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Automatic unbalance correction of rotors by sympathetic phase inversion of ultraviolet-curing resin

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ABSTRACT

We developed an automatic unbalance correction technique for unbalanced rotors using a sympathetic phase inversion of ultraviolet (UV)-curing resin. Correcting the unbalanced weight during production is essential for various industrial rotors. The reduction of the cost and time of the correction process of unbalance during production is of great importance; however, the correction must have high precision, particularly for low-cost rotors such as polygon scanner motors and hard disks. In this paper we propose a new technique for correcting the unbalance of polygon scanner motors. Our system rotated a rotor on a translational oscillation table at a speed higher than that of the resonance rotation speed. The rotor exhibited runout opposing the unbalanced weight at this speed, and UV-curing resin preliminarily injected into the rotor also positioned itself opposite the unbalanced weight. UV light at this point cured the resin to immediately counter the unbalanced weight. Our experimental system confirmed the feasibility of this correction technique and reduced the unbalanced weight to 20% of that before the correction. This was in good agreement with the theoretical analysis.

1. Introduction

Precision high-speed rotors such as polygon scanner motors and magnetic disks must have low unbalance. The precise correction of unbalance leads to rotors with higher rotation speed and lower vibration and noise. For low-cost rotors, the rapid correction of unbalanced weight at a low cost is of great importance.

Many motors have various passive balancing systems to suppress the axial runout of their rotors near their whirling speeds [1,2]. These techniques, however, cannot easily be applied to precision high-speed rotors. The polygon scanner motor shown in Fig. 1 (by Konica Minolta Business Technologies, Ltd.) rotates at 20,000–60,000 rpm in a laser printer and its unbalance is precisely corrected to less than 1 mg cm (the mass of the rotor is 35 g). The automatic balancing system is a well-known passive balancing technique, particularly for removable unbalanced weights. Circumferential fluid is used to balance drums in washing machines [3], and balls are used to balance optical disk drives [4–6]. These balancers oppose the unbalanced weight at speeds higher than the resonance. The sympathetic phase inversion explains this phenomenon. In the above systems, the resonant frequencies are designed to be lower than the regular frequencies. A design that allows changes in the regular rotation speed enables more effective balancing.

In this study, we propose the automatic unbalance correction of high-speed rotors using sympathetic phase inversion of ultraviolet (UV)-curing resin (Fig. 2) [7]. A translational oscillation system holds a rotor with an unbalanced weight and a motor. When the phase of the rotor inverts at a higher speed than the resonance rotation speed, UV light solidifies the UV-curing resin diagonally opposite the unbalanced weight. Therefore, the unbalance of the rotor is automatically corrected. The corrected rotor can be installed on another spindle or in other products. We clarified the principle of this correction technique and indicated the critical design parameters. Furthermore, we carried out an experiment to confirm the feasibility of the principle using prototype rotors of the size used in polygon scanner motors.

2. Principle of automatic unbalance correction using UV-curing resin

In this section we explains the principle of our automatic unbalance correction method using UV-curing resin. Fig. 3(a) and (b)

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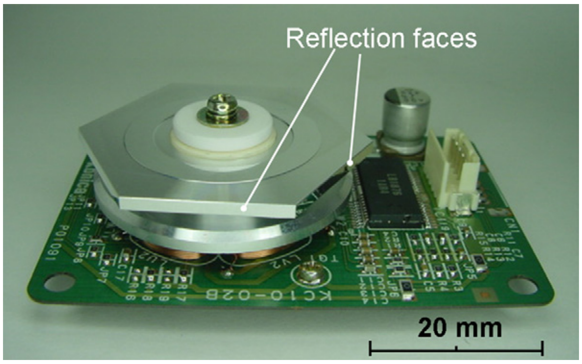

Fig. 1. Polygon scanner motor by Konica Minolta Business Technologies, Ltd. (regular rotation speed: 20,000–60,000 rpm).

