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# RESEARCH ON SYMPTOM SENSITIVITY OF A MECHANICAL SYSTEM STATE IN ORGANIC DUST CONDITIONS

Zbigniew Burski∗, Joanna Tarasińska∗∗

∗Department of Vehicles and Engines,

∗∗Department of Applied Mathematics

Agricultural University of Lublin, Poland

**Summary**. The paper presents the analysis of influence of chosen exploitation and environmental factors (oil polluted by organic dustiness among others) on the vibrations of a cylinder sleeve in the S-4002/3 engine. The following parameters of the vibration spectrum were analysed: the average level of vibrations, the maximum level of vibrations, the frequency of the maximum vibration level and the average frequency.

**Key words:** mechanical system, exploitation, diesel engine, organic dust

## INTRODUCTION

Working environment has a significant influence on the intensity of wear in engine units of industrial machines and vehicles and the research area presented in this paper concentrates on an increased dust level effect. As can be seen in literature concerned with this issue, in the final years of the 20th century that was the basic problem of the exploitation investigations home and abroad [Baczewski *et al.* 1977, Cieślikowski 1996, Dziubak and Tylicki 1998]. Those researches are now being continued [Burski *et al.* 2002, Cieślikowski 1994, 1996a, b, Dziubak and Tylicki 2000], as they are indispensable for the efficiency of air filters construction, their usefulness and optimisation of periodic service terms. An evaluation of air dust effect on the kinematics pair friction and the consequences of its dynamic influence are seen as less significant. Most research concerns inorganic dust due to a more intensive machine units wear. The present paper is concerned with an effect of organic dust on the dynamics of kinematics pair vibrations of a machine unit.

## THE AIM OF THE PAPER

The aim of this paper is to evaluate the influence of organic dustiness of the air on the vibrations of a cylinder sleeve in the S-4002/3 engine with piston-rings-cylinder system with initial (technological) clearance and under the conditions of limiting wear.

## METHODOLOGY AND RESEARCH CONDITIONS

### Research conditions

The carried out research was conducted in laboratory conditions by the method of experimental simulation on a model measurement stand and concerned measurements of vibrations dynamics of the cylinder sleeve in a S-4002/3 engine in the conditions of the lubricating oil dusting with organic dust. The tests were carried out in a laboratory, in an enclosed space with room temperature 18-20°C with low air humidity.

The investigations concerned two states of PRC (piston-rings-cylinder) unit: of technological (initial) clearance and of limiting wear. Vibrations measurements were taken at measurement stands, considering the standard directions of vibrations effect on staff and surroundings [Cempel 1989]. Model (standard) oil and polluted oil samples in the quantity of 2cm$^3$ per each measurement cycle were evenly spread on the surface of the cylinder sleeve. After energetic equilibrium was achieved in the unit, the temperature of the cylinder tube changed depending on the state of the tested unit. During the work of a unit at technological state it was 70±5 °C and in the case of limiting wear 55±5 °C.

### The characteristics of the tested material

In the simulation tests of air pollution organic dust was used, taken from the inner walls of a combine filter in the BIZON REKORD combine, during bean harvesting for grains, with low air humidity. In order to determine the grain contents of the dust, a sieve dry analysis was made according to PN-71/M-94008. The dust mass was weighed on electronic scales with the precision up to 0,002 g.

Table 1. The properties of the examined material

| The examined material | Dust fraction | | | | pH value |
|---|---|---|---|---|---|
| | ∅>0.5 | ∅ 0.25-0.5 | ∅ 0.1-0.25 | ∅ <0.1 | |
| Organic dust | 0.48% | 47.74% | 40.66% | 11.12% | 4.75 |
| | sample characteristics | | | | relative viscosity °E |
| | standard oil Superol SAE 15/40 | | | | 7.2 |
| | 8 mg/m$^3$ of organic dust | | | | 9.1 |
| | 16 mg/m$^3$ of organic dust | | | | 9.32 |
| Attention. The dust concentration 8 mg/m$^3$ is achieved by mixing 0.32 g of dust with 2 cm$^3$ of engine oil. The dust concentration 16 mg/m$^3$ is obtained by mixing 0.64 g of dust with 2 cm$^3$ of engine oil (according to the Central Laboratory in Warsaw). | | | | | |

In order to determine pH of the dust, tests were made by the electromotor method with the counter EpH-117/118 of the firm Aalsmer-Holland with the precision ±0.01 pH. The results of the examined material's properties measurements are presented in Table 1.

