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STATISTICAL FEATURE ESTIMATIONS OF THE PROCESS DESCRIBING OBJECT CONDITION CHANGE FOR MAINTENANCE DECISION

The papers shows the two ways of condition assessment of two objects which are in two different conditions. One way based on tradition assessment show difficulties in proper differentiation of two object conditions. Second new way shows the solution for proper object condition assessment. The paper shows that at the base of any object condition assessment is factor analysis of design, production technology, operation and change of condition.

1. INTRODUCTION TO ESTIMATION

Before I start let me define some basic terms. First let me define the term statistical estimation, which comes from estimation theory.

Estimation theory is a branch of statistics and signal processing that deals with estimating the values of parameters based on measured/empirical data. The parameters describe an underlying physical setting in such a way that the value of the parameters affects/imitates the distribution of the measured data. An estimator attempts to approximate the unknown parameters using the measurements. It includes: point estimation, interval estimation, hypothesis testing or statistical significance testing. In estimation theory, it is assumed that the desired information is embedded in a noisy signal. Noise adds uncertainty, without which the problem would be deterministic and estimation would not be needed. Statistics is a mathematical science relates to the collection, analysis, interpretation or explanation, and presentation of data. It also pro-

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vides tools for prediction and forecasting based on data. It is applicable to a wide variety of academic disciplines. Statistical methods can be used to summarize or describe a collection of data. In the described case object condition change the measured data have statistical properties it comes from the possible object behavior as condition of object change. Using the statistical values representing the measured data one should infer the object condition. So statistical feature estimations of the process describing object condition change for maintenance decision is discussed in the paper.

The decision is based on inferring process. Inference is the act or process of deriving a conclusion based solely on what one knows. Inference is studied within several different fields. Statisticians have developed formal rules for inference (statistical inference) from quantitative data. Artificial intelligence researchers develop automated inference systems. Statistical inference is inference about a population from a random sample drawn from it or, more generally, about a random process from its observed behavior during a finite period of time. In the presented case the inferring process is also based on knowledge which comes from factors analysis [1], which have influence to measured values, in this case vibration signals. Because of statistical nature of the signal statistical inference will support the decision.

2. INTRODUCTION TO DATA ANALYSIS

Data are obtained from measurements. The measured value is acceleration [m/s^2] as a course of time [s]. An example of such a course is given in Fig. 1, such course is called as the signal. Because it is the acceleration signal course it may be also called the vibration signal. To get some knowledge from the signal it is a need to make signal analysis. Many tools may be used for the signal analysis. One may also measure others values, which are connected with the object operation. Some other values are given in Fig. 2.

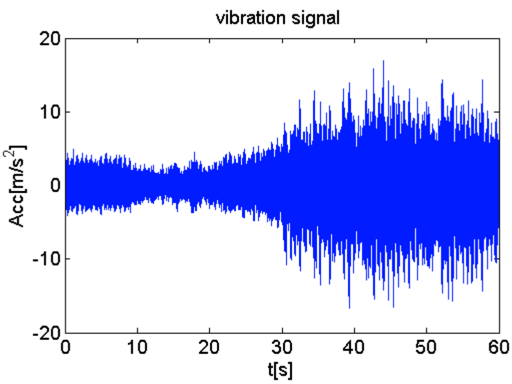


Fig. 1. Course of acceleration signal

a) b)

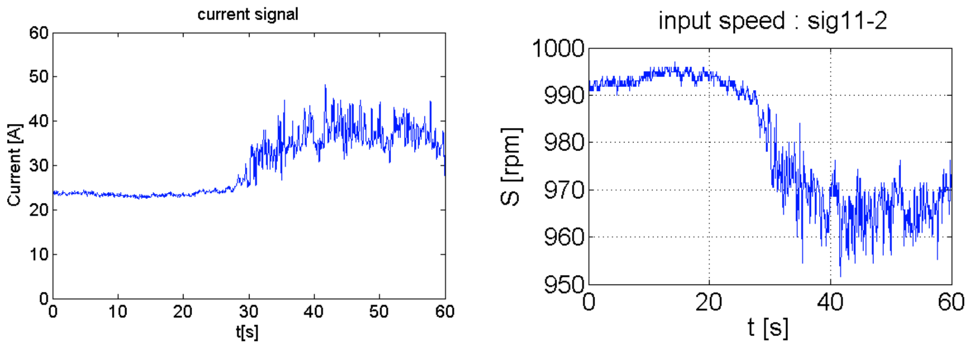


Fig. 2. Values variation as function of time [s]: a) instantaneous electric current consumption in [A], b) instantaneous input shaft rotational speed [RPM]

