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A Compact Maglev Pediatric Ventricular Assist Device with An Axial Gap Type Self-bearing Motor

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Abstract

Miniaturization of magnetically suspended motor has been strongly demanded to develop implantable continuous flow pediatric ventricular assist devices (VADs) with excellent blood compatibility. This study develops a compact axial gap type self-bearing motor for pediatric VADs. The magnetically levitated motor has a top stator, a bottom stator, and a centrifugal closed impeller which is sandwiched between both stators with identical shape. The impeller axial position is regulated with vector control. The inclination angle of the impeller is regulated using P+/-2-pole theory. The double stator self-bearing motor can enhance torque production with small device size. This paper investigates a miniaturized axial gap type self-bearing motor with height reduction considering anatomical compatibility for long-term in vivo evaluation of the magnetically levitated pediatric VAD. The developed self-bearing motor has an outer diameter of 30 mm and a height of 29 mm. The constructed magnetically levitated centrifugal blood pump was driven with non-contact operation in a closed loop circulation circuit. The maglev pediatric VAD prototype indicated that the flow rate can be regulated in the range of 0.5-2.5 L/min against a head pressure of 60-100 mmHg. The vibration amplitude of the levitated impeller was 0.02 mm in the axial direction, and the tilt angle was about 0.2 deg. The developed pediatric VAD demonstrated sufficient hydraulic and magnetic suspension performance for use in animal testing with device implantation.

Keywords : Self-bearing motor, axial gap type, centrifugal blood pump, pediatric VAD, miniaturization

1. Introduction

An only clinically available ventricular assist device (VAD) in the world for pediatric circulatory support is the extracorporeal pulsatile-flow EXCOR pediatric developed by BerlinHeart Inc. (Baldwin et al., 2006). Extracorporeal pulsatile flow VADs have issues with thrombus formation due to periodical blood stagnation in the pump chamber, and infection at the inlet/outlet tube through the skin. An implantable continuous flow VAD is required (Gibber et al., 2010) to minimize the risks of thrombus formation and infection caused by blood pump configuration, however the rotary blood pumps using mechanically contacting bearings have difficulty overcoming the issues of hemolysis and thrombus formation at the bearing. In recent years, there has been a strong demand for implantable continuous-flow pediatric VADs with a small, high-performance impeller non-contact suspension mechanism with excellent blood compatibility.

A maglev pediatric VAD that utilizes an axial gap type double-stator self-bearing motor has been developed in our research group (Baldwin et al., 2006). The design of the device geometries considering anatomical compatibility is being discussed to conduct animal trials using developed VAD system. This paper investigates a small, thin self-bearing motor for an implantable pediatric VAD for long-term animal trials with device implantation. Motor geometries are designed with 3D magnetic field analysis using the finite element method (FEM). A magnetically levitated centrifugal blood pump is fabricated, and a magnetic levitation control system for the double stator self-bearing motor is developed. Finaly, the pump characteristics for the pediatric circulatory support and the non-contact impeller suspension characteristics are evaluated.

2. Materials and Methods

2.1 Double stator axial gap type self-bearing motor for pediatric VAD

2.1.1 Overview of maglev pediatric VAD

A schematic view of the proposed magnetically levitated pediatric VAD is shown in Fig. 1. The maglev pediatric VAD consists of a top stator, a bottom stator and a levitated impeller which is sandwiched between identically shaped motor stators. The self-bearing motor enables non-contact impeller suspension and higher torque production with a double stator structure. The proposed pediatric VAD employs a centrifugal blood pump with a closed impeller. The motor stator has six slots, and concentrated windings for impeller suspension and rotation control are placed on each salient pole. Four-pole permanent magnets are mounted on the top and bottom surfaces of the impeller shroud. The levitated impeller has the same inner hole diameter on the shroud to make a balance axial thrust force acting on top and bottom surface and to have washout blood flow in the pump chamber.

