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Self-balancing system of the disk on an elastic shaft

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ABSTRACT

This paper presents an analysis of the automatic balancing of a rigid disk mounted on an elastic shaft. The balancing system consists of two drums at a variable distance from the disk and free balls (or rollers) inside the disk. The balls are able to change positions with respect to the rotor and compensate for rotor unbalance. This paper presents the equations of motion for the disk as well as for the balls during balancing. It is shown that the balls can compensate a part or all of the rotor unbalance depending on the positioning of the drums. There are vibratory forces that push the balls to new positions; these are responsible for the behavior of the balls and the final results. The vibratory forces are defined as a function of the system's parameters and they determine the position of equilibrium of the balls. The stability and efficiency of the method is analyzed in this paper.

1. Introduction

Unbalanced rotating equipment causes vibration, noise, loss of accuracy, excessive wear and increased maintenance costs. The high angular speeds encountered in current rotating machinery impose rigorous requirements on rotating mechanisms. The problem of vibration of the rotor as a result of its unbalance is analyzed in many publications, e.g. [1]. The distribution of masses around the axis of rotation varies during the operation of a machine or each time the machine is restarted and the conventional balancing method with a fixed counterbalance becomes impracticable.

Therefore, self-balancing methods are practiced in these rotating systems where the role of balancing bodies is performed using an arrangement of balls, rollers, or sometimes liquid, in a ring or rings fixed to the rotor or a groove in the rotor.

The first patents for automatic balancing with liquid are dated 1915 by Leblance [2] and 1934 by Thearle [3,4] (for balancing using balls). The phenomenon of automatic balancing has always been interesting for scientists and engineers and many papers have been published presenting some interesting aspects of practical application [5–13]. Most of the papers analyze a rigid rotor with the balls on one or two planes. In some papers authors have analyzed the behavior of a disk on an elastic shaft with the balls on the same plane as the disk [14,15]. In this case, the elasticity of the shaft plays the same role as the elasticity of the suspension of the bearings. The resultant elasticity of the system is a combination of the stiffness of the bearing supports and the shaft. The inertia of the disk, its position on the shaft, and the elasticity of the shaft define the natural frequencies of the system.

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Some authors have applied the ball balancer to hand-held equipment with rotating elements (e.g., hand grinders, optic discs) [13,16–21]. This makes the machine run more quietly, with a smoother cut, and increases the lifetime of the grinding disks, thus significantly ensuring faster and more pleasant work.

The author of this article studied the possibilities of the automatic balancing of a rigid rotor in one and two planes and the results of the investigation are given in the paper [22]. It was shown that there are vibratory forces which define the equilibrium positions of the balls with respect to the rotor and final efficiency of the system.

Liquid can also be used as a free element. Indeed, some experiments have been carried out using liquid to balance the drum of a washing machine [23–27]. Washing machines and centrifuges are the best examples of practical applications of self-balancing methods. In this case, the distribution of mass is different at each start and the mass distribution also changes during the hydro-extracting of the clothes. A ring with liquid inside it is fixed to the rotating basket. The liquid occupies a part of the inner ring space. When the rotating basket vibrates, the vibratory force pushes the liquid into a position opposite the basket unbalance; but this method is not very efficient [23]. In some papers the authors conclude that this method is both effective and applicable; however, the results given in their papers show that the efficiency of the experiments is close to zero. Their theoretical models are incomplete and, therefore, there are great differences between the theoretical and experimental results.

While it is known that a rigid rotor with balls on two planes can be balanced 100% if certain conditions are met, there are some other factors which decrease the efficiency of the method [28]. Some authors try to improve the efficiency of an automatic ball balancer, e.g. [29].

Sometimes it is not possible to place free-balancing elements on the same plane as the disk and it is not obvious if the balls are able to balance the system. This paper tries to explain which part of the disk's initial unbalance and vibrations can be compensated by the balls if the distance between the disk and the balls increases. The results of this paper may be used for properly designing a system for the elimination of dynamic forces and vibrations.

The paper is organized in such a way that it first presents the model and its restrictions, the differential equations which define the behavior of the system (Sections 2 and 3), a simulation of the behavior of the disk and free balls during balancing, the resultant unbalance of the system (Section 4), the vibratory forces which define the balls behavior, the final position of the balls (Section 5) and also the stability of this position (Section 6).

2. Physical and mathematical models

The balancing system consists of disk 1 with the mass M, two drums 2 and 6, free elements (balls or rollers) 3 and 4, the elastic shaft 5, and the bearings at the ends of the shaft 1 and 8–Fig. 1. It is assumed that the masses of the shaft, drums, and balls are very small with respect to the mass of the disk. The XYZ is a space-fixed reference frame, $x_1y_1z_1$ is a reference frame that is fixed to the center of the disk and it changes the angular position with the disk, xyz is a reference frame fixed to the disk and rotates with it. The displacements of the disk and two drums are defined by the coordinates x and y with the index defining their position on the shaft, as shown in Fig. 1. It is assumed that the displacements of points 2 and 3 are equal, the same for points 4 and 5, 6 and 7. The displacements of points 2, 4 and 6 are different from one another as a result of the deformation of the shaft.

The mass center of disk C is at a distance e from the axis of rotation of the rotor, which gives a static unbalance Me. The spin velocity of the disk ω is constant.

The vibrations of the disk are defined in the XYZ reference frame. The linear displacements of the center of the disk are x_4, y_4 and its angular displacements are defined by the small Euler angles Φ_4 and θ_4 – Fig. 2. To obtain the equations of motion from Lagrange's equations, the kinetic and potential energy for all elements of the system must be determined.

The kinetic energy from the translation T_{tr} and rotation T_{rot} motion of the disk is

$$T_{tr} \cong \frac{1}{2}M\left[(\dot{x}_4 - e\omega \sin \omega t)^2 + (\dot{y}_4 + e\omega \cos \omega t)^2 + (\dot{\phi}_4 e \sin \omega t - \dot{\theta}_4 e \cos \omega t)^2\right], \tag{1}$$

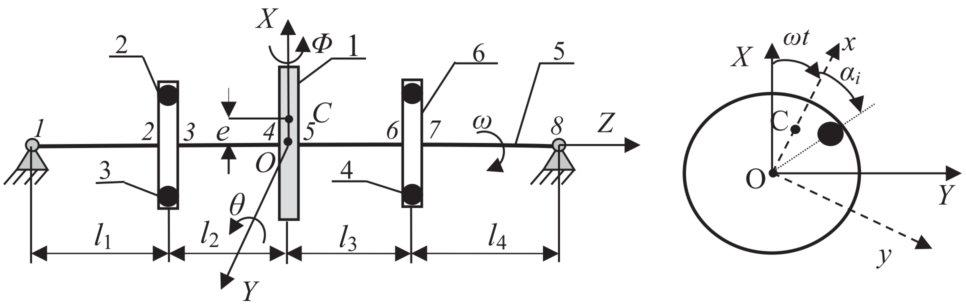

Fig. 1. Analyzed system, 1-disk, 2-left drum, 3-balls in the left drum, 4-balls in the right drum, 5-shaft, 6-right drum, 1 and 8-bearings.