Radial position active control of double stator axial gap self-bearing motor for pediatric VAD

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Abstract
In the last decade, ventricular assist devices (VADs) such as continuous flow rotary blood pumps have been successfully applied to advanced heart disease patients for bridge to transplantation and destination therapy. The success with VAD technology has recently increased significant clinical need for pediatric VADs. However, VADs which are applicable to infants and small children are still in a development stage because of severe design requirements such as long life expectancy, minimal blood damage and miniature device size. Magnetic levitation is an essential technology to enhance durability and blood compatibility of rotary VADs due to elimination of mechanical contact and wear. Miniaturized magnetic systems have strong potential to develop the pediatric VAD. In this study, a novel axial gap double stator self-bearing motor which can control five-degrees of freedom (5-DOF) of rotor postures have been developed for pediatric VAD. The motor has a top stator, a bottom stator and a levitated rotor driven as a synchronous permanent magnet motor. The rotor is axially suspended between the stators which have an identical structure. A double stator mechanism enhances a higher torque production and regulates radial position through active control. This paper proposes a concept of radial position active control and the magnetic suspension ability of developed self-bearing motor. The rotor is successfully levitated and rotated up to 6400 rpm without any physical contact with 5-DOF active control in the air. The radial oscillation amplitudes are actively suppressed with the proposed radial position control concept. The developed 5-DOF controlled self-bearing motor which is suitably miniature as an actuator for pediatric VAD indicates sufficient capability of the magnetic levitation and non-contact rotation.

Key words: Self-bearing motor, 5 degrees of freedom, Radial position active control, Ventricular assist device, Pediatric

1. Introduction

Mechanical circulatory supports have been clinically applied to adult heart failure patients due to the high rate of heart disease and the shortage of donor hearts. The successful use of ventricular assist devices (VADs) in adult patients over the last decade has led to increased interest in this technology for pediatric patients (Baldwin, et al, 2006; Gibber, et al, 2010; Noh, et al, 2005; Takatani, et al, 2005). However, the majority of VADs for pediatric heart disease have been applied to patients older than 10 years of age due to limitations of device size and structural functionalities. Thus, demands for pediatric VADs specifically designed for both infants and small children have been recently promoted widely. The pediatric VADs has to satisfy following design requirements: 1) high durability for long term support of patients, 2) minimal blood damage and no thrombosis formation in the pump cavity, 3) miniature device size in order to be fully implanted in a small peritoneal cavity from birth to more than two years of age, and 4) wide operational range from 2000 rpm to 5000 rpm in order to regulate the pump flow rate according to growth of pediatric patients. Due to significant advantages of eliminating mechanical wear components compared to traditional
contact bearing systems, application of magnetically suspended motors in VADs have been main focus of the research (Farrar, et al, 2007; Hoshi, et al, 2006; Timms, et al, 2011; Yumoto, et al, 2009). Magnetically suspended rotary VADs offers advantages of contactless motor drive such as high speed rotation, no material wear, zero friction, less heat generation, better durability and better blood compatibility of the devices. However, the magnetic air-gap of magnetically suspended motors applied for rotary VADs needs to be quite larger than typical industrial magnetic bearing applications in order to avoid blood cell destruction due to the high shear stress which is produced in with a smaller air gap. These circumstances significantly reduce the magnetic suspension force and torque capacity. This reduction of magnetic suspension force and torque causes both a deterioration of magnetic suspension stability. In order to stable magnetic suspension, 5-degrees of freedom (DOF) of rotor postures should be stabilized actively. In a conventional 5-DOF controlled maglev motor, at least four actuators, two radial magnetic bearings (MBs), an axial MB and a motor are required. All of these components make device larger and more complicated. In this study, a novel 5-DOF controlled axial gap double stator self-bearing motor was proposed to overcome magnetic performance drawbacks due to the large air-gap length. The objectives of this paper were to demonstrate the radial position control capability and examine the feasibility of miniaturized 5-DOF controlled motor for pediatric VAD.

