of magnetic field and magnetic induction intensity of the actuator in the condition that the actuator isn't powered are showed as Fig.4 and Fig.5.

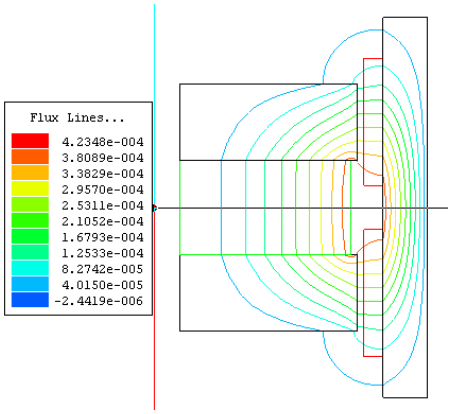


Fig 4 – Distribution of magnetic field

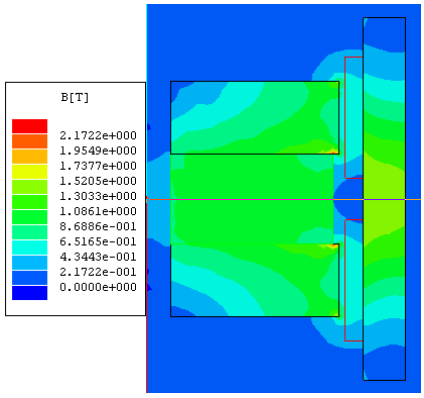


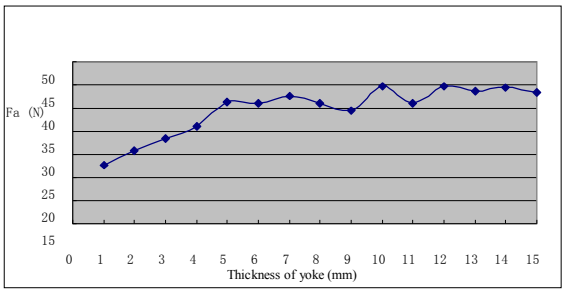
Fig 5 – Distribution of magnetic induction intensity

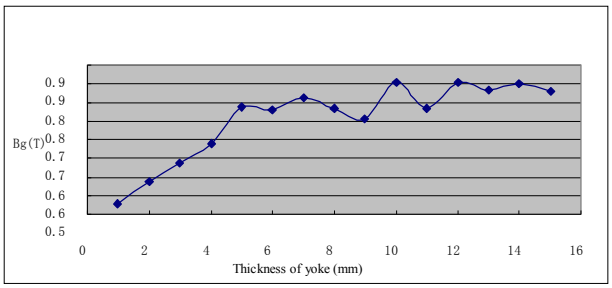
From Fig.4, we can see that almost all of magnetic lines distribute along the closed magnetic circuit consists of upper and lower yoke, air gap, coil, and the outer magnetic cylinder. It means there is no magnetic dispersion, the design is reasonable.

Fig.5 shows that only the joint of yoke and permanent magnetic is slightly saturated, the whole model has a very good magnetic energy utilization rate. In conclusion, the design of magnetic circuit is feasible.

3.2 Optimal Analysis of the Thickness of Yoke

When the magnetic coil is electrified by current 1A and other dimensions keep invariable, we change the thickness of yoke of the NFAEA from 1mm to 15mm. The impact of the thickness on electromagnetic force, Fa, and magnetic induced intensity of coin, Bg, is shown as Fig.6.





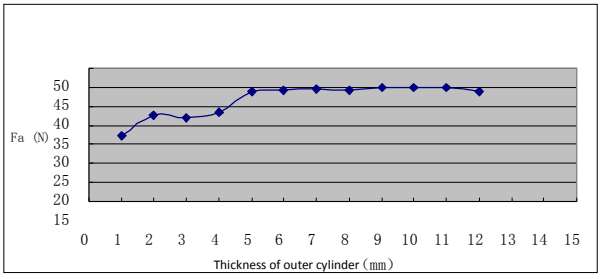
(a) F_a vs. the thickness of yoke (b) B_g vs. the thickness of yoke

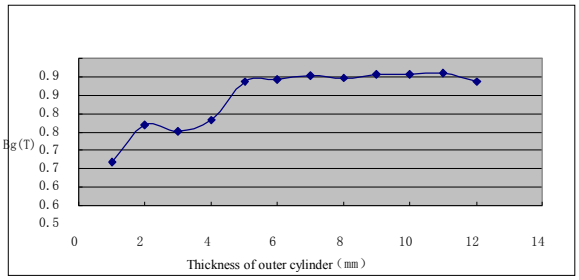
Fig 6 – Impacts of the thickness of yoke on electromagnetic force and magnetic induced intensity

