A Survey of Automatic Balancing Methods for Shafts in Motion

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***Abstract*—In this paper a discussion is presented on using various mechatronic systems for automatic balancing to be used for shafts in motion. A general classification of such balancing methods is presented. Also, a method of determining effectiveness of named autonomous balancing solutions is shown and discussed on example of patented and currently used methods. This discussion serves as entrance point to finding a novel most effective solution of automatic shaft balancing system.**

***Index Terms*-automated balancing, shaft balancing, control methods**

I. Introduction

A common knowledge is that any type of a body rotating around some axis needs to be well balanced around this axis in order to ensure constant moment of inertia in every phase of the motion and no vibrations generated during operation. Such precautions are necessary because of drive purposes – the linear transmission of a torque from the motor onto rotating body is being achieved that way. Also, reduction of vibrations results in no external forces generation acting on the bearings which are being used in order to provide smooth motion of the body. Such approach extends their lifetime greatly and is necessary for providing correctness of work all the time.

The conclusion is that preserving balanced state in all rotation elements is a necessity, therefore a number of methods have been created in order to restore equilibrium in unbalanced rotating members. A typical example of such actions is balancing of car wheel after tire change. In such situation such wheel is being rotated around fixed axis of rotation. When such wheel stops on itself, the lightest area that generates unbalance is located on top of the system. The equilibrium is being restored by adding balancing stones to the rim. This method works well, yet it requires removal of whole wheel, placing it on additional machine and going through whole balancing process – couple of times in many cases. The same problem is present for other bodies to be balanced, like various shafts, spindles, grinding wheels, hard drive plates, etc.

A number of inventors tried to overcome that problem and enable the balancing process to be done on given element without removing it from the machine, or – even better – without stopping the operation of such element, which means that the balancing process occurs constantly and can be used for shafts and other elements being in motion.

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This paper presents a survey of known methods for such autonomous balancing methods and systems for shafts in motion. Its purpose is to find if there is a place for improvement in this area of technology and to point directions of possible development.

II. General Classification

Information found in the literature show that there are three main methods of balancing rotating bodies. First one is to remove material somehow from the element itself or from some additional element located on the body to be balanced. On the contrary, in the other possibility the material is being added to the element of rotation. As before, it might be necessary to include some kind of additional element that will allow of such actions to be performed. Third method, the most commonly used one, is to equip given rotating body with a balancing system with a kind of movable masses. If a force generated by the unbalance is being detected for some rotating element, the system unblocks the movable masses in order to use a centrifugal force to spark off their motion until the whole system reaches equilibrium state one more time, after what the masses are being blocked again. In next subsections the detailed description of used methods is presented.

A. Material Removal

The first method group bases on a fact, that in case of finding unbalance in a rotating object it is possible to remove part of the material in order to generate circumferential force opposite to force of unbalance. There is couple of examples of how such process could have been performed, like for example milling part of the material of given body [1] or heating the surface to the point in which material vaporizes by means of a laser [2] or electric arc [3]. Yet, all these methods cannot be used for body in motion, as it is not possible to perform the removal process fast enough. And besides that, the whole idea of removing material in a presented way is far from being perfect, as it requires some additional material to be added to balanced element, so it could be removed afterwards, or – in worst case scenario – the part of material of balanced object itself would have to be removed. Such solution cannot work in long-life processes, because there is no possibility to use them all the time without the need to stop the motion of a body in

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order to change the additional part or the object itself for the new one at a point when no further balancing is possible.

Nevertheless, there is a description of a balancing method basing on material removal, which does not require the object to be stopped for the process to be done, nor it doesn't cause any damage to the surface of the body. Such method has been described in [4]. The idea is to prepare an object to be balanced in a correct way or to equip it with some adequate equipment. Despite which method is selected, it is necessary to make a number of holes close to the perimeter of the rotating object. The holes should be displaced next to each other by given distance. Also, all of these holes serve as guides for balancing masses that need to be placed inside them (Fig. 1).

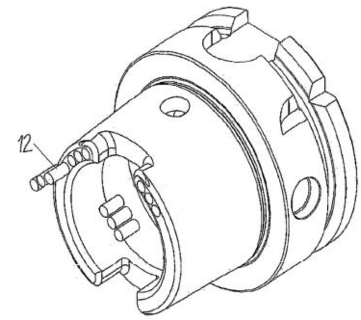

Figure 1. Removal of masses [4]

While the body is in equilibrium, it rotates normally with all masses present, yet if some unbalance force is detected, a balancing mass or number of masses are being removed from the guides causing circumferential force to appear in order to restore equilibrium to the system. The solution is not perfect, as it is not possible to generate balancing force of any given volume.

