Automatic Ball Balancer Using Permanent Magnets to Reduce Transient Vibration

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The conventional automatic ball balancer (ABB) reduces the mass unbalance of a rotating body by locating balls to the opposite side, thereby suppressing the steady-state vibration. However, the transient vibration increases due to rotating balls in such a way that they increase the mass unbalance before moving to the opposite side of the mass unbalance. We propose an ABB using permanent magnets (APM) that reduces the vibration of a rotating system, not only in the steady state but also in the transient state. The proposed APM is composed of four balls and two permanent magnets attached to a conventional ABB system. We designed the permanent magnets of the APM by using the multi-physics finite-element software COMSOL. We investigated the behavior of the rotating balls and the vibration suppression due to the APM by using the multi-body dynamic program ADAMS to validate the effectiveness of the proposed APM.

Index Terms—**Automatic ball balancer (ABB), magnetic force, mass unbalance, permanent magnet, transient vibration.**

I. INTRODUCTION

MASS unbalance of a rotating body in a machine generates centrifugal force and periodically excites the bearings and supporting structure, which generates noise and vibration. Various designs and devices have been developed and applied to reduce the noise and vibration caused by eccentric mass. One type of vibration reduction device is the automatic ball balancer (ABB) used in optical disk drives and front-loading washing machines. Because vibration in front-loading washing machines occurs mostly during the spin-dry cycle, which impairs washing performance and structural durability, high-quality front-loading washing machines have started to use ABB to reduce vibration. The vibration reduction effect of the ABB can be explained by the Jeffcott theory [1]. If the rotational angular velocity of the rotating body is not close to the natural frequency of the system, the balls inside the ABB tend to rotate to the opposite side of the mass unbalance to reduce the mass unbalance. Previous research on ABB vibration reduction has focused on the reduction of steady-state vibration. Chung and Ro [2], Hwang and Chung [3], and Jwa *et al.* [4] proposed single, double, and triple race types. They investigated the effect of vibration reduction on each type of ABB and the stability of the system.

An ABB plays an effective role in reducing steady-state vibration, but it sometimes amplifies transient vibration before balls move to the opposite side of the mass unbalance. Transient vibration shortens the life of the washing machine because the amplitude rapidly increases during a short period of time. Several reports have improved transient vibration caused by ABB. Choi and Shime [5] proposed a method of mounting two ABBs with different oil viscosities on the front and rear sides of a front-loading washing machine. A phase difference occurs between the balls that rotate in the front and rear sides due to the different viscosities, so their phase difference reduces the transient vibration. However, at least two ABBs and oils with different viscosities are required. Kim and Na [6] proposed a method to distribute the eccentric mass by adding a spring between the balls inside the ABB to reduce the transient vibration. However, this design increased the steady-state vibration, so they suggested that the stiffness of the ball springs should be optimized to meet the performance requirement. Hredzak and Guo [7]–[9] proposed an electromechanical balancing device for active vibration control of hard disk drives. They controlled the position of the balls in the circumferential groove of the rotor using the electromagnet. However, since the balls move in a circumferential direction, the size of the rotor increases, and the structure of the device becomes complicated. Recently, Jung *et al.* [10] suggested a two-plane balancing method to predict the location of the mass unbalance in front-loading washing machines and to control both the transient and steady-state vibrations. However, there was a discrepancy between their simulation and experiment.

In this paper, we propose an ABB using permanent magnets (APM) that can reduce the vibrations of a rotating system, not only in the steady state but also in the transient state. The APM is composed of four balls and two magnets attached to a conventional ABB system. We calculated the magnetic force required to restrain the motion of the balls in the transient state, and we also present the optimal design of the permanent magnets to generate constant attractive magnetic force. We developed a dynamic analysis model of a front-loading washing machine by using ADAMS, and we analyzed the steady-state and transient vibrations of a washing machine without ABB, a washing machine with ABB, and a washing machine with APM.