### The characteristics of the forces in the piston-rings-cylinder system

In order to calculate the forces acting on the tested measurement system conventional formulas were used, usually applied at endurance calculations of the PRC system in engine [Grigorjew and Wlijanije 1974]: mass force $P_b$, coming from the masses doing the forward-turning movement (52 rad/s); the maximum gas force ($P_{gmax}$) coming from the pressure of gases in the cylinder; the mean of the two forces ($P_{max}$); the maximum force of the piston pressure on the cylinder surface $N_{max}$ (Table 2).

Table 2. The results of the measurements of the maximum forces influencing the piston-rings-cylinder system

| Kind of a force [kN] | New PRC system – technological state | | | Worn out PRC system – limiting weare | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 |
| $P_{g\ max}$ | 3.43 | 3.17 | 3.15 | 2.11 | 1.77 | 1.68 |
| $P_b$ | 0.343 | 0.30 | 0.29 | 0.316 | 0.27 | 0.24 |
| $P_{max}$ | 3.087 | 2.87 | 2.85 | 1.794 | 1.50 | 1.44 |
| $N_{max}$ | 0.308 | 0.287 | 0.285 | 0.179 | 0.15 | 0.44 |

1-model oil, 2 – organic dust 8 mg/m$^3$, 3 – organic dust 16 mg/m$^3$

**Research stand and measurement equipment**

The tests were carried out on a model test stand containing a ring/cylinder system with a single PRC unit of a S-4002/3 engine driven by an electrical engine. The applied measurement equipment track was presented in the works [Burski *et al*. 2002].

## THE APPLIED STATISTICAL METHOD

The measurements of the vibrations of a piston-rings-cylinder system were conducted with 16 frequencies $f_i$ (315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, 6300, 8000, 10000 Hz) creating a spectrum of the vibrations. Such spectrums were obtained for different levels of chosen environmental and exploitation factors [Cempel 1989, Burski *et al*. 2002].

The following five factors were taken into account:
– the condition of the system (new, worn),
– the presence of a compression chamber (with or without it),
– three planes of the vibrations (transversal, longitudinal, vertical),
– two measuring points (N and N`), according to (N`) and opposite to (N) the direction of the rotations of the crankshaft,
– the pollution of the oil (the standard oil, the oil with organic dust 8mg/m$^3$, the oil with organic dust 16 mg/m$^3$).

For each of 72 combinations of the above-mentioned factors the values of accelerations $a_i = a(f_i), i = 1,\ldots,16$ were obtained.

For the statistical analysis the following random variables representing the spectrum were chosen:
– the average acceleration of the vibrations – the variable $MA$ , calculated as

$$MA = \frac{1}{2(f_{16} - f_1)} \sum_{i=1}^{15} (a_i + a_{i+1})(f_{i+1} - f_i) ,$$

(the weighted mean corresponding to the integral mean for continuous spectrum $a(f)$)
– the maximum acceleration of the vibrations – the variable MaxA,

– $MaxA = \max(a_i, i = 1,\ldots 16)$ ,
– the frequency at which the maximum acceleration of the vibrations was observed – the variable *F*,
– the average frequency – the variable *MF*, describing „the centre of gravity" for spectrum, calculated by formula

$$MF = \frac{\sum_{i=1}^{15}(a_i f_i + a_{i+1} f_{i+1})(f_{i+1} - f_i)}{\sum_{i=1}^{15}(a_i + a_{i+1})(f_{i+1} - f_i)} .$$

Each of the above-mentioned random variables focuses only on a certain aspect of the spectrum. For each of them the statistical analysis of variance (ANOVA) was done in order to study the influence of the considered factors on the variable. Because only one value of a variable in each cell (i.e. each combination of factors) was observed, the statistical analysis was divided into two stages:

1. all possible four-factors ANOVA were performed in order to eliminate the factor with the least influence on the variability of the variable. The model with the smallest mean square error was chosen.
2. If one of the factors in the model chosen in the first stage was insignificant with all its interactions the further reduction of the model was done .

