T H E A R C H I V E O F M E C H A N I C A L E N G I N E E R I N G

VOL. LVII 2010 Number 3

10.2478/v10180-010-0017-8

Key words: positive-displacement pump, signal analysis, diagnostic of machines

JERZY STOJEK *

APPLICATION OF TIME-FREQUENCY ANALYSIS FOR DIAGNOSTICS OF VALVE PLATE WEAR IN AXIAL-PISTON PUMP

This study presents a possibility of detecting wear of a valve plate in multi-piston axial pump based on time-frequency analysis of measured signals. Short-time Fourier transform *STFT* and the generalized Wigner-Ville algorithm *WVD* were used for this purpose. The tests were carried out on a multi-piston axial pump with swinging plate, in which the worn valve plates were mounted. Valve plate wear was related with the formation of flow micro-channels between the pump suction hole and its pumping hole on the plate transition zone surface. The developed channels initiate flow of the operational fluid, the results of which is lack of leak-tightness between suction and pumping zones, associated with a decrease in operational pressure and drop in general efficiency.

1. Introduction

The function of plate-type distribution unit in multi-piston pumps is supplying operational medium from the suction channel into the displacement chamber of co-operating impeller (when located within suction zone) and carrying it away into pressure conduit (when located within the pressure zone) [6]. Proper construction of the valve plate is one of the most difficult operations during the pump designing process. The following pump parameters depend on the plate construction and its co-operation with the impeller: volume efficiency (possibility of obtaining high pumping pressures), pump noise level, and pump's operational durability. A trial of using the time-frequency analysis for defining wear of the valve plate, based on measured signals of the pump body vibration, has been undertaken in the present study.

* *AGH University of Science and Technology, Department of Process Control, al. Mickiewicza 30, 30-059 Cracow, Poland; E-mail: Stojek@imir.agh.edu.pl*

www.czasopisma.pan.pl PAN www.journals.pan.pl

2. Description of the tested object

Multi-piston axial positive-displacement pump of constant efficiency was the subject of the examinations. Operation of such pumps (Fig. 1) is based on distribution of the fluid flow to and from impeller cylinders via stable valve plate, which is perpendicular to the axis of rotation of the pump cylinder. During rotational movement, the impeller's face co-operates with the valve plate, sliding along its surface. Two kidney-shaped holes are drilled in the valve plate (Fig. 1). The suction hole is separated from the compression hole by a transition zone, the so-called bridge. Wear of the valve plates, associated with its frictional wear, is caused, among other things, by the decay of lubrication layer between the plate surface and the impeller face, what is accompanied with formation of flow micro-channels on the bridge of plate surface. The developed channels initiate flow of the operational fluid between suction and compression zones, what results in the loss of leak-tightness, reduction of volumetric efficiency and a decrease in operational pressure.

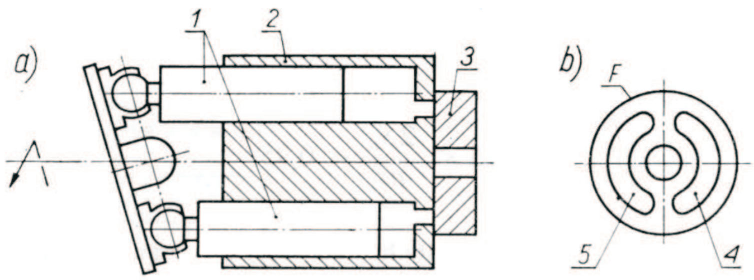

Fig. 1. General scheme of axial multi-piston pump: a) cross-section, b) valve plate, 1. pistons, 2. impeller, 3. valve plate, 4. suction hole, 5. compression hole [5]

3. Causes of valve plate damages

Decay of lubrication layer between impeller face and stable surface of the pump plate is the major cause of the micro-channel formation on the plate surface. Insufficient thickness of the lubrication layer can result from improper exploitation of hydraulic system, for example too high operational temperature and the associated critical reduction of the working fluid viscosity. Hard particles of the oil impurities that appear in result of insufficient filtration, additionally contribute to degradation of the plate surface. All these factors, combined with high operational pressure of the pomp, lead

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

to the occurrence of mixed or dry friction, and consequently friction wear of mating parts. Additionally, in the case when axial piston pump is utilized with negative overlap of valve plate, the transition zone between the suction hole and the compression hole is highly exposed to cavitation. Examples of photographs of valve plates of an efficient element, and two worn elements, are shown in Fig. 2.