To start signal analysis one should take into account many factors as it is stated in [1] these factors can be divided into four groups namely: design, technology/manufacture, operation, change of condition, Fig. 3. To consider the design factors one should examine the diagnosed object specification.

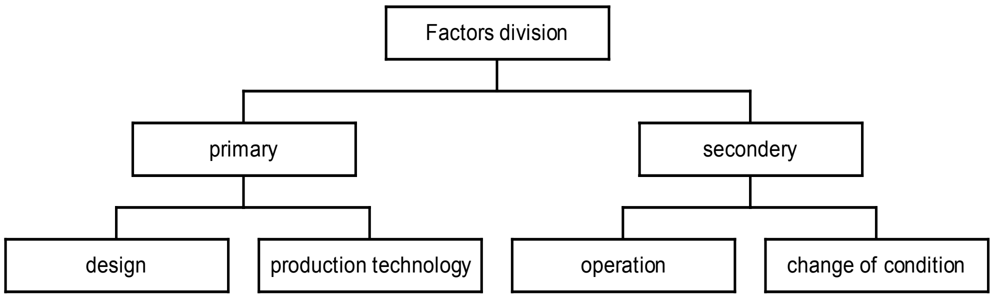


Fig. 3. Introductory division of factors influencing vibration signals

3. OBJECT AND SIGNAL PRESENTATION

The diagnosed object is a multistage gearbox used in the drive unit of a bucket wheel excavator (Fig. 4). In considered case the gearbox design is unique and complex. Because of the high power and small size requirements the designer decided to use power sharing (50% of the power goes through gear wheels z_3–z_5 to the first pinion z_8 while the other 50% goes through gears z_6 and z_7 to the second pinion z_8). In the descried case the diagnostic task is to diagnose the condition of the gearbox second stage, namely a planetary stage with a meshing frequency (in this case) of 99.9 Hz for geared wheels z_3–z_5.

a) b)

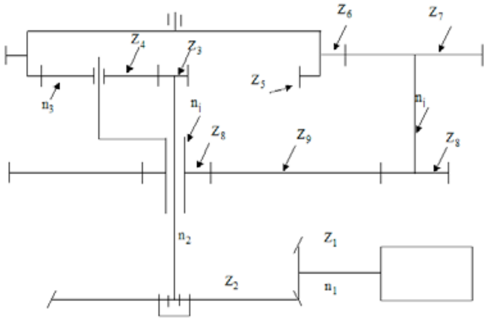


Fig. 4. Diagnosed object: a) scheme of gearbox, b) view of machine

The bucket wheel excavator's primary task is to dig the ground (overburden and lignite) and transport it to a conveyor system. Because of the varying properties of the excavated ground and the manual control, the machine operates in a wide range of non-stationary operating conditions. This can be referred to as general variation in operating conditions. There is also cyclic variation in operating conditions, which is connected with the nature of the digging process [2] and the design of the bucket wheel excavator. The distinction between general and cyclic variation in operating conditions is crucial for this machine: the general variation in operating conditions defines the range/level of external load while the cyclic variation in operating conditions is used (because of its cyclic nature) as the basis for signal segmentation In the considered case, the bucket digging cycle is $T_b \approx 1$ s. A time fragment of a chart showing electric current consumption variation with period $T_b \approx 1$s is presented in Fig. 5a). The current consumption is proportional to the load and the level of load changes slowly. The spectrum of the current envelope is shown in Fig. 4b, where a dominant component is visible at a frequency of ~1 Hz, which is equivalent to digging frequency f_b and bucket digging cycle $T_b \approx 1$ s.

