On-Line Balancing Of Rotors

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ABSTRACT

Rotor balancing needs to be re-examined in the present day's context. With the advancement in control strategies and active vibration control using magnetic bearings, a new look to improve the existing balancing methods is thus, very essential. In the present paper, different methods in rotor balancing have been studied and a chronological record is prepared. The existing approaches and recent trends towards on-line balancing have been reviewed. This paper suggests for a new look at flexible rotor balancing for on-line balancing techniques. Scope for future work on on-line balancing has been identified through different comparative tables. Some new techniques for on-line rotor balancing using feedback controls are discussed on their feasibilities for practical application.

INTRODUCTION

Rotating mass imbalance causes increased vibrations of high speed machine tools, turbo-machinery etc. during operation and might bring limitations to the start-up and shut-down procedures, i.e., when the rotor passes through critical speeds. Because of these reasons it is useless to rebalance the rotor after a certain time with a conventional method (needless to say that this would also be extremely expensive). Hence it would be most useful to balance the rotor automatically during operation. However, in most automatic balancing systems no computation of the instantaneous resulting system unbalances takes place while correction masses are being applied. So errors in computation will only be detected afterwards, when checking the balancing condition. Measurement of the system vibration, computation of the unbalance, and adjustment of the correction masses are to be performed continuously and simultaneously.
The contribution of this paper resides in developing an optimal control strategy for reduction of vibration levels of rotors by online balancing using electromagnetically actuated balancing heads.

**ROTOR BALANCING: OVERVIEW**

This section is intended to give a general idea of the various techniques that have evolved over the years in the field of rotor balancing. A detail classification of the various balancing methods is shown in Fig. 1.

![Classification of Balancing Methods](image)

**Fig. 1: Classification of Balancing Methods**

In a recent survey [1], Zhou and Shi reviewed research work on active balancing methods and gave an extensive list of references also containing a passive approach. The *modal balancing method* and the *influence coefficient method* (ICM) are the main methods for balancing flexible rotors [2-4]. The former uses the modal parameters and the modal breakdown of the initial unbalance distribution, the rotor being balanced at its critical speeds, step by step, mode after mode. This method is mostly used to balance high-speed machinery with a number of critical speeds. ICM consists of evaluating the influence of trial masses on the orbits of the planes to be balanced (Eq. 1). The solution of

\[ \tilde{v} = \tilde{v}_s + \tilde{C}\tilde{w} \]  

(Eq. 1)
the associated inverse problem (Eq. (2)) gives the ideal correction mass combination that minimizes the vibration levels of the balancing planes [5]. The unified balancing method attempts to combine the advantages of the modal method and the ICM to achieve a better result with fewer trial runs. By this method critical and off-critical speeds can be balanced simultaneously without jeopardizing the speeds already balanced. The theoretical basis of this method is described in detail in [6].

Active balancing system incorporates balance mass actuators that can change a rotating machine’s mass balance state while the machine is operating. Steady state vibration caused by time varying rotating mass imbalance can often be controlled using such active balancing system [7-8]. A successful extension of the ICM (Eq. (2)) to the online estimation and active control was achieved by Dyer and Ni [9], where the influence coefficient matrix is obtained through experimental trial runs. As noted by Bishop [10], single-plane active balancing should be sufficient for systems in which one vibration mode dominates dynamic response at each rotational speed of interest. However many high speed rotating machines which operate at speeds in between flexible shaft bending mode frequencies require multiple plane balancing [11]. Steady-state influence coefficient-based optimal control strategies have been presented for rotating systems both with active balancers [11] and with stationary actuation schemes such as magnetic bearings [12] and piezoelectric actuators [13]. Although balancing at a single working speed is common in practice, as discussed before, balancing during speed-varying periods [14] is also needed.

NEW TRENDS IN ON-LINE ROTOR BALANCING

A comparative tabular analysis of various current techniques and their scope in online rotor balancing has been made, of which some are discussed below.

