Gearbox damage process

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Abstract. The paper summarises the consideration which is based on the former publications presented in MSSP, European Journal of Mechanics - A/Solids, Key Engineering Materials and others published by the author together with his colleagues. Based on the publication, the conclusion is drawn that the gearboxes may be classified as compound or complex and they consist of one or more stages. The stages of complex gearboxes should be properly separated and later the condition of the stages evaluated using the suitable way of condition monitoring and diagnostic inferring. The stages are treated as a separate unit, which consists of gears, bearings and supported structure. For an each gear stage evaluated, it’s characteristics are a relation of the diagnostic feature as the function of an external load. It can also be called the susceptibility characteristic to the external load.

1. Introduction

Gearbox is a system which may appear as a one stage gearbox or as a compound or a combination of compound and complex gearboxes. Most research on the gearbox damage process is done on the one stage gearbox. One stage gearbox system consists of gears, bearings and a case. Till now researches considering the damage process of a gearbox, all the elements treat separately. For example, one may investigate the possibility of monitoring of a rolling element bearing faults by simulating an artificial fault on one element of rolling elements bearing, an inner, outer ring or ball. One may investigate, during condition monitoring, an artificial breakage of a gear tooth. It is the wrong way of investigating of the degradation process and condition monitoring, investigation and assessment of gear faults. It is a fundamental methodology error, because this investigation does not have too much in common with real degradation process. First of all, one ought to treat a gearbox stage as a unit. For this unit, it is a necessary to develop the measure of its condition. The measure should be made under different values of external loads. The measure of one stage gearbox condition appears to be a linear function of applied external load [1]. This measure should be evaluated after a gearbox run in. In the case of the compound or complex gearbox, the measure of condition should be evaluated for each stage of the gearbox, treating the stage as a unit. That means, separately for a cylindrical stage, bevel stage or worm stage if one is considering the compound gearbox. In the case of complex gearboxes, which incorporate planetary stages, one should give more attention to division the system into subsystems and reduce the complex system into the separate stages. An example of a complex gearbox system is given in Fig.1. For each stage, there is a need to evaluate the measure of its condition in the process of a gearbox condition change.
2. Vibration as the measure of gearbox condition

To understand the relation between vibration generated by a gearbox stage and a gearbox stage condition, there is a need to give some consideration if one wants to treat a gearbox stage as a unit. For an effective gearbox diagnostics and condition evaluation, on the basis of vibration signal analysis, it is recommended to consider factors influencing vibration signals. The factors can be divided into four groups, namely: design, production technology, operation, and condition change. The very good illustration of the influence of mentioned factors on gearbox vibration signals is presented by many papers using mathematical modelling and computer simulation. It is presented by the author in papers [2-5]. The paper [5] gives consideration on different gearbox diagnostics methods and how the factor’s considerations show its limitation. It is shown in papers [1] and [6-11] that such operational factor, as a varying external load, needs to be taken into consideration. It is also crucial to take into consideration an environmental factor as harsh environment conditions surrounding the gearbox influence the way of gearbox vibration analysis, [5]. The new feature for monitoring the condition gearboxes in non-stationary operating conditions is presented in [1] [5], [7], [8], [10]. Many factors; influencing gearbox vibration and its use to gearbox condition monitoring is presented in [11]. Special attention is given when a gearbox’s external load is non-stationary, causing non-stationary vibration signals.

As it was mentioned, one can start the factor division [11] from the division of factors influencing diagnostic signals. Any new gearbox can be characterised, from vibration analysis point of view, by primary factors which can be divided into the design and the production technology factors as it is given in Fig.2. When the gearbox is in operation vibration generated by it have influence secondary factors, which can be divided into the operation and the change of condition factors, Fig.2.

Figure.1 Bucked wheel driving system consisting of a bevel stage and a complex gearbox system