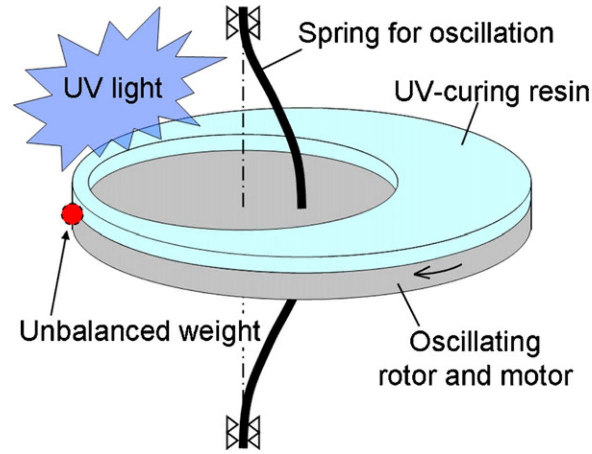

Fig. 2. Schematic of automatic unbalance correction using UV-curing resin.

shows schematic diagrams of oscillation models without and with UV-curing resin, respectively. These schematics show rotors and motors including some unbalanced weight. The equation of motion of the basic oscillation model (Fig. 3(a)) is

$$M\ddot{r} + c\dot{r} + k\boldsymbol{r} = M\boldsymbol{\varepsilon}\omega^2 \cos\omega t \tag{1}$$

The oscillating mass is expressed as M, i.e., the sum of the mass of the rotor (M_{rot}) and that of the motor (M_{mot}). The rotation speed (angular frequency) is ω, the spring constant and damping constant of the rod spring are k and c, respectively, the runout of the rotor is $\boldsymbol{r}$ (vector), and the unbalanced weight (moment) is $M\boldsymbol{\varepsilon}$ ($\boldsymbol{\varepsilon}$: vector). That is, $\boldsymbol{\varepsilon}$ is the relative position of the center of gravity of the rotor (**G**) from the center of rotation (**S**).

When we introduce a liquid (UV-curing resin in this study, mass: m_l) into the rotor, as shown in Fig. 3(b), the inside wall of the liquid remains concentric with the center of oscillation. The amount of liquid is sufficient for the inside wall not to interfere with the outside wall. When the relative position of the center of rotation **S** from the center of oscillation **O′** is $\boldsymbol{r}'$, the moment change caused by the liquid is $-m_e\boldsymbol{r}'$ (m_e: mass corresponding to the unfilled liquid). Therefore, the change in the unbalance position $\boldsymbol{\varepsilon}'$ (relative position of the new center of gravity of rotor **G′** from the center of rotation **S**) is expressed as

$$\boldsymbol{\varepsilon}' = \frac{M\boldsymbol{\varepsilon} - m_e\boldsymbol{r}}{M + m_l} \tag{2}$$

Also, the length from the center of oscillation to the center of rotation is

$$\left|\boldsymbol{r}'\right| = \frac{\Omega^2}{\sqrt{(\Omega^2 - 1)^2 + (2\zeta\Omega)^2}}\left|\boldsymbol{\varepsilon}'\right| \tag{3}$$

where

$$\zeta \equiv \frac{c}{2\sqrt{(M + m_l)k}} \tag{4}$$

$$\Omega \equiv \frac{\omega}{\omega_n} \tag{5}$$

$$\omega_n \equiv \sqrt{\frac{k}{M + m_l}} \tag{6}$$

ζ is the damping ratio, Ω is the rotation speed ratio, and ω_n is the resonance rotation speed (resonant radiation frequency). Then, the correction factor (CF) η, which we define as [unbalanced

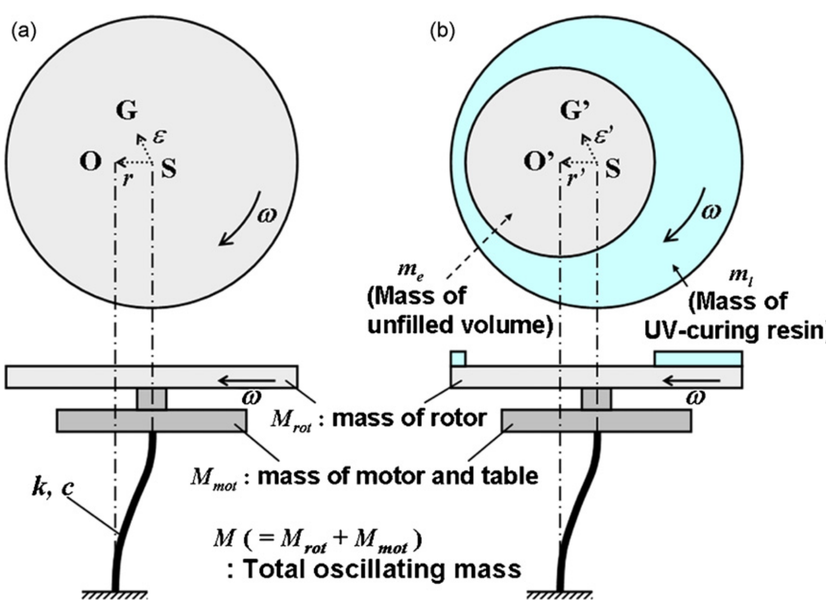

Fig. 3. Oscillation models (a) without and (b) with UV-curing resin.

