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ROBUST MECHATRONIC CONDITION MONITORING AND DIAGNOSTIC METHOD FOR GEARBOXES

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In the paper is discussed the new gearbox model which may be used for condition monitoring for faults detection. The model should develop for each stage of a gearbox. The model is obtained from results of measurements. The measurements are done on real object after its run in. The model is obtained by linear regression analysis. The new concept of gearbox model is especially suitable for the case of varying load condition. The model is developed for planetary gearbox, which is incorporated in the system consisting of many stages as a bevel stage, and cylindrical stages. The discussion shows the possibility of replacement the analytical model into the physical model. The simplicity of this model quarantines its robustness.

1. INTRODUCTION

In [1] according H.J. Koriath, M. Romer mechatronic systems are composed of:

- a basic mechanical structure which generates a certain carrying behaviour or movement,
- sensors which collect information on the system or the environment,
- processors evaluating the information and generating correcting variables according to certain rules,
- actuators in which the correcting variables are converted into forces, movements, electrical voltages or other values which act on the basic system or its environment.

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It is obvious, that the sensors and actuators form a link between energy and information. For an object condition monitoring, diagnostic and maintenance according [2] the mechatronic system should include the following:

- there should be enough detailed off-line signal processing and evaluation for information collection through sensors on a system condition.
- additional detailed processing may be done in a separate processing unit.

In the conclusions given in [2] there is also stated that the idea of robust model-based fault diagnosis, according to [3] should be taken into consideration when developing diagnostic systems for gearboxes in on-line use. But in the solution of robust model-based fault diagnosis we need a verified mathematical model that should be used in each separate case. In the presented paper there is presented the model describing the gearbox condition. It is the new model, which may be used when the external load is varying and it can be also use when one measure the condition of the object at least two levels of load. One form of a load variability is described in [4]. The vibration signal load dependency, which is caused by the change of gearbox condition change is presented for the first time in [5]. In the this case the load dependency was characterised under two different steady loads. This characteristic can be called the static characteristic. In [6] there is presented the load dependent characteristic, which may be called the statistical load dependent characteristic. The mentioned characteristics are described by linear functions obtained from the regression analysis.

2. THE DIAGNOSTIC MODEL

The condition of two cooperated gears can be described by the vibration spectrum as is given in figure 1, which gives the vibration spectrum for a two stage gearbox. It is the result of computer simulation according to the gearbox model presented in [7]. The details on many results from computer simulations for one stage gearbox are given in [8]. The principles of one stage mathematical modelling for a one stage gearboxes are given in [9]. In figure 1 mashing frequencies and their harmonic components for the first gear stage are denoted as f_{z1}; $2f_{z1}$; $3f_{z1}$ and for the second stage are denoted as f_{z2}; $2f_{z2}$; $3f_{z2}$. Modulation components are denoted as $-f_{z2}$; $+f_{z2}$ and $-2f_{z2}$; $+2f_{z2}$. The amplitudes of the meshing frequencies are the measure of a gear cooperating condition. As the general measure of gear condition is taken an amplitude arithmetic sum of components. The sum of amplitude components is a measure of distributed imperfections or distributed faults and as it is shown in [6] is the measure of teeth misalignment caused by frictional bearing wear. The shaft misalignment is mostly the root cause of gearbox condition change [6].

To get knowledge on gear behaviour many factors should be considered as it is given in publications [2] to [9] the factors can be divided into four groups namely;

design, production technology, operation, change of condition. Using presented models one may generate vibration signal and get its spectrum. One can use a verified model for which spectrum from the model will be equivalent to the spectrum measured from real gearbox, which run in industry condition. It has been found that it very difficult tusk to get such verified model and equivalent vibration signals. It has also found that under condition of varying load as it is described in [4] and [6] the tusk is more even more difficult. To present the problem the study on varying load will be given in the next chapter.