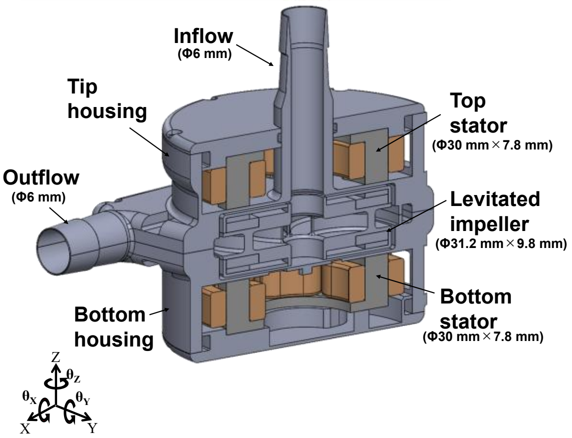


Fig. 1 Schematic of the proposed pediatric VAD with axial gap type double stator self-bearing motor

2.1.2 Impeller suspension principle of the developed self-bearing motor

An axial position (Z) and a rotating speed (ωz) of the levitated impeller are controlled by a three-phase and four-pole rotating magnetic field, while radial positions (X, Y) and inclination angles around the radial axes (θx, θy) are controlled by a three-phase and two-pole rotating magnetic field. All axes and rotations of the levitated impeller are actively controlled independently by superimposing four-pole and two-pole control magnetic fields shown in Fig. 2. An axial position of the levitated impeller is regulated with an imbalance force generated in the magnetic attractive forces at the top and bottom of the levitated impeller by field strengthening and field weakening. The rotation speed of the levitated impeller is controlled by the q-axis component of the three-phase and four-pole current. An inclination torque around the radial axes and a radial suspension force are generated simultaneously by two-pole control magnetic field shown in Fig. 3. The inclination torque and radial suspension force can be generated independently by regulating the torque and force produced by the top and bottom stators. The proposed self-bearing motor can be driven as a three-axis controlled maglev motor because the axial gap motor has passive stability due to magnetic coupling force (Osa et al., 2012).

