New Mount with Moving-Coil-Type Electromagnetic Actuator for Naval Shipboard Equipment

가동코일형 전자기식 작동기를 결합한 함정 탑재장비용 마운트 개발

Y. H. Shin[†], S. J. Moon*, W. J. Jung** and J. J. Jeon**

신 윤 호 · 문 석 준 · 정 우 진 · 전 재 진

(Received July 4, 2013 ; Revised September 3, 2013 ; Accepted September 14, 2013)

Key Words : Hybrid Mount(복합형 마운트), Electromagnetic Actuator(전자기식 작동기), Moving Coil Type(가동코일형), Naval Shipboard Equipment(함정 탑재장비)

ABSTRACT

In this study, a new hybrid mount with a moving-coil-type electromagnetic actuator is developed to reduce the vibration transmitted from naval shipboard equipment to the ship hull structure. The detailed design of the hybrid mount is determined through several design stages with electromagnetic numerical analysis using Maxwell software. The hybrid mount, which combines a rubber mount with an electromagnetic actuator, has a fail-safe function for shock resistance. The mount is fabricated and tested using a universal testing machine to check the design specifications. Finally, control tests are carried out on the hybrid mount to confirm its performance and applicability.

요 약

이 연구에서는 함정탑재 장비의 진동으로부터 기인되는 고체음의 저감을 목표로 새로운 형태의 복합형 마운트를 개발하였다. 수동형 마운트와 비접촉식 전자기식 작동기 또는 관성력형 작동기로 구성된 복합형 마운트가 우수한 성능을 보유한다는 선행연구 결과를 바탕으로 이 연구에서 개발된 복합형 마운트는 기존의 검증된 수동형 고무마운트와 전자기식 작동기를 비접촉식으로 결합한 형태이며, 내충격 성능을 고려하여 설계하였다. 먼저 장비로부터 유발된 진동이 외부로 전달되는 성분의 차단에 대해 복합형 마운트의 효과적인 구성요소 배치형식을 제안하였으며, 여러 설계인자를 고려한 초기 설계안을 제시하고, 마운트 설치 시 문제원인이 될 수 있는 내충격 성능을 고려한 최종 설계를 수행하였다. 설계된 복합형 마운트를 제작하고, 실험을 통해 성능을 검토하였다.

1. Introduction

Most equipment operated under harsh conditions has a mount installed at the bottom. Such mounts support the static load of the equipment and pro-

[†] Corresponding Author ; Member, Korea Institute of Machinery & Materials

E-mail : shinyh77@kimm.re.kr

Tel : +82-42- 868-7211, Fax : +82-42-868-7418

* Member, Korea Institute of Machinery & Materials

** Member, Agency for Defense Development

A part of this paper was presented at the KSNVE 2013 Annual Spring Conference

‡ Recommended by Editor SungSoo Na

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tect it from external disturbances, helping it to perform its intended functions. Naval shipboard equipment must strictly comply with defense specifications in terms of its features while also remaining capable of performing its intended functions. To this end, it is imperative to use a mounting system that provides a good performance in terms of reduction of noise and vibration transmitted to the hull and protects the equipment from external shock. Today, passive rubber mounts (e.g., U.S. Navy standard mounts, Wiroflex mounts) are widely used on most equipment in naval ships.

In addition to defense capabilities, studies are currently underway to improve the noise and vibration performance of equipment in terms of precise processing and semiconductor use. Research is also ongoing in the development of a hybrid mount system that can actively provide control force to a passive mount based on the signal from the source of noise/vibration^(1,2,3). The developed hybrid mount combines a stacked piezoelectric actuator or an electromagnetic actuator with an air spring, presumably operating at a frequency of 80 Hz. In the defense sector, studies are being conducted to reduce the probability of detection of a ship by enemies by decreasing structure-borne noise caused by vibrations originating from equipment. Most notable is research into a hybrid mount that combines a passive rubber mount and a piezoelectric actuator^(4,5). These studies indicate that a piezoelectric actuator, by nature, reduces noise/vibration only at high frequency ranges above 100 Hz.

In this paper, a new hybrid mount capable of reducing structure-borne noise caused by naval shipboard equipment has been developed. Existing literature⁽⁶⁾ shows that passive mounts and hybrid mounts consisting of non-contact electromagnetic actuators or inertial force actuators deliver good performance. The hybrid mount presented in this paper combines a proven passive rubber mount with an electromagnetic actuator to effectively re-

duce the force transmitted from equipment to a ship hull while considering shock resistance. First, the most effective layout of mount components was identified in light of vibration transmissibility from equipment to supporting structures. The initial design draft based on various factors was presented, and the final design was subsequently decided considering shock resistance, which can cause problems when the mount is in service. The designed hybrid mount was then fabricated and tested to measure its performance.

