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Vacuum chamber-free centrifuge with magnetic bearings

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Centrifuges are devices that separate particles of different densities and sizes through the application of a centrifugal force. If a centrifuge could be operated under atmospheric conditions, all vacuum-related components such as the vacuum chamber, vacuum pump, diffusion pump, and sealing could be removed from a conventional centrifuge system. The design and manufacturing procedure for centrifuges could then be greatly simplified to facilitate the production of lightweight centrifuge systems of smaller volume. Furthermore, the maintenance costs incurred owing to wear and tear due to conventional ball bearings would be eliminated. In this study, we describe a novel vacuum chamber-free centrifuge supported by magnetic bearings. We demonstrate the feasibility of the vacuum chamber-free centrifuge by presenting experimental results that verify its high-speed support capability and motoring power capacity. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4820242]

I. INTRODUCTION

Centrifuges, which are widely used in the fields of cellular and molecular biology, biochemistry, and polymer science, are devices that separate particles of different densities and sizes through the application of a centrifugal force.[1–4] Centrifugal force is proportional to the rotational speed and distance from the center of rotation. The relative centrifugal force (RCF), which refers to the unit of the centrifugal force in centrifuges, is given by Eq. (1).

$$RCF = r\omega^2/g, \tag{1}$$

where r is the distance from the rotational center (m), ω is the angular velocity (radian/s), and g is the gravitational acceleration (m/s^2). Centrifuges are generally classified as shown in Table I.[5] Figure 1 shows the simple configuration of a conventional centrifuge. A flexible shaft connects the motor shaft and the rotor, and the rotor including the centrifuge tubes rotates in the vacuum chamber. Moreover, the motor shaft is supported by ball bearings, of which the operating speed limit is less than 1 000 000 DN. Here, DN is the product of the inner diameter of the bearing in mm (D) and the maximum speed in rpm (N).[6] For example, in the case where the speed limit of the ball bearing is 600 000 DN and the maximum speed is 100 000 rpm, the outer diameter of the shaft that contacts the ball bearings should be less than 6 mm. As long as ball bearings are applied to the centrifuge, the diameters of the motor shaft and flexible shaft must decrease as the operating speed of the centrifuge increases. A smaller diameter shaft has its limitations with regard to transmitting torque to the rotor; further, overcoming the friction against the surrounding air is difficult. Furthermore, the ball bearings themselves cause friction loss owing to contact with the motor shaft. For this reason, centrifuges require a vacuum chamber to minimize the friction loss caused by windage.[1] A vacuum permits high rotational speed of the rotor within the limited motor power. However, to create a vacuum, a vacuum pump, and diffusion pump are also required in addition to a vacuum chamber. Vacuum-related equipment, which occupies about 50% of the volume in centrifuge systems, makes the systems bulky and complicated.[1–4] In addition, additional time and power are required for the vacuum chamber to reach the specified vacuum level before the rotational speed attains the set speed and to release the vacuum at the end of the operation. Another disadvantage of the vacuum chamber is that complicated methods to create a seal between the vacuum and non-vacuum components are required. The driving component, comprising the motor and ball bearings, should be isolated from the vacuum chamber because there is outgassing from the bearing lubrication and cooling systems. In this study, we present a novel vacuum chamber-free centrifuge supported by magnetic bearings to eliminate the abovementioned problems. One of most important feature of magnetic bearings is that they can actively control the unbalance response especially due to the sample concentrations or the exchange rotor in centrifuges, which is not possible with ball bearings. Many strategies to control the unbalance response are presented by Schweitzer and Maslen.[7] While the maximum speed of ball bearing is 1 000 000 DN, the maximum speed of magnetic bearing is 4 500 000 DN.[8] Therefore, by applying magnetic bearings to the centrifuges, the shaft diameter can be increased; in addition, a high torque that sufficiently overcomes the windage loss can be transmitted from the motor to the rotor.[9] Furthermore, owing to the absence of any bearing friction loss because the rotating shaft does not come into contact with any other component, the motor capacity need not be increased greatly despite the windage loss from the rotor. To verify the feasibility of the proposed method, we have developed a prototype centrifuge with magnetic bearings. Centrifuges have been frequently mentioned as good applications of magnetic bearings in many literatures.[1,10,11] However, any significant study on the lab centrifuge with magnetic bearings has not been reported yet. Therefore, this study also has a meaning to

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TABLE I. Classification of centrifuges.