2. Materials and methods

2.1 Structure and control principle of 5-DOF controlled self-bearing motor

The proposed 5-DOF controlled self-bearing motor shown in Fig. 1 is a permanent magnet synchronous motor which has a top stator, a bottom stator and a levitated rotor. The levitated rotor is axially sandwiched by both stators and that have an identical structure. A double stator mechanism enhances a rotating torque production and also realizes the proposed 5-DOF active control of levitated rotor postures. Two types of concentrated windings are independently wound on each stator tooth. An axial position (z) and rotating speed (ωp) of the rotor are regulated by using a vector control algorithm which can generate axial suspension force and rotating torque with a single rotating magnetic field (Asama, et al, 2013; Nguyen, et al, 2011; Osa, et al, 2012; Ueno, et al, 2000). The axial position of levitated rotor is actively regulated by field strengthening and field weakening as shown in Fig. 2. An axial attractive force $F_z$ and a rotating torque $T_{\theta p}$ produced by the double stator are described by Eq. (1) and (2). These equations use of the magnetic flux density produced by rotor permanent magnets $B_p$, inner and outer radius of rotor $r_1$ and $r_2$, pole pair number of rotor permanent magnet $M$, number of turns in windings $N$, air-gap length of $z$, d-axis current $i_d$ and q-axis current $i_q$. The d-axis current of the top stator must be opposite in magnitude to the d-axis current of the bottom stator, so if the d-axis current is negative in the bottom the d-axis current must be positive in the top stator and vice versa. On the other hand, both q-axis currents of the two stators are supplied in same direction.

$$F_z = \frac{2}{3} \frac{(r_2^2 - r_1^2) \pi B_p}{z} N i_d$$ (1)

$$T_{\theta p} = \frac{2}{3} \frac{(r_2^2 - r_1^2) \pi B_p}{N} i_q$$ (2)
From Eq. (1) and (2), axial attractive force and rotating torque are controlled independently with d-axis and q-axis current.

As shown in Fig. 3, a single rotating control flux density based on P ± 2 pole algorithm produces a restoring torque and a radial suspension force simultaneously (Osa, et al, 2012). In this theory, two rotating magnetic fields are assumed to be distributed in the air gap. One is a P pole magnetic field produced by the permanent magnet of the levitated rotor. The other is P plus or minus 2 pole magnetic field produced by the control windings. Each rotating magnetic fields are rotating with common electrical rotating angular frequency. In axial gap self-bearing motors, these two magnetic fields allow producing restoring torque \( T_{θx}, T_{θy} \) and radial suspension forces \( F_x, F_y \) in arbitrary rotor rotating angles. The restoring torque and the radial suspension force can be produced independently with double stator mechanism. Fig. 4 shows the principles of inclination control around y-axis and radial position control in x direction of levitated rotor. Both stators produce restoring torque in the same direction; the radial forces produced by stators cancel each other, and the restoring torque produced as shown in Fig. 4(a). In contrast, the restoring torque produced by top stator and bottom stator is regulated in opposite direction, and then the radial suspension force can be generated as shown in Fig. 4(b). In a similar manner, the inclination control around x-axis and the radial position control in y direction are available. Consequently, the inclination angles \( θ_x, θ_y \) and the radial positions \( (x, y) \) of levitated rotor can be controlled by regulating the magnitude and the direction of restoring torque and radial suspension force according to excitation currents fed into top stator and bottom stator.

When the restoring torque and the radial suspension force are proportional to excitation current, these are given by Eq. (3) and (4) using a restoring torque constant \( k_{Tθ} \) and a radial suspension force constant \( k_{Fx} \).

\[
T_{θ} = k_{Tθ} i \\
F_x = k_{Fx} i
\]
A total restoring torque and a radial suspension force acting on levitated rotor with double stator mechanism are given by Eq. (5) and (6) when excitation current of top stator and bottom stator are defined as $i_{\text{top}}$ and $i_{\text{bottom}}$ respectively.

$$T_\theta = k_{T\theta}(i_{\text{top}} + i_{\text{bottom}})$$  
$$F_x = k_{Fx}(i_{\text{top}} - i_{\text{bottom}})$$

When the both excitation current $i_{\text{top}}$ and $i_{\text{bottom}}$ are equal, only the restoring torque can be produced. In that case, the motor is operated as a 3-DOF controlled self-bearing motor.