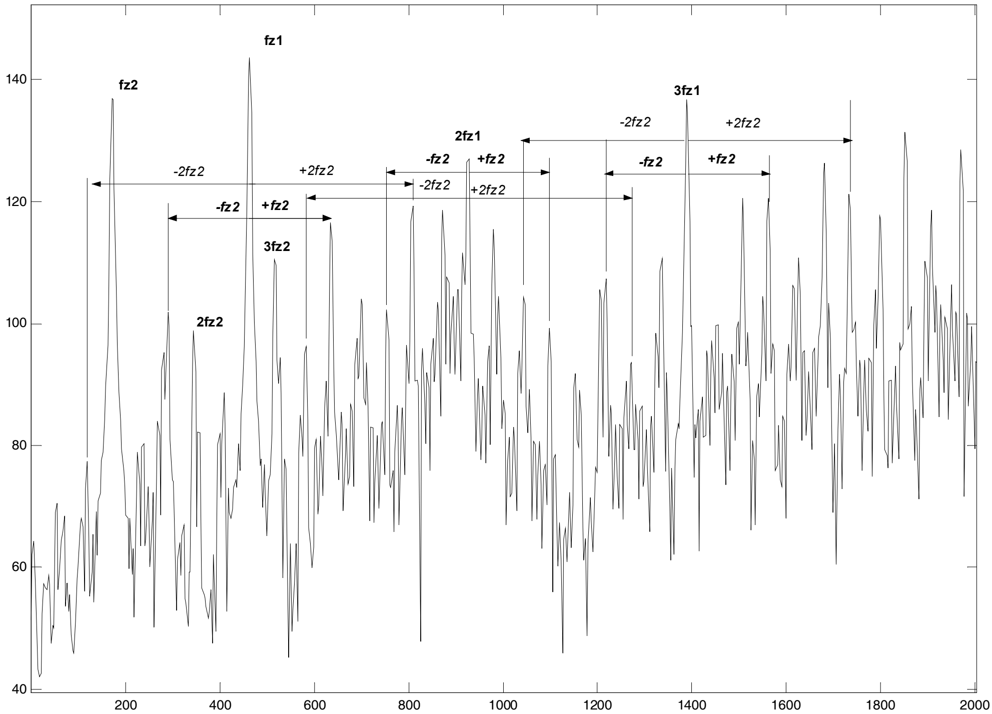

Fig. 1. Vibration spectrum of the signal obtained by computer simulation using the model given in [7]: f_{z1}; $2f_{z1}$; $3f_{z1}$ – meshing frequency and its components for first stage of gearbox and for second stage: f_{z2}; $2f_{z2}$; $3f_{z2}$; modulation components: $-f_{z2}$; $+f_{z2}$ and $-2f_{z2}$; $+2f_{z2}$ [7]

3. VARYING LOAD DESCRIPTION

The influence of external load variation on the vibration signal is illustrated in figure 2 which shows: a) the general electric current consumption, b) the instantaneous electric current consumed by the motor, c) the instantaneous input rotation speed [RPM] (obtained using a tacho signal) and d) the vibration signal.

According to figure 2, in the operating conditions existing during signal acquisition one may get signals with different amplitudes and other properties. Therefore, it is crucial to take into account the operating conditions to extract diagnostic features and also it should be considered during the diagnostic reasoning process.