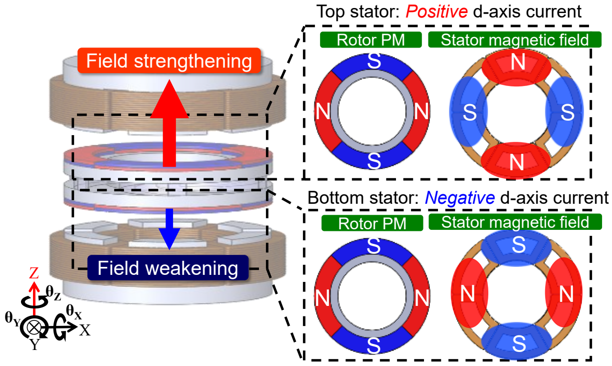


Fig. 2 Axial position control

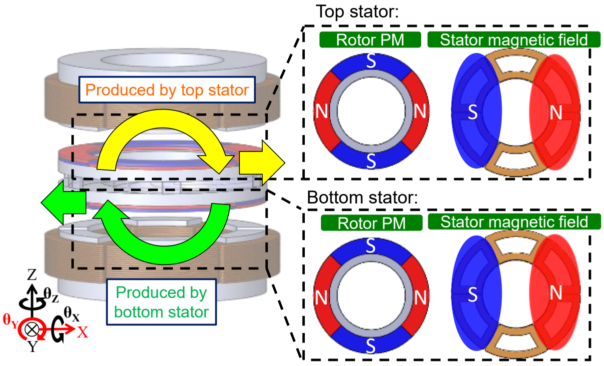


Fig. 3 Inclination angle control

2.2 Design of double stator self-bearing motor with 3D FEM analysis

A previously developed motor, which has an outer diameter of 22 mm and a height of 11.3 mm, was designed as vertical cylinder shape to ensure the suspension force and torque production with longer salient poles enhancing the magnet motive force using higher number of windings turns (Osa et al., 2021). In contrast, this study redesigns the magnetic circuit geometries as disk shaped motor to have almost inversed aspect ratio of the previously developed motor considering anatomical compatibility of the pediatric VAD. The height of the salient poles and the thickness of the stator and rotor back yoke were reduced in order to reduce the height of the motor. The outer diameter was enlarged to 30 mm enlarging the effective cross-sectional area to compensate for the deterioration of the suspension force and torque capacity caused by the reduction in the number of turns due to the reduction in the salient pole height. Geometries of the stator teeth should be carefully determined since the excessively large cross-sectional area may cause an increase in negative stiffness. For this reason, the effective cross-sectional area was adjusted while changing the salient pole inner diameter and slot width. And the teeth shape was determined at the point to have well balance between the negative stiffness and suspension force. The inner diameter was changed in the range of 21-25 mm, and the slot width was changed in the range of 4-8 mm. Due to the height of the eddy current displacement sensor, the minimum teeth height was determined to 6 mm. In this design, the outer diameter is 30 mm, the inner diameter is 21.4 mm, the slot width is 6 mm, and the salient pole height is 6.8 mm. The outer diameter of the permanent magnet is 30 mm, the inner diameter is 18 mm, and the thickness is 0.8 mm. In addition, the thickness of the stator and rotor back yoke is determined to 1.5 mm, considering the magnetic saturation due to the magnetic flux generated by the permanent magnet and electromagnet. As a result, the motor's outer diameter is 30 mm and its total length is 29 mm. The axial suspension force, the negative stiffness, and the torque constant were estimated as 3.8 N/A, 32 N/mm, and 16.1 mNm/A, respectively.

2.3 Fabrication of double stator self-bearing motor and centrifugal blood pump

The stator geometries of a self-bearing motor were designed using finite element method three-dimensional magnetic field analysis. The aim of this study is to make the motor thinner for considering device implantation. Deterioration of the suspension force due to the reduction in the turn numbers of windings according to decrease in the salient pole height was compensated by adjusting the outer diameter of the motor to increase the cross-sectional area of the salient pole resulting in increase in the suspension force and torque production. The slot width was also adjusted to avoid an excessive reduction in the number of windings turns. A double-stator self-bearing motor with an outer diameter of 30 mm and a height of 29 mm was designed and fabricated based on the analysis results, and it is shown in Fig. 4. 124 turns of copper wire with a diameter of 0.3 mm are wound on each stator tooth. A neodymium (N-48H) magnet with a thickness of 0.8 mm was used to generate the rotor field. A pump housing made by polycarbonate and a titanium impeller as shown in Fig. 3 were fabricated to evaluate the hydraulic characteristics and impeller suspension performance of the developed blood pump. The developed blood pump has a double volute structure, which can mechanically suppress the radial fluid force acting on the impeller. The levitated impeller has an outer diameter of 31.2 mm, a height of 9.8 mm, and a mass of 26.6 g. The acceptable range of impeller movement in the pump housing is ±0.3 mm and ±0.7 mm in the axial and radial directions, respectively, and it can incline ±1.1 deg around the radial axes. The air gap when the impeller is magnetically levitated at the magnetic center position in the axial direction is 1.3 mm.