	Low-speed centrifuge	High-speed centrifuge	Ultracentrifuge
Speed range (rpm)	2000–6000	18 000–30 000	35 000–120 000
Max. RCF	8000	100 000	700 000
Applications	Nuclei, plasma membranes, whole cells	Lysosomes, peroxisomes, mitochondria, protein precipitation	Nanoparticles, poteins, receptors, ribosomes, lipoproteins, viruses

present a case study on the high-speed centrifuge or ultracentrifuge supported by magnetic bearings.

II. SYSTEM CONFIGURATION

Figure 2 shows the configuration of the proposed vacuum chamber-free centrifuge. A fixed-angle rotor is assembled with the shaft, which is supported by magnetic bearings and directly driven by a permanent magnet synchronous motor (PMSM). The length of the shaft is designed to be as short as possible to increase the first bending mode frequency. The motor was designed to have 20-kW rated power at 100 000 rpm. Upper and lower radial magnetic bearings are controlled to maintain a radial gap of 0.4 mm between the radial bearings and the shaft. These bearings, which are of the homopolar type, can reduce the eddy current loss and heat generation due to high-speed shaft rotation by minimizing the magnetic field variation in the circumference of the magnetic core of the shaft.[7] The thrust magnetic bearing located at the bottom of the centrifuge is controlled to maintain an axial gap of 0.6 mm between the thrust bearings and the shaft. The radial and thrust magnetic bearings are both hybrid magnetic bearings with permanent magnets that generate a bias flux and increase efficiency.[9] Table II shows the specifications of the radial magnetic bearings and the thrust magnetic bearing which are designed to support the rotor-shaft assembly with a mass of 4.1 kg. The fabricated magnetic bearings are shown in Figure 3.

III. DESIGN OF ROTOR AND SHAFT

The shaft was constructed by assembling a motor magnet (NdFeB), shaft studs (SUS304), magnetic core rings (S55C), and a sleeve (Inconel 718). The dimensions of the shaft should be carefully determined because the NdFeB magnet has a relatively low tensile yield strength of 80 MPa. In addition, a pre-compressive stress should be applied on the motor magnet by using an interference fit with the sleeve to reduce the tensile stress against the centrifugal force. Table III shows the dimensions of the motor magnet and the sleeve. The maximum Von Mises stress at the center of the motor magnet under a rotating speed of 100 000 rpm was predicted to be less than the tensile yield strength, as shown in Figure 4.

The titanium alloy rotor was designed to have a maximum diameter of 96 mm, a maximum RCF of 500 000, and a mass of 1.16 kg; hence, the total mass of the rotor-shaft assembly was 4.1 kg. If the shaft is supported by magnetic