B. Material Adding

Another possibility to balance an object is to add some material in given point of such body in order to generate circumferential force for balancing purposes. As in previous group of methods, there is a number of solutions based on the described idea, yet not all of them are possible to be used in a body being in motion. For example in [5] authors show a method in which they add material by spraying a composite powder onto a surface of balanced body. In [6] a method is shown where a number of pits need to be drilled in the surface of the object – they are being filled with fast-hardening material, as needed in order to restore equilibrium. Other solutions are based on welding techniques. The simplest one [7] shows that if needed, a weld is being placed on the object's surface. In case of [8, 9] a mass is being placed on the surface and then it's being welded down to make it stable, either with the use of an electric arch or laser. It is possible to remove paint from the particular point of an object if needed.

As before, there are methods possible to be used without stopping the rotation of balanced body. The first one is described in [10] and it again bases on adding a fast-hardening substance onto the object's surface (Fig. 2).

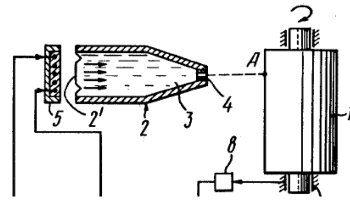

Figure 2. Adding of fast-hardening material [10]

The added substance is a ferromagnetic, as in order to shot it onto the object an electromagnetic impulse is being used.

Another example of method for the body in motion is quite similar to one described in previous subsection. There are two, quite similar methods presented in [11, 12]. First one bases on series of grooves added on the surface parallel to the axis of rotation of a body (Fig. 3a), another one requires a number of holes to be drilled in a face of balanced body, also parallel to the axis of rotation (Fig. 3b).

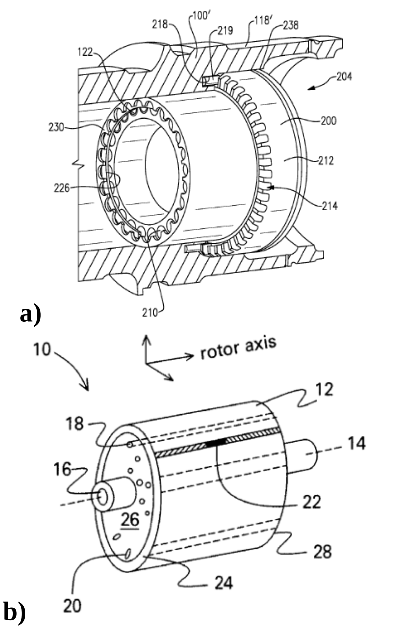

Figure 3. a) Adding material into a) grooves; b) holes [11, 12]

The groves and holes are initially empty, while as unbalance appears, a balancing mass is being inserted inside some of them and restores equilibrium. The solution presented in Fig. 3a has the same disadvantages as the one being shown in Fig. 1 – the generated balancing force cannot be changed fluently. Such problem is being solved in the solution presented in Fig. 3b, as the drilled holes have various diameters, therefore it is possible to apply various masses into them, generating various balancing force. Yet, such solution complicates insertion mechanism greatly.

C. Moving of Masses

The last possibility described in the literature is to equip the balanced object with a device possessing some movable elements (masses). The relative motion of these masses can be used in order to generate balancing force, if such is needed. Such masses can be made and moved in variety of ways, yet some similarities can be seen and so the methods can be classified.

The first method is to move the masses peripherally, which means that 2, 3 or 4 masses (in most cases) are individually placed near the perimeter of the body to be balanced. Their dependent displacement is being used in order to generate circumferential balancing force. The masses can be made in variety of ways, for example they can have a form of balls (Fig. 4 a, b, c) [13, 14, 15], carriages (Fig. 4 d, e) [16, 17], some nonsymmetrical part of the overall element (Fig. 4 f, g, h) [18, 19, 20].

