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An enhanced real-time dynamic imbalance correction for precision rotors †

Jung Kwan Lee[1], Sang Bong Lee[1], Hyungpil Moon[1], Dongho Oh[2] and J. C. Koo[1,*]

[1]*School of Mechanical Engineering, Sungkyunkwan University, Suwon, 440-746, Korea*
[2]*Department of Mechanical Engineering, Chungnam National University, Daejeon, Korea*

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Abstract

Even a moderate mass imbalance of a high-precision rotor produces a significant level of vibration when it spins at high revolutionary speed such as 10,000 rpm or faster. As a result, many attempts have been made for the development of dynamic rotor balancing methods mostly by the precision mechanical system industry; however, intensive studies about the fundamental principles from a theoretical point of view should be carried out further. In the present paper, a new dual axes dynamic imbalance correction method is introduced and tested through simulations. The proposed method is more efficient and effective than its predecessors.

Keywords: Precision rotor; Mass imbalance; Impact balancing method

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1. Introduction

Maintaining a firm rotation of axis and homogeneous material distribution around the axis may be one of the most critical aspects in designing high-speed rotors. As applications employing the rotors expand to various industrial and consumer products, the rotational speed increases and vibration requirements intensify. Consequently, the countereffects generated by the mass imbalance aggravate the complexity of the overall design and manufacturing processes of the precision rotors. For example, even a slight assembly misalignment of a rotor revolving at high rotational speed (e.g., 10,000 rpm or higher) creates a significant level of vibration that often excites some of structure natural frequencies, which hamper the accomplishment of the primary function of the rotor or result in a catastrophic system failure.

In spite of the significance of maintaining mass balance, there are few effective balancing methods available for actual industrial volume productions. This is mainly because the consideration of inhomogeneous material distribution of the contributing mechanical parts and the anticipation of dynamic effects caused by accumulation of assembly clearances at the design stage are just not practical and are also impossible. In other words, even though a rotor design secures the mass balance at the design stage, it is not necessarily extended to the fabrication steps. Thus, recognizing the problems related to acquiring balance in productions, some efficient but not very effective methods are developed mainly by hard disk drive designers who have to deal with high precision and high rotational speed rotors [1]. Those include either adding counter masses after imbalance measurement of an assembled rotor or aligning the center of disks to the rotation center during an assembly process [2-4]. Unlike those passive balancing methods described above, this study presents an active method that divides the revolving surface into eight sections and inserts steel balls in order to maintain the balance [5].

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*Corresponding author. Tel.: +82 31 290 7454, Fax.: +82 31 290 5889
E-mail address: jckoo@skku.edu

However, as mentioned, those methods may work efficiently for volume productions, which could tolerate certain amount of imbalance-related dynamics, but may not be effective tools if achieving an absolute accuracy of mass balance is desired. A typical example of the case is a micro-size precision rotor involving a number of complex tiny parts.

Noting the functional limitations of the conventional method in terms of balance correction accuracy, this work develops a dynamic active method using external impact [6]. For superior accuracy in precision rotor manufacturing, many products adopt technology and deliver excellent mass balance-related dynamic characteristics. Despite successful implementations in many volume productions, the method has not been systematically reviewed because no analytical work has been performed, and the development has relied on empirical trial-and-error-based tests. In addition, the heavy dependency on the empirical methods without a solid analysis appears as a critical limitation when a rotor loads multiple disks and renders the brilliant idea impractical.

Recognizing the aforementioned limitations of the impact method, attempts are made in the present work to construct a systematic way to correct the imbalance so that its application extends to multi-disk problems. A careful consideration of both eccentricity and phase of the disks using a numerical model leads to a strategy development for the impact force application. The developed logic is verified through hardware tests.