As shown in Fig.6, we get that with the increase of the thickness of yoke F and Bg increases within a certain range, and remain stable after a critical value. That's because when the thickness of yoke is small, magnetic saturation trend exists in the magnetic field (shown as Fig.5) and it decreases with the increase of thickness of yoke. When the thickness is 12mm, the saturation phenomenon just disappears and the magnetic field achieve a highest energy utilization rate.

3.3 Optimal Analysis of the Thickness of Magnetic Conductive Outer Cylinder

When the magnetic coil is electrified by current 1A and other dimensions keep invariable, we change the thickness of magnetic conductive outer cylinder of the NFAEA from 1mm to 12mm. The impact of the thickness on electromagnetic force, Fa, and magnetic induced intensity of coin, Bg, is shown as Fig.7.





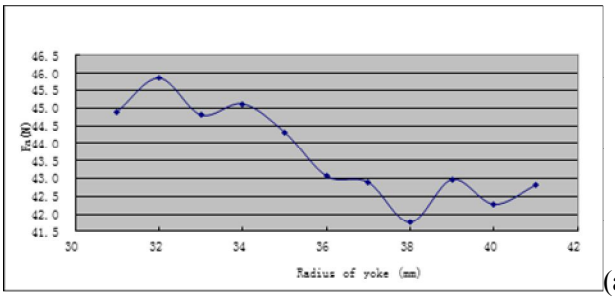
(a) F_a vs. the thickness of outer cylinder (b) B_g vs. the thickness of outer cylinder

Fig 7 – Impacts of the thickness of magnetic conductive outer cylinder on electromagnetic force and magnetic induced intensity

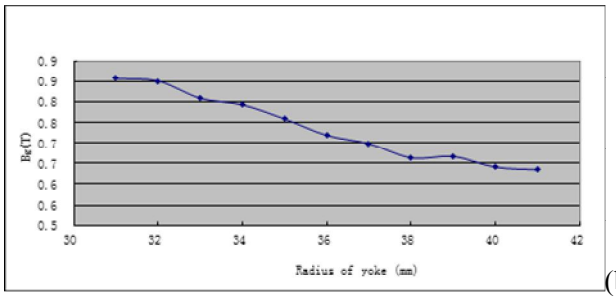
From Fig.7, we get that with the increase of the thickness of magnetic conductive outer cylinder F and Bg increases within a certain range, and remain stable after a critical value. When the thickness is small, a thinner cylinder leads to a higher energy utilization rate and a smaller area of magnetic saturation. The magnetic intensity and electromagnetic force will keep stable after the energy utilization reaches its highest value. Considering the factors such as processing installation, we choose 7mm as the thickness of magnetic conduction outer cylinder.

3.4 Optimal Analysis of the Radius of Yoke

We change the radius of yoke of the NFAEA from 31mm to 41mm while holding all other variables constant. The impact of the radius on electromagnetic force, Fa, and magnetic induced intensity of coin, Bg, is shown as Fig.8.



(a)



(b)

Fa vs. the radius of yoke B_g vs. the radius of yoke

Fig 8 – Impacts of the radius of yoke on electromagnetic force and magnetic induced intensity

Fig.8 shows a clearly difference between these two tendency charts. Compared with electromagnetic force, the magnetic intensity shows a more stable downtrend. We can analysis this difference by using this equation below.

$$B_g = F_a / IL \tag{4}$$

I is electric current, *L* presents the length of coil which is in the magnetic field. As the electricity area of coil-section keeps invariable, so *L* varies with the increase of yoke radius. So the trend of electromagnetic force is no longer proportional to magnetic intensity. Considering the effectiveness of NFAEA, we select 32mm as the radius of yoke.

3.5 Design of NFAEA Prototype

On the basis of the result of optimal analysis, the mechanical designing size can be gotten. The size is shown as Table 1.