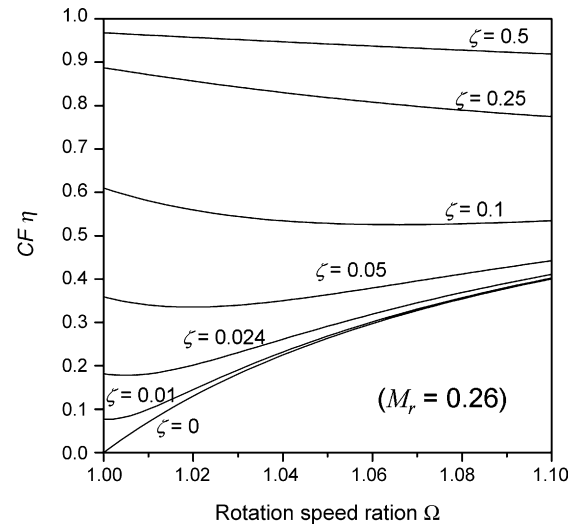

Fig. 4. Analytical CF as a function of rotation speed ratio (Ω), when $M_r = 0.26$ (experimental value in this study) and $\zeta = 0$, 0.01, 0.024, 0.05, 0.1, 0.25, and 0.5.

weight after correction/unbalanced weight before correction] ($\equiv (M+m_l)|\boldsymbol{\varepsilon}'|/M|\boldsymbol{\varepsilon}|$), is

$$\eta = \sqrt{\frac{1+(2\zeta\Omega/\Omega^2-1)^2}{(1+M_r\Omega^2/(\Omega^2-1))^2+(2\zeta\Omega/(\Omega^2-1))^2}} \quad (7)$$

where the mass ratio (MR, ratio of the mass corresponding to unfilled volume divided by oscillating mass) is defined as

$$M_r \equiv \frac{m_e}{M+m_l} \quad (8)$$

A smaller η indicates a more effective correction of unbalance. From Eq. (7), three variables determine CF: the rotation speed ratio (Ω), MR (M_r), and the damping ratio (ζ). Fig. 4 shows CF curves as functions of rotation speed ratio when the mass ratio is 0.26, which is used in the experiment, for various of ζ (0, 0.01, 0.024, 0.05, 0.1, 0.25, 0.5). The rotation speed ratios that minimize CF are different for different damping ratios. A higher damping ratio leads to a degradation of CF. When $\zeta = 0.024$ (used in the experiment), CF is minimized when $\Omega = 1.0015$. Thus, only two design parameters determine the minimum CF: mass ratio and damping ratio. Fig. 5 shows plots of each minimum CF ($\eta_{\min}$) as function of M_r (0–0.1) and ζ (0–0.05). A higher M_r and a lower ζ result in a better CF. In other words, a better design has a larger m_e (the mass corresponding to the unfilled volume) and a lower M (total mass of the rotor including mount and motor). A suitable design should also minimize the damping ratio of the oscillation system.

3. Design of flow guide for UV-curing resin and translational oscillation system for automatic unbalance correction

Fig. 6 shows a schematic diagram of a flow guide for UV-curing resin and the translational oscillation system. When the diameter of the outside wall is $2R$, that of the inside wall is $2D$, and the depth is t, the mass corresponding to the unfilled volume (m_e) is $\rho\pi D^2 t$ (ρ: mass density of the UV-curing resin) and the mass of the UV-curing resin is $\rho\pi(R^2-D^2)t$. Eq. (7) implies that M_r should be maximized; therefore, D and R should also be maximized. However, for efficient correction, D and R should be designed so that the amount of UV-curing resin is sufficient for the inside wall not to interfere with the outside wall, i.e., $R-D<|\mathbf{r}'|$ ($|\mathbf{r}'|$: runout radius upon correction). The outer radius R and depth t are maximized with the constraint of