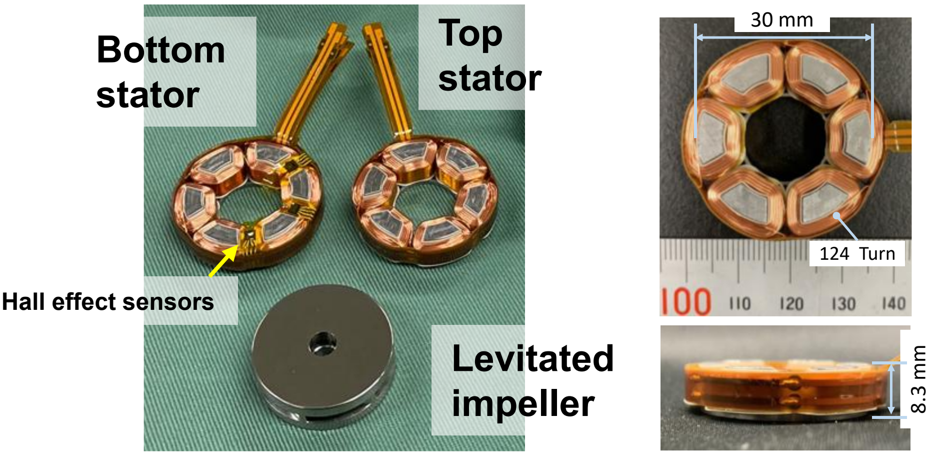


Fig. 4 Fabricated axial gap type self-bearing motor

2.4 Magnetic suspension and rotation control system for the developed pediatric VAD

Three eddy current sensors (PU-03A, Applied Electronics Corporation) measure an axial position and inclination angles around x and y axes of the levitated impeller. Other two eddy current sensors measure radial positions of the levitated impeller in x and y direction. Three Hall Effect sensors (Asahi KASEI Corporation) measure a rotating angle of the levitated impeller with a sensitivity of 30 degrees electrical angle. Digital PID controllers are implemented on a microprocessor board MicrolabBox (dSPACE GmbH, Paderborn Germany) with MATLAB/Simlink for impeller position control and rotation. A block diagram for axial position and rotation control, and inclination angle control are shown in Fig. 5 and Fig. 6, respectively. A PID feedback loop calculates positive and negative d-axis current to produce an axial suspension force. A PI feedback loop regulates q-axis current of both stators based on a conventional rotating speed control. Required current for inclination angle control are calculated by other two PID feedback loops to calculate amplitude and phase angle of two-pole rotating magnetic field produced by the top and bottom stators. PID controllers are designed to calculate the required control current. Parameters of the digital PID controllers for impeller suspension and rotation were preset based on the measured suspension force and torque characteristic, manually tuned and determined in dynamic performance evaluation. Sampling and control frequency is 10 kHz. Excitation current is supplied by twelve single phase PWM current amplifier (JSP-090-10, Copley Controls) to both motor stator windings.

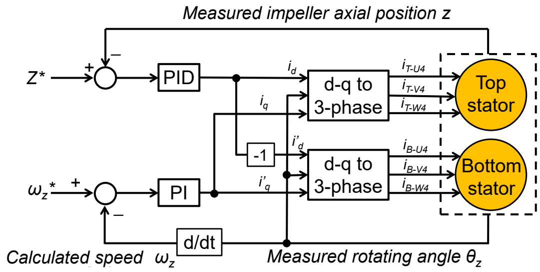


Fig. 5 Axial positoin and rotation speed control system

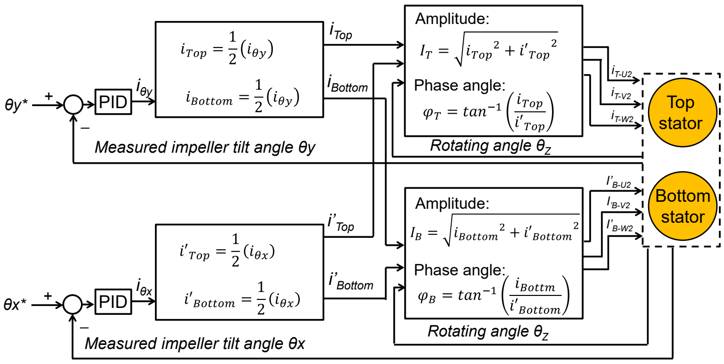


Fig. 6 Inclination angle control system

2.5 Evaluation of hydraulic characteristics and magnetic suspension performance

A closed loop circulation circuit shown in Fig. 7 was constructed to evaluate the hydraulic characteristics of the maglev blood pump for a pediatric VAD and the impeller suspension performance of the developed self-bearing motor during pumping. The blood pump was operated at 2600-3200 rpm, and the pump operating point was changed by adjusting the circuit resistance. The 5-axis of the impeller positions were measured using eddy current displacement sensors. The impeller postures and rotating speed are controlled with PID controllers, and each control gain was manually tuned to achieve vibration suppression for the representative operating points. The vibration amplitude was calculated from sampled data of the axial position, radial position and inclination angles of the levitated impeller sampled at 10 kHz for 1 second.