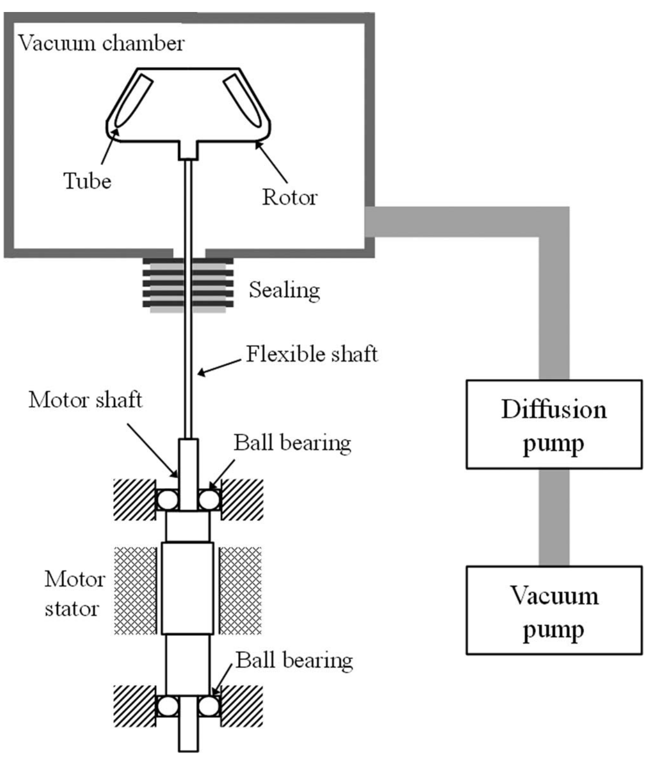

FIG. 1. Configuration of conventional centrifuge with vacuum chamber.

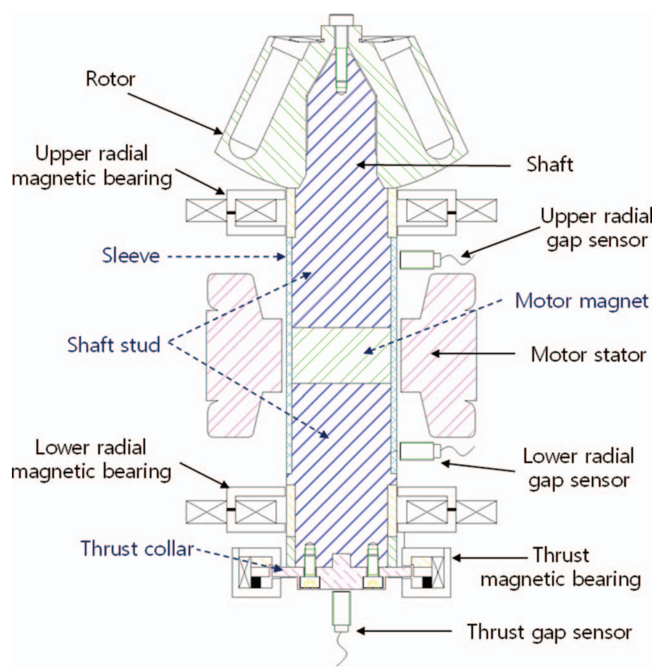

FIG. 2. Configuration of vacuum chamber-free centrifuge.

TABLE II. Specifications magnetic bearings.

	Specifications	
Item	Radial magnetic bearings	Thrust magnetic bearing
Core material of stator	Pure iron	Pure iron
Core material of shaft	S55C	S55C
Nominal gap	0.4 mm	0.6 mm
Minimum gap	0.2 mm	0.3 mm
Maximum gap	0.6 mm	0.9 mm
Coil turns	56	40
Thickness of permanent magnet	0.1 mm	5 mm
Pole-face area	1.15×10^{-4} m^2	7.29×10^{-4} m^2
Current gain	8.20 N/A	19.0 N/A
Position gain	-1.33×10^5 N/m	-3.18×10^4 N/m