The analysis of variance needs assumptions about the normality of the analysed random variables and the homogeneity of variances in the groups. The assumption about the lack of correlation between means and standard deviations in the groups is also necessary for a correct analysis [Statistica PL 1997]. If these assumptions are not fulfilled, some transformations of the variables can be performed. The following transformations were applied:

– for variables *MA* and *MaxA* their natural logarithms were taken,
– for variable F the frequencies were numbered according to their growing order (1 for 315 Hz, ..., 16 for 10000 Hz).

The LSD (Least Significant Difference) can be used in order to determine the statistically significant differences between means in groups. For the analysed variables the Fisher's LSD on the level 0,05 was applied.

All the calculations were done by means of STATISTICA programme. Table 3. shows the names of the factors in ANOVA.

Table 3. The explanations of the factors used in ANOVA

| The name of the factor | Piston-rings-cylinder system (PRC) | Chamber | Plane | Point | Oil |
|---|---|---|---|---|---|
| The number of levels | 2 | 2 | 3 | 2 | 3 |
| The explanation of the levels and abbreviations used in figures | -new (N)<br>-worn (W) | –without compression (not C)<br>–with compression (C) | –transversal (T)<br>–longitudinal (L)<br>–vertical (V) | N<br>N' | –standard oil (I)<br>–oil+organic dust 8 mg/m$^3$ (II)<br>–oil+organic dust 16 mg/m$^3$ (III) |

## THE STATISTICAL ANALYSIS OF THE AVERAGE ACCELERATION OF THE VIBRATIONS

In the first stage of the analysis the point of measurements turned out to have the least influence on the variable, and the four-factor analysis PRC×Chamber×Plane×Oil was chosen. Table 4 shows the significant effects on 0,05 level in four-factors ANOVA for the variable $\ln(MA)$. Fig. 1 presents the diagram of the three-directional interaction PRC×Chamber×Oil and Fig. 2 – the plane effect.

Table 4. The results of four-factor ANOVA for the variable $\ln(MA)$

| 1 – PRC, 2 – Chamber, 3 – Plane , 4 – Oil | | | | | | |
|---|---|---|---|---|---|---|
| effects | *df* for effects | *MS* for effects | *df* for error | *MS* for error | F | p |
| 1 | 1 | 23.91714 | 36 | 0.065760 | 363.7052 | 0.000000 |
| 2 | 1 | 8.29371 | 36 | 0.065760 | 126.1215 | 0.000000 |
| 3 | 2 | 1.82331 | 36 | 0.065760 | 27.7269 | 0.000000 |
| 12 | 1 | 0.50205 | 36 | 0.065760 | 7.6346 | 0.008964 |
| 124 | 2 | 0.42940 | 36 | 0.065760 | 6.5298 | 0.003805 |

So, the statistical analysis of the variable *MA* gives the following conclusions:

- there is no significant influence of the point of measurements on the average acceleration of vibrations,
- for new PRC the average acceleration is less then for worn PRC,
- the presence of the compression in the chamber decreases average acceleration of vibrations,
- the average acceleration of vibrations in the transversal plane is higher than in other planes.

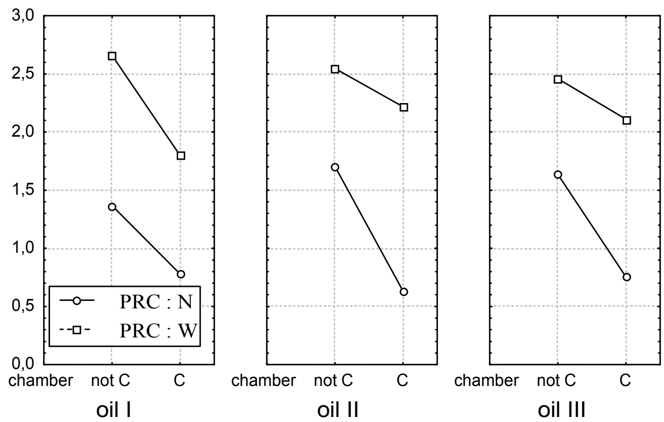


Fig. 1. The diagram of the three-directional interaction PRC×Chamber×Oil for $\ln(MA)$. LSD $\approx 0.3$

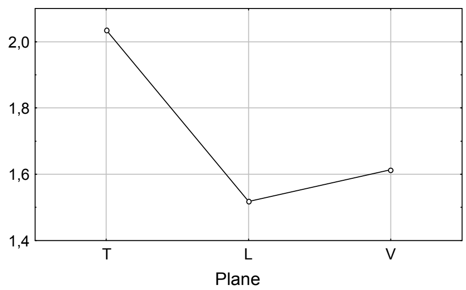


Fig. 2. The diagram of plane effect for $\ln(MA)$ . LSD ≈ 0.15.