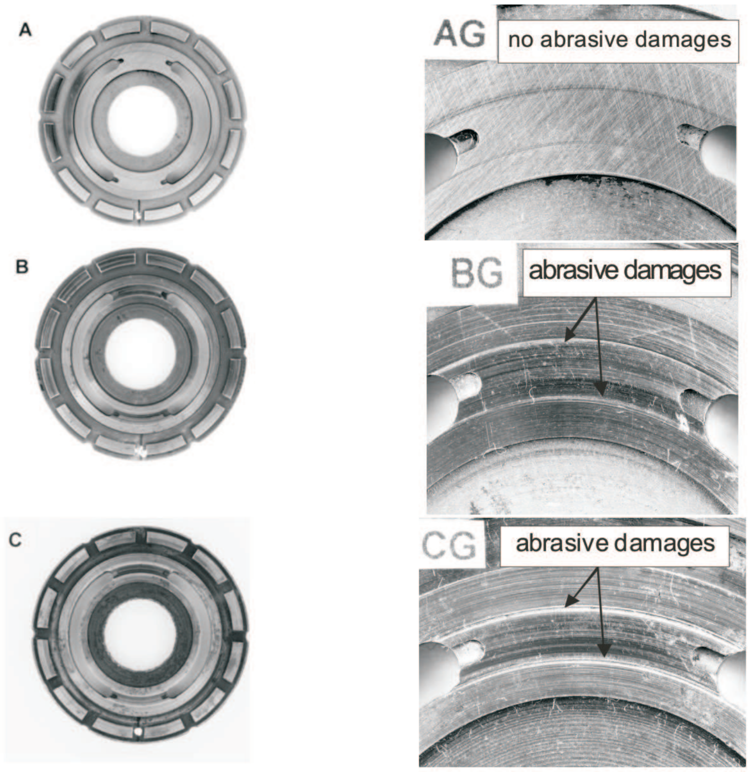

Fig. 2. Valve plates with magnified wear zone: a) plate without wear (type A), b) plate with wear of the depth of 0.01 mm (type B), c) with wear of the depth of 0.05 mm (type C)

4. Testing stand and measurement description

The scheme of the laboratory stand used in the tests is shown in Fig. 3. The stand consists of: the pump *P* with worn valve plate, the set of hydraulic elements (servo-valve, throttle valve, cut-off valve and a set of filters) with the transducers of: flow rate, static and dynamic pressure, and the transducers used for measurement of pump body vibration.

The influence of valve plate on the positive-displacement pump operation was examined by changing the worn valve plates in the pump body. The plates

www.czasopisma.pan.pl www.journals.pan.pl

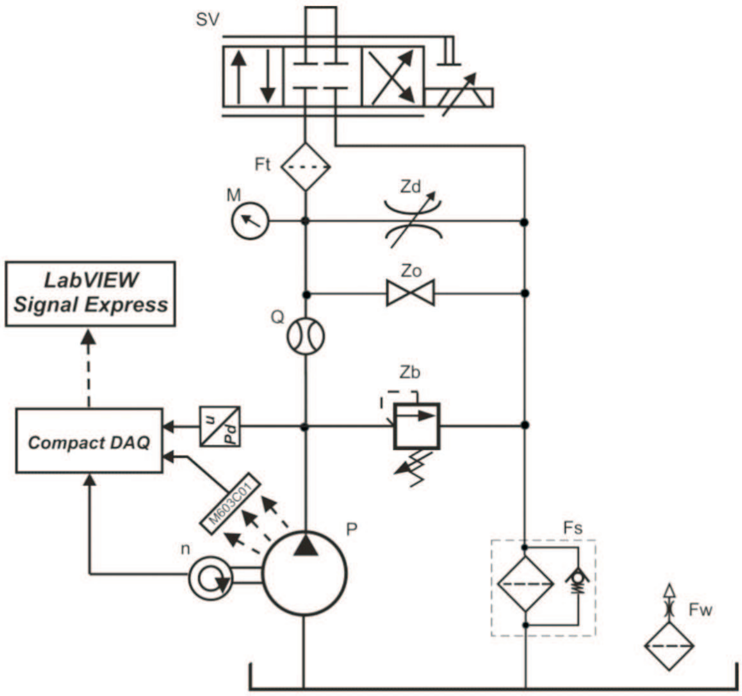

Fig. 3. Hydraulic scheme of experimental stand: P – pump with worn plate, SV – servo-valve, Zb – maximal valve, Zd – throttle valve, Zo – cut-off valve, Ft – pressure filter, Fs – low-pressure filter, Fw – inlet filter, M – manometer, n – tachometer, Q – flow-meter