2. System model and simulation set-up

In order to develop a new systematic impact application method for mass imbalance correction, a numerical model that mimics a hard disk drive disk pack is prepared using a commercial simulation code. In the model shown in Fig. 1, two thin rigid disks are loaded onto a rotating shaft and the radial clearance between disk inner diameter (ID) and shaft outer diameter (OD) is set at 20 um. A spacer is inserted between the two disks to maintain a proper separation. Those disks and a spacer are tightened with a preloaded clamp that is located on the top disk and screwed onto the top of the rotating shaft. As a result, if the shaft spins, the clamp should rotate; then, the disks and spacer should also rotate as the preload in axial direction creates frictional torque on each surface of the disks.

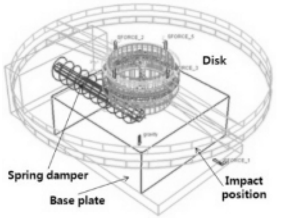


Fig. 1. A simulation model of a precision rotor with two rigid disks.

Note that since the disks are fastened only by friction and there are clearances between the disks and the rotational shaft, a certain amount of external shock can change the relative position of geometric centers of the shaft and disks [6]. The model parameters are cited from a commercial hard disk drive design.

Of course, the deliberately misaligned disk centers may either alleviate or aggravate the overall mass imbalance of the rotor depending on the relative locations of the individual mass centers. With an external shock input while the rotor spins, the movements of those two disks are identical provided the friction coefficients of all contact surfaces are equal. In reality, however, each surface has been given a different friction coefficient and it results in a complicated dynamic event when an external shock is applied. In other words, since the movements of each disk by the shock input might vary as a result of the different frictional resistant forces, a well-coordinated dual plane imbalance correction strategy should be arranged for a successful multiple disk imbalance correction.

3. Rotor imbalance correction method

Using the model presented in the previous section, an effective and accurate dual plane rotor imbalance correction method is developed in this section. It is necessary that the various distinct frictions of each disk be carefully accounted for a successful development.

As shown in Fig. 2, an initial set-up of an imbalanced rotor and two deliberately misaligned disks that are represented with masses (M_R and M_B) and offset distances (L_R and L_B) in the lumped model are loaded on a rotating shaft with a phase difference θ. Hence in the model, the overall imbalance amount can be determined with a combination of mass, eccentricity, and phase.

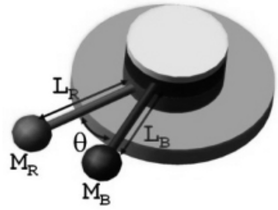


Fig. 2. A lumped model representing mass imbalances with phase.

Considering the initial disk eccentricities, a hypothesis for the reduction of the imbalance could be that if an impact input were applied not on the center line of θ but from the opposite side of the eccentricity, the offset amount L_X could be reduced. In reality, however, the application of an impact presumed by the hypothesis may enlarge the angle θ owing to the different friction coefficients of each surface, although the eccentricities L_R and L_B may be slightly reduced. Hence, a more effective correction strategy should be able to reduce the angle θ before reducing the eccentricities L_X. As shown in Fig. 3(a), applying an impact input from the side of eccentricity instead of applying it from the opposite side as described in the hypothesis, the new method will decrease the angle θ. Thus if the second shock is given from the other side as shown in Fig. 3(b), the eccentricity will be reduced. An iteration of these steps will bring the imbalance amount close to asymptotically zero.

There is another method that is also effective to reduce the angle θ. As depicted in Fig. 4, an impact input from a line perpendicular to the center of θ will reduce the angle θ. From an empirical evaluation of those two methods, the angle reduction accuracies of the two are similar.

A numerical example case is shown in Fig. 5 for verification. The initial imbalance 62.34 mg·cm is reduced to 3.76mg· cm, which is about 94% reduction of the imbalance after seven impact inputs.