## THE STATISTICAL ANALYSIS OF THE MAXIMUM ACCELERATION OF THE VIBRATIONS

For the variable MaxA the four-factor analysis PRC×Chamber×Plane×Oil was also chosen. Taking logarithm of MaxA has decreased the correlation between means and standard deviations in the groups (from 0.545 to 0.234). It has also improved homogeneity of variances and the normal plot of residuals.

In Table 5 the significant (on the level 0.05) effects in PRC×Chamber×Plane×Oil ANOVA are presented.

Table 5. The results of four-factor ANOVA for the variable $\ln(MaxA)$

| 1 – PRC, 2 – Chamber, 3 – Plane , 4 – Oil | | | | | | |
|---|---|---|---|---|---|---|
| effects | *df* for effects | *MS* for effects | *df* for error | *MS* for error | F | p |
| 1 | 1 | 15.20198 | 36 | 0.068856 | 220.7805 | 0.000000 |
| 2 | 1 | 11.98046 | 36 | 0.068856 | 173.9940 | 0.000000 |
| 4 | 2 | 0.31001 | 36 | 0.068856 | 4.5024 | 0.017981 |
| 12 | 1 | 0.35098 | 36 | 0.068856 | 5.0973 | 0.030123 |
| 13 | 2 | 0.42756 | 36 | 0.068856 | 6.2096 | 0.004821 |
| 23 | 2 | 0.59124 | 36 | 0.068856 | 8.5866 | 0.000893 |
| 123 | 2 | 0.26608 | 36 | 0.068856 | 3.8643 | 0.030177 |
| 124 | 2 | 0.50915 | 36 | 0.068856 | 7.3945 | 0.002040 |

Fig. 3 and 4 present the diagram for four-directional interaction. (LSD ≈ 0.532).

From the results presented in Table 5 and Figures 3, 4 we can conclude the following:

– the point of measurements have a very slight influence on the maximum acceleration of vibrations,
– new PRC gives lower maximum acceleration than the worn one. The only insignificant differences are between new and worn PRC: with compression, standard oil, transversal plane;

without compression, polluted oil, longitudinal and vertical planes;
- compression most significantly reduces maximum acceleration. The only insignificant differences are: with new PRC, transversal and longitudinal planes, standard oil; worn PRC, transversal and longitudinal planes, polluted oil;
- the influence of the organic dust in the oil is of little importance, only for worn PRC, with compression chamber, transversal plane the standard oil gives lower maximum acceleration than oil with organic dust.

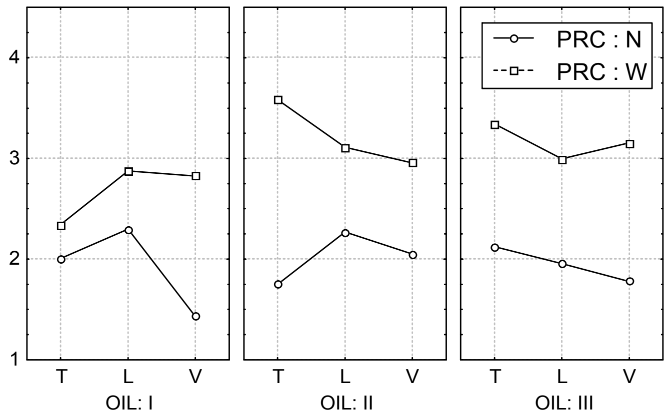


Fig. 3. The diagram of the four-directional interaction PRC×Chamber×Plane×Oil for $\ln(MaxA)$, chamber with compression.