Figure.2 Introductory division of factors influencing vibration signals
The design factors are related to new gearboxes that are characterized by the geometrical and the material factors, Fig.3. The macro-geometrical factors give the structural form and the material factors given by the material modules describe properties of a gearbox/object, Fig.3. When the object is exited by a force impulse, described by delta function, the excitation reveals the structural form dynamic properties. When describing the macro-geometrical factors by examining of the response of the structural form, one ought to take into consideration the stiffness factors, described as the constant or variable, Fig.3. As one considers the outer structure form (housing), it may be stated that it has constant stiffness properties. But when one takes into consideration the gearing and rolling element bearings, one ought to be conscious of variable stiffness properties that change the system from linear to nonlinear. The structure form is also characterized by the unperfections described by the dimension and shape deviations. Important factors describing the design of gearboxes are the numbers of the gear teeth and the rolling element bearing parameters given by the number of rolling elements, a mean dimension of a bearing. The micro-geometrical factors are described by the suffice roughness parameters. The material factors are described by it’s constant and variable properties. The constant properties are described by material constants such as the stiffness and non-dilatational E and G modulus. Material properties should be extended by the lubricated oil properties. The primary factors have also incorporate the production technology factors caused by not fulfilling of the design specification during the production and an improper assembly, Fig.3. All the factors mentioned above have the influence on dynamic properties when the described system is under influence of the
secondary operation factors when joint influence of the operation, change of condition and environment factors, when the object is in operation for some period of time, is considered, Fig.4. The environment factors are described by the dustiness, humidity, and temperature. The operation factors are characterized by the load and rotation velocity. The load is described as the periodic and not periodic variable or the constant or slow variable. Also, the rotation velocity can be described as the constant or variable. The condition change factors are characterized by the abrasive frictional wear; the distributed and local faults. The abrasive frictional wear causes the element misalignment and impulsive interaction. The distributed faults are caused by: pitting, scuffing, erosion. The local faults are caused by the crack, breakage and spalling, or the chipping.

There have been many methods developed to detect gearbox faults by treating each fault separately, as presented in [13] to [14], but influence of varying load is not considered in these papers. On the basis of the above consideration, one can develop vibration signal properties that lead to the way of choice of vibration signal analysis, the gearbox degradation scenario, and the condition inferring process. The stages of complex gearboxes, as is given in Fig.1, should be properly separated.

The example of a diagnosed heavy machinery object is a complex multistage gearbox used in the drive unit of a bucket wheel excavator given in Fig.1. The condition monitoring for the system is given in papers [1] and [7] to [10]. The system consists of a bevel stage, gear $z_1$ and $z_2$, 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

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

where:

- $n_{2j}$ – related to an arm speed rotation of a gear $z_3$ [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 Fig.1. The complete ratio of the system is

$$u_c = u_uu_p$$

The bevel stage ratio equals to

$$u_u = \frac{z_2}{z_1}$$

The planetary gearbox ratio equals to

$$u_p = 1 + \frac{z_5}{z_3} + \frac{z_5z_6}{z_3z_6}$$

This ratio is developed for the complex gearbox on condition that the two pinions $z_8$ rotate with $n_j$ RPM

The cylindrical stage gear ratio equals to

$$u_w = \frac{z_0}{z_8}$$

The arm/carrier speed rotation

$$n_j = \frac{n_2}{u_p}$$
Beside the planetary stage in the system given in Fig.1 one can recognise, a bevel stage with gears $z_1$ and $z_2$ for which a meshing frequency is

$$f_{12} = \frac{n_1 z_1}{60}$$

(7).

A meshing frequency for the cylindrical stage with gears $z_6$ and $z_7$ is

$$f_{67} = \frac{n_6 z_7}{60}$$

(8)

and for the cylindrical stage with gears $z_8$ and $z_9$ is

$$f_{89} = \frac{n_8 z_9}{60}$$

(9).

Summing up, one can see the bevel stage with the meshing frequency given by (7), the planetary stage with the meshing frequency given by (1), cylindrical stage (gears $z_6$ and $z_7$) with the meshing frequency given by (8), and second cylindrical stage (gears $z_8$ and $z_9$) the meshing frequency given by (9). So for condition assessment of the system given in Fig.1 there is a need to assess four gear stages.

3. Description of gearbox degradation

As it was stated in introduction, the most common assumption is that only one fault occurs in the diagnosed object, [14] to [15]. So the degradation is thought as a development of one fault in the object. This assumption hardly ever occurs in industrial condition. It is mostly stated that the change of rolling element bearings condition is caused by a fault, which may occur in an inner, outer ring or ball as the primary cause of bearing condition change. In a paper [1] it is stated that the primary cause of bearing condition change and its degradation is due to the abrasive frictional wear of rolling elements bearings. This type of fault is not directly measured using vibration signals but it may be inferred as it is given in [1]. Thinking of the degradation/damage process, one should take into consideration interaction of the gearbox elements as it is given in Fig.5, [6]. The abrasive frictional wear is caused by the influence of the dusty industrial environment, which means the influence of fine particles, mostly of silica, that get into lubricated oil. Generally, to develop the suitable condition monitoring and diagnostic method there is a need to see the gearbox and its stages in the whole system as it is given in Fig.6, [7].