In paper [3] the hypothesis is given that there is a linear dependence between the external load and the vibration parameter/feature representing the gear condition was formulated. At the time when the paper was published there was no possibility to fully test out the hypothesis. The latter applies to two-stage gearboxes operating in mining transportation systems (belt conveyors) [3].

For other "mining" (mainly planetary) gearboxes the nature of factors like: the external load dependence and the influence of load variation on the vibration signal was studied in previous works [4]. The influence of external load variation on the different parameters and the vibration signal over time is illustrated in Figs. 1 and 2, which show the vibration signal in the form of acceleration [m/s^2] and in Fig. 2a) the instantaneous electric current consumed by the motor in [A], b) the instantaneous input rotational speed [RPM] (obtained using a tacho signal).

According to Fig. 1 and 2, in the operating conditions existing during signal acquisition one may get signals with different amplitudes and properties. Therefore it is crucial to take into account the operating conditions to extract diagnostic features and also during the diagnostic reasoning process.

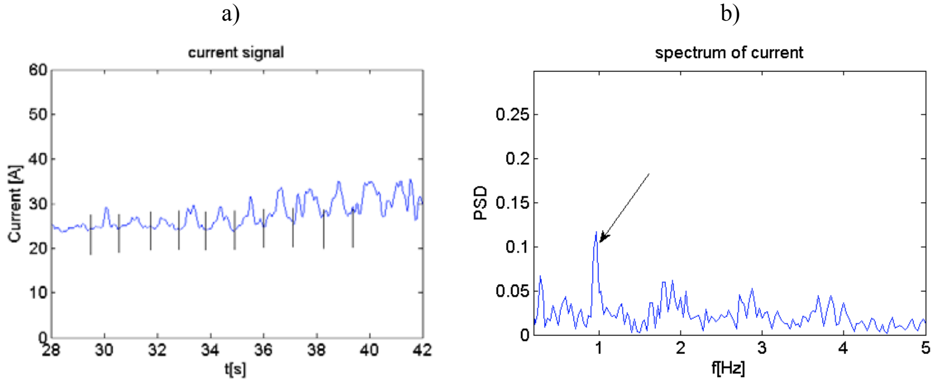


Fig. 5. Time fragment of electric current consumption (a) and its spectrum (b)

4. DATA PRESENTATION

As underlined in the previous chapter, considering the wide variation in operating conditions and the dependence between the operating conditions and the diagnostic features, there is a need to take the operating conditions (operation factors [1]) into account during the reasoning process (Fig. 3). If the operating conditions are neglected, one may obtain an unclear basis for diagnostic decision taking due to the crossing effect between the good condition and the bad one on a diagnostic feature distribution map (Fig. 6) for two gearboxes when one is in good condition (the distribution marked with circles) and one is in bad condition (the distribution marked with stars). Figure 6 shows distributions of features (Figs. 6a and c) and the probability of occurrence of the vibration diagnostic features (Figs. 6b and d) for many sets of 60 s measurements.

The vibration diagnostic feature is the sum of 10 amplitudes of the meshing components from the short time acceleration spectrum, where the (1 s) period is equivalent to the digging period. Figures 6a and b show all the data, whereas Figs. 6c and d show the data after the data for the starting and idle operation of the bucket wheel excavator have been rejected. Fig. 6d shows that the distributions of the features still overlap each other after the data selection. According to Figures 1 and 2, there is a dependence between the operating conditions indicator (load, rotational speed) and the vibration amplitude, which is positive for the current consumed by the motor and negative for the instantaneous speed.

As already mentioned, the sum of 10 amplitudes of the meshing components in the spectrum is used as the diagnostic feature describing the condition of the planetary stage. One should note that because of speed variation an order spectrum was calculated to avoid the smearing effect [5]. The data (speed profile calculation, signal segmentation, operating conditions parameterisation, etc.) preparation stage is described in previous papers [6, 7].