The double stator mechanism with both vector control algorithm and P ± 2 pole algorithm offers 5-DOF control of the levitated rotor postures without any additional active or passive magnetic bearings. Thus, the proposed 5-DOF controlled self-bearing motor has advantages of compactness and simplification of device structure compare to conventional 5-DOF controlled maglev motors.

### 2.2 Theoretical calculation of radial position control system

Rotor dynamics in the radial direction is mathematically modeled based on the Newton’s equation of motion. In this section, only one formula in x direction is considered because a formula in y direction can be given in a similar manner. Two radial magnetic forces are acting on the rotor in the case of radial position control. One is a magnetic suspension force produced by applying an excitation current to the radial position control electromagnet. The other is a magnetic coupling force which is a radial restoring force produced by rotor permanent magnet flux density. The radial coupling force is proportional to the radial rotor position when the rotor displacement is assumed to be small. A radial stiffness is defined as $k_x$ indicating a ratio between the radial restoring force and the rotor radial displacement. Hence, a motion equation of the rotor radial direction is given as follow.

$$m\ddot{x} = k_{Fx}i - k_x x$$  

From Eq. (7), a transfer function between the excitation current and the rotor radial position is calculated.

$$P_x(s) = \frac{X(s)}{I_X(s)} = \frac{k_{Fx}}{ms^2 + k_x}$$

PID controller is designed to suppress the radial rotor vibrations and regulate the rotor radial positions. An input of the PID controller is error between a target rotor radial position and an actually measured rotor position. The output of the PID controller is command excitation current for regulating radial position of the rotor. A transfer function of the PID controller is described by using a proportional gain of $K_{Px}$, an integral gain of $K_{Ixs}$, a derivative gain of $K_{Dxs}$ and a time constant $T$.

$$C_x(s) = K_{Px} + \frac{K_{Ixs}}{s} + \frac{K_{Dxs}}{T_{Dxs}s + 1}$$

Consequently, a block diagram of the radial position control system is shown in Fig. 5. Gain margin and phase margin of the radial position control system are 13 dB and 58 degrees respectively.
2.3 FEM analysis and fabrication of 5-DOF controlled self-bearing motor

The principle of radial suspension force production was confirmed by using three dimensional magnetic field FEM analysis. A pole pair combination and detailed geometries of proposed 5-DOF controlled self-bearing motor were determined in FEM analysis. A double stator axial gap self-bearing motor which has twelve motor stator slots and eight rotor poles shown in Fig. 6 were developed based on the results from the FEM analysis. Fig. 7 shows the geometric parameters of the developed motor stator core and levitated rotor including permanent magnets. The developed motor has an outer diameter of 28 mm, a height of 41 mm and a magnetic air-gap length of 1.5 mm. The weight of the levitated rotor is 25 g. The thickness of the rotor permanent magnets is 0.7 mm. A core material of stator and rotor is bulk soft iron (SU1-1). The permanent magnets are made of Nd-Fe-B which has a coercivity of 907 kA/m and a residual flux density of 1.36 T. The number of turns in the concentrated windings wound on each stator tooth is 58. The diameter of isolated copper wire is 0.3 mm.

2.4 5-DOF control system

A diagram of 5-DOF control system is shown in Fig. 8. Three eddy current sensors (PU-03A, Applied Electronics Corporation) are set onto inner side of stator tooth to measure axial position and inclination angles around x and y axes of the levitated rotor. Other two eddy current sensors are set on x-axis and y-axis to measure radial positions of the levitated rotor. Three Hall Effect sensors (Asahi KASEI Corporation) are set at stator slots to detect the rotating angles of the levitated rotor with a sensitivity of 30 degrees electrical angle. The rotating speed at increments of 90 degrees (mechanical angle) is determined by calculating time derivative of rotating angles. In other words, the rotating angle is divided by the time to rotate the rotor 90 degrees. 5-DOF control and rotating speed regulation are carried out with digital PID controllers that are implemented on a micro-processor board DS1104 (dSPACE GmbH, Paderborn Germany) with MATLAB/Simlink. Power amplifier (PA12A, Apex Microtechnology Corporation) supplies the calculated command excitation current to control windings of both stators. Sampling and control frequency is 10 kHz.
A block diagram for axial position and rotation control is shown in Fig. 9. The axial position of the levitated rotor is stabilized by regulating d-axis current $i_d$ with a PID feedback loop. The PID controller calculates $i_d$ from the error between detected axial position $z$ and target axial position $z^*$. The target position $z^*$ is the center of the motor, and it is set to zero. Positive and negative d-axis currents which are for field strengthening and field weakening generate an unbalanced magnetic attractive force in rotor axial direction. The rotating speed is controlled by regulating q-axis current $i_q$ with the PI feedback loop. The detected rotating speed $\omega_z$ is compared with a target rotating speed $\omega_z^*$. The calculated q-axis current for both stator windings are equal to $i_q$. The d-axis current $i_d$ and the q-axis current $i_q$ are transformed into three-phase current $i_u$, $i_v$, and $i_w$. Then these currents are supplied to axial position and rotation control windings of both stators to generate an eight pole rotating magnetic field.