II. ANALYSIS OF THE ATTRACTIVE MAGNETIC FORCE

A. Washing Machine With APM

Fig. 1 shows a simplified front-loading washing machine model with APM. It is composed of a tub, four spring dampers,

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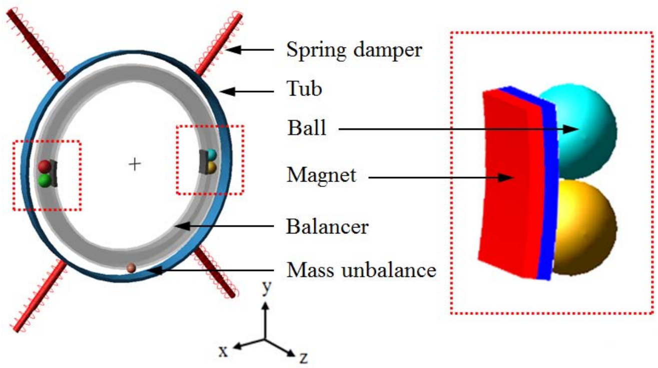


Fig. 1. Structure of the proposed APM.

mass unbalance, and an APM. The APM is composed of four balls and two permanent magnets attached to a conventional ABB system. The two permanent magnets are positioned 180° apart, and two balls are stuck to a permanent magnet by attractive magnetic force.

B. Magnetic Force and Design of the Permanent Magnets

The principle of APM can be explained by the centrifugal force due to the mass unbalance and the attractive magnetic force between a ball and a permanent magnet. In the transient state, each of the two balls stuck to a permanent magnet is positioned 180° apart, so the APM does not generate any mass unbalance, and only the source of the centrifugal force is the pre-existing mass unbalance of the rotating tub. When the rotating speed of the tub reaches a steady state, the centrifugal force of the ball is designed to be greater than the attractive magnetic force, and the balls are released from the permanent magnets. At this point, the condition of the attractive magnetic force can be expressed as follows:

$$|F_{\text{mag}}| < m_b r \omega^2 \tag{1}$$

where F_{mag}, m_b, r, and ω are the attractive magnetic force between a ball and the permanent magnet, the ball mass, the radius of the rotational path of the ball, and the angular velocity of the APM, respectively. The ball mass, the radius of the rotational path of the ball, and the angular velocity of the APM are set to be 0.05 kg, 145 mm, and 140 rpm, respectively. The attractive magnetic force required to hold a ball is calculated to be 1.5 N.

We developed a 3-D finite-element model of APM that consists of two balls, a permanent magnet, and the surrounding air, as shown in Fig. 2(a). This model was developed to investigate the attractive magnetic force between a ball and a permanent magnet, as shown in Fig. 2(b). The finite-element model is discretized by 1 589 760 elements with ten-node tetrahedral elements with 3 852 652 degrees of freedom. The permanent magnet is a ferrite with a residual flux density of 0.415 T, and the ball is STB2 (bearing steel). The ball diameter is 19 mm, and the thickness of the magnet was increased from 6 to 7 mm by 0.1 mm increments. We used the multi-physics software, COMSOL, to solve the magnetic field by considering the nonlinear B–H characteristics of the ball. The radial attractive magnetic force of the ball and that of the permanent magnet were calculated using the Maxwell stress tensor method. Fig. 3 shows that the attractive magnetic force increases with the increase in the thickness of the permanent magnet. When the thickness is 6.33 mm, the attractive magnetic force is calculated to be 1.5 N.

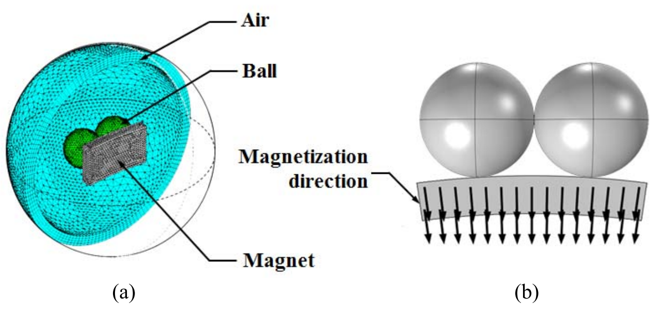


Fig. 2. (a) Finite-element model of the proposed APM. (b) Magnetization direction of the permanent magnet.