used in the examinations differed in the depth of worn flow grooves: 0.01mm for the plate of type B, and 0.05 mm for type C (Fig. 2). Additionally, for comparison, we performed examinations of a new pump with a valve plate without wear (plates of type A, Fig. 2). The measurements of physical values (vibration, flow, static and dynamic pressure) were carried out in the following conditions of pump operation:

- no pressure at the pump outlet,
- loading of the pump outlet with static pressure of 70 bar,
- loading with dynamic, periodically periodically-variable pressure.

The measurements of acceleration of the pump body vibration [3] were taken for three measurement axes (X, Y, Z) using vibration transducers mounted, prior to the tests, on the pump body near the valve plate. 16-bit measurement cards, co-operating with a signal-conditioning system and programmed by Signal Express in the LabView environment, were applied in the measurements of physical quantities. The measured data were stored on the computer disc, and then subjected to numerical analysis with use

www.czasopisma.pan.pl www.journals.pan.pl

the of Matlab-Simulink program. A general view of the pump with mounted vibration transducers and example vibration courses measured during one period of rotation of the pump's shaft is shown below (Fig. 4).

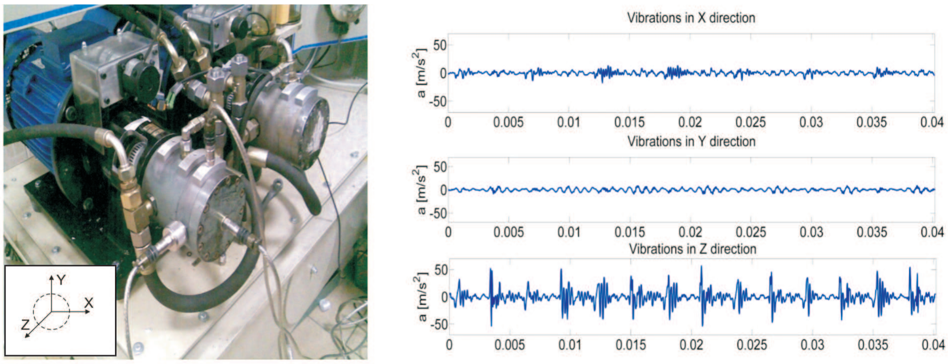

Fig. 4. Distribution of measurement transducers on the body of tested pump, and example vibration course for three measurement axes

5. Application of time-frequency analysis

The vibration accelerations, measured in the three axes, were examined with respect to time and frequency. Short-time Fourier transform *STFT* and Wigner-Ville transform (*WVD*) [7] were used for this purpose. As compared with the Fourier transform, which allows for the analysis in frequency domain only, the short-time Fourier transform *STFT*, commonly used in the analysis of non-stationary signals, allows us to obtain a three-dimensional image of the process course (its amplitude) the function of time and frequency. In the analysis of non-stationary signals, *STFT* is expressed as [5]:

$$X(t, f) = \int_{-\infty}^{+\infty} x(t) \cdot w(t-\tau)\, e^{-j2\pi f \tau} d\tau \tag{1}$$

where:

$x(t)$ – tested time function of physical quantity,

$w(t-\tau)$ – time window function of constant width τ.