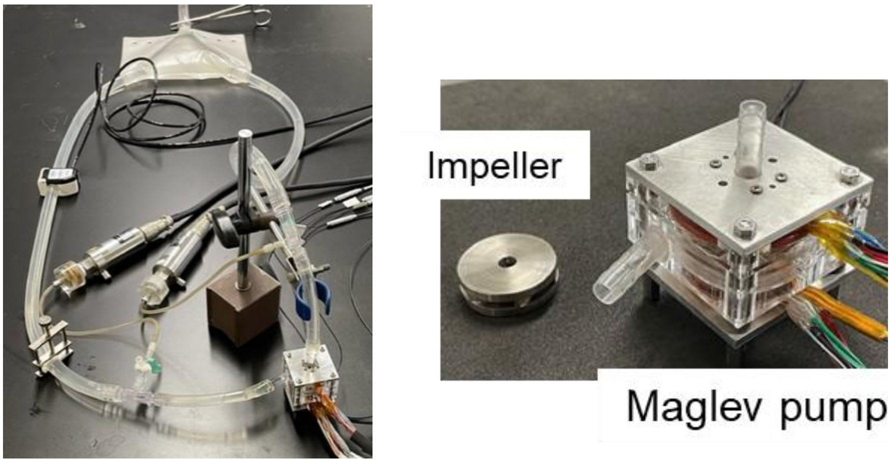
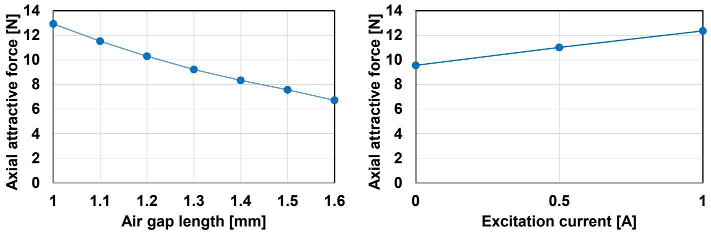


Fig. 7 Closed loop circulation circuit with the developed maglev pediatric VAD prototype

3. Results

The relationship between the air gap length and the axial suspension force produced by the single stator, and the relationship between the excitation current and the axial suspension force at the air gap length of 1.3 mm are shown in Fig. 8. The excitation current is also a variable parameter, and the excitation current is between 0 A and 1 A. The axial magnetic suspension force is inversely proportional to the air gap length, and the negative stiffness calculated from the slope of the suspension force generated in non-excitation is 20.7 N/mm. The axial suspension force coefficient calculated by the produced suspension force with respect to unit excitation current for the air gap of 1.3 mm is 2.8 N/A. The rotating torque generated by the single stator with an air gap length of 1.3 mm is shown in Fig. 9. The developed self-bearing motor indicated a torque constant of 19.4 mNm/A regardless of the rotating speed.



(a) Force with different air gap (b) Force with different current

Fig. 8 Axial attractive force

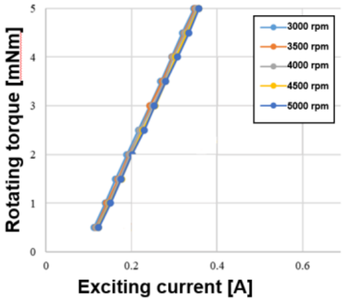


Fig. 9 Rotating torque characteristics

HQ characteristics of the developed blood pump are shown in Fig. 10. The blood pump can produce a flow rate in the range of 0.5-2.5 L/min against a head of 60-100 mmHg at a rotating speed of 2800-3200 rpm. The hydraulic efficiency of the blood pump estimated from the motor torque characteristics was approximately 11-23% at the expected operating point. The axial oscillation amplitude of the levitated impeller under all pump driving conditions is shown in Fig. 11, and the inclination angle is shown in Fig. 12. The axial oscillation amplitude of the levitated impeller was less than 0.02 mm, which was sufficiently small compared to the maximum blood gap of 0.3 mm. The amplitude of the inclination angle was also small at 0.2 deg compared to the acceptable inclination angle of 1.1 deg. The passively stabilized radial position of the impeller was also sufficiently suppressed as shown in Fig. 13, and non-contact impeller suspension was demonstrated. The low energy input for magnetic suspension and rotation with 1.0-2.5 W was achieved.

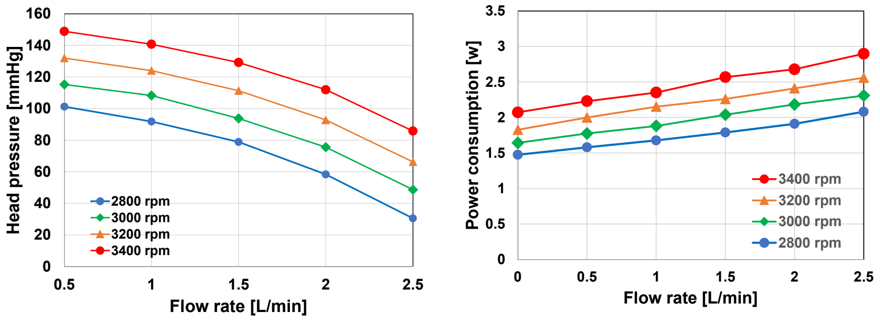


Fig. 10 HQ characteristics and power consumption of the developed centrifugal blood pump