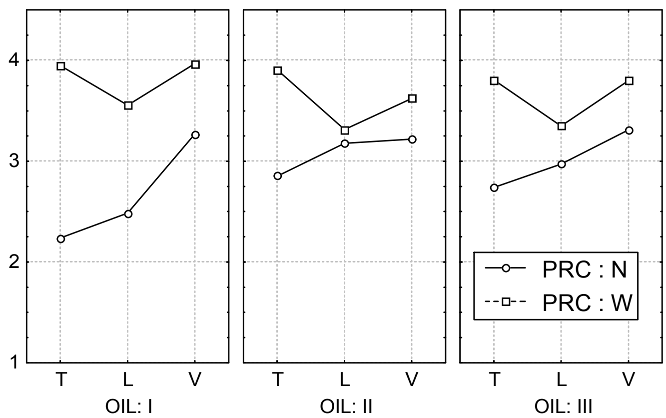


Fig. 4. The diagram of the four-directional interaction PRC×Chamber×Plane×Oil for $\ln(MaxA)$, chamber without compression

## THE STATISTICAL ANALYSIS OF THE VARIABLE *F*

The pollution of oil turned out to have the least influence on the frequency at which the maximum acceleration of the vibrations was observed. Table 6 presents the significant on the level 0.05 effects in four-factors ANOVA PRC×Chamber×Plane×Point.

It can be seen from Table 6 that plane of vibrations has the greatest influence on the variable F. The diagram of the four-directional interaction is given in Fig. 5 and 6 LSE equals approximately 2.22.

Table 6. The results of four-factors ANOVA for the variable *F*

| 1 – PRC, 2 – Chamber, 3 – Plane, 4 – Point | | | | | | |
|---|---|---|---|---|---|---|
| effects | *df* for effectst | *MS* for effects | *df* for error | *MS* for error | *F* | *p* |
| 1 | 1 | 22.22222 | 48 | 1.833333 | 12.12121 | 0.001073 |
| 3 | 2 | 86.84722 | 48 | 1.833333 | 47.37121 | 0.000000 |
| 12 | 1 | 8.00000 | 48 | 1.833333 | 4.36364 | 0.042040 |
| 13 | 2 | 6.01389 | 48 | 1.833333 | 3.28030 | 0.046205 |
| 23 | 2 | 15.09722 | 48 | 1.833333 | 8.23485 | 0.000842 |
| 14 | 1 | 14.22222 | 48 | 1.833333 | 7.75758 | 0.007634 |

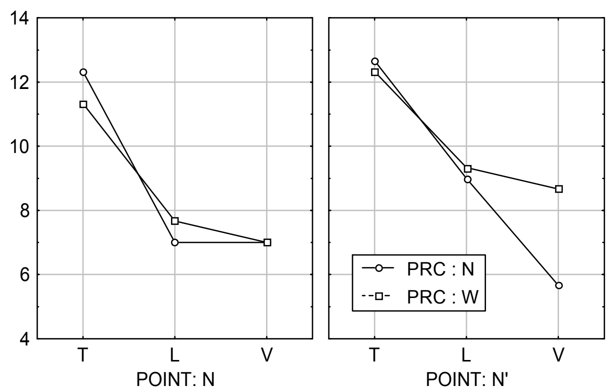


Fig. 5. The diagram of four-directional interaction PRC×Chamber×Plane×Point for the variable *F*, chamber without compression

The statistical analysis of *F*, given in Table 6 and Figures 5, 6, leads to the following conclusions:

- the organic dust in oil has little influence on the frequency at which the maximum acceleration occurs;
- worn PRC raises *F* in the case of point N', vertical plane, chamber without compression and in the case of chamber with compression, longitudinal and vertical planes. In all the other cases there are no significant differences between new and worn PRC;

– the variable *F* in the case of transversal plane is the highest. The exception to this rule is the measurement in point N', chamber with compression, worn PRC.

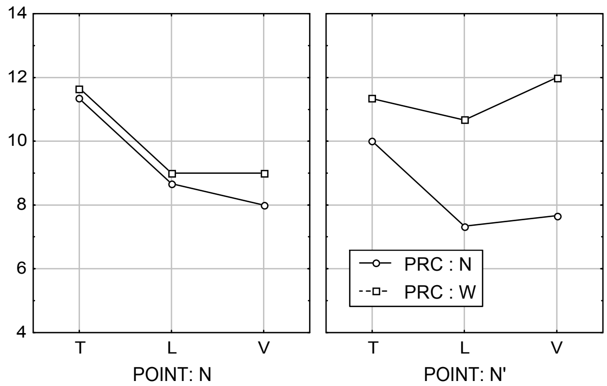


Fig. 6 The diagram of four-directional interaction PRC×Chamber×Plane×Point for the variable F, chamber with compression

## THE STATISTICAL ANALYSIS OF THE AVERAGE FREQUENCY OF THE VIBRATIONS

The oil and the point of measurements had the least influence on the average frequency of vibrations. The Table 7 presents significant effects in three-factors ANOVA PRC x Chamber x Plane.