2. Conceptual Design of Hybrid Mount

The hybrid mount presented in this study is based on an existing proven passive rubber mount. Figure 1 shows the cross section of a rubber mount produced in Korea, which is based on a standard mount used by the U.S. Navy. This study is aimed at developing a hybrid mount with a static load of 250 kg, maximum control force of 120 N, and maximum controlled displacement of ± 1 mm. The upper limit of the control frequency range of the mount was set at 300 Hz or lower.

Based on findings from studies on the dynamic characteristics of a hybrid mount that depend on the mount layout⁽⁶⁾, the placement of the passive element and the actuator was determined by analyzing the amount of noise transmitted to the ground. Consequently, a non-contact parallel-type mount (see Fig. 2(a)) and an inertial mass-type mount (see Fig. 2(b)) were considered. The latter was then excluded from the concept design because its control depends on the weight of the inertial mass. This resulted in the selection of the former as the concept design, which consisted of a rubber mount, which is a passive component, and an electromagnetic actuator. Whereas the rubber mount is responsible for supporting the static load, isolating unwanted vibration at high frequencies, and absorbing shock as a fail-safe device, the electromagnetic actuator is expected to reduce

vibrating peaks and enhance the vibration performance at high frequencies. At frequency ranges below 300 Hz, the electromagnetic actuator is known to give better performance than other actuators such as piezoelectric actuators.

During the concept design stage for the electromagnetic actuator, a moving-coil-type actuator (in

Fig. 1 Drawings of the passive mount, 6K900⁽⁷⁾

(a) Non-contact type

(b) Inertia type

Fig. 2 Schematic models for hybrid mounts⁽⁶⁾

which the coil section moves) and a moving-magnet-type actuator (in which the permanent magnet moves) were considered. This paper, however, discusses only the use of the former. To ensure that the structure of the passive mount does not change, the electromagnetic actuator was designed to be located under the passive mount. The moving-magnet-type actuator will be considered in another paper in the near future.

The two models shown in Fig. 3 were considered during the first-stage concept design for the electromagnetic actuator. In the figure, blue represents permanent magnets; red, coils; and green, metal to create magnetic circuits. The stator consists of a permanent magnet and a piece of metal for the creation of a magnetic circuit, whereas the mover consists of a bobbin with a coil wrapped around it to a certain thickness. The permanent magnet generates a magnetic field within the air gap in which the mover moves. When current runs along the coil of the mover within the generated magnetic field, power is generated to activate the mover vertically. The direction and strength of the force within the actuator depend on the direction and strength of the current running through the coil. The model in Fig. 3(a) shows that the permanent magnet (PM) is located along the outer circumference of the stator, whereas the model in Fig. 3(b) shows that the PM is within the stator. The models were analyzed using Maxwell⁽⁸⁾, which is commercial FEM-based solution software, under the assumption that the coil is wrapped with 300 turns and the air gap is 1 mm.

Fig. 3 First-stage designs for an electromagnetic actuator

Fig. 4 Second-stage design for an electromagnetic actuator

It was found that the requirement for control was fully met. In terms of cost, the model in Fig. 3(b) is more competitive than the one in Fig. 3(a), but both weigh approximately 11 kg and thus need to be reduced in weight.

The second-stage concept design is shown in Fig. 4. This design involves arranging permanent magnets both inside and outside the mover to enhance the magnetic force, resulting in a reduction in weight compared to that in the first-stage concept design (from 11 kg to 9 kg). The improved magnetic force can increase the width of the air gap. The metal used to create a magnetic circuit within the actuator is ferrite chrome steel (SS430), and the permanent magnet is made of sintered neodymium zinc boron (N42H). The coil is of the self-bound type, with a diameter of 1.3 mm (AWG #16).

3. Basic Design of Hybrid Mount

Any mount aboard a naval ship must be designed such that it can withstand shock from military engagement or an assault. In other words, the design of a hybrid mount must take into account its shock resistance. One of the ways to ensure such resistance is to have a fail-safe capability that can protect equipment on the top of the mount from external shock at all times. Because the passive rubber mount selected for this study has proven shock resistance, the focus of the design needs to be placed on preventing the resistance from being impaired by the electromagnetic

(a) Static deflection

(b) Dynamic deflection

Fig. 5 Deflection of the passive mount

Fig. 6 Third-stage design for an electromagnetic actuator

actuator. Installing equipment at the top of the mount can cause static deflection on the rubber mount (see Fig. 5(a)) which, if a shock load is applied, can lead to large-scale dynamic deformation (see Fig. 5(b)).

