Determination of the Optimal Position of Pendulums of an Active Self-balancing Device

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Abstract. The demand of the modern manufacturing industry for machines with high motion speed leads to increased load and vibration activity of the main elements of rotor systems. Vibration reduces operating life of bearings, has adversary effects on human organism, and can cause accidents. One way to compensate for a rotating rotor's imbalance is the use of active self-balancing devices. The aim of this work is to determine the position of their pendulums, in which the imbalance is minimized. As a result of the study, a formula for determining the angle of the pendulums was obtained.

1. Introduction

At present, introducing new technologies and increasing the efficiency of manufacturing processes require the design of high-performance machines with high motion speeds, high performance reliability and precision. One of the main components of modern machines are high-speed rotating elements (rotor systems) with a high load capacity and vibration activity. The presence of vibration leads to heavy wear of bearings, and, in some cases, decreases the accuracy of the performance of a device's or machine's functions. Vibration has a direct impact on humans, decreasing one's performance.

Modern methods and ways of balancing of rotating rotors allow to balance them to the high class of accuracy. In some cases, the initial balancing during operation of the device or machine is compromised and does not meet the requirements. For example, in industrial fans this happens due to uneven carbon buildup on the blades. In different centrifuges, change of imbalance occurs very quickly and with every start. Therefore, for such types of machines, automatic rotor balancing becomes necessary.

Presently, machine designers use active self-balancing devices (SBDs) for spinning rotors. They allow to decrease instrument and equipment vibration, decrease the wear of bearings and other rotating parts. As a result, the operating life of instruments and machinery increases. Self-balancing devices are divided into 2 types: active and passive. In passive devices, balancing weights move freely under the effect of internal forces, but in the active ones, this happens by means of some outside force [1]. Both of them have their advantages and disadvantages. The main advantage of passive SBDs is their simplicity. They do not require external power supply and complex control schemes, so they are

usually quite compact and easy to manufacture. But the main disadvantage of passive SBDs is that they decrease the vibration only at speeds above critical, i.e. above resonance. In the area below resonance, such devices only increase the imbalance of the system and worsen the resonance transition [2-4]. Active SBDs do not have this disadvantage – they work at all rotor speeds, but their structure is complex and they need complex control systems [5-7].

Since the balancing process in the active SBDs does not depend on the rotor speed, and the speed and trajectory of the balancing weights are determined by the imbalance and depend on the kinematic model, the type of the balancing weights displacement drive and the sensitivity of the measuring system, it is obvious that active SBDs can achieve high accuracy of the installation of the balancing weights in the positions that ensure the maximum possible balance of the rotor in accordance with the hardware configuration. Active SBDs are based on the principle of closed-loop automatic control systems and consist of a large number of individual blocks that perform different functions. Eventually this leads to increased complexity of such devices, their bulkiness and high cost.

Active SBDs differ in the method of searching for positions of the balancing weights on SBDs with random search and SBDs with guided movement of the balancing weights. Devices with random search are constructed so that random search provides independence of their work from the rotor speed. The disadvantage of such system is that the imbalance can increase indefinitely [5], and balancing time is not constant due to the random nature of the search. However, the balancing process may be made more reliable if we introduce some regularity in the random search method.

Balancing devices with guided movement of the balancing weights do not require the measure of the imbalance phases and can operate with a measuring system that shows only the presence of vibration in supports and the change in their amplitude. This measuring system is simpler and more reliable because it has less components and functions.

Figure 1 shows the basic scheme of an active SBD. They work on the following principle: a vibration sensor measures the vibration in the machine's casing or support and feeds the data to a controller, where it is processed. The controller gives control signals to drive mechanisms, which set balancing weights relative to the rotor in such a way that they compensate for its imbalance and dampen the vibration.
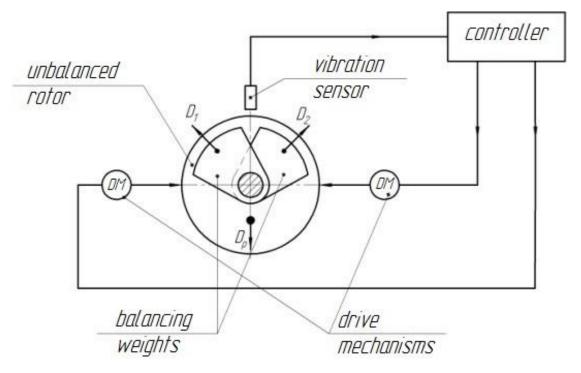

Figure 1. Basic scheme of an active SBD

2. Determination of the pendulums' position

Because the main vector of the system imbalance and the balancing weights (pendulums) are in different planes, complete equilibration of the system cannot be achieved. Consequently, dynamic reactions will appear in rotor supports. The aim of this work is to find the position of the pendulums, in which the influence of the residual imbalance is minimal.