Table 1 – The mechanical designing size of the NFAEA

Internal diameter of permanent magnet	Outside diameters of permanent magnet	Height of permanent magnet
8mm	62mm	15mm
Internal diameter of yoke	Outside diameter of yoke	Thickness of yoke
8mm	64mm	12mm
Internal diameter of magnetic conductive outer cylinder	Outside diameter of magnetic conductive outer cylinder	circle number
72mm	86mm	139
Height of upper cylinder	Height of lower cylinder	Height of actuator
83.5mm	80mm	167.5mm
Diameter of coil	Effective length of coil	coil resistance
0.47mm	60.7m	6.2Ω

4. EXPERIMENTAL INVESTIGATION

This section describes the series of experiments that were performed to test the NFAEA's properties. Natural frequencies under different conditions were obtained from the acceleration response curve measured by acceleration transducer and showed in Table 2.

Table 2 – Natural frequency of different positions measured by experiments

Number	Height z（mm）	Stiffness of the vertical component k’	Natural frequency (Hz)
4	0	$k' = k$	26.250
3	7.5	$k' = 3k/4$	31.500
2	15	$k' = k/2$	33.000
1	22.5	$k' = k/4$	30.000
0	30	$k' = 0$	22.750

From the experiment above, we found that the nature frequency peaks of NFAEA at point “0” and “4” (shown as Fig.5) are most obvious of all, so we choose them as the experimental points. Fig.9 shows the experimental program based on x-LMS algorithm and Fig.10 shows the primary equipment used during the experimental tests

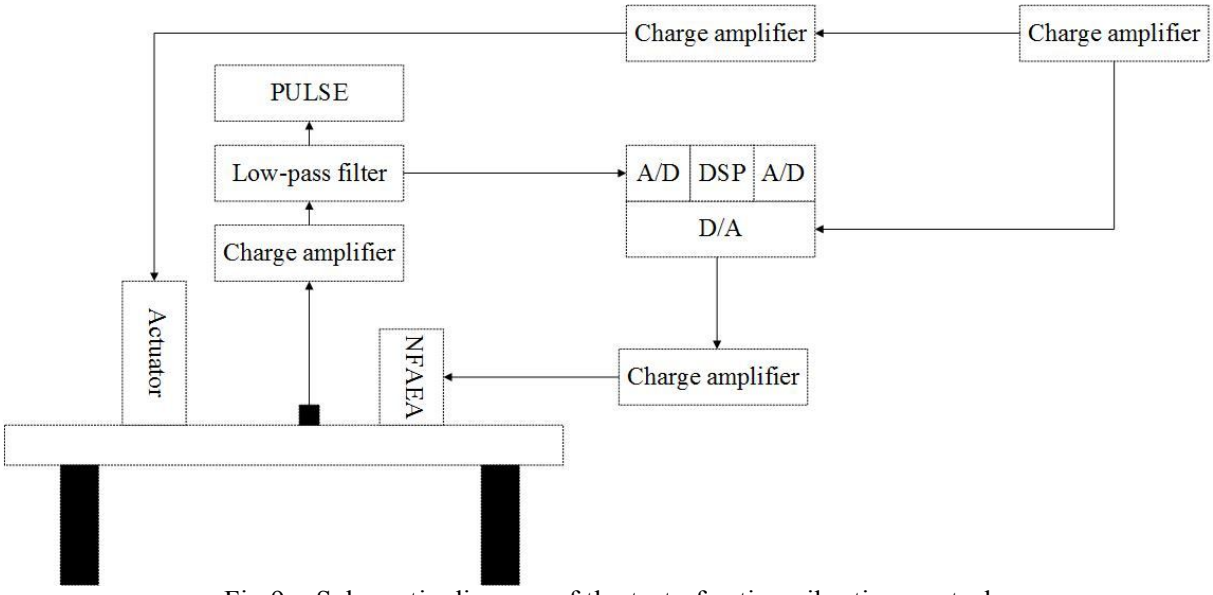
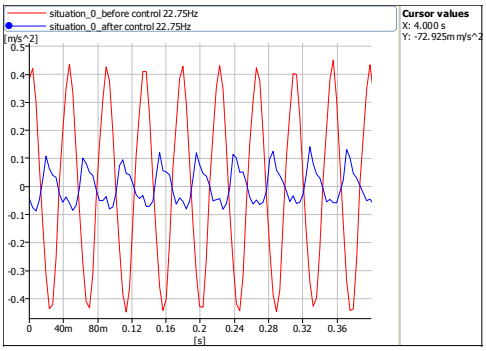