In this analysis, frequency analysis of successive fragments (blocks) of the measured signal $x(t)$ is performed by multiplying it by the window function $w(t-\tau)$ of constant width. The consecutive fragments of the signal are tested independently, combining spectrum components with time. Constant width of the localization window is one of the method disadvantages. Because of inverse proportionality between window width and frequency

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

resolution, with the use of narrow window we obtain good time resolution, on the expense of frequency resolution of the tested signal, and vice versa. Thus, selection of the window width is a compromise between resolutions in time and frequency domain. The obtained results are also considerably influenced by the shape of time window used in the analysis. Errors related to the spectrum leakage effect occur in the case of rectangular window. One can minimize these errors using windows of more gentle slope shape (for example triangular, Hanning, Hamming, etc.). However, the use of such windows results in signal power losses, because the signal amplitude is reduced at the beginning and at the end of the window range. The method of minimizing this phenomenon consists in overlapping the time window. Each sample of the signal time-train is subjected to more than one analysis using the algorithm of fast Fourier transform FFT, for example double analyses in the case of 50% window overlap, or triple analyses in the case of 75% window overlap. The result is that the samples whose amplitudes are reduced to zero within a single window, appear within the next ones with unchanged amplitudes.

Besides of the short-time Fourier analysis *STFT*, an additional time-frequency transformation, called the Wigner-Ville (WV) [7] transform, was applied in the examination of vibration courses:

$$WV(t, f) = \int_{-\infty}^{+\infty} x\left(t + \frac{\tau}{2}\right) \cdot x^*\left(t - \frac{\tau}{2}\right) e^{j2\pi f\tau} d\tau \tag{2}$$

where:

$x^*(t)$ – complex conjugate of $x(t)$,

τ – shift in time domain.

Wigner-Ville representation is characterized by the greatest energy concentration within time-frequency space (the best total resolution), and it perfectly depicts linear modulation of the signal frequency (what is impossible in the case of *STFT* analysis). In practice, because of the occurrence of spurious mutual interferences of oscillatory character between various spectrum components (the so-called skew spectra), which considerably hinder interpretation of the results, a generalized version of the transform, the so-called pseudo- Wigner's-Ville's *WVD* representation, is often used (Eq. (3)). This generalization consists in smoothing the Wigner's representation with one of the available weight functions [4]. Consequently, the influence of parasitical skew spectra is limited:

$$WVD(t, f) = \int_{-\infty}^{+\infty} \left| w\left(\frac{\tau}{2}\right)\right|^2 \cdot x\left(t + \frac{\tau}{2}\right) \cdot x^*\left(t - \frac{\tau}{2}\right) e^{j2\pi f\tau} d\tau \tag{3}$$

$x^*(t)$ – complex conjugate of $x(t)$,

www.czasopisma.pan.pl PAN www.journals.pan.pl

$w\left(\frac{\tau}{2}\right)$ – time window function,
τ – shift in time domain.

The algorithm implementing this transform in the Matlab-Simulink environment uses, among other things, a double Fourier transformation. Additionally, in order to avoid aliasing phenomena, the analogue signal is sampled with a frequency at least twice greater than the Nyquist frequency [2]. In the performed examinations, the signals were recorded with a constant sampling frequency f_p = 40 kHz.

6. Results of examinations

Synchronously averaged courses of the pump body vibrations (per single rotation of the pump shaft) were used in the analysis of the measured signals. The examinations were conducted at a constant nominal rotational speed of the pump n=1450 rpm. The functions of constant Hamming window of time range τ = 1.6 ms, which were shifted to overlap the consequent windows with 75% overlapping factor, were used for calculating time-frequency distributions. The obtained time-frequency representations *STFT* and *WVD* for the tested valve plates are collected in the diagrams shown below, separately for each measurement axis.

