SELF-UNBALANCE-CORRECTION TECHNIQUE FOR PRODUCTION PROCESS OF PRECISION HIGH-SPEED ROTORS

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INTRODUCTION
The unbalances of precision high-speed rotors, such as polygon scanner motors (FIGURE 1), optical disk drives, or hard disk drives, must be precisely corrected during their production. Although the precise correction of the rotors leads to higher rotation speed and low rotation noise, cost reduction of the unbalance correction process is essential.

Various passive balancing systems for suppression of the axial runout of the rotors around the whirling speeds have been applied to various rotors [1][2]. However, these techniques cannot be used for precision high-speed rotors. The polygon scanner motor shown in FIGURE 1 (by Konicaminolta, Ltd.) is precisely corrected to under 1 mg·cm (the mass of the rotor is 35 g). And now, the automatic balancing system is known as a passive balancing technique, particularly for removable unbalanced weights. Washing machines are balanced using fluid balancer [3], and optical disk drives are balanced using ball balancers [4]. In this study, we applied the automatic balancing systems to the production process for high-speed rotors. We named this technique, “self-unbalance-correction (SUC)”, and we carried out an experiment to confirm the principle using rotors of the size used in polygon scanner motors.

SELF-UNBALANCE-CORRECTION (SUC)
We propose two variations of the SUC technique and demonstrate experiments to confirm the principles. One of them uses ultraviolet (UV) -cured resin (FIGURE 2), and the other uses ball balancers and adhesive (FIGURE 3). In both techniques, a rotor of unbalanced weight is set on a rotational translation oscillation system. When the phase of the rotor is inverted after achieving oscillation resonance, the balancers (UV-cured resin or ball balancers) diagonally opposite the unbalanced weight are fixed to the rotor. Therefore, the unbalance of the rotor is automatically corrected.
PRINCIPLE OF SUC USING UV-CURED RESIN

Here, we explain the principle of SUC using UV-cured resin. The equation of the basic oscillation model (FIGURE 4, left) is

\[ M \ddot{r} + c \dot{r} + kr = Me^2 \omega^2 \cos \omega t \]  

(1).

The mass of the rotor is \( M \), the rotation speed (angular frequency) is \( \omega \), the spring constant and damping constant of the rod spring are \( k \) and \( c \), respectively, the runout of the rotor is \( r \) (vector), the unbalanced weight (moment) is \( Me^2 \) (vector). That is, \( e \) is the relative position of the center of gravity of the rotor (G) from the rotation center (S).

When the liquid (mass: \( m_l \)) is added to the rotor, as shown in FIGURE 4, right, the inside wall of the liquid is concentric with the oscillation center. The amount of liquid is sufficient for the inside wall not to interfere with the outside wall. When the relative position of the rotation center \( S \) from the oscillation center \( O' \) is \( r' \) (vector), the moment change caused by the slanted liquid is \(-m_e r' \) (\( m_e \): mass corresponding to the unfilled liquid). Therefore, the changed unbalance position \( e' \) (relative position of the new center of gravity of rotor \( G' \) from rotation center \( S \)) is expressed as

\[ e' = \frac{Me - m_l r'}{M + m_l} \]  

(2).

Also, the length from the oscillation center to the rotation center is expressed as

\[ r = \sqrt{(\Omega^2 - 1)} \]  

\[ \Omega = \frac{\omega}{\omega_n} \]  

\[ \omega_n = \frac{k}{M + m_l} \]  

(3), (4), (5).

\( \zeta \) is the damping ratio, \( \Omega \) is the rotation speed ratio, and \( \omega_n \) is the oscillation rotation speed. Then, the correction factor (CF) \( \eta \) (unbalanced weight after correction / unbalanced weight before correction = \( (M+m_l)|e'| / Me^2 \)) is expressed as

\[ \eta = \frac{1 + \left( \frac{2 \zeta \Omega}{\Omega^2 - 1} \right)^2}{\left( 1 + \frac{m_e}{M + m_l} \right)^2 + \left( \frac{2 \zeta \Omega}{\Omega^2 - 1} \right)^2} \]  

(7).

From this equation, the rotation speed ratio for the smallest CF is determined by the oscillation system (\( M \) and \( k \), i.e., \( \omega_n \)). Therefore, only two design parameters need to be considered for a better (lower) CF; mass ratio \( (m_e / M + m_l) \) and damping ratio \( \zeta \). In other words, the volume of the unfilled part should be maximized and the total mass of the rotor (including mount and motor, etc.) should be as small as possible. The damping of the oscillation system should also be as small as possible. Quantitative values will be given later.