- **Thermally Controlled Non-Contact On-Line Balancing** - This technique of balancing a large turbo generator was proposed by [15]. Mounting some heating elements and using them as actively controlled actuators exploited the sensitivity of rotor unbalances to thermal asymmetries in the rotor.

- **Automatic Balancing or Auto-Balancing** - Automatic balancing means balancing with the help of balancing devices mounted on rotors or shafts for balancing, or further correction, during the operation of the machine. These may incorporate passive control
using ball balancing (Fig. 2), as in [6], or active controlled motorized balancing heads, effectively discs, mounted on flexible shafts [7].

- Active Magnetic Bearings (AMB) - With no physical contact between a rotor and its housing, magnetic bearings (Fig. 3) do not wear or fail from material fatigue. It has several advantages viz. low friction, no lubricant, high rotational speeds of rotor, low maintenance cost, infinite stiffness, more choice in the design of bearing dynamics, and potential for vibration control, while the disadvantages are few like requirement of active control and low force to weight ratio. Some experiments in the control of unbalance response using AMB can be found in [12].

- Spray Automated Balancing of Rotors (SABOR) - It uses the Fuel Air Repetitive Explosion process of metal film deposition to apply discrete amounts of metallic or ceramic particles to a spinning rotor [14]. In this way, without stopping the rotor, its mass eccentricity is changed in a manner designed to reduce the vibration sensed by a balancing machine.

**TYPICAL RESULTS WITH ON-LINE BALANCING USING EBR**

The current on-line rotor balancing systems are made up of four major parts: the balanced rotor system, the sensor, the controller and the balancing regulator among which the former two are well known while the later are still being researched. The controlling method of the online balancing regulator has been designed according to whether the position of the correction mass is able to be detected accurately in few or more trial runs. The electromagnetic balancing regulator (EBR) which operates in
accordance with the motor principle adopts an optimum seeking rule [18]. When the electromagnetic torque generated by the electric current which is fed into the coils on the stator is more powerful than the joint torque between the slide plate seats, the slide plate and the correction mass rotate circumferentially and there is an angle displacement with respect to the balanced shaft (Fig. 4).

Fig. 4: Design of the balancing regulator. 1: sensor for detecting the position of mass; 2: stator; 3: reflection film; 4: press board; 5: slide plate; 6: slide plate seat; 7: correction mass; 8: balanced shaft; 9: screw and spring

A control scheme has been developed such that when the vibration of the rotor increases to a certain extent, it judges whether to perform balancing or not, detects the positions of the correction masses, calculates the unbalance on the rotor and determines the optimum position of each correction mass. A particularly attractive feature of the system is that it provides a vibration feedback and a position feedback, so that after the correction masses are driven to move a detectable angle displacement separately, their influence on vibration can be determined. This is analogous to the trial weight and to the influence coefficient calculation process of ICM, but avoids the need to stop the rotor for each trial weight addition. In view of the fact that the majority of rotors work at a relatively constant rotating speed whether they are rigid or flexible, the on-line balancing is carried out at the same constant speed.

Balancing Method for the Electromagnetic Balancing Regulator

Considering \( P \) measuring points and \( N \) balancing planes, the vibration correlation of the balancing regulator will be:

\[
\tilde{v}_{(P \times 1)} = \tilde{v}_{e(P \times 1)} + \tilde{C}_{(P \times N)} \tilde{w}_{(N \times 1)}
\]

where,
\[ \tilde{w} = [u_o(e^{i\beta_{11}} + e^{i\beta_{12}}), \ldots, u_o(e^{i\beta_{N1}} + e^{i\beta_{N2}})]^T \] (4)

In the virtue of the linear Eq. (3) with the impel forces of initial unbalance \( \tilde{v}_o \) and balancing force \( \tilde{w} \) on the right side the balancing aim is to adjust \( \beta_{ni} \) \((n=1, 2, \ldots, N)\) to minimize \( |\tilde{v}| \). Here \( \tilde{v} \) and \( \tilde{w} \) are measurable, \( \tilde{w} \) is controllable and \( \tilde{v}_o \) and \( \tilde{C}^r (P \times N) \) are unknown. The vibration caused by initial unbalance, which is constant during a process of balancing, is determined by few initial test runs. Then the influence matrix is evaluated. Once this is done for different rotating speeds, a curve-fitting can give influence coefficient values for any speed of the rotor.