To obtain suitable sets of measurement values several actions have been undertaken. In Figure 6a) are gathered all values of measurements for two objects; one which is expected to be in good condition marked by a circle and second, which is expected to be in bad condition marked by a star. On the base of the measurements probability of occurrence has been counted and the results are plotted in Fig. 6b. For the results critical analysis is given. And is concluded that in the plot there given results on which have influence different phenomena, and the data presentation should be improved. For the proper data classification should be known some classification criteria for data different phenomena separation. The data which were measured for unloaded machine were rejected. The data after suitable classification are presented in figures 6c) and d). Figures 6a) and b) gives more clear statistical data description/presentation. Under normal statistical analysis one may calculate a mean value and standard deviation for the analysed data. To make machine condition assessment one make take the difference of two mean values. When comparing the means of two samples, the null hypothesis is that there is no difference between the population means, while the alternative hypothesis is that there is a difference between the population means. A difference between two means could be signal-sided that $\mu_1 < \mu_2$ or $\mu_2 > \mu_1$. As it seen from Fig. 6 that data from two objects overlap each other. Further normal practice is to assess confidence intervals for evaluated means value. From the Fig. 6 one may say in advance that for the two sets of data the confidence intervals are different, standard deviations are different and they grow as the sate/condition is worsen. That cause that is difficult to make assessment of object condition. One may stated that simple statistical analysis do not give the good solution for the object condition assessment. If one look at data distributions it is seen that the standards deviations for two sets are obviously different and situations seems to be not normal. We may expect that the standard deviation of the data for the object in the bad condition is grater in comparing to the data in good condition but the difference in the standard deviations seems to be not normal. Concluding, there should be the factor, which cause that unexpected situation. One may expect that between two object conditions there is a big difference so there is a need to find another way of data analysis to show the clear difference between two object conditions. This new way is given in [9].