PRINCIPLE OF SUC USING BALL BALANCERS AND ADHESIVE

In the second technique, balls that balance the unbalanced weight are fixed to the rotor. The rotor is mounted on an oscillation translation system similar to the SUC using UV-cured resin. FIGURE 5 shows a schematic of SUC using two ball balancers. If there was no friction between the balls and the wall, the balls would be positioned at certain positions above the oscillation resonance and the unbalanced weight would be perfectly corrected. At this time, instant adhesive, with mass significantly smaller than that of the ball balancers, could be used to fix the balls.

\[ \text{FIGURE 5. Oscillation model of ball balancers (in the case of two balls).} \]
However, in an actual system, balls encounter friction from the guide wall. This is because CF has a limit. FIGURE 6 shows the forces applied to the ball and their values. According to the sine and cosine laws,

$$\frac{\varepsilon}{\sin \alpha} = \frac{l}{\sin \beta} \quad (8),$$

$$l = \sqrt{R^2 + \varepsilon^2 - 2R\varepsilon \cos \beta} \quad (9).$$

The counterforce from the oscillation center is

$$F_c = m_s \omega^2 \quad (10).$$

From Eqs. (8)-(10), the driving force $F_D$ and the friction force from the wall $f$ are expressed as

$$F_D = F_c \sin \alpha = m_s \varepsilon \alpha^2 \sin \beta \quad (11),$$

$$f = \mu F_c = \mu F_c \cos \alpha \equiv \mu m_s \omega^2 \quad (12),$$

where \( \left(\varepsilon / l\right), \left(\varepsilon / R\right) \ll 1 \).

The ball balancers are fixed when the driving force $F_D$ balances the friction force $f$. Then, the stable position of the ball balancers is independent of the mass and the rotation speed. However, the rotation speed must be selected to be above the oscillation resonance. Therefore, the only method of obtaining better CF is to reduce the friction. The effect of friction on balancing has been reported in studies on the automatic ball-balancing system for optical disk drives [5][6].

FIGURE 6. Actual forces applied to ball balancers.

**EXPERIMENT ON SUC USING UV-CURED RESIN**

We carried out an experiment to demonstrate SUC using UV-cured resin. FIGURE 7 shows the experimental setup and TABLE 1 shows the values used in the experiment. We used NOA81 by NORAND, Ltd., as the UV-cured resin. The viscosity is 300 cps and the density is 1.1. The precuring time is 10 sec and completion time is shorter than 60 sec when UV of over 2 W/cm² is applied. The initial unbalanced weight was set at 80 mg cm.

FIGURE 7. Experimental setup for SUC using UV-cured resin.

**TABLE 1. Designated values in experiment to demonstrate SUC using UV-cured resin.**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>60 [g]</td>
</tr>
<tr>
<td>$K$</td>
<td>6400 [N/m]</td>
</tr>
<tr>
<td>$C$</td>
<td>0.94 [Ns/m]</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>0.024</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>3120 [rpm]</td>
</tr>
<tr>
<td>$M_l$</td>
<td>0.5 [g]</td>
</tr>
<tr>
<td>$M_e$</td>
<td>16 [g]</td>
</tr>
</tbody>
</table>

FIGURE 8 shows the experimental result of SUC using UV-cured resin. The experimental CF has good agreement with theoretical values. The rotor unbalance was actually corrected by the UV-curing, and the runout was reduced to 20% of the original runout at all frequencies. A lower damping ratio of the spring and a greater mass ratio of the rotor will result in better CF.
**EXPERIMENT ON SUC WITH BALL BALANCERS AND ADHESIVE**

We demonstrated SUC using ball balancers and adhesive. The experimental setup is shown in FIGURE 9. TABLE 2 shows the values used in the experimental system. Again, we obtained unbalance correction, as shown by the blue bars in FIGURE 10. However, there is some scatter around the displacement peak of 400 µm (CF = 27%). We applied vibration (1.8 G) to reduce the friction between the balls and the wall. Then we confirmed the improvement of CF, as shown by the red bars in FIGURE 10 (average CF = 15%). Uncorrected samples (CF = 100%) are caused by undesirable stable situations, where the two balls are positioned at opposite sides to each other.

**FIGURE 9.** Experimental setup of SUC using two ball balancers.

**TABLE 2.** Designated values for experiment to demonstrate SUC using ball balancers.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M )</td>
<td>500 [g]</td>
</tr>
<tr>
<td>( K )</td>
<td>2050 [N/m]</td>
</tr>
<tr>
<td>( \omega_n )</td>
<td>510 [rpm]</td>
</tr>
<tr>
<td>( m_b )</td>
<td>1.14 [g]</td>
</tr>
<tr>
<td>( R )</td>
<td>22 [mm]</td>
</tr>
</tbody>
</table>

**FIGURE 10.** Experimental result of SUC using two ball balancers.

**ADVANCED SUC BY MULTISTEP PROCESS**

We also briefly mention multistep SUC for obtaining superior CF. FIGURE 11 shows a rotor with multiple balancer guides. Repetitive correction and fixation using balancers will realize near-perfect correction.

**FIGURE 11.** Multistep process.

**CONCLUSION**

We proposed a self-unbalance-correction (SUC) technique for precision high-speed rotors. We demonstrated SUC using UV-cured resin and ball balancers. The best correction factor, obtained using UV-cured resin, was 20%, and the average correction factor obtained using ball balancers was 27%. Furthermore, the addition of vibration reduced the friction of the balls and further improved the correction factor to 15% on average.

**REFERENCES**