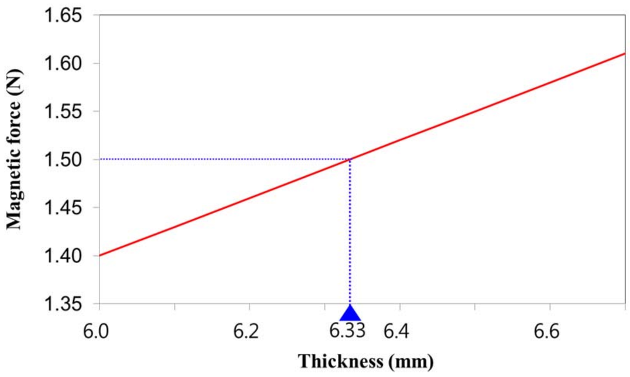


Fig. 3. Magnetic force due to the thickness of the permanent magnet.

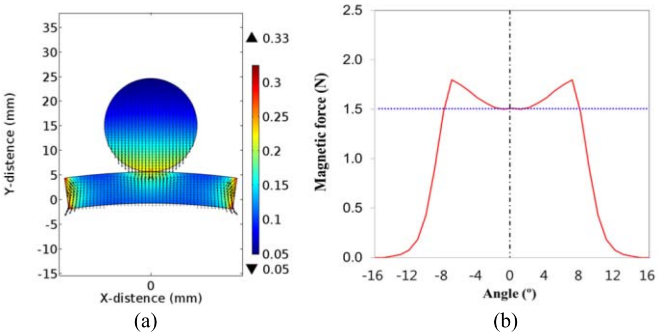
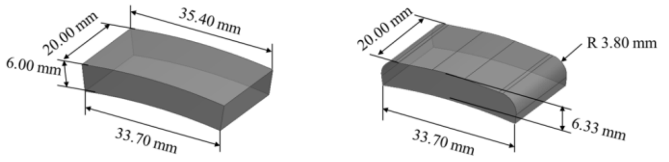


Fig. 4. (a) Magnetic flux density of the initial design of the permanent magnet. (b) Attractive magnetic force due to the relative position between the ball and the center of the permanent magnet.

As a ball moves to the edge of the permanent magnet, the attractive magnetic force increases due to the concentration of the magnetic field at the edge of the permanent magnet, which changes the ball-release time. Fig. 4(a) shows that the magnetic flux density of the 6.33 mm permanent magnet is concentrated at the edge. Fig. 4(b) shows that the maximum magnetic force is 1.8 N at the edge. The attractive magnetic force should be 1.5 N irrespective of the relative position of the ball and the permanent magnet in order to release the ball smoothly due to the centrifugal force while the tub reaches the steady-state velocity. The initial design of the



(a) (b)

Fig. 5. (a) Initial design of the permanent magnet. (b) Opitimal design of the permanent magnet.

TABLE I

MASS PROPERTIES OF THE APM PARTS

Items	Weight (kg)	Mass center *(x,y,z)*	*Ixx* (kg·mm^2)	*Iyy* (kg·mm^2)	*Izz* (kg·mm^2)
Balancer	3.000	0,0,0	19100.3	19100.3	37856.4
Tub	1.000	0,0,0	15978.8	15978.8	31831.3
Mass unbalance	0.200	0,-155,0	4.1	4.1	4.1
Left magnet	0.085	-127,0,0	4.1	3.2	1.0
Right magnet	0.085	127,0,0	4.1	3.2	1.0

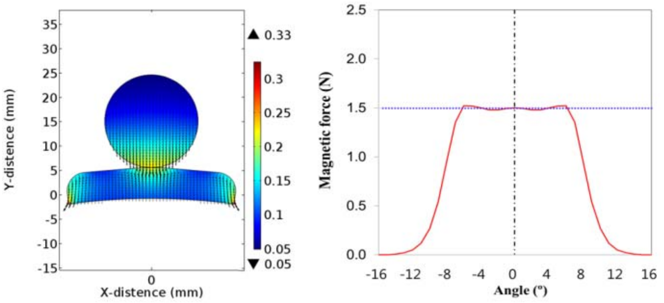
permanent magnet in Fig. 5(a) has been optimized to Fig. 5(b) by changing both ends of the edge in order to generate a constant 1.5 N irrespective of the relative position of the ball and the permanent magnet. The concentration of the magnetic flux density of the permanent magnet was reduced, as shown in Fig. 6(a), and the attractive magnetic force is a constant 1.5 N in the range of −7° to 7°.