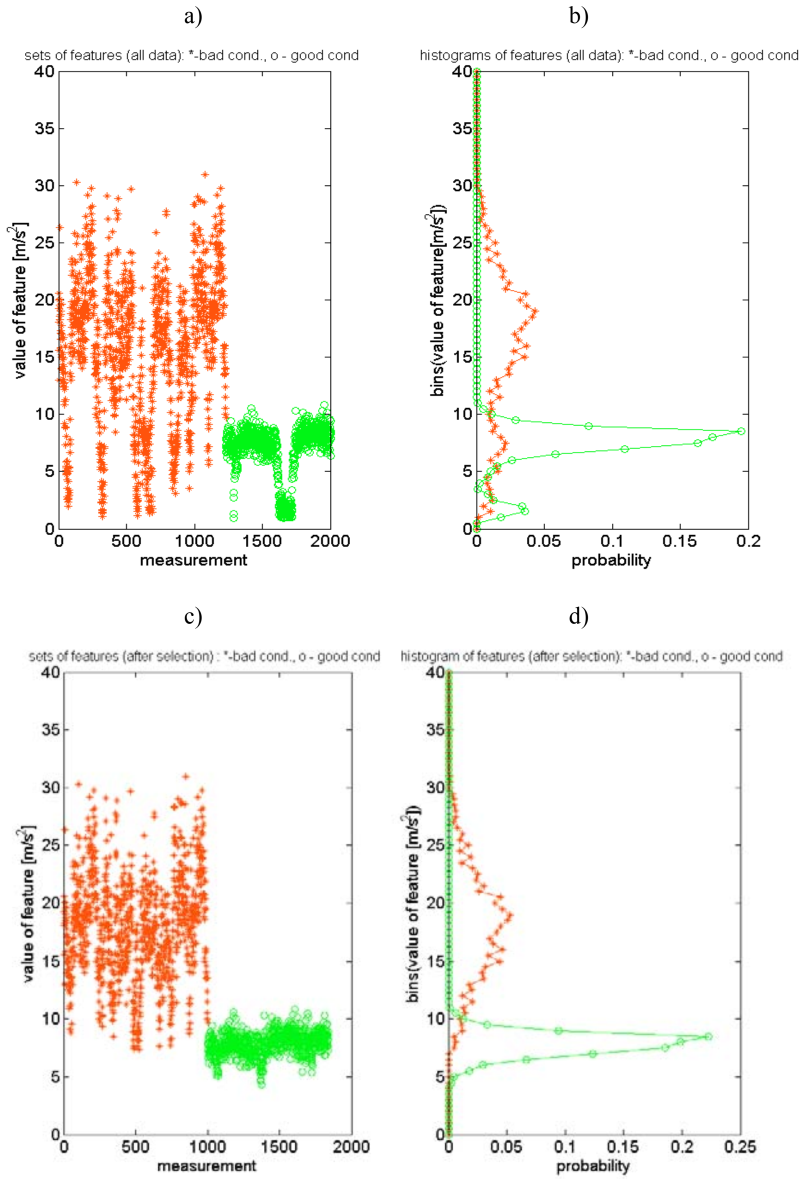


Fig. 6. Probability of feature distributions for two diagnosed objects: circle marked distribution for object in good condition and star marked distribution for object in bad condition; a) for all measurements b) for measurements with properly loaded gearboxes

5. FACTOR AND STATISTICAL ANALYSIS

As described in [4], the relation between the operating conditions and the signal amplitude depends on the condition of the gearbox. In [4], the load susceptibility of the machine was suggested as the basis for diagnostics. It was found there that the acceleration signal envelope is proportional to load variation for the gearbox in bad condition (before replacement) and for the gearbox in good condition (after replacement). The acceleration signal envelope shows deeper amplitude modulation for the gearbox in bad condition than for the gearbox in good condition. According to [4], the deeper amplitude modulation is due to the greater load susceptibility of the gearbox. As an extension of the approach given in [4] according to [9] a new feature-being the sum of 10 amplitudes of the meshing components from a short time spectrum equivalent to bucket period $T_b \approx 1$s of the rotation tracked signal – is proposed. To clarify the a way of finding the new feature there have been done computer simulations for generation vibration signals when a gearbox is loaded by two different value of loads. The results are given in Figs. 7 and 8. In Figure 7 one can see time course acceleration signals but in Fig. 8 one can see its spectrums with meshing components from the sum of ten components diagnostic feature values are assessed. The calculated features are represented as a points (stars or circles) in Figs. 6 or 9 but for real signals not for simulated signals.

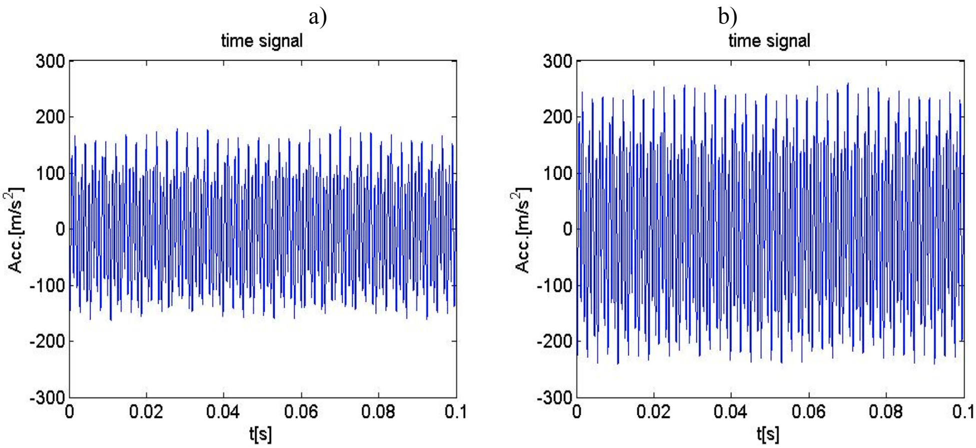


Fig. 7. Results of simulation: acceleration signal for:
a) e = 20 um, L = 1.0 b) e = 30 um, L = 1.0

Also for industrial measurements from the segments of time signal a frequency analysis where done, which examples are given in Fig. 9. From the sum of 10 amplitude frequency components a measure of machine part condition (MPC) is defined.

a) b)