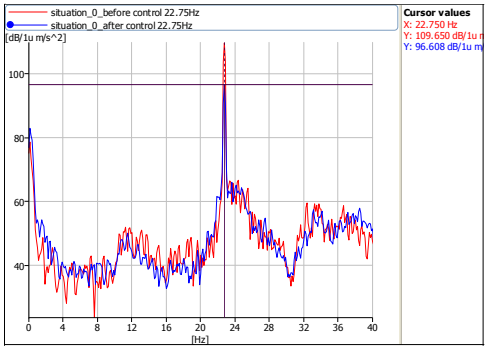
Fig 9 – Schematic diagram of the test of active vibration control

Fig 10 – primary equipment used during the experimental tests

Single frequency sinusoidal signal (22.75Hz) was applied to experimental system and the effectiveness of active control could be got by using x-LMS algorithm. We measured the effectiveness of active vibration control of “0” and “4” respectively which was showed as Fig.11 and Fig.12.

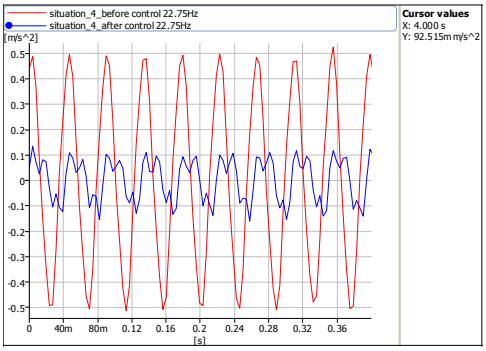


(a) Comparison in time domain

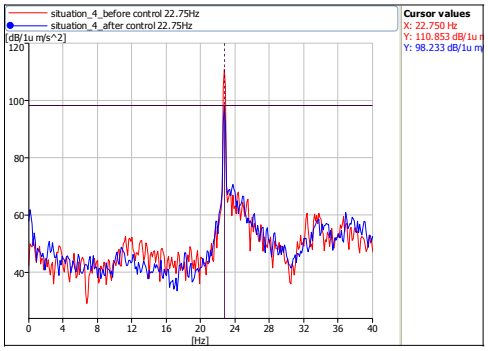


(b) Comparison in frequency domain

Fig 11 – Comparison the effect of position “0” before and after controlling at frequency 22.75Hz



(a) Comparison in time domain



(b) Comparison in frequency domain

Fig 12 – Comparison of the effect of position “4” before and after controlling at frequency 22.75Hz

As shown in Fig.11, when the trestle was vibrated at the frequency of 22.75Hz, the magnitude of the vibration at position “0” decreased 13.0dB. However, in the results of Fig.12, only 12.6dB at position “4”. Considering the nature frequency of NFAEA (position “0”) was 22.75Hz, while setting others variables constant, we found that when the NFAEA worked at the frequency could result in a better effectiveness of vibration control, about 0.4dB. It meant that NFAEA output much more electromagnetic force.

Next, we performed these experiments, including Single frequency control experiment of 26.25Hz, Dual frequency control experiments of 22.75Hz&35Hz and 26.25Hz&35Hz, and summed up them as Table.3.

Table 3 – Controlling effect at different positions

Frequency	22.75Hz	26.25Hz	22.75Hz&35Hz		26.25Hz&35Hz	
			22.75Hz	35Hz	26.25Hz	35Hz
Position 0	13.0	11.3	21.5	10.4	14.3	2.5
Position 4	12.6	18.3	12.9	9.2	20.3	5.2

From Table.2 we knew that the natural frequency is 22.75 at position “0”, and 26.25 at position “4”. The results of single frequency experiment showed that NFAEA of each position could reach its best controlling effects if it worked at its natural frequency. As shown in Table.3, compared with 35Hz, 22.75 always leaded to a better controlling effect at both position “0” and “4”. That’s because 22.75Hz was much closer to natural frequencies of these two positions. As 22.75Hz was the natural frequency of position “0”, so the controlling effect of “0” was better than “4”. The closer to natural frequency the excitation was, the better controlling effect we would get. Same analysis method was applied to condition of 26.25Hz&35Hz, and it verified the explanations we made above.

5. CONCLUSIONS

In this paper, a natural frequency adjustable electromagnetic actuator has been designed based on detailed analysis of actuator magnetic circuit characteristics by ANSOFT electromagnetic field finite element analysis software. As for its main performance parameter we made optimal design and set up experiment bench to test it. Finally, we did active control experiment by x-LMS algorithm. The experimental result indicates that this actuator can output the best control force at any nature frequency of those five positions. By adjusting the natural frequency, it can preferably solve the problem of multi–frequency vibration.

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