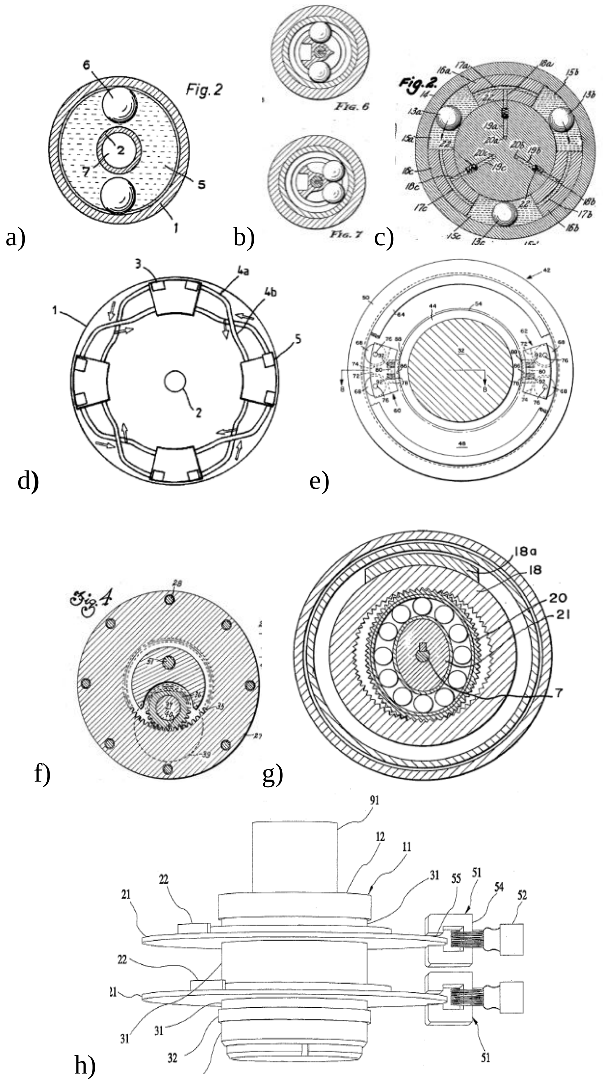

Figure 4. a) balls moving in damping medium [13]; b) balls propelled by slider [14]; c) balls moved by fluid pressure [15]; d) carriages moved pneumatically [16]; e) carriages with brakes [17]; f) mass connected to a cog [18]; g) mass moved by harmonic drive [19]; h) masses placed on the plates [20]

The motion of the masses is being done using variety of methods. For example they can be moved using pressure of a medium (Fig. 4 a, c, d), or they can be pushed by a slider connected to special rail shape (Fig. 4 b). The masses can be moved using gears with self-locking mechanism or brakes (Fig. 4 e, f, g). It is also possible to use electricity in order to propel the masses – Figure 4h shows an example in which eddy currents are used to rotate plates with balancing masses. Other examples can be seen in Fig. 5a, where two Halbach cylinders are being used to move the mass [21] or in Fig. 5b, which presents electromagnets propelling ferromagnetic particles for balancing purposes [22].

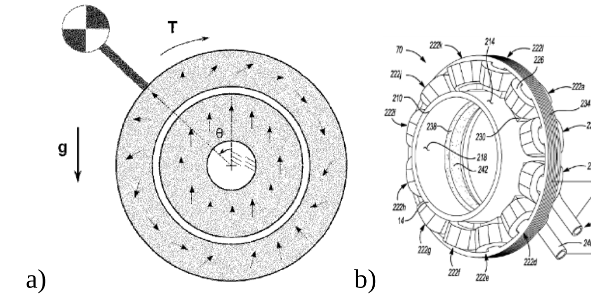

Figure 5. a) Halbach cylinders rotating a mass [21]; b) electromagnets moving particles [22]

Another idea of balancing a body using the motion of masses is to move them circumferentially. In such case in the initial state the moving elements are located in the same range from the axis of rotation, yet if the unbalance occurs, they are being moved towards or backwards from the rotation axis. The method is not very popular, yet some examples can be found as well. They can be seen in Fig. 6.