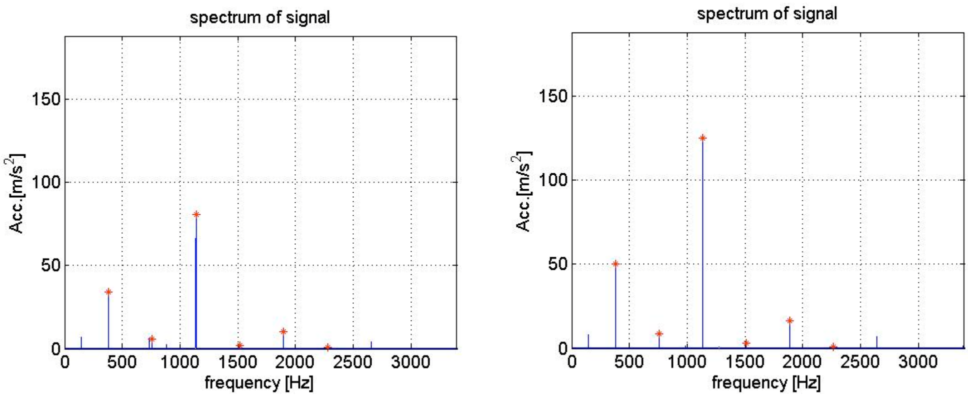


Fig. 8. Spectra of simulated signals:
a) e = 20 um, L = 1.0, b) e = 30 um L = 1.0

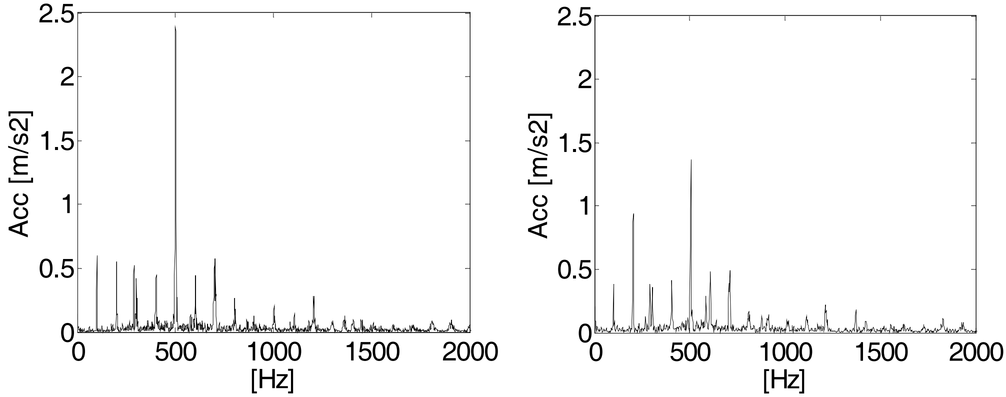


Fig. 9. Examples of segment frequency analysis

Figure 10a) shows feature distributions for bad (stars) and good (circles) condition as a function of instantaneous speed for the full range of operating speed. Each plot point marked with a star or a circle is determined from the ten components obtained from a signal spectrum analysis. The harsh environment in which the gearbox operates is the factor [1] which can change its condition. The change is caused by the abrasive frictional wear of the components, especially the rolling bearings. Therefore one should take the following into consideration:

- The operating time is about 10 000 h for the gearbox in good condition and about 20000h for the gearbox in bad condition.

- It is recommended that after dismantling a gearbox which has been in operation for 20 000 h:
  – all the rolling bearings with exceeded allowable radial backlash are replaced by new ones,
  – almost all the gears (scuffs and micro-cracks occur on the teeth) are improved by grinding.

As mentioned earlier, a gearbox in bad condition is more susceptible to load than the gearbox in good condition. The degree of this susceptibility is the new gearbox condition feature. The diagnostic feature calculation procedure is automated.

The new diagnostic approach 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:

$$y = ax + b$$

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 (the expected linear relation only) is illustrated in Fig. 9b. The part of the plot whose diagnostic features would be sought as equivalent to small load has been removed. Ultimately, the following regression equations for the load yielding (susceptibility) characteristics of the object in respectively good condition