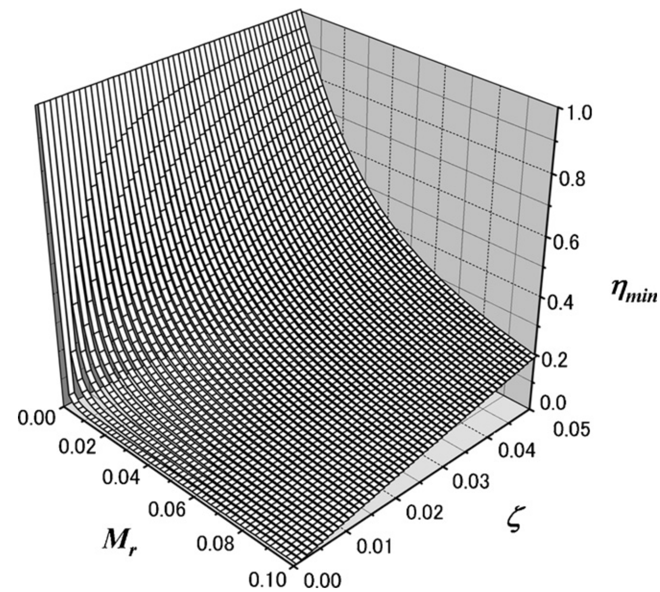

Fig. 5. Analytical minimum correction factor ($\eta_{\min}$) as function of mass ratio (M_r) and damping ratio (ζ).

the largest intended rotor size. Another restriction is that the center of the outside wall must be located on the center of rotation, and the analytical CF was derived taking this requirement into account.

The translational oscillation system holds a rotor. At least three rod springs restrict its motion only in the horizontal direction as shown in Fig. 6. In this system, both ends of each rod spring are fixed in the bending direction. Thus, we can express the total spring constant k as follows;

$$k = n\frac{3EI}{l^3} = \frac{3\pi n d^4 E}{64 l^3}, \quad (8)$$

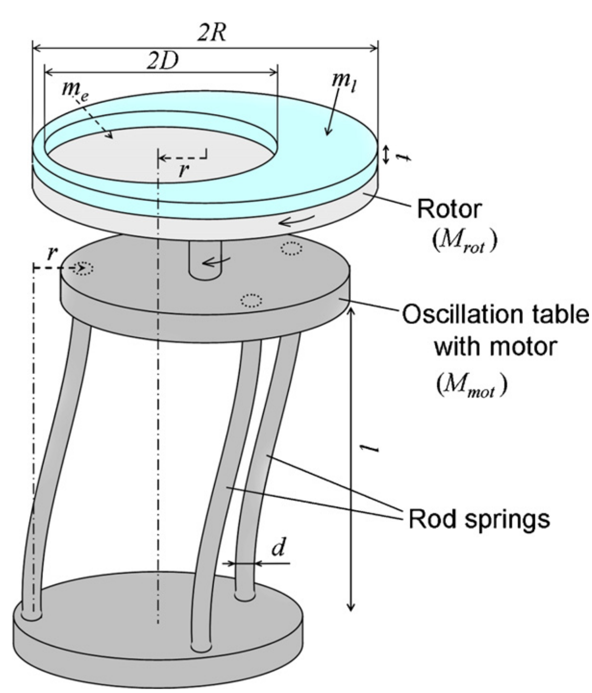

Fig. 6. Design parameters of flow guide for UV-curing resin and translational oscillation system.

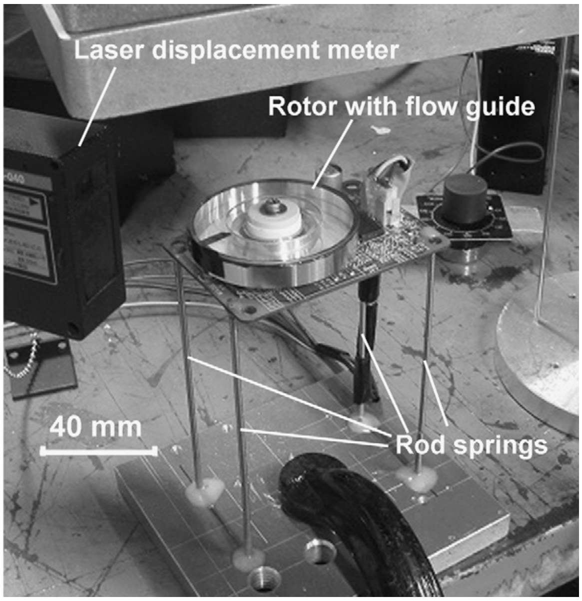

Fig. 7. Experimental setting for automatic unbalance correction system using UV-curing resin.