Let us consider a mechanical system in Figure 2. A rotor with an unbalanced disc has the imbalance D and rotates on the supports A and B, the distance between which is l. Balancing weights, namely the pendulums with the imbalance Dm, deviate from the vector of the disc imbalance at the same angle φ. The distance between the pendulums is c, the distance between the support and the central SBD plane is a, the distance between the central plane of the SBD and the disc is b.
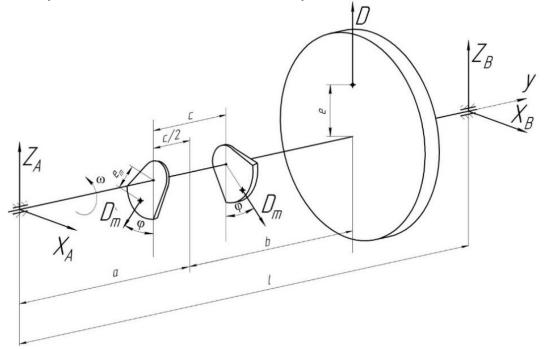

Figure 2. Basic scheme of an active SBD.

In terms of the equilibrium conditions, the components of the reactions in the bearings are equal to:

$$Z_A = \frac{2\,D_m \cos\varphi\,(l-a) - D\,(l-a-b)}{l};$$

$$Z_B = \frac{2\,D_m \cos\varphi\,a - D\,(a+b)}{l};$$

$$X_A = X_B = \frac{D_m \sin\varphi\,c}{l};$$

Accordingly, the overall reactions are:

$$R_A = \sqrt{\left(\frac{2\,D_m \cos\varphi\,(l-a) - D\,(l-a-b)}{l}\right)^2 + \left(\frac{D_m \sin\varphi\,c}{l}\right)^2};$$

$$R_B = \sqrt{\left(\frac{2 D_m \cos\varphi\, a - D(a+b)}{l}\right)^2 + \left(\frac{D_m \sin\varphi\, c}{l}\right)^2};$$

The objective of the research is to find the angle φ, at which the dynamic reactions in the bearings are minimal:

$$F = \left(R_A(\varphi) + R_B(\varphi)\right) \to \min.$$

We can consider the function containing the squares of the reactions to simplify calculations:

$$F = \left(R_A^{\,2}(\varphi) + R_B^{\,2}(\varphi)\right) \to \min.$$

The squares of the reactions are:

$$R_A^{\,2} = \left(\frac{2 D_m \cos\varphi\,(l-a) - D(l-a-b)}{l}\right)^2 + \left(\frac{D_m \sin\varphi\, c}{l}\right)^2;$$

$$R_B^{\,2} = \left(\frac{2 D_m \cos\varphi\, a - D(a+b)}{l}\right)^2 + \left(\frac{D_m \sin\varphi\, c}{l}\right)^2;$$

In order to find the extremum of the function, let us take the derivative and set it equal to zero:

$$\frac{d(R_A^{\,2} + R_B^{\,2})}{d\varphi} = 0;$$

After the transformations, we get:

$$\frac{\left(-16\,a^2 - 8\,l^2 + 16\,a\,l + 4\,c^2\right)D_m^2 \cos\varphi\sin\varphi + \left(-8\,l\,a + 4\,l^2 + 8\,a^2 - 4\,l\,b + 8\,a\,b\right)D_m\,D\sin\varphi}{l^2} = 0;$$

or

$$\left(-8\,a^2 - 4\,l^2 + 8\,a\,l + 2\,c^2\right)D_m^2 \sin(2\varphi) + \left(-8\,l\,a + 4\,l^2 + 8\,a^2 - 4\,l\,b + 8\,a\,b\right)D_m\,D\sin\varphi = 0;$$

By solving the equation for φ, we finally obtain:

$$\varphi = \operatorname{arctg}\left(\frac{\sqrt{-\left(-8\,l\,a + 4\,l^2 + 8\,a^2 - 4\,l\,b + 8\,a\,b\right)^2 D_m^2\,D^2 + 4\left(-8\,a^2 - 4\,l^2 + 8\,a\,l + 2\,c^2\right)^2 D_m^4}}{\left(-8\,l\,a + 4\,l^2 + 8\,a^2 - 4\,l\,b + 8\,a\,b\right)D_m\,D}\right)$$

3. Conclusions

Active SBDs of different types allow to achieve high-precision balancing and performance at all frequencies of rotor rotation. However, these devices are complex. The higher the accuracy of the

device, the more complex and more perfect the elements should be. These systems are huge, massive, and, most importantly, expensive. In is reasonable to apply this type of balancing devices in equipment where the technological process requires high balancing accuracy and where it is economically feasible to use high-precision measuring systems and drives.

In recent years, there has been a further development of active balancing devices, measuring systems, automated corrective mass movement control systems, as well as improvements in hardware. This study resulted in obtaining a formula for determining the angle of SBD pendulums, in which total dynamic reactions in the bearings are minimal. This allows to continue improving the properties of active SBDs in the simplest, most reliable and effective way, i.e. by improving their design, kinematic layout, which in turn are determined by the drive type.

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