$$y = -0.12x + 120$$

and bad condition

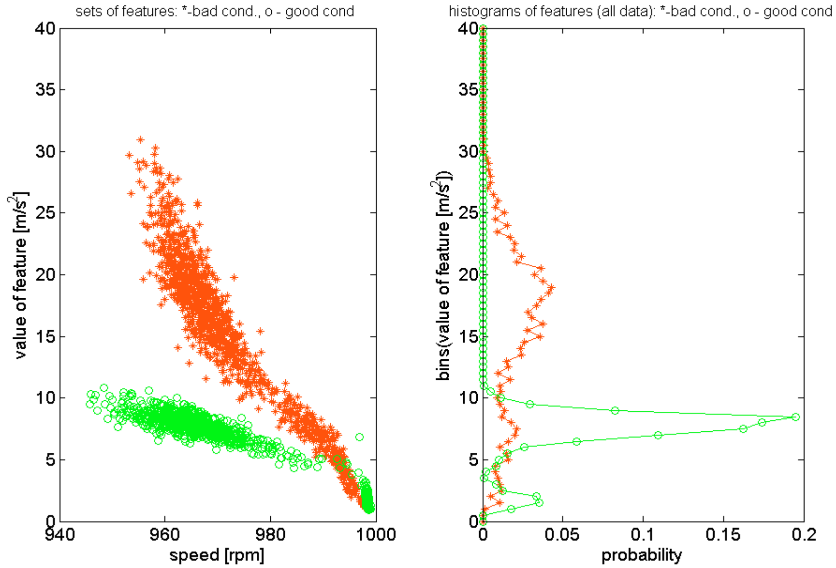
$$y = -0.52x + 550$$

were obtained.

In order to describe the quality of the regression, classic parameter R^2 was used as the indicator of the fitting of the calculated curve equation to the set of data. It should be noted that $R^2\_{\text{GOOD}} = 80\%$ and $R^2\_{\text{BAD}} = 83.3\%$.

Parameters "*a*" and "*b*" are proposed as the measure of machine condition. If one considers that for different machine conditions for the small load case the amplitudes of the vibration signals are very similar (i.e. the curves describing the conditions of the object have a common point), there is theoretically no need to use "a" and "b" simultaneously since the information would be considered redundant. In order to notice any difference in gearbox condition is better to illustrate the whole function. When examining the regression line, one may decide to estimate the nonlinear regression.

a)



b)

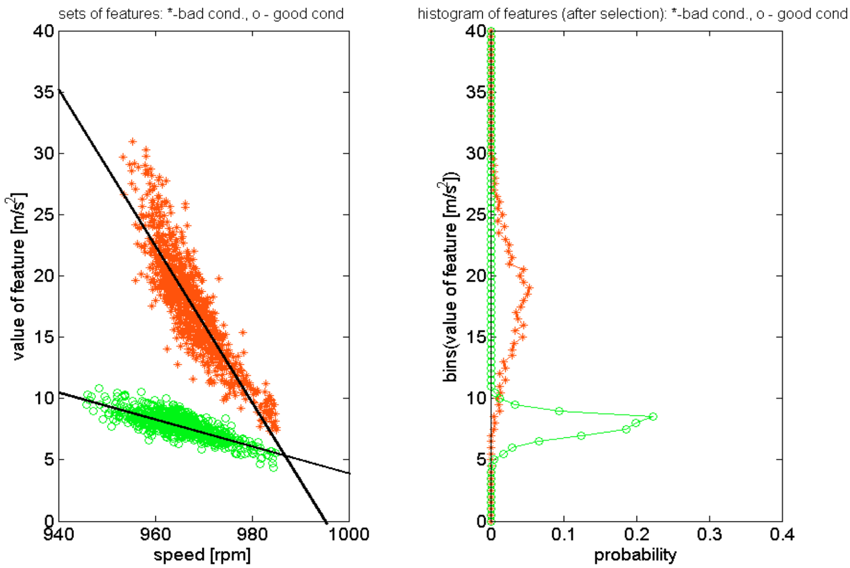


Fig. 10. Distribution of features for bad (stars) and good (circles) condition as function of instantaneous speed and its probability: a) full range of operating speed, b) limited range of operating speed for properly loaded gearboxes (linear relation only)

The fact that scuffs and micro-cracks are found on the teeth in gearboxes being in bad condition shows that operation of gears under increased rolling element bearing backlash causes changes in tooth surface condition. Thus no linear regression can be expected. This problem requires further research.