When the second-stage concept design presented in Section 2 is applied to the hybrid mount, large-scale dynamic deformation occurs after a shock load is applied, causing interference between the stator and the mover. To prevent such interference, the design was modified as shown in Fig. 6 to ensure that the stator is not located under the mover. The gray part in Fig. 6 is connected to the rubber mount. It is made of stainless steel to avoid any loss of magnetic force. It was ensured that the height of the entire hybrid mount is less than twice the height of the passive

Fig. 7 Electromagnetic analysis results

mount and that its structure is simple enough for easy production. Its air gap is 2 mm, its coil is wrapped with 270 turns, and its weight is 10 kg.

Figure 7 shows the results obtained from analysis using Maxwell for one cross section only. The results give an insight into the magnetic flux density and force created at the mover and the stator when currents of 1, 2, and 3 A were applied to the coil. The magnetic flux density increased in proportion to the magnitude of the current applied, and the increased density at the air gap caused the actuator to gradually have additional force of 80, 160, and 230 N. The deflection caused by a static load, as shown in Fig. 5(a), depends on the weight of the equipment mounted on the top of the mount. There is a possibility that a change in the magnitude of the static deflection will re-define the relative locations of the coil and the permanent magnet, affecting the force of the actuator.

Fig. 8 Electromagnetic force w.r.t. static deflection

Fig. 9 Hybrid mount with the electromagnetic actuator

Table 1 Design specifications of the electromagnetic actuator

Item	Value
Electrical air gap	5 mm
Mechanical air gap	2 mm
Wire specification	1.3 mm $\times$ 270 turns
Weight	$\sim$ 10 kg
Resistance	1.17 Ω
Inductance	0.20 H

The effect of a change in the weight of the mounted equipment was therefore explored, and some simulations were performed for a change from -4 mm to 7 mm in deflection at a design load of 250 kg. The simulation results are shown in Fig. 8. It was found that the degree of deflection affects the magnitude of the force created. In this study, we expect that, based on the characteristics of the passive mount, the change in the

static deflection will be less than ± 2 mm and the change in the force will be around 20 %.

The design specifications and parameters derived finally are summarized in Table 1. The draft design for the hybrid mount incorporating an electromagnetic actuator based on the stated specifications and parameters is shown in Fig. 9. The black and blue parts combined represent the rubber mount: black represents steel, and blue represents rubber.

4. Fabrication and Performance Evaluation

4.1 Fabrication of Hybrid Mount

As mentioned in Section 2, the passive mount 6K900, whose performance is equivalent to that of a standard mount used by the U.S. Navy, was employed as the passive rubber mount. The moving-coil electromagnetic actuator presented in Section 3 was manufactured in-house. The metal used to create the magnetic circuit was ferrite chrome steel (SS430), whereas the permanent magnet was made of N42H. The magnet was built by manufacturing 20 smaller magnet pieces through discretization and assembling them into a ring shape. This was done because building a single-piece ring-shaped magnet is unfeasible. The coil is of the self-bounded type, and some duration after current runs through it, it suffers from partial melting of the sheath covering it. The diameter was finally determined at 1.3 mm in light of the current applied. All other parts than the one necessary for the creation of a magnetic circuit were made of non-magnetic stainless steel to avoid magnetic flux leakage.

Figure 10 shows the manufactured stator and the mover and the assembled hybrid magnet. The stator consists of a permanent magnet and other components. A closer look at the photos shown in Fig. 10(a) will reveal that gray pieces of the permanent magnet are interconnected within the

stator. The mover, as shown in Fig. 10(b), consists of a coil and other components. A look at the figure reveals a wire for applying current. Figure 10(c) shows an electromagnetic actuator, consisting of a stator and a mover, attached to the bottom of a passive rubber mount. It also shows that the actuator is connected to an installation jig.