A diagram for the inclination angle and radial position control is shown in Fig. 10. The inclination angle $\theta_z$ control corresponds to the radial position $x$ control, and the inclination angle $\theta_y$ control corresponds to the radial position $y$ control. The inclination angles and the radial positions of the levitated rotor are controlled by regulating the amplitude, the direction of the restoring torque and the radial suspension force. The required excitation current for generating the restoring torque and the radial suspension force, $i_{r_y}$ and $i_{r_x}$, is calculated using the PID feedback loop. The excitation current for top stator and bottom stator, $i_{top}$ and $i_{bottom}$, is calculated using the PID feedback loop. The excitation current for top stator and bottom stator, $i_{top}$ and $i_{bottom}$, is determined from $i_{r_y}$ and $i_{r_x}$, respectively. In a similar manner, excitation current $i'_{top}$ and $i'_{bottom}$ that are to control inclination angle $\theta_z$ and radial position $y$ are calculated with another PID feedback loop. The amplitude and phase angle of the two-phase current $i_{a}$, $i_{b}$, $i'_{a}$ and $i'_{b}$ are determined from $i_{top}$, $i_{bottom}$, $i'_{top}$ and $i'_{bottom}$ respectively. Consequently, these excitation currents are supplied to the inclination angle and radial position control windings to generate six poles rotating magnetic field.
2.5 Radial suspension force and stiffness measurement

The primary objective of the study was to determine the radial suspension capability of proposed 5-DOF controlled self-bearing motor. Initially, the radial suspension forces with varying excitation currents and radial displacements were measured to confirm the newly proposed radial position control theory. A radial force measurement system is shown in Fig. 11. The rotor is fixed to a linear slider connected with a load cell in order to restrict the rotor movement in the axial direction $z$ and the rotational direction $\theta_x$, $\theta_y$. At first, both centers of the rotor and stator are aligned. The radial suspension forces were evaluated by changing the excitation current from -2 A to 2 A. In order to characterize a dynamic property in rotor radial translation motion, the radial restoring forces were then measured by displacing the rotor radially from the center position up to 1.0 mm with micrometer at the excitation of 0 A.

2.6 Frequency response of radial position control

The 5-DOF controlled self-bearing motor was assembled as shown in Fig. 12, and combined with the digital control system. The rotor was levitated without rotation. The initial parameters for the PID controller were determined based on the limit sensitivity method. Maximum values of the gains were fixed from the current limitation of 3 A. The optimized gains shown in Table I were then tuned manually to minimize the rotor oscillation amplitude. The frequency response of radial position control system was measured with a frequency sweeping method using a FFT analyzer (DS-2100, DS-0264, Ono Sokki Corporation). A sinusoidal disturbance was added to the measured radial position and the disturbance frequency was varied from 1 Hz to 1 kHz. An input and an output in the frequency response are the disturbance signals and the actual rotor radial displacements respectively.
2.7 Comparison of 5-DOF control and 3-DOF control

The magnetic suspension characteristics in the radial directions (x, y) were evaluated under 3-DOF control and 5-DOF control in order to demonstrate the advantages of proposed 5-DOF control. The movable range of levitated rotor in radial and axial directions was \( \pm 0.5 \text{ mm} \) and \( \pm 0.3 \text{ mm} \), respectively. The inclination range of the levitated rotor was \( \pm 1 \text{ degree} \). The PID gains of the 5-DOF control were same as given in Table I. In case of the 3-DOF control, PID gains of the radial position controller were zero. The P gain and I gain of a rotating speed PI controller were 0.00075 A/rpm and 0.007 A/(sec \( \cdot \) rpm) respectively. As a first step, the radial vibration waveforms at a rotating speed of 0 rpm were evaluated. Then, the levitated rotor was accelerated in rotational direction \( \theta_z \), and maximum oscillation amplitudes in the radial direction were measured. The maximum oscillation amplitude was defined as half of the peak-to-peak value of rotor vibration.