Figure 10 shows how the data for two gearbox condition cases can be present and to obtain the clear difference for two different gearbox condition cases. The kea for data separation for two different condition is factor analysis. In this case the factor analysis led to that, that in data presentation influence of varying load should be explored. In Figure 10 the diagnostic features are presented as a function of input shaft rotation RPM. In this case the diagnostic features are negatively correlated with rotation. It comes directly from an electric motor characteristic given in Fig. 11 in which one see that with increase of the load/moment decrease the rotation (RPM) and vice verse with the increase of rotation the load/moment decrease.

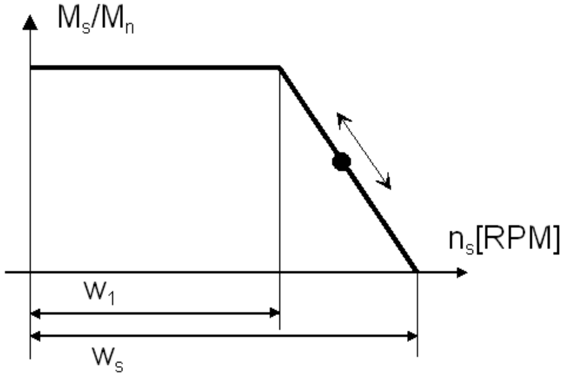


Fig. 11. Electric motor characteristic; M [Nm], W [rad/s], n_s [RPM]

6. CONCLUSIONS

The papers gives the evidence that tradition statistical analysis does not give a good assessment of object/gearbox condition deference if one tries make the condition assessment on the two sets of measurements, which belongs to two objects and they are in very different condition. Finding in tradition way the basic statistical parameters as a mean value and standard deviation one does not get good parameters for showing the difference in an object condition. Only factor analysis, which leads to root cause analysis together with proper signal analysis, which comes from the former analysis gives successful results.

So a new approach to the condition monitoring of the planetary gearbox working under time varying load has been presented. Load susceptibility is used as the measure of gearbox condition, instantaneous input speed is the indicator of the operating conditions and the parameter describing the sum of vibration meshing component amplitudes related to the analysed gearbox stage is the indicator of the diagnostic feature. It is the clear evidence that the operating condition should be taken into consideration.

A diagnostic decision can be taken on the basis of the parameters obtained from the regression procedure. From the classical spectral based feature versus the operating conditions indicator it follows that this relation is linear in a limited range of operating conditions.

It was shown that for a gearbox in good condition the dependence between the instantaneous input speed and the diagnostic feature is characterized by a small inclination of the regression line described by parameter "*a*". As the condition changes, "*a*" increases. The difference was found by analysing the results of the calculation of the regression equation parameters for the data sets.

If the relation between load and rotational speed is linear, considering that the relation between rotational speed and the diagnostic feature was proved to be linear with negative "*a*", the relation between load and the diagnostic feature is also linear, but with positive "*a*".

The obtained results of leaner regression shows the model for machine in good and bad condition. One can make general statement that if the object is in good condition it shows a small load susceptibility and as the gearbox change the condition the load susceptibility increases.

The author and a few other researchers, e.g. [8], emphasize that the diagnosis of machines without properly taking into account the external load represents a wrong approach. The obtained distributions of features for good and bad condition unequivocally confirm the above statement. For no load/small load cases the recognition of different technical states is very difficult or impossible.

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ESTYMACJA CECH PROCESU OPISUJĄCEGO ZMIANY STANU OBIEKTU W CELU PODJĘCIA DECYZJI EKSPLOATACYJNEJ

W pracy przedstawiono dwa sposoby oceny stanu dla dwóch obiektów znajdujących się w różnych stanach technicznych. Stosując tradycyjny sposób oceny stanu technicznego napotkano na trudności w ocenie różnic między stanami. Drugi nowy sposób pokazał że istnieje możliwość lepszego rozróżniania stanów. Praca przedstawia, że u podstawy każdego sposobu oceny stanu technicznego powinna się znajdować analiza czynników konstrukcyjnych, produkcyjnych, operacyjnych i zmiana stanu technicznego.