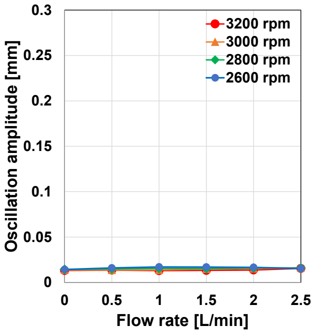


Fig. 11 Axial oscillation apmlitude

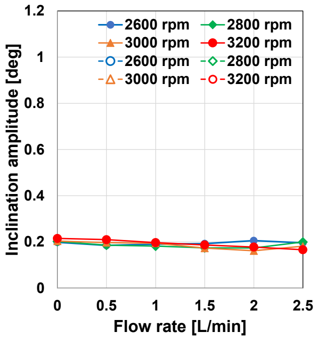


Fig. 12 Inclination angle amplitude

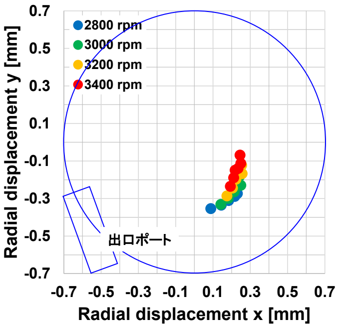


Fig. 13 Impeller radial position

4. Discussion

Non-contact impeller suspension technique using maglev motor significantly contributes to enhance the durability and blood compatibility of the continuous flow implantable VADs (Kevin et al., 2001, Lin et al., 2015, Kurita et al., 2018). Miniaturization of the maglev motor considering anatomical compatibility plays a significant role in the next generation implantable pediatric VADs development.

The compact axial gap type self-bearing motor with height reduction was designed using 3D FEM magnetic field analysis. Although the motor outer diameter in this paper is larger than that of the previously developed motor, the device height reduction to directly access the pump to the apex contributes to improvement of anatomical fitting. The self-bearing motor still has a possibility for further diameter miniaturization through magnetic circuit optimization.

The static characteristics of suspension force of the developed self-bearing motor indicated that the magnetic force acting on the impeller can be balanced over the movable range of the impeller. In addition, the torque capacity has been improved by the enlargement of the impeller diameter, and the operating point of the blood pump can be lower than that of the previously developed blood pump, which will be advantageous in terms of rotation characteristics.

The pump could be driven without mechanical contact in the closed loop circulation circuit. The developed pediatric VAD prototype was able to regulate the flow rate over a wide range by changing the pump speed, and demonstrated the sufficient pump performance in response to the patient's growth. The vibration amplitude of the levitated impeller is sufficiently small so that blood cell destruction due to high shear stress caused by narrow blood gaps would not occur. In addition, since there is no physical contact, the possibility of thrombus formation due to scratches would be quite small. The impeller radial position passively stabilized changed according to the pump speed and flow rate. Although the outer diameter of the blood pump was enlarged, the flow path width of the volute part was not changed due to the constraints of the diameter of the outlet port, and the radial fluid force could not be completely suppressed due to the imbalance in the pressure distribution caused by the difference in fluid resistance at the two volutes. However, there was no contact between the impeller and the casing at all operating points, and non-contact suspension was sufficiently ensured. From the viewpoint of biocompatibility, reduction of the temperature rise is one of the most important issues in this pump, the policy of three-axis control for low power consumption is appropriate.

In the future, evaluation of the circulatory support performance of the blood pump connected to a mock circulation system that simulates hemodynamics, and to evaluate the magnetic levitation stability in an experimental system with pulsatility and disturbances force. Finally, blood compatibility will be evaluated through animal testing.

5. Conclusion

The miniaturized axial gap type self-bearing motor with an outer diameter of 30 mm and a height of 29 mm considering an anatomical fitting was developed for chronic animal trials with device implantation. The pump characteristics and magnetic suspension performance of the developed blood pump demonstrated that the pump achieved non-contact impeller suspension and sufficient for pediatric circulatory support. In the future, the impeller dynamics in transient position control and shock durability testing will be carried out.

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