4.2 General Performance Experiment

A universal testing machine (UTM) was used to test the performance of the electromagnetic actuator fabricated according to the design specifications

(a) Stator part

(b) Mover part

(c) Assembled hybrid mount

Fig. 10 Assembled hybrid mount and element parts

presented earlier. As shown in Fig. 11, the hybrid mount was placed in the UTM, and a force sensor was connected to the top of the mount. The experimental configuration is shown in Fig. 12. The UTM applied a force of 250 kg, which is equivalent to the weight of the equipment on the top of the mount. A DC driver is set up to supply current to the electromagnetic actuator. The driver receives power necessary for operation from a power supply. A pulse generator (B&K Pulse, LAN-XI) is used to control the amplitude and waveform of the current supplied. The force sensor measures the force generated from the mount and transmits the measured data to the computer

for storage. The stored data are analyzed to evaluate the performance of the hybrid mount.

A single-frequency sinusoidal wave was applied to measure the force generated from the actuator. The experiment was conducted at an interval of approximately 10 Hz for the frequency range of 10~100 Hz and at an interval of 25 Hz for the 100~300 Hz range. Figure 13 shows the experimental results when currents of 1 and 2 A_{rms} were applied. The results reveal that the force decreases dramatically as the frequency increases before stabilizing in the range of above 100 Hz. The results also show that the force increases with stronger currents. When the current is 1 A_{rms}, the maximum force is 980 N at 10 Hz and 60 N at 300 Hz. This implies that the requirement of a maximum force of 120 N as set out in the design specifications is fully met in the low frequency range, but that an

Fig. 11 Experimental setup

Fig. 12 Experimental configuration

(a) 1 A_{rms} input current

(b) 2 A_{rms} input current

Fig. 13 Experimental results

input current of approximately $3 A_{rms}$ is required to meet the requirement in the high frequency range.

4.3 Control Performance Experiment

A control performance experiment was performed on the manufactured hybrid mount to determine its applicability. In general, a mount can perform its intended function stably when it works with three others as a group. In the current stage, however, only one mount was tested to evaluate its applicability.

The experimental configuration is shown in Fig. 14. An electromagnetic exciter was placed at the top of the hybrid mount in lieu of equipment. The exciter was necessary because only one mount was tested here whereas four mounts are required to install equipment with excitation. Weights were added until the rated load reached 250 kg, and mass was placed at the top of the exciter to generate greater excitation. An electromagnetic exciter can produce a maximum force of 500 N. The same components as those shown in Fig. 12 were used for the experiment, except for the accelerometers (B&K 4507-002) at the top and bottom of the mount, which were used to measure vibration carried through the mount. In fact, the controller only uses signals from the accelerometer installed at the bottom. The controller (dSpace, DS1103)⁽⁹⁾ was intended to control the electromagnetic actuator at the hybrid mount. The control algorithm was implemented using Filtered-X LMS^(10,11) and focused only on single sinusoidal wave vibration. A control algorithm was designed using MATLAB/SIMULINK⁽¹²⁾; the algorithm was used in the dSpace controller to regulate the electromagnetic actuator.

The experiment was performed in the range of 10~300 Hz. As a typical example, the results from the test performed at 26.7 Hz are shown in Fig. 15. In the figure, the blue line represents acceleration when the electromagnetic actuator is not in

Fig. 14 Experimental setup

Fig. 15 Experimental results

operation (control off), whereas the green line represents acceleration when it is in operation (control on). The top graph shows the acceleration signals measured at the top of the mount, whereas the bottom graph shows the acceleration signals measured at the bottom of the mount. A comparison of the two graphs reveals that the acceleration signals at the bottom of the mount are better regulated through the electromagnetic actuator. It also reveals that the control at the bottom of the mount also contributes to a slight decrease in vibration at the top. These results suggest that the hybrid mount presented in this paper has good applicability.

5. Conclusion

This paper presents a method of designing, fab-

ricating, and testing a new type of hybrid mount capable of reducing structure-borne noise caused by naval shipboard equipment. The key findings of the study are as follows:

- The hybrid mount is developed to reduce the transmitted force from equipment to the supporting structure by reducing the base acceleration by using a viscoelastic mount and an electromagnetic actuator.

- The developed hybrid mount is composed of a proven passive rubber mount and a moving-coil electromagnetic actuator. It is ideal for reducing vibration at a low frequency range under 300 Hz, and it has a fail-safe capability that can protect equipment on the top of the mount from external shock loads.

- The moving-coil electromagnetic actuator is designed such that it fully meets the desired specifications in terms of the characteristics of the coil, permanent magnet, and magnetic circuit.

- A hybrid mount was fabricated based on the design and tested using a hydraulic universal testing machine to determine its performance. The test reveals that the mount is fully compliant with the design specifications at the frequency range of interest. A series of experiments were performed to assess the control performance of the hybrid mount, and the results confirmed its applicability.