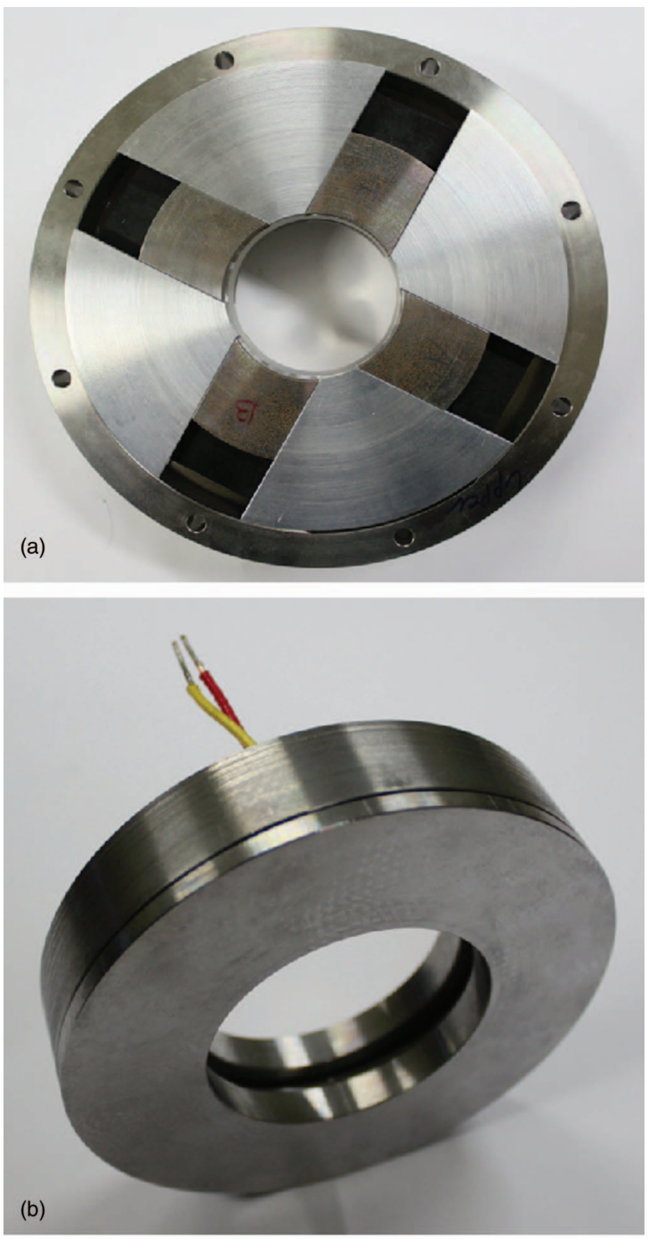

FIG. 3. Fabricated magnetic bearings. (a) Radial magnetic bearing; (b) Thrust magnetic bearing.

TABLE III. Mechanical dimensions of motor magnet and sleeve.

Item	Dimensions
Outer diameter of motor magnet	41.8 mm
Inner diameter of sleeve	41.8 mm
Outer diameter of sleeve	49.0 mm
Interference fit	210 μm

bearings, the first bending mode frequency should exist far enough from the operating frequency for stable rotation. The first bending mode frequency was predicted by rotordynamic analysis and verified through an impact test; the results are shown in Table IV. Even for the rotor-shaft assembly, the first bending mode frequency existed sufficiently far from 1667 Hz, which corresponds to the rotating speed of 100 000 rpm, and the unbalance response was predicted to be less than 4 μm across the entire range of rotational speeds from 0 to 100 000 rpm. The fabricated rotor and shaft are shown in Figure 5.

IV. EXPERIMENTS

A. Motoring test and unbalance response

The fabricated centrifuge supported by magnetic bearings is shown in Figure 6. The magnetic bearing controller—composed of a PID (proportional integral derivative) controller, notch filters, and low-pass filters—is implemented with a 10-kHz sampling frequency and the sensorless motor driver controls the rotational speed.[12,13] First, the spin-up and spin-down test with a shaft only (without rotor) was repetitively performed up to 95 000 rpm to confirm the structural strength of the shaft and the stability of the magnetic bearings. The magnetic bearings stably supported the shaft with a zero-to-peak radial displacement of less than 3 μm across the entire range of rotation speeds, and there is not any noticeable change of unbalance response even at the 95 000 rpm (Figure 7). It means that the shaft has sufficient structural strength to endure the centrifugal force up to the speed range

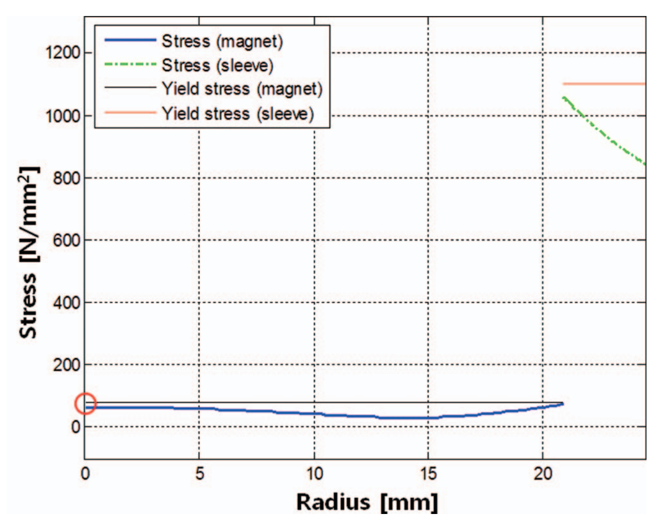

FIG. 4. Von Mises stress in motor magnet and sleeve at 100 000 rpm.