3. Experimental results

3.1 Radial stiffness measurement

The developed motor produced radial suspension force according to proposed radial position control concept. The relationship between the radial suspension force and the excitation current is displayed in Fig. 13 (a). The developed 5-DOF controlled self-bearing motor produced radial suspension force of \( \pm 0.8 \text{ N} \) by varying excitation current from -2 A to 2 A. The radial suspension force to excitation current gradient of developed motor was 0.4 N/A. An acceleration coefficient defined as a mass specific force index to indicate the dynamic suspension ability was 16 m/s\(^2\)A. The radial restoring force with different rotor positions are shown in Fig. 13 (b). The restoring force is proportional to the radial displacement, and the gradient of the least square approximation showed a radial stiffness of 0.4 N/mm. The actual measurement data produced a similar results to the results produced in the magnetic field FEM analysis.

3.2 Frequency response of radial position control

Fig. 14 shows the bode diagrams of radial position control system. Solid lines show actual measurement results. Dashed lines display results of theoretical calculation based on equation (8) and (9). Both measurement results and theoretical calculation results indicate almost same gain and phase characteristics. The measurement results displayed similar characteristics in x direction and y direction. The resonant peaks in x and y directions are observed at 24 Hz and 30 Hz. The frequency bandwidths are 125 Hz in x direction and 112 Hz in y direction.

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Table 1  PID control gains for 5-DOF controller.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Radial position</th>
<th>Axial position</th>
<th>Inclination angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.73 [A/mm]</td>
<td>10 [A/mm]</td>
<td>2.0 [A/deg]</td>
</tr>
<tr>
<td>I</td>
<td>0 [A/sec mm]</td>
<td>0.01 [A/sec mm]</td>
<td>0.024 [A/sec deg]</td>
</tr>
<tr>
<td>D</td>
<td>0.045 [A sec/mm]</td>
<td>0.01 [A sec/mm]</td>
<td>0.003 [A sec/deg]</td>
</tr>
</tbody>
</table>

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Fig. 12  Photograph of assembled 5-DOF controlled self-bearing motor.
Fig. 13 Measurement radial suspension force: (a) Actively produced radial force and excitation current characteristics, (b) Restoring force and rotor radial displacement characteristics.

Fig. 14 Bode diagrams obtained from the results of frequency response of radial position control system.

Fig. 15 Radial displacement waveforms of levitated rotor at a rotating speed of 0 rpm: (a) 3-DOF of levitated rotor postures were controlled, (b) 5-DOF of levitated rotor postures were controlled.
3.3 Comparison of 5-DOF control and 3-DOF control

Fig. 15 shows the vibration waveforms of levitated rotor in radial directions at rotating speed of 0 rpm. The vibration amplitudes were less than 10 μm in both the 3-DOF control and the 5-DOF control. However, the levitated rotor was periodically fluctuated in the radial direction under the 3-DOF control as shown in Fig. 15 (a). The periodical radial fluctuation of the levitated rotor was sufficiently suppressed with 5-DOF control as shown in Fig. 15 (b).

The rotor was successfully levitated and rotated without any physical contact. The radial oscillation amplitudes of the levitated rotor with the 3-DOF control and the 5-DOF control are shown in Fig. 16. The maximum rotating speed of developed motor was increased from 5400 rpm to 6400 rpm by implementing the 5-DOF control. At a rotating speed of 6400 rpm, current levels of three-phase current and two-phase current are 0.4 A and 1.0 A respectively. Under the 3-DOF control, the double peaks of radial oscillation amplitude were observed with the rotating speeds under 2000 rpm. Except peak oscillations, the radial oscillation amplitudes were around 100 μm. By contrast, under the 5-DOF control, with rotating speeds under 2000 rpm, the resonances were successfully suppressed with the radial position active control. The oscillation amplitudes were less than 80 μm over every rotating speeds. These results demonstrate the potential of proposed radial position active control.