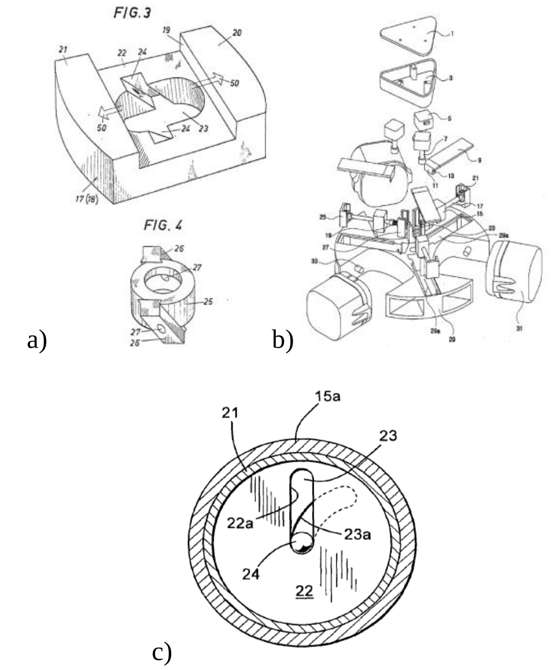

Figure 6. a) rings with guides [23]; b) screw and nut method [24]; c) guiding groove [25]

In an example presented in Fig. 6a the balanced object is to be equipped with two pairs of presented ring – one is stationary, the other one moves, as necessary [23]. Authors of [24] propose to use three balancing masses, each one to be propelled by DC motor with screw and nut gear, which makes it possible to move the masses individually. Third solution is to balance the object using ball's motions – it is being done by rotating two plates with groves of special shape [25].

Last and most commonly used method of balancing using the motion of masses is to rotate nonsymmetrical masses. A great number of such solutions can be found in the literature, making such solution the most popular one between ones described above. The principle remains the same in most of the solutions – two or more masses are being placed on the opposite sides of balanced element and remain stable. Yet, if an unbalance appears, the masses are being released and moved relatively to each other in order to generate a circumferential force. Volume of this force is being change with the relevant position of the masses, reaching its maximum as the masses coincide.

The differences are in masses shapes and forms, as they can be done as plates of special shape (Fig. 7a, b, c, d) [26, 27, 28, 29], sleeves with cutaways (Fig. 7e) [30], or simply cuts done in elements (Fig. 7f, g) [31, 32].

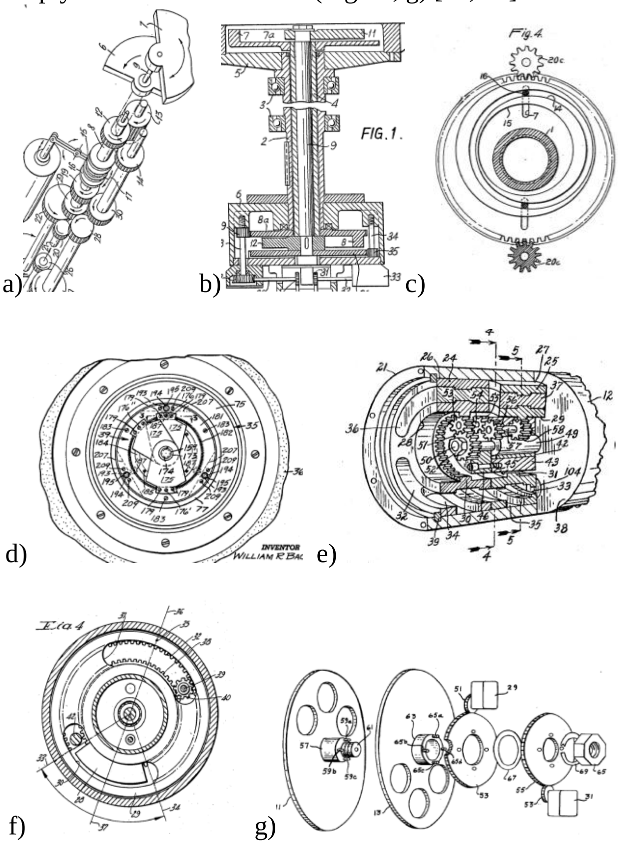

Figure 7. a) masses moved with a gear located next to object [26]; b) masses controls located inside the balanced shaft [27]; c) masses in form of eccentric disks with gears [28]; d) two pendulums with the same axis of rotation [29]; e) sleeve with cutaways being part of a planetary gear [30]; f) disk with nonsymmetrical cutaway as a part of planetary gear [31]; g) two disks with cuts propelled by servodrives [32]

Another matter to be discussed is a method of controlling such balancing equipment. The most common method is to control them using a drive with a set of gears that transfer torque. In most cases these gears are located next to the balanced element in order to not interfere with its work process. There are some exceptions to that – an author of [27] shows how to propel balancing masses using drive located inside the balanced shaft, which of course must be hollow (Fig. 7b). There is another solution different from most common ones – in publication [33] there is an example of drives that propel balancing masses motion are being moved along with these masses (Fig. 8a). To conclude one needs to mention that there are some examples of different control methods, like – for example – solutions shown in [34, 35, 36] where the control medium is a compressed air.