- The performance evaluation of a mount system consisting of four mounts is necessary to determine the exact performance of hybrid mounts. Further research using the mounting system presented in this paper will be conducted.

Acknowledgement

The research described in this paper was funded by the Agency for Defense Development.

References

(1) Moon, S. J., Jung, H. J., Shin, Y. H., Jang, D.

D., Jeong, J. A. and Moon, Y. J., 2011, Development of a Hybrid Mount System Combined Airspring with Piezostack Actuator for Microvibration, *Transactions of the Korean Society for Noise and Vibration Engineering*, Vol. 21, No. 1, pp. 56–65.

(2) Moon, S. J., Park, S. H., Jeong, J. A., Huh, Y. C., Kim, C. H. and Choi, S. M., 2011, A Study on the Development of a Hybrid Electromagnetic Actuator Against Microvibration, *Transactions of the Korean Society for Noise and Vibration Engineering*, Vol. 21, No. 5, pp. 475–483.

(3) Kim, H. T., Kim, C. H., Kang, S. B., Moon, S. J. and Lee, G. S., 2013, A Hybrid Structure of Dual Stators and a Pneumatic Spring for Resonance Control in an Air Mount, *Journal of Electromagnetic Analysis and Applications*, Vol. 5, No. 3, pp. 114–119.

(4) Moon, S. J., Kwak, J. S., Chung, J. H., Ji, Y. J., Yoon, J. S., Choi, S. M., Lee, H. Y., Jung, W. J. and Ki, D. J., 2010, A Study on the Hybrid Mount Against Vibration and Shock for Naval Ships, *Shock and Vibration*, Vol. 17, No. 3, pp. 269–283.

(5) Moon, S. J., Choi, S. M., Nguyen, V. Q., Oh, J. S., Choi, S. B., Chung, J. H., Kwon, J. I. and Jung, W. J., 2013, An Inertia-type Hybrid Mount Combining a Rubber Mount and a Piezostack Actuator for Naval Shipboard Equipment, *International Journal of Naval Architecture and Ocean Engineering*, Vol. 5, No. 1, pp. 62–80.

(6) Cho, H. Y., Moon, S. J., Shin, Y. H., Jung, W. J. and Won, M. C., 2012, A Comparative Study on the Dynamic Characteristics and Control Performances of Hybrid Mounts According to Element Configuration, *Transactions of the Korean Society for Noise and Vibration Engineering*, Vol. 22, No. 6, pp. 551–558.

(7) Super Century. [online] Available at: <<http://www.super-century.com/>> [Accessed April 2013].

(8) ANSYS Maxwell, ANSYS Inc. [online] Available at: <<http://www.ansys.com/>> [Accessed August 2013].

(9) dSpace System, dSPACE GmbH. [online] Available at: <<http://www.dspace.com/>> [Accessed August 2013].

(10) Widrow, B. and Stearns, S. D., 1985, *Adaptive Signal Processing*, Prentice-Hall.

(11) Hakansson, L., Clasesson, I. and Stureson, P. O., 1998, *Adaptive Feedback Control of Machine-Tool*

Vibration Based on the Filtered-X LMS Algorithm, International Journal of Low Frequency Noise, Vibration and Active Control, Vol. 17, No. 4, pp. 199~213.

(12) MATLAB/SIMULINK, The Mathworks, Inc. [online] Available at: <<http://www.mathworks.com/>> [Accessed August 2013].

Yun-ho Shin received his Ph.D. from Dept. of Mechanical, Aerospace and Systems Engineering at KAIST in 2009, respectively. He has worked at Korea Institute of Machinery and Materials from 2010. His research interests include active vibration control, wind turbine control and naval ship survivability.

Seok-jun Moon received his Ph.D. from Dept. of Naval Architecture and Ocean Engineering at Seoul National University in 1995. He has worked at Korea Institute of Machinery and Materials from 1996. His research interests in-

clude structural control devices, wind turbine control and energy harvesting solution.

Woo-Jin Jung received his BS and MS degrees from Korea Aerospace University in 1985 and 1987 respectively, Ph.D. from Pusan National University in 2003. He is currently a principal researcher at the Agency for Defense Development, Korea. His research interests are underwater acoustic stealth technologies.

Jae-Jin Jeon received a BS degree from Yonsei University in 1982, MS and Ph.D. from KAIST in 1984 and 1987 respectively. He is currently a chief of underwater stealth division at the Agency for Defense Development, Korea. His research interests are underwater acoustic stealth technologies.