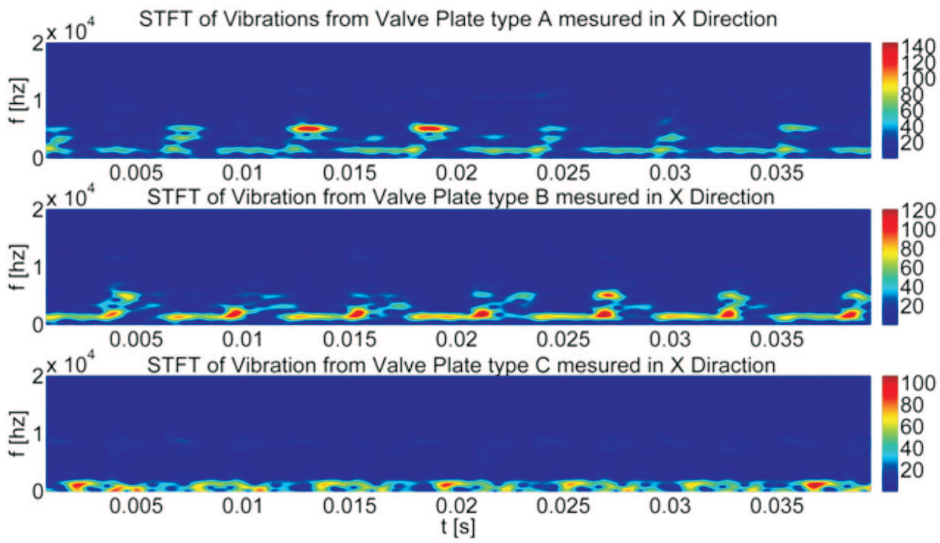

Fig. 5. Time-frequency representation STFT of signals measured along the axis X for: a) unworn valve plate, b) worn valve plate - depth = 0.01mm, c) worn valve plate - depth = 0.05mm

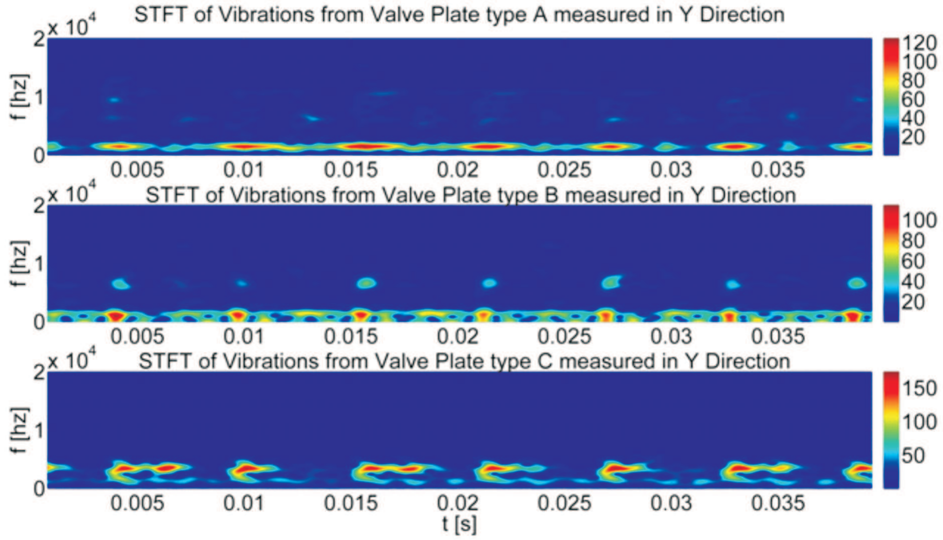

Fig. 6. Time-frequency representation STFT of signals measured along the axis Y for: a) unworn valve plate, b) worn valve plate - depth = 0.01mm, c) worn valve plate - depth = 0.05mm

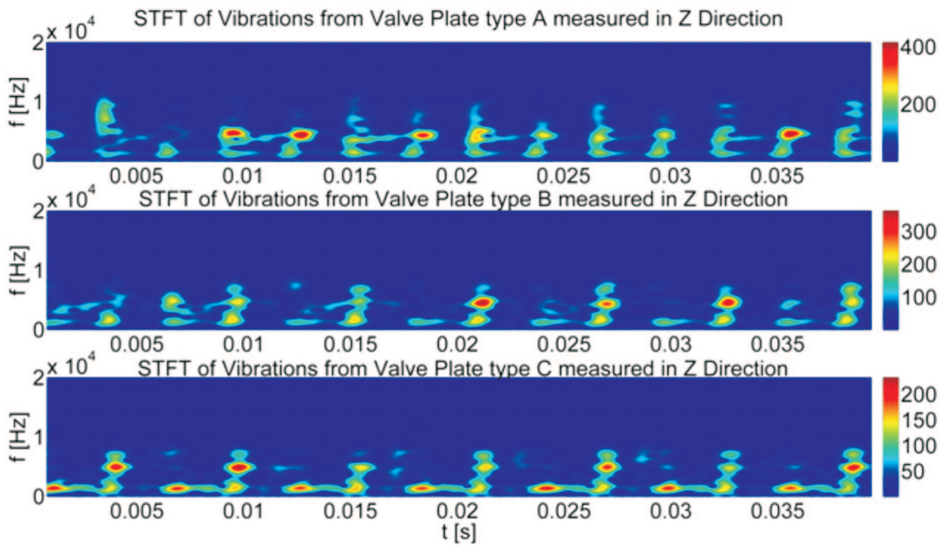

Fig. 7. Time-frequency representation STFT of signals measured along the axis Z for: a) unworn valve plate, b) worn valve plate - depth = 0.01mm, c) worn valve plate - depth = 0.05mm

The analysis of time-frequency representations prepared in the form of bit maps can be based on both quantitative and qualitative analyses. Qualitative assessment is reduced to verbal description of the examined representations.

