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A method of reducing windage power loss of a high-Speed motor using a viscous vacuum pump

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ABSTRACT

A new structure for reducing the windage power loss of a high-speed rotor using a spiral grooved viscous vacuum pump combined with an aerodynamic step thrust bearing is proposed. The proposed structure can pump out the air from within the sealed space of the motor housing by using the pumping effect of the spiral grooves and thereby reduce the windage power loss of the rotor. In addition, a small gap was automatically formed between the rotor and the viscous vacuum pump by using the force balance between the aerodynamic step thrust bearing and the elastic material supporting the flat plate of the vacuum pump. It was numerically shown that the proposed structure could reduce the pressure in the sealed space of the motor housing to 0.02 MPa at 30,000 rpm at a gap of 10 μm. In addition, the calculated results at 10,000 rpm were compared with the experimental results and showed good agreement and the proposed structure was very useful in reducing the windage power loss of a high-speed motor.

1. Introduction

Electric motors used in hybrid and electric vehicles continuously require improvement in performance, such as output power, motor weight and size, rotational speed, and power consumption. The rotational speed of motors used in vehicles has increased in recent years with the achievement of higher output power. With the increase in rotational speed, larger windage power loss is usually generated by the rotor, in particular for rotors with complex shapes of the outer periphery. To reduce the windage power loss of a high-speed rotor, some effective methods have been proposed.

A number of works [1–3] studied a flywheel generator system in which the flywheel rotated in a vacuum container to reduce the windage power loss of the flywheel. Ajisman et al. [4] investigated the windage power loss of a flywheel in a housing filled with H_2 and SF_6 gas mixtures and confirmed that the proposed gas mixtures could significantly reduce the power loss compared with air. However, these two methods had some disadvantages; they needed vacuum pumps or gas compressors to maintain the condition in the flywheel container constant and these devices also required space.

To address these issues, a method using the rotation of a shaft was proposed. Matsumura et al. [5] proposed the method of using the pumping effect of a gear pump to reduce the pressure in a sealed housing. Yoshimoto and Takahashi [6] and Yoshimoto et al. [7] proposed a method of reducing the pressure in a laser scanner housing by a viscous vacuum pump with herringbone grooves (Fig. 1) and showed that the windage power loss of the proposed scanner motor could be reduced by 50% over a conventional scanner (Fig. 2.). Yoshimoto et al. [8] described a viscous vacuum pump using spiral grooves that could also function as an aerodynamic thrust bearing and showed the usefulness of reducing the windage power loss of a laser scanner. In the application of a viscous vacuum pump to laser scanners, the gap of the viscous vacuum pump could be easily kept constant because the output power and the size of the laser scanner were usually small and, hence, the thermal deformation of the scanner structure was also small. However, when these viscous vacuum pumps are applied to a high-speed motor with large output power, the effect of the thermal deformation of the shaft on the gap of the viscous pump has to be taken into account because of temperature variation of the motor. This means that a mechanism for adjusting the gap of the viscous pump by itself is necessary in the application to a high-speed motor with large output power.

In this paper, we propose a viscous vacuum pump combined with an aerodynamic step thrust bearing, which could adjust the

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Nomenclature

f_e Imposed load on an elastic material
G Mass of air involved in a sealed space
h Bearing clearance
h_d Groove depth
$H_d = h_d/h_r$ Dimensionless groove depth
h_r Bearing clearance in the ridge region
h_g Bearing clearance in the groove region
h_s Step depth of an aerodynamic bearing
n Number of grooves
p Pressure
p_a Ambient pressure
p_i Pressure in the sealed space
$P_i = p_i/p_a$ Dimensionless pressure in the sealed space
P_u Final pressure in the sealed space
q Mass flow rate in the bearing clearance
r_2 Outer radius of spiral grooves
r_1 Inner radius of spiral grooves
r_{e2} Outer radius of elastic material
r_{e1} Inner radius of elastic material
r_o Outer radius of step bearing pads
r_i Inner radius of step bearing pads
r_{po} Outer radius of pocket of step bearing pads
r_{pi} Inner radius of pocket of step bearing pads
R Gas constant
t Time
T Gas temperature
V_i Inner volume of the sealed space
r and θ Radial and circumferential coordinates, respectively
α Ratio of the groove width to the (ridge + groove) width
β Groove angle
δ Deformation of elastic material
$\lambda = p_a\lambda_a/p$ Molecular mean free path
λ_a Molecular mean free path at atmospheric pressure (= 0.064 μm)
$\Lambda = 6\mu\omega r^2/p_a h_r^2$ Bearing number
μ Viscosity of air
ρ Density of air
ω Angular velocity
ξ and η Boundary-fitted coordinates