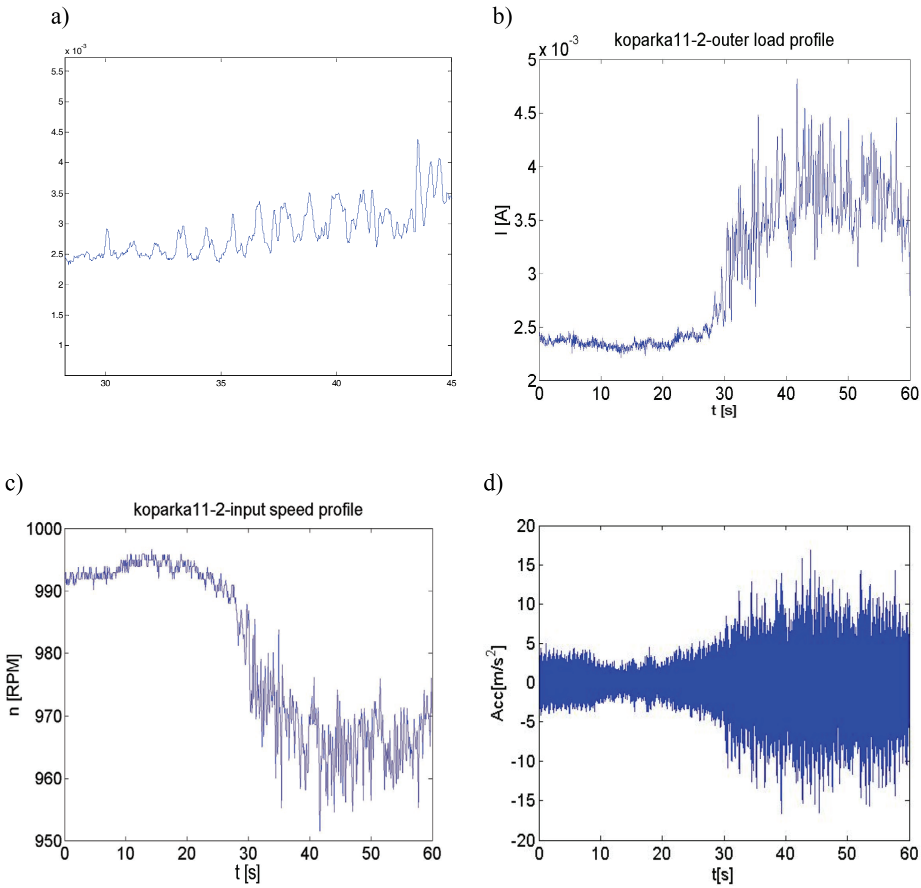

Fig. 2. Variation in: a) general electric current consumption,
b) instantaneous electric current consumption,
c) input shaft rotation speed RPM, d) vibration signal

4. MODEL-BASED FAULT DIAGNOSIS

Model-based fault detection and isolation (FDI) makes use of mathematical models of the gearbox system. According to [2] and [3] model-based fault diagnosis can be defined as the determination of faults of a system from comparison of available system measurements with a priori information represented by the system's mathematical model, through generation of residual quantities and their analysis. A residual is a fault indicator or an accentuating signal, which reflects the faulty situation of the monitored system. A traditional approach [3] to fault diagnosis in the wider application context is based on "hardware (or physical/parallel) redundancy" methods which use multiple lanes of sensors, actuators, computers and software to measure and/or control a particular variable. The major problems encountered with hardware redundancy are extra equipment and maintenance and cost and, further more the additional space required accommodating the equipment.

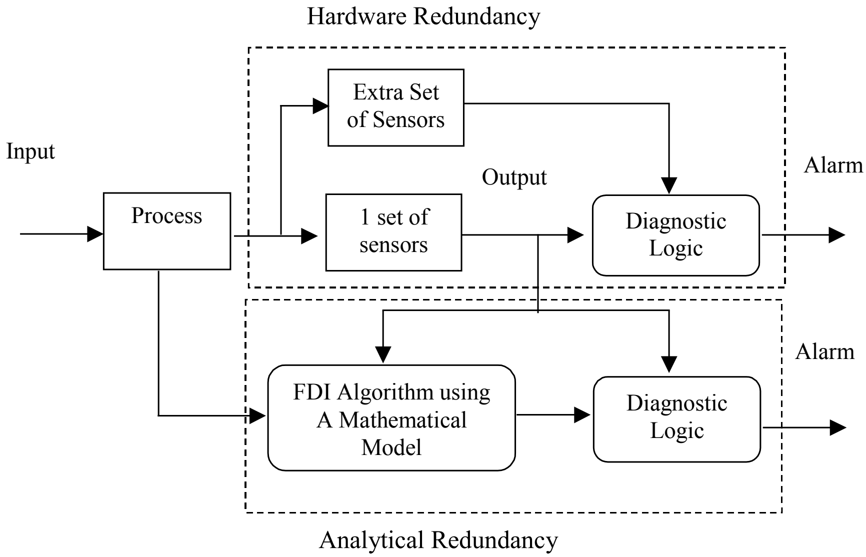

Fig. 3. Hardware vs. analytical redundancy [3]

Figure 3 illustrates the hardware vs. analytical redundancy concepts. No additional hardware faults are introduced into an analytical redundant scheme, because no extra hardware is required, hence analytical redundancy is potentially more reliable than hardware redundancy.

In this paper is given some way of other concept than analytical redundancy, which comes from a new diagnostic approach.

The new diagnostic approach [5] and [6] aims to discover the relation between the operating conditions and the feature for a particular object whose condition is unknown, i.e. to determine the following regression equation for a given data set:

$$Y = ax + b \tag{1}$$

where:

y – the value of the diagnostic feature,

x – the operating conditions (instantaneous speed in this case) indicator,

a, b – the parameters to be determined.