During the identification process for mass adjustment of the \( n \)th balancing head \((n = 1, \ldots, N)\) the goal function \( |\tilde{v}| \) may increase, because the correction masses can rotate only in one direction. In order to minimize this effect, the ‘optimum seeking method’ is introduced: for the \( n \)th \((n = 1, \ldots, N)\) balancing head, first, move either correction mass; then if the goal function \( |\tilde{v}| \) decreases, move it continuously; but if the goal function \( |\tilde{v}| \) increases, move the other correction mass for the same angle displacement. The masses which make \( |\tilde{v}| \) decrease are given the priority to rotate. We can then control each mass to rotate to its optimum position to finish the balancing.

If we consider a head and a measurement plane, Eq. (3) can be simplified as:
\[ \tilde{v} = \tilde{v}_o + \tilde{C}^r (e^{i\beta_1} + e^{i\beta_2}) \] (5)

Among them, \( \tilde{v} \), \( \beta_1 \), \( \beta_2 \) can be measured at any time and \( \tilde{C}^r \) can be determined by moving the correction masses. Keeping all the above in view, an advanced control scheme was simulated in a MATLAB program and its effects on the EBR are listed in Table 1.

<table>
<thead>
<tr>
<th>Rotating Speed (rpm)</th>
<th>Initial pos. of masses, angles ( \beta_1, \beta_2 ) (deg)</th>
<th>End positions of masses, angles ( \beta_1, \beta_2 ) (deg)</th>
<th>Initial Vibration (( \mu m ))</th>
<th>End Vibration (( \mu m ))</th>
<th>Identified influence coefficient ( C )</th>
<th>Identified initial vibration ( \tilde{v}_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1659</td>
<td>68, 21</td>
<td>227, 129</td>
<td>11.16</td>
<td>0.0315</td>
<td>( 3.84 \times 10^{13} )</td>
<td>( 5.07 \times 10^{12} )</td>
</tr>
<tr>
<td>1785</td>
<td>266, 235</td>
<td>126, 30</td>
<td>13.00</td>
<td>0.0330</td>
<td>( 4.0 \times 10^{12} )</td>
<td>( 5.3 \times 10^{13} )</td>
</tr>
<tr>
<td>1845</td>
<td>193, 195</td>
<td>115, 45</td>
<td>11.80</td>
<td>0.0039</td>
<td>( 3.86 \times 10^{13} )</td>
<td>( 6.32 \times 10^{13} )</td>
</tr>
<tr>
<td>1770</td>
<td>205, 240</td>
<td>45, 127</td>
<td>12.21</td>
<td>0.0138</td>
<td>( 3.84 \times 10^{13} )</td>
<td>( 5.81 \times 10^{13} )</td>
</tr>
</tbody>
</table>
CONCLUSION

There is a lot of scope in advancing this method by adopting more robust control and experimentally verifying it on high speed flexible rotors for practical applications. The EBR can be also tested for performing multi-plane balancing using Influence-Coefficient method. In future, it is intended to apply Hybrid balancing techniques for rotor operation beyond several critical speeds to avoid high vibrations during run-up /run-down or during speed-varying conditions.

NOMENCLATURE

$\mathbf{C}$  Influence coefficient (matrix) vector, $\mu m (kg m/s^2)^{-1}$

$\mathbf{C}'$  Product of mass and radius of the correction mass and $\mathbf{C}$, $\mu m s^{-2}$

$Uo$  Product of mass and radius of each correction mass in the EBR, $kg m$

$\beta_{n1},\beta_{n2}$  Angular pos. of the two correction masses in the $n^{th}$ balancing head, rad

$\mathbf{v}$  Vibration at measurement points, $\mu m$

$\mathbf{v}_o$  Vibration caused by initial unbalance, $\mu m$

$\mathbf{w}$  Balancing force vector, $kg m/s^2$

REFERENCES