III. DYNAMIC ANALYSIS MODEL AND VIBRATION DUE TO THE ABB AND APM

A. Dynamic Analysis Model

A dynamic analysis model was developed by using ADAMS multi-body dynamics software. Table I shows the mass and mass moment of the inertia of the APM parts for dynamics analysis. The tub and balls are connected through a revolute joint, and the tub is supported by four springs and four dampers with a stiffness coefficient of 500 N/m and a damping coefficient of 10 N·s/m, respectively. In addition, the non-contact conditions were defined to prevent direct contact between the balls. The analysis model is assumed to start to rotate at 3 s and to increase linearly to a steady-state rotating speed of 300 rpm at 18 s, and then the analysis model maintains the steady-state rotating speed at 300 rpm. The step size is determined to be 36 000 steps at 300 rpm so that the dynamic model is simulated whenever it rotates 1°.

The magnetic force defined in Fig. 6(b) is included in the dynamic analysis model, which has two cases, i.e., case1, where the ball is attached to the permanent magnet, and case2, where the ball is separated. The balls rotating inside the ABB are attracted by the magnetic force whenever the distance from the permanent magnet reaches within a range of 16°, as shown in Fig. 6(b).



(a) (b)

Fig. 6. (a) Magnetic flux density of the optimal design of the permanent magnet. (b) Attractive magnetic force due to the relative position between the ball and the center of the permanent magnet.

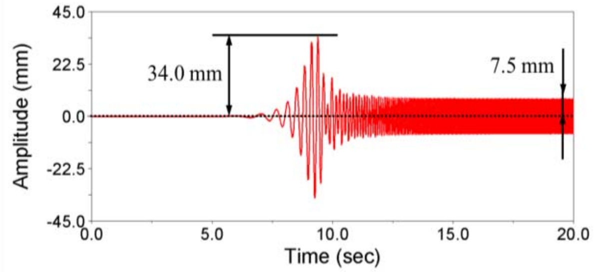


Fig. 7. Simulated vibration of the tub in a washing machine.

B. Vibration Due to ABB and APM

Fig. 7 shows the simulated vibration of the tub in a washing machine without ABB, and the maximum transient and steady-state vibrations are 34 and 7.5 mm, respectively. Fig. 8(a) and (b) shows the vibration of a tub with the conventional ABB and the proposed APM. As shown in Fig. 8(a), the transient vibration increases to 44.5 mm, and the steady-state vibration decreases to 1.1 mm. As shown in Fig. 8(b), the washing machine with the proposed APM decreases both the transient and steady-state vibrations to 34 and 1.1 mm, respectively.

Fig. 9 shows the behavior of the balls and mass unbalance in the conventional ABB. As shown in Fig. 9(a), the mass unbalance is located at the same position of the balls when the tub starts to rotate. In the transient state, as shown in Fig. 9(b) and (c), the balls are still near the mass unbalance, which increases the centrifugal force due to the rotating balls. In the steady state after the balls move to the opposite side of the mass unbalance, as shown in Fig. 9(d), the mass unbalance is reduced due to the balls and the consequent vibration, as shown in Fig. 8(a).

Fig. 10 shows the behavior of the balls and mass unbalance in the proposed APM. As shown in Fig. 10(a) and (b), the APM does not increase the mass unbalance in the transient state because each of the APM is located 180° apart, and the balls are stuck to the permanent magnet. The transient vibration due to the proposed APM is the same as that due to a conventional washing machine without ABB. Once the balls are released from the permanent magnet, they move to the opposite side of the mass unbalance, and they decrease the mass unbalance and the centrifugal force. The steady-state vibration due to the proposed APM is the same as that of the ABB, as shown in Fig. 8(b).