Table 7. The results of four-factors ANOVA for the variable *MF*

| 1 – PRC, 2 – Chamber, 3 – Plane | | | | | | |
|---|---|---|---|---|---|---|
| effects | *df* for effects | *MS* for effects | *df* for error | *MS* for error | *F* | *p* |
| 1 | 1 | 4244119 | 60 | 170685 | 24.8652 | 0.000006 |
| 2 | 1 | 1115638 | 60 | 170685 | 6.5362 | 0.013118 |
| 3 | 2 | 10409762 | 60 | 170685 | 60.9882 | 0.000000 |
| 13 | 2 | 1487594 | 60 | 170685 | 8.7154 | 0.000475 |

The diagram of two-directional interaction PRC x Plane is presented in Fig. 7 and the influence of compression in the chamber in Fig. 8.

It should be mentioned that in this case not all the assumptions of ANOVA are fulfilled. Namely, the hypothesis about the homogeneity of variances in groups is rejected by Bartlett's test on significance level 0.05 and neither logarithm nor square root can improve this. But the statistic *F* is considered to be robust against such violation of the assumptions.

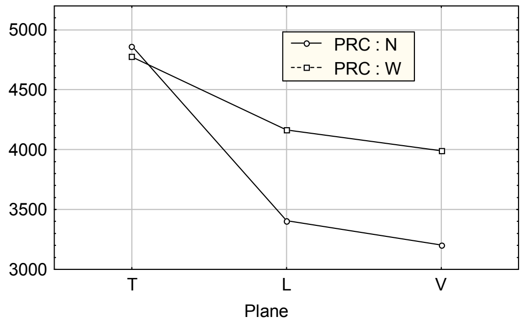


Fig. 7. The diagram of interaction PRC x Plane for the variable MF. LSD≈337

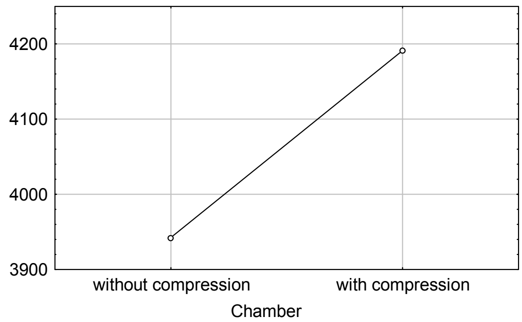


Fig. 8. The influence of compression in the chamber. LSD≈195

Considering the results in the table 7 and Fig. 7, 8 we have the following conclusions:

– the influence of organic dust in oil and the point of measurements on the value of average frequency are rather small,
– the presence of compression in the chamber shifts the spectrum of vibrations to higher frequencies,
– worn PRC causes the shift of the spectrum to higher frequencies. Only differences between new and worn PRC in the transversal plane are insignificant.

## CONCLUSIONS

The paper justifies the need for taking into consideration in the dynamics of a kinematics pair with forward-turning movement (PRC) the influence of environmental factors in the form of organic dust in machine units. The specialist literature points out that even the modern air filters (GF-7.60) used in tractors or automotive agricultural vehicles, due to dust reemission, do not fully prevent the pollution of lubricating oil. The importance of this problem grows as the drought periods grow longer during field and transport works in agriculture, particularly on loess soils.

The carried out research showed a significant sensitivity of the amplitude spectrum parameters to the applied research conditions.

The condition of PRC has the greatest influence on the average acceleration and the maximum acceleration of the vibrations. In the case of limiting wear both of them are much higher than in the case of initial clearance.

The plane of vibrations has the greatest influence on the average frequency and the frequency of the maximum acceleration. In most cases both of them have the greatest value in transversal plane.

Oil pollution has a significant influence on the average acceleration and the maximum acceleration of the vibrations but this dependency is dominated by other factors and can be visible only in multi-directional interactions.

The effect of compression in the chamber is the most visible for the average and maximum accelerations. In the case of compression both of them are lower.

It should be mentioned that all the dependencies between the considered variables and factors are very complicated and can be described mostly by the between-factors interactions.

The presented results of the statistical significance and the acting factors interactions for vibroacoustic symptoms can be also applied at agri-food industry where internal transport of raw materials and cereal products exists as well as their processing, causing air dusting nearby machine units.

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