where n is the number of the rods (Fig. 6 shows the case of 3), I is the geometric moment of inertia, d is the diameter, l is the length, and E is the Young's modulus of each rod.

4. Experiment for demonstrating automatic unbalance correction

We carried out an experiment to demonstrate our automatic unbalance correction method using UV-curing resin. Fig. 7 shows the experimental setting of the translational oscillation system with four rod springs and rotors with a flow guide ($2R = 54$ mm, $t = 10$ mm). The motor contains an air dynamic bearing and the circuit substrate, which are the same as those of an actual polygon scanner motor. We used NOA81 by Norand, Ltd., for the UV-curing resin. The viscosity is 300 cP and the density is 1.1 g/cm^3. The precuring time was 10 s and the casting time of the UV light, with intensity of over 2 W/cm^2, was shorter than 60 s. Table 1 shows the values of the parameters used in the experiment. The resonance rotation speed was 3120 rpm. The initial unbalanced weight was 80 mg cm. We monitored the rotor rotation speed using a photoelectric element and its runout diameter using a laser displacement meter. We calculated the damping constant by measuring the decrease in the oscillation amplitude after knocking the oscillation table with a hammer.

Table 1
Parameters for demonstrating automatic unbalance correction system using UV-curing resin.

Symbol	Content	Value
M	Total mass of rotor and table	60 [g]
k	Spring constant	6400 [N/m]
c	Damping constant	0.94 [Ns/m]
ω_n	Resonance rotation speed	3120 [rpm]
m_l	Mass of UV-curing resin	0.5 [g]
m_n	Mass of unfilled volume	16 [g]
ζ	Damping ratio	0.024
M_r	Mass ratio	0.26

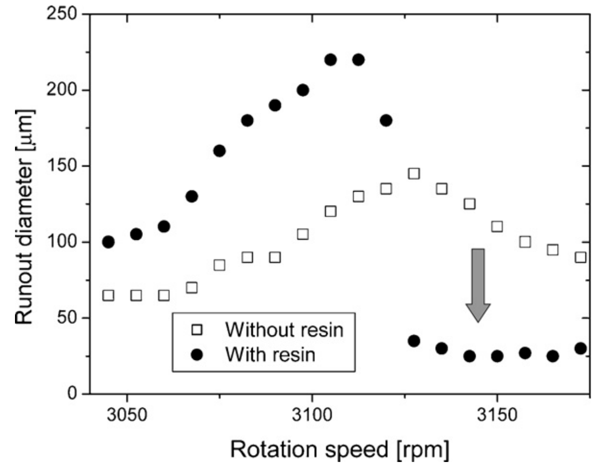

Fig. 8. Experimental result of the runout diameter as a function of rotation speed, with and without UV-curing resin.

5. Results and discussion

First, we rotated the rotor near the resonance rotation speed with and without the UV-curing resin. Fig. 8 shows the measured runout diameter as a function of rotation speed. When the rotor turned at speeds less than the resonance rotation speed, the runout with the resin was larger than that without the resin because the phase of the resin matched that of the rotor unbalance. However, at speeds above the resonance rotation speed, the runout rapidly decreased due to phase reversal. The runout diameter was proportional to the unbalanced weight. Fig. 9 shows the experimental CF calculated from the runout diameters before and after correction together with the theoretical CF curve. The errors were caused by the laser displacement meter. The CFs deviated from the theoretical values by several percent.

In the second stage, UV light cured the resin and corrected the rotor unbalance. The best CF we accomplished was 20% (runout diameter of 140 μm reduced to 30 μm), i.e., an 80% reduction of the unbalance. Fig. 10 shows a rotor corrected by UV-curing resin. The runout was reduced to about 20% of the original runout at all speeds near the resonance rotation speed as shown in Fig. 11. The volume reduction of the UV-curing resin upon completion was sufficiently small not to change the CF. The UV-curing resin should have moved together with the flow guide; however, we did not experiment with other resins with other viscosities. Thus, whether or not other resins behave similarly remains unknown.