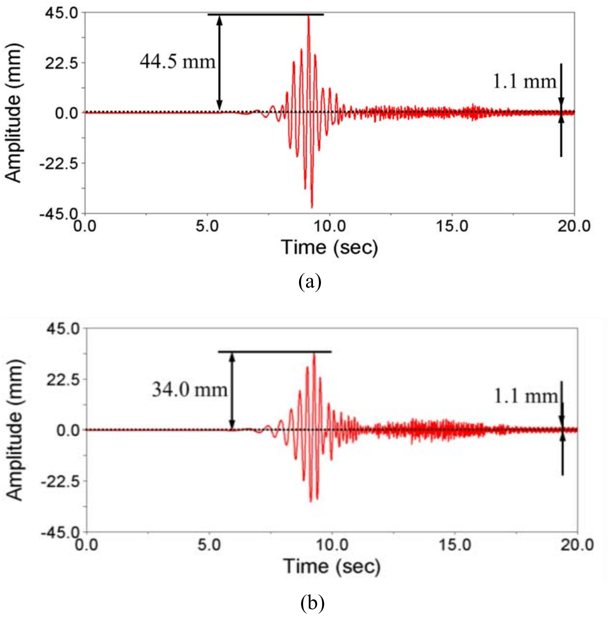


Fig. 8. (a) Simulated vibration of the tub in a washing machine with ABB. (b) Simulated vibration of the tub in a washing machine with APM.

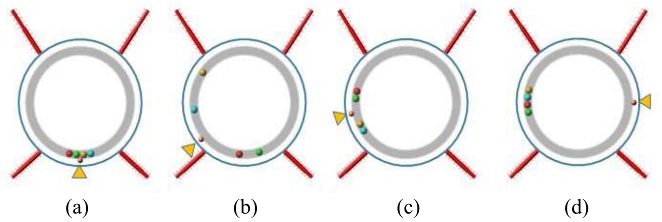


Fig. 9. Behavior of a washing machine with ABB. (a) 0–7 s. (b) 7–10 s. (c) 10–18 s. (d) 18–20 s.

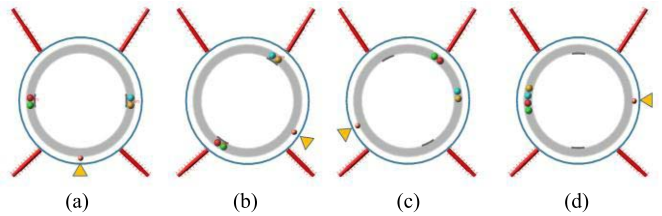


Fig. 10. Behavior of a washing machine with APM. (a) 0–7 s. (b) 7–10 s. (c) 10–18 s. (d) 18–20 s.

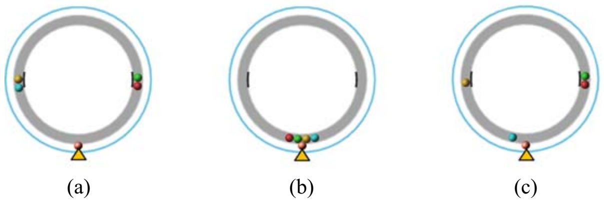


Fig. 11. Position of the balls after rotation is completed. (a) Two balls are attached to the permanent magnet. (b) All four balls are located at the bottom of race. (c) Some balls are attached to the permanent magnet and the remaining balls are located near the bottom of race.

After the rotation comes to a stop, there are several possible locations of balls, as shown in Fig. 11; two balls are attached to each permanent magnet or all four balls are located near the bottom of race due to gravity or some balls are attached to the permanent magnet and the remaining balls are located near the bottom of race. For Fig. 11(b) and (c), we performed the simulation with the APM slowly rotated 360° in the clockwise direction and −360° in the counterclockwise direction by using a step function, and we found that the two balls are nicely attached to the permanent magnet, as shown in Fig. 11(a). Once we have the initial position of balls in the APM by applying this startup algorithm, we can effectively suppress the vibration of rotating systems with the application of the proposed APM in the next run.

IV. CONCLUSION

We proposed an APM to reduce the vibration of the rotating system in both the steady and transient states effectively. We designed the permanent magnets to generate a constant attractive magnetic force to hold the balls while not increasing the mass unbalance in the transient state. The balls are released smoothly in the steady state, in which the centrifugal force is greater than the attractive magnetic force, and they reduce the mass unbalance, centrifugal force, and vibration. We verified the behavior of the balls and the effectiveness of the APM by utilizing the ADAMS software. This paper contributes to effective suppression of the vibration of rotating systems with the application of the proposed APM.

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