A regression analysis for a limited range of operating speed (linear relation only) is illustrated in figure 4. For example for a planetary gearbox the following regression equations for the load yielding (susceptibility) characteristics of the object in respectively good condition

$$y = -0.12x + 120 \tag{2}$$

and bad condition

$$y = -0.52x + 550 \tag{3}$$

were obtained.

The above two equations gives two models one for the object in good condition and one for the object in bad condition. The models are obtained on the real objects under normal operation of the object. As one can see the models are very simple. The model belongs to one stage planetary gearbox, which is incorporated into the system (Fig. 5). The planetary stage consists of gear marked as z_3, z_4, z_5. The condition of this set of gears is based on a mashing frequency given by a statement

$$f_{34} = f_{45} = \frac{n_{2j} z_3}{60} = \frac{(n_2 - n_j) z_3}{60} \tag{4}$$

where:

n_{2j} – related speed rotation of a shaft which rotates with the speed rotation n_2 [RPM],

n_2 – absolute speed of the second shaft [RPM],

n_j – arm/carrier speed rotation [RPM],

z_3 – number of teeth in gear 3.

To use the above statement one ought have more statements which are connected with the gearbox system given in figure 5. The complete ratio of the system is

$$u_c = u_s u_p u_w \tag{5}$$

The bevel stage ratio equals to

$$u_s = \frac{z_2}{z_1} \tag{6}$$

The planetary gearbox ratio equals to

$$u_p = 1 + \frac{z_5}{z_3} + \frac{z_5 z_z}{z_3 z_6} \tag{7}$$

The cylindrical stage gear ratio equals to

$$u_w = \frac{z_8}{z_9} \tag{8}$$

The arm/carrier speed rotation

$$n_j = \frac{n_2}{u_p} \tag{9}.$$

The considered planetary gearbox has two degree of rotating freedom. It means that gear z_3 and z_5 rotate when the system is in operation. In most cases of planetary gearboxes the gear z_5 is standstill. To diagnose the whole system there is a need to evaluate the models (Fig. 4) for all gear stages (Fig. 5) that are the bevel stage – gears (z_1, z_2), planetary stage – gears (z_3, z_4, z_5), cylindrical stage – gears (z_8, z_9) and the cylindrical stage – gears (z_6, z_7).

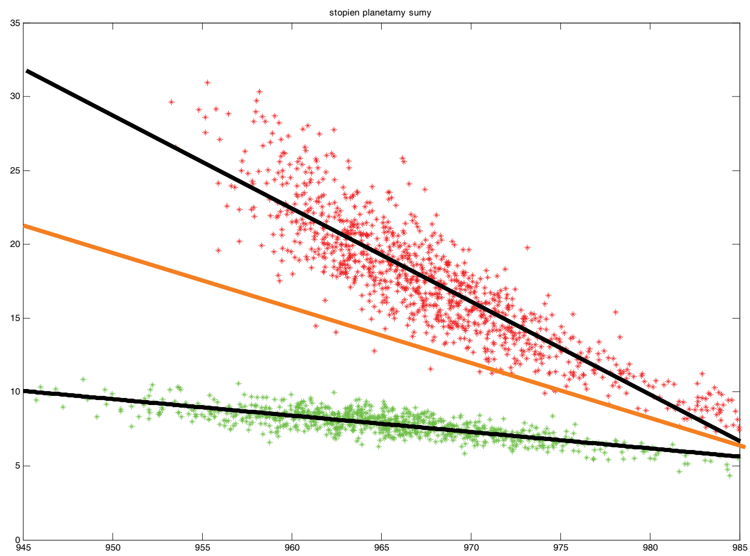

Fig. 4. Statistical regression models for two planetary gearboxes in good and bad condition

The model given in figure 4 (green) is developed after a run in of a gearbox systems. It is postulated that is no need to develop any other model because if we get wrong measurements we do not get a similar linear relation as it is given in figure 4. We do not need to make any simulations using the analytical model. The gearbox model is developed at beginning of using the system from real measurements.