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

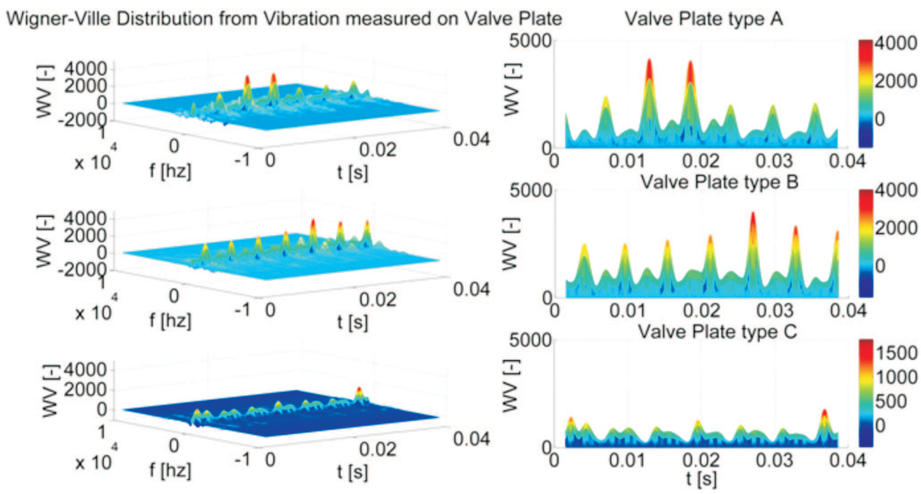

Fig. 8. Representation of time-frequency WVD of vibration signals measured along axis X for a) unworn valve plate, b) worn valve plate - depth = 0.01mm, c) worn valve plate - depth = 0.05mm

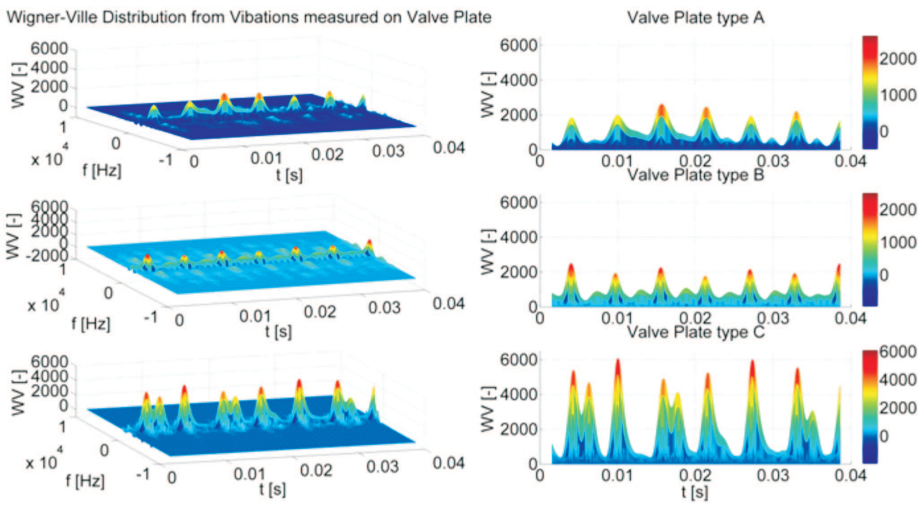

Fig. 9. Representation of time-frequency WVD of vibration signals measured along axis Y for a) unworn valve plate, b) worn valve plate - depth = 0.01mm, c) worn valve plate - depth = 0.05mm

In the case when quantitative measure is used, one usually determines a numerical measure of a chosen parameter.

Quantitative assessment of the influence of changes of the valve plate was made in order to facilitate the analysis of the obtained time-frequency representations STFT. The root-mean square value was taken as the measure