![Figure.5 Interaction of gearbox elements and influence of environment [6]](image-url)
In [1] and [8] results are given which show that with the change of planetary gearbox condition, the diagnostic features increased according to regression function as is given in (Fig.7), [1] and so is shown in [8] using computer simulations for a one stage from a double stage gearbox and for a planetary gearbox.

![Figure 6](image1.png)

**Figure. 6** The whole system elements interaction [6]

The diagnostic features are presented as a function of an input shaft rotation RPM. In this case the diagnostic features are negatively correlated with rotation speed.

![Figure 7](image2.png)

**Figure. 7** Load susceptibility/yielding characteristic as diagnostic features for planetary gearbox as a function of rotation speed RPM; for a gearbox in good (“o” dots) and bad condition (“x” dots) [1]

It comes directly from an electric motor characteristic given in Fig.8, in which one see that with the increase of the load/moment decrease the rotation (RPM) and vice versa with the increase of rotation the load/moment decrease. This mentioned rule holds for a part of a motor characteristic under normal operation of a motor, when rotation speed vary from $\omega_1$ to $\omega_2$ rad/s or in equivalent values $n_1$ to $n_3$ RPM.
Fig. 7. shows a linear regression model for the gearbox stage in good and bad condition. This model is used in [12] for developing the robust mechatronic condition monitoring and diagnostic method for gearbox stages.

| Gearbox stage |
|---------------|
| **System of elements** |
| {electric engine, coupling or input shaft}, gears, bearings, |
| {output shaft, coupling, driven machine} |
| **Factors influencing vibration** |
| design, production technology, operation, condition change |
| **Scenario of degradation** |
| interaction of gearbox elements, environment |
| **Condition physical description** |
| unbalance, misalignment, pitting, scuffing, fracture, increase |
| of rolling element bearing backlash |
| **Mental transformation** |
| local faults, distributed faults |
| **Signal analysis tools** |
| spectrum, load yielding characteristic |
| **Inferring** |
| gear condition |

**Figure.9** Scheme of elements of vibration gearbox stage diagnostic method

To understand the gear stage degradation, it is good to consider the scheme presented in Fig. 9.
In Fig. 7, universal characteristics are given for a planetary stage from the system presented in Fig. 1. There are two linear characteristics given, which describe the planetary stage in two conditions; good and bad. The characteristics describe the stage as a unit, which means condition of gears, bearings and bearing supported structure. To assess the whole system, in Fig. 1, there is a need to estimate condition of all stages of which the system consists: the bevel stage with the meshing frequency given by (7), the planetary stage with the meshing frequency given by (1), cylindrical stage (gears \( z_6 \) and \( z_7 \)) with the meshing frequency given by (8), and second cylindrical stage (gears \( z_8 \) and \( z_9 \)) and the meshing frequency given by (9). As it is postulated, the load susceptibility/yielding characteristics, as diagnostic features, give estimation of the whole stage: gears, bearings and bearing supported structure. There are different bearing faults, which cause the change of the load susceptibility/yielding characteristics. One of them is sliding wear of a bearing elements at it is the case which occurs in the case of the system given in Fig. 1 where after disassembling of the system in bad condition all bearings show over limited backlash, which causes the change of condition for all gear stages. For the planetary stage in Fig.7, the change is seen in the load susceptibility/yielding characteristics from good to bad. In this case, there is not the other way of evaluating the occurred backlash using vibration signal. In the case of local faults occurring in rolling element bearings, one can evaluate them using the way described in [9] or [14], [15].

4. Conclusion

The paper’s effort is to stress that when describing the gearbox degradation process, one should take into account the complete object properties. The completeness of the object description is based on factor analysis namely on: design, production technology, operation, change of condition factors. The susceptibility/yielding characteristics for a given stage are shown, and as they change, the given gear stage undergoes the degradation process. These characteristics are the universal quality measures of a gearbox stage. They can be evaluated at any time of the gearbox life.

All presented relations of the diagnostic feature - load or diagnostic feature - rotation speed/frequency are linear. Therefore, based on the results obtained in [1] and results of computer simulations [8], one can come to conclusion that the reason of gearboxes’ bad condition is the increased uneven backlash in rolling element bearings, which causes misaligned gear teeth cooperation. It can be also inferred that after prolonged gear cooperation in the condition of teeth misalignment, one may expect change of the gearbox condition in form of pitting or in other form, which causes distributed faults as the result of inner overload and causes the gear cooperating characteristics to modify, as described in [8].

Acknowledgment

This paper was financially supported by Polish State Committee for Scientific research 2010-2013, no.N504 147838

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