4. Discussion

Magnetic suspension technique is a strong candidate for VADs to improve device durability and reduce blood damage. In the implantable pediatric VAD, size of magnetic suspension system is severely limited and magnetic air-gap is relatively large. The newly proposed 5-DOF controlled double stator axial gap self-bearing motor is one of the appropriate concepts to miniaturize the magnetically levitated system with large air-gap and guarantee non-contact stable levitation.

The results of developed radial suspension force shown in Fig.13 (a) indicate that the amplitude and direction of the radial suspension force are able to be regulated by varying excitation current. The radial position control system is further stabilized by utilizing the radial restoring force according to the rotor radial displacement. By assuming viscoelasticity of the air is negligible, the radial position control system can be described as single DOF spring-mass system. A natural frequency of the system was calculated to be 28 Hz by using double stator radial stiffness of 0.8 N/mm and the levitated rotor weight of 25 g. Effects on radial fluid forces developed in the pump cavity and dumping force derived from the viscoelasticity of blood must be considered in a blood pump operation.

The frequency response tends to the vibration characteristics of the single DOF spring-mass system. The resonant frequencies in x and y directions are approximately equal to calculated natural frequency of 28 Hz. The low suppression of resonant frequency comes from weak performance of the radial suspension force production. Higher suppression performance would be achieved by optimizing the magnetic circuit geometries and combination of the pole number.
At the rotating speed of 0 rpm, the magnetically levitated rotor was fluctuated periodically under the 3-DOF control. The most dominant frequency components of the rotor fluctuation in x and y directions were analyzed with Fast Fourier transform (FFT) shown in Fig. 17. Amplitude spectrum was calculated from 4096 data of radial rotor displacement which was sampled with a sampling frequency of 10 kHz. The dominant frequencies were calculated as 25 Hz in the x direction and 28 Hz in the y direction. The dominant frequencies were approximately equal to both calculated natural frequencies and the resonant frequencies observed from the bode diagrams.

The magnetic suspension performance of the developed motor was sufficient to maintain non-contact suspension and rotation at required rotating speeds for the pediatric VAD. At every rotating speed, the maximum radial oscillation amplitudes were much smaller than initial clearance of 500 μm with both the 3-DOF control and the 5-DOF control. However, under the 3-DOF control, the maximum oscillation amplitude increased at rotating speeds of 300 rpm, 1600 rpm and 1800 rpm. The first increase of radial oscillation was due to unstable characteristics at lower rotating speeds. The second increase of the radial oscillation at rotating speeds of 1600 rpm and 1800 rpm was caused by resonance when the angular frequencies come close to the resonant frequencies. By contrast, the instability at lower rotating speeds and the resonant were suppressed with the radial position control, and the proposed 5-DOF control concept demonstrated a potential of the stable levitation and rotation. The maximum rotating speed of 6400 rpm in 5-DOF control was fixed due to a limitation of the frequency bandwidth of the radial position control as shown in Fig. 14. However, the maximum rotating speed is indicating sufficient rotating capability for the pediatric VAD which requires a possible operational speed range from 2000 rpm to 5000 rpm.

Future tasks are to develop a magnetically suspended pediatric VAD with developed 5-DOF controlled self-bearing motor and to evaluate the pump performance as well as the magnetic suspension ability and the rotor dynamics during pumping. Future design of the levitation system will focus on considering the effect of hydraulic force and viscoelastic characteristics.

5. Conclusions

The novel concept which can actively control 5-DOF of rotor postures by utilizing two types of magnetic fields based on the vector control algorithm and the P±2 pole algorithm was proposed for pediatric VAD. The proposed motor produced the sufficient radial suspension force to suspend the levitated rotor radially. The developed 5-DOF controlled self-bearing motor was successful with stable levitation and rotation. The resonances in the rotor radial directions were significantly suppressed with radial position active control. The results verified the sufficient radial position control capability and structure of 5-DOF controlled self-bearing motor. The proposed double stator structure and 5-DOF control mechanism contribute to the miniaturization of self-bearing motor system.

References