TABLE IV. Prediction and impact test results for first bending mode frequency of rotor-shaft.

	Shaft only		Rotor-shaft assembly	
	Prediction	Impact test	Prediction	Impact test
First bending mode frequency (Hz)	4016	4028	2335	2584

of ultracentrifuge. Next, the motoring test with the rotor-shaft assembly was performed. The unbalance response was less than 4 μm as predicted up to 45 000 rpm, whereas it increased up to 8 μm at 55 000 rpm (Figure 8). The reason why the unbalance response was larger than predicted is surmised as follows. At a standstill, the first bending mode frequency is over 2500 Hz because the rotor is in contact with the shaft at both the neck and end of the shaft (Figure 2). As the rotational speed increases, the rotor is separated from the neck of the shaft owing to the centrifugal force, and the entire mass of the rotor is concentrated at the end of the shaft. This reduces the first critical bending speed of the rotor-shaft assembly. The rotordynamic analysis assuming this situation predicted that the first critical bending speed would decrease to about 60 000 rpm. Therefore, the rotor-shaft assembly method should be improved in further studies to maintain the contact status in the rotor-shaft assembly and increase the rotational speed stably.

B. Measurements of motoring power

The motoring power under atmospheric conditions was measured with a power meter in the range of 0 to 50 000 rpm.

FIG. 5. Fabricated rotor-shaft. (a) Shaft only; (b) Rotor-shaft assembly.

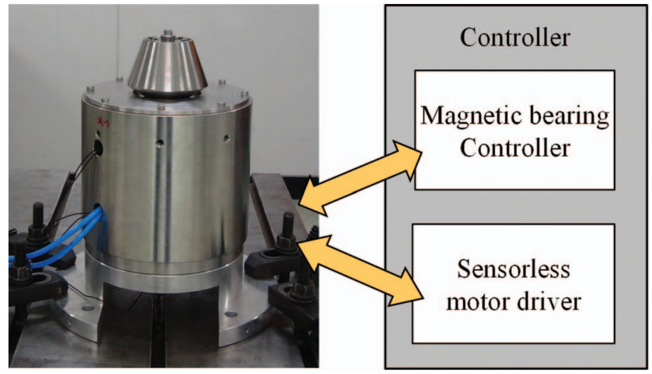

FIG. 6. Fabricated centrifuge and controller layout.

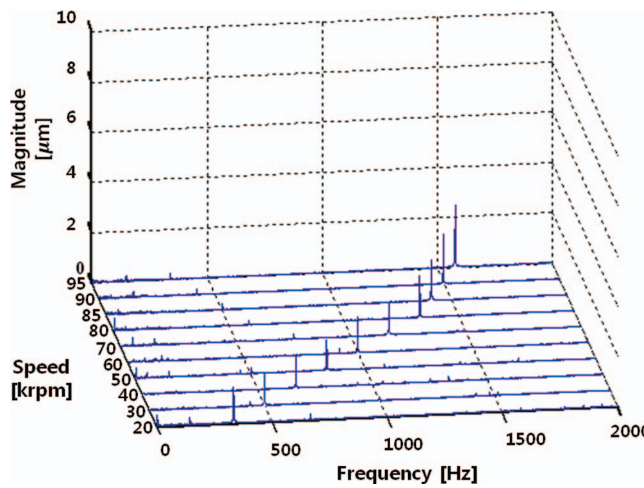

FIG. 7. Cascade plot of upper radial vibration from 10 000 to 95 000 rpm in case of shaft only.