4. Verification test

In order to verify the feasibility of the proposed method, a hardware test is performed. A precision fluid dynamic rotor that is used for a hard disk drive is mounted on a table that can be moved freely toward any direction through linear guides. The imbalance of the rotor spinning at 120 Hz is monitored with a force transducer and impacts are applied using a solenoid that is controlled by a real-time controller. The initial vibration spectrum measured from the rotor is normalized and shown in Fig. 6(a), while the final spectrum after imbalance correction is provided in Fig. 6(b). The figures show that the imbalance amount that is represented by 120 Hz peak is reduced from 1 to 0.08, which is about 92% reduction.

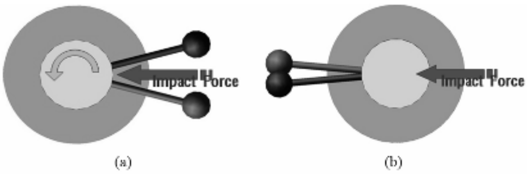


Fig. 3. (a) Correction of the phase angle and (b) eccentricity.

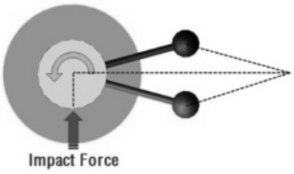


Fig. 4. Reduction of phase angle θ.

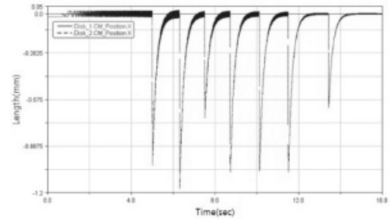
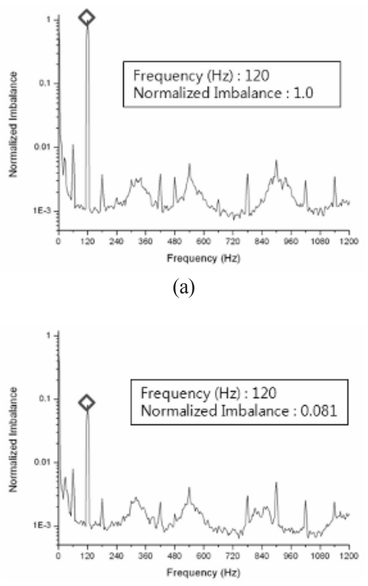


Fig. 5. Imbalance correction result.

5. Conclusion

As one of the most important dynamic specifications of precision high-speed rotors, maintaining mass imbalance in controllable boundary limits should be of primary interest in many industrial applications. In the present work, a new dual plane imbalance correction method that accounts for both magnitude and phase is developed and tested for verification with a hardware test. Considering complicated frictions between the rotor components, the development of an efficient and effective method for adjusting the mass imbalance constitutes the key contribution of the present work. From the hardware verification test aspect, the proposed method demonstrates a significant accuracy improvement in mass imbalance correction compared to its predecessor [6]. Certainly, the method can be directly applied to volume production



(a)

(b)

Fig. 6. (a) Imbalance of a rotor before and (b) after correction.

of precision rotors.

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Jung Kwan Lee is currently a masteral student in the School of Mechanical Engineering at Sungkyunkwan University Korea. He received his B.S. degree from Sungkyunkwan University. His primary research interests are rotor design, analysis, and rotor dynamics.

Hyungpil Moon received his Ph.D. degree in mechanical engineering from the University of Michigan in 2005. He was a post-doctoral fellow at Carnegie Mellon University. He joined the faculty of the School of Mechanical Engineering at Sungkyunkwan University in 2008.

Dongho Oh received his Ph.D. degree from KAIST in 1996. He worked as a Principal En-gineer of Samsung Electronics and SAIT. Dr. Oh is currently an Associate Professor at the Department of Mechanical Engineering at Chungnam National University.

Ja Choon Koo is an associate professor of the School of Mechanical Engineering at Sungkyunkwan University Korea. He was an engineer at IBM Corporation, San Jose, California. He received his Ph.D from the University of Texas at Austin. His primary research interests are analysis, and control of dynamic systems, mechatronics, sensors, and actuators.