In a gearbox system evaluation one has to consider a degradation model as it is discussed in [10]. It is mostly stated that the change of rolling element bearings condition is caused by faults, which may occur in an inner, outer ring or ball as the primary

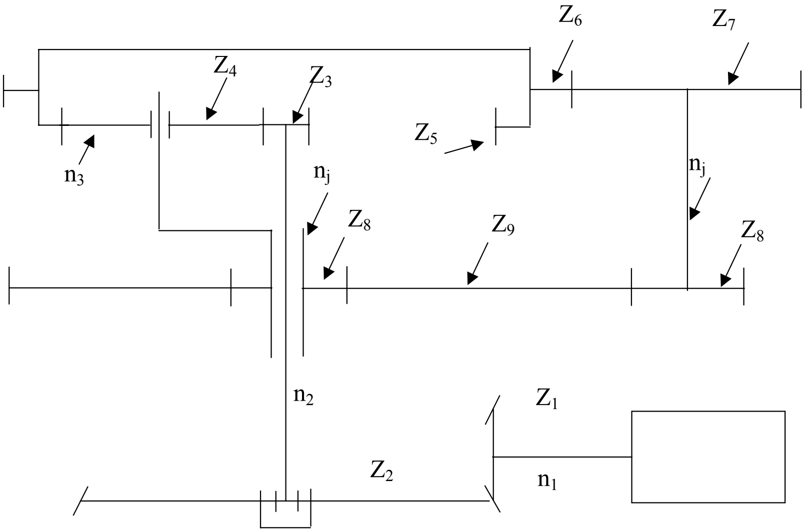

Fig. 5. Bucket wheel driving system

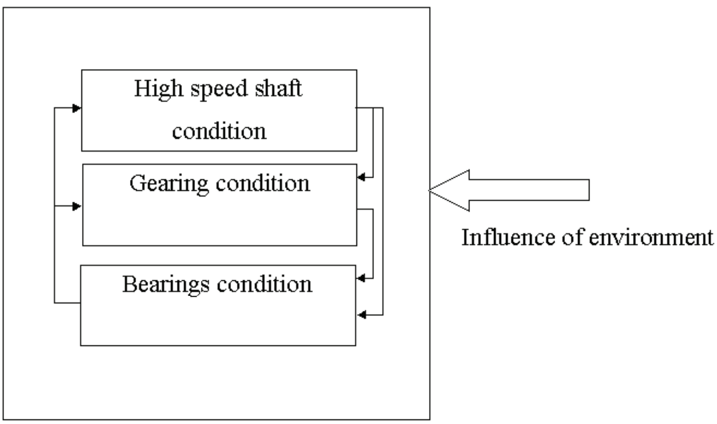

Fig. 6. Interaction of gearbox elements and influence of environment [5]

cause of bearing condition change. In a paper [6] it is stated that the primary cause of bearing condition change and its degradation is caused by the abrasive frictional wear of rolling elements bearings. This type of the fault is not directly measured using vibration signals but it may be inferred as it is given in [6]. Thinking of the degradation model one should take into consideration interaction of the gearbox elements as it is given in figure 6 [5]. The abrasive frictional wear is caused by the influence of an industry environment. That means the influence of fine particles of silica, which get into lubricated oil. Generally, to develop the suitable degradation model one should take in to account all factors which have influence to the vibration diagnostic signals [7, 9]. The proposed model obtained from measurements on the real object gives the model, which incorporates all the factors, which have influence on vibration signals. To detect the faults the suitable regression line should be evaluated as is given in figure 4 (red points). The difference between two regression lines can be expressed by a and b value, statement [1].

5. CONCLUSION

The paper gives new proposal for a gearbox condition model. It is shown that there is no need to use an analytical model of a gearbox. The analytical model is replaced by the gearbox model obtained from measurements on the real object when the one is in good condition after run in.

ACKNOWLEDGMENT

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NIEZAWODNA MECHATRONICZNA METODA MONITOROWANIA DIAGNOSTYKI DLA PRZEKŁADNI ZĘBATYCH

W pracy przedstawiono nowy model, który można wykorzystać dla monitorowania i wykrywania uszkodzeń przekładni zębatych. Należy utworzyć model dla każdego stopnia przekładni. Model otrzymuje w wyniku pomiarów na obiekcie rzeczywistym po dotarciu obiektu. Do określenia modelu wykorzystuje się analizę liniowej regresji. Koncepcja modelu przekładni jest szczególnie przydatna przy zmiennych warunkach obciążenia. Model otrzymano dla przekładni planetarnej, która stanowi zwięzłą całość z innymi stopniami systemu przekładni zębatych składającego się z przekładni stożkowej i przekładni walcowych. Dyskusja pokazuje, możliwość zastąpienia modelu analitycznego modelem fizycznym. Mała złożoność modelu gwarantuje jego niezawodne funkcjonowanie.