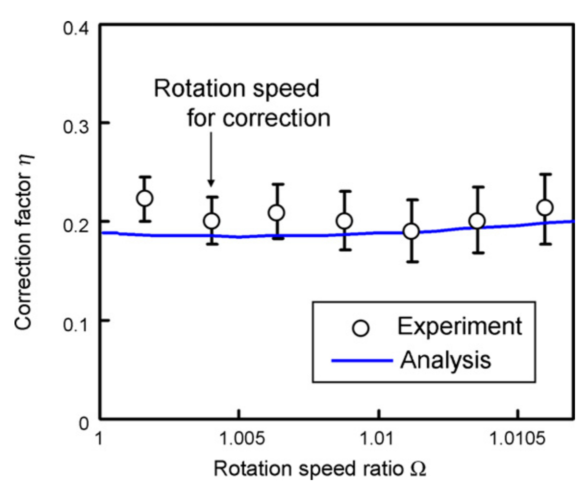

Fig. 9. Correction factor as a function of Ω obtained by experiment and analysis.

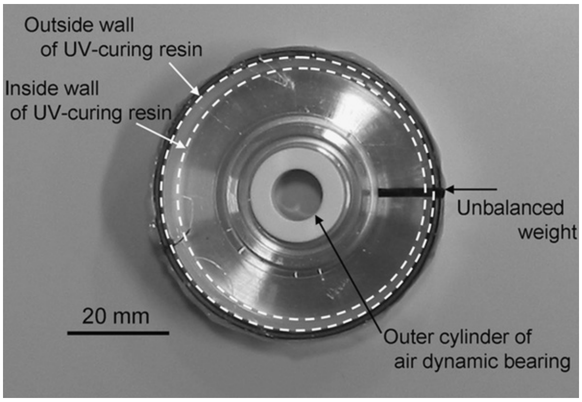

Fig. 10. Rotor corrected by UV-curing resin.

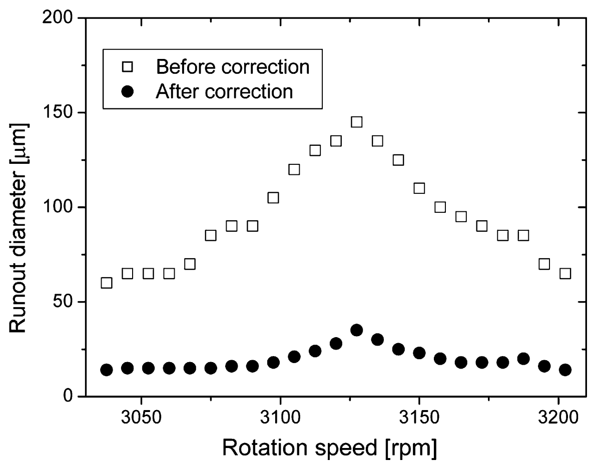

Fig. 11. Runout diameter before and after automatic unbalance correction.

We have demonstrated a design concept for achieving a better CF. However the actual CF was limited by our experimental equipment; the MR was limited by the size of the target rotor and the density of the balancer liquid (in this paper, UV-curing resin). The most critical element for improving the CF is the reduction of the damping ratio of the oscillation system. When the rod springs were thinner and longer, the damping ratio was smaller. This would, however, lead to a lower spring constant and lower resonance rotation speed. Also, the minimum rotation speed of the air dynamic bearing used in this study limited the reduction of the damping ratio.

6. Future work

The CF was limited to 20% in this study, but multiple flow guides will further improve the CF. Furthermore, two-dimensional (2D) flow guides and an oscillation system with 2D modes can simultaneously correct 2D unbalances. Such a 2D method will be useful for correcting the unbalance of rotors with long spindles.

7. Conclusion

We proposed an automatic unbalance correction technique for precision high-speed rotors. A sympathetic phase inversion of UV-curing resin enabled automatic unbalance correction. The best correction factor obtained for a rotor that we designed with the size of a polygon scanner motor was 20%. This correction method has the potential to eliminate human judgment and feedback control using displacement sensing. Our concept can be used to realize an extremely low cost unbalance correction technique for the production of rotors.

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