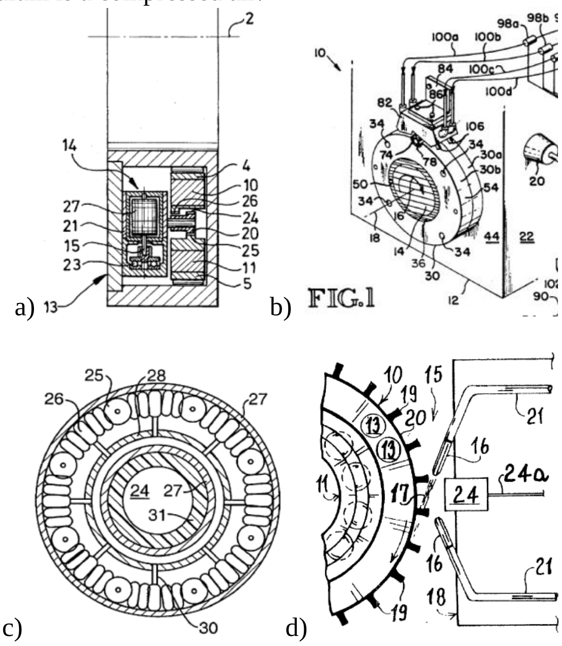

Figure 8. a) control drive moving along with masses [33]; b) masses propeled by a turbine [34]; c) a disk with number of grooves controlled by compressed air [35]; d) disk moved by two air jets [36]

There are couple ideas on how use such a medium to control the motion of balancing masses. One example is shown in Fig. 8b, where the air is being processed onto a turbine which motion propels the rotation of masses. Another idea is to make balancing mass in a form of a disk with number of grooves and chambers (Fig. 8c) which generate rotating motion of that disk after being powered with a compressed air. The simplest example can be seen in Fig. 8d, where the balancing mass is connected to a disk with number of blades. Next to the disk there are two air jests located, which blow an air onto the blades, making the disk rotate.

III. Finding of the Most Effective Method

As was mentioned before, the last group of balancing methods seems to have least disadvantages, as it does not wear over time and in all cases provides a fluent control of the volume of balancing force. A method of moving nonsymmetrical masses has also the greatest number of various examples of how the process can be performed, and how the devices to perform the balancing process can be made. It is worth noticing that most of presented examples uses the same control method: an electric motor with a set of gears that are being used to move the masses. There are some other attempts to solve that differently, like for example by using compressed air, yet the main focus remains unchanged. It shows that there is a great potential of the development of such methods. For example, in a great number of applications the free space on the shaft that could be used in order to install the balancing equipment is really limited, e.g. fumes fans used in power plants offer no more than 100 mm free axial space on the shaft. Some of the examples described in the previous section provided balancing opportunity in a limited space, e.g. ones presented in Fig. 4h or 5b – both using electricity as propulsion. If they are to be combined with devices using unsymmetrical masses, it would be a pretty novel solution. Yet, using such combination in given example would be problematic for many reasons as well. For example a problem of locking the masses in given stable position after balancing process completion would have to be solved. The balancing device combining these features is being currently developed and will be presented in future publications.

IV. Summary

The number of references used in this paper show the importance of automatic balancing means. Also one can clearly see that solution to solve that problem were being seek throughout the decades, and yet still new concepts are being found. This paper presented a survey of methods already found and described, but also a comparison of them were made and some new development direction were offered. All of presented mechanisms show the complexity and utility of automatic balancing devices that can be used for bodies in motion, which are a clear example of the great variety of how the mechatronic systems can be used.

Conflict of Interest

Author declares no conflict of interests.

Author Contributions

Paweł Żak created this paper completely.

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His main work experience is connected to Lodz University of Technology. He started to work as an assistant in 2011 and held this position until 2015 when he was promoted to lecturer, which is his job title until now. Starting from 2011 he additionally held number of additional positions, such as researcher, tutor, students supervisor. He was also the main investigator of two research grants (2011-2013, 2018-2021) and investigator in 5 other research grants (2011-2014, 2013-2015, 2014-2017, 2016-2019, 2018-2021). He was also a coordinator of international educational grant (2017-2018).

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