Subscript
r Ridge region
g Groove region

gap by itself even if the shaft length changed by temperature variation. Our aims were to confirm experimentally that the proposed mechanism could adjust the gap of the viscous vacuum pump by itself and reduce the pressure in the motor housing, and to predict numerically the pumping characteristics required to design the proposed structure by using optimal parameters.

2. Proposed structure of a viscous vacuum pump combined with aerodynamic step thrust bearing

Fig. 3 shows the geometrical configuration of the circular flat plate with a viscous vacuum pump combined with an aerodynamic step thrust bearing. Spiral grooves functioning as a viscous vacuum pump are formed at the outer region of the circular plate and at the inner region; an aerodynamic step thrust bearing is formed.

Fig. 4 shows the method of installation of the flat plate to the high-speed motor. The circular flat plate with a viscous vacuum

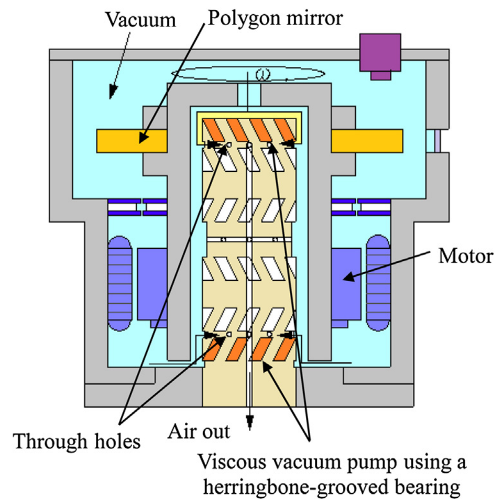

Fig. 1. Laser scanner motor with a viscous vacuum pump for reducing windage power loss.

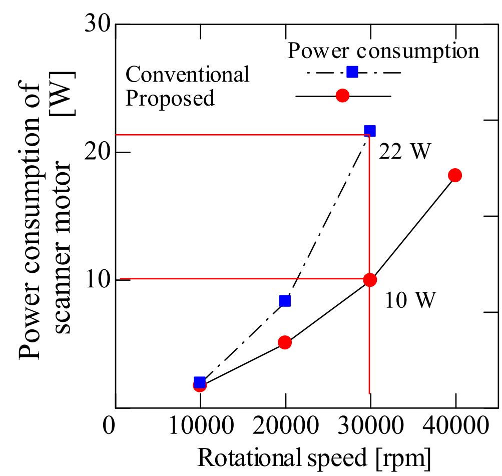

Fig. 2. Comparison of windage power loss between the proposed and conventional laser scanners.
(The proposed laser scanner was designed to reduce the pressure in housing less than 1kPa at 30,000 rpm)

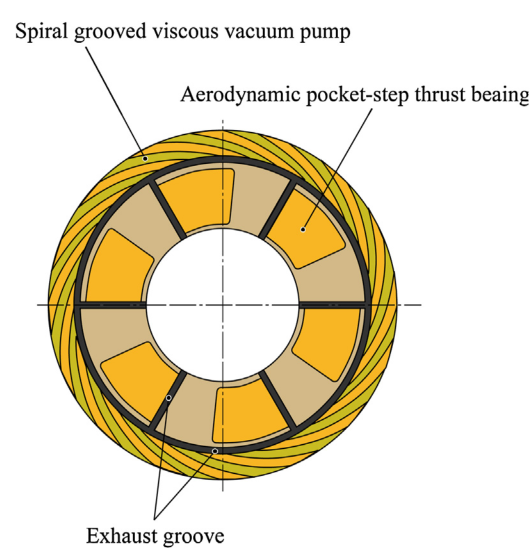

Fig. 3. Circular flat plate with a viscous vacuum pump combined with an aerodynamic step thrust bearing.

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