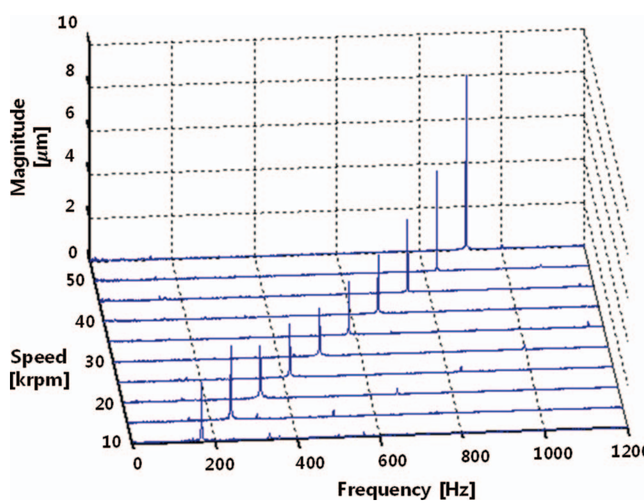

FIG. 8. Cascade plot of upper radial vibration from 10 000 to 55 000 rpm in case of rotor-shaft assembly.

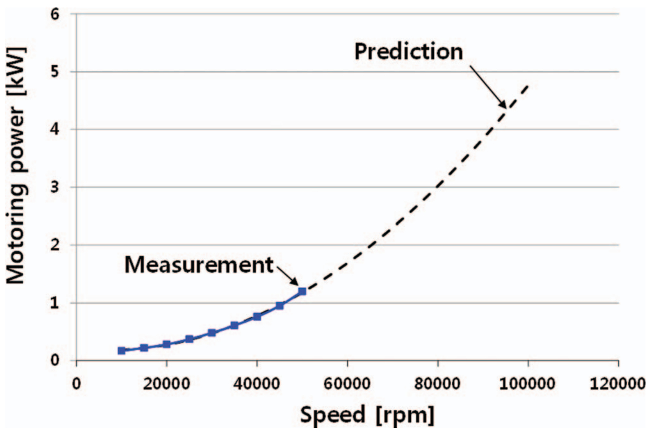

FIG. 9. Measured and predicted results of motoring power.

Subsequently, the motoring power at higher rotational speeds was predicted using curve fitting, as shown in Figure 9. Even at 100 000 rpm, the motoring power was predicted to be only 4.7 kW. This leaves enough margin, given that the rated power of the designed motor is 20 kW at 100 000 rpm. The elimination of the bearing friction loss owing to the magnetic bearings appears to have added the margin of motoring power despite the large increase in windage loss.

V. CONCLUSION

On the basis of the experimental results, we confirmed the feasibility of a vacuum chamber-free centrifuge. The shaft and rotor-shaft assembly could be stably supported by magnetic bearings up to 95 000 rpm and 55 000 rpm, respectively, and the motor power was predicted to be sufficient to overcome the windage loss even at 100 000 rpm. In this study, we focused on verifying the high-speed supporting capability of the magnetic bearings, the structural strength of the shaft, and the motoring power capacity. Therefore, examination of the rotor design and rotor-shaft assembly method was insufficient; moreover, the motoring test for the rotor-shaft assembly stopped at only 55 000 rpm, which corresponds to a maximum RCF of 152 000. However, this issue could be improved in the future. If centrifuges could operate under atmospheric conditions as described in this paper, all vacuum-related components such as the vacuum chamber, vacuum pump, diffusion pump, and sealing could be removed. The design and manufacturing procedure for centrifuges could then be greatly simplified, and lightweight centrifuge systems of smaller volumes would become possible. Furthermore, maintenance costs incurred owing to the wear and tear caused by conventional ball bearings would be eliminated. However, the proposed centrifuges could be more expensive than conventional centrifuges because of the requirement of additional hardware components for magnetic bearings such as electromagnets, gap sensors, and a magnetic bearing controller. Nevertheless, the new method has considerable potential for achieving higher rotational speeds, which are needed to increase the RCF beyond that of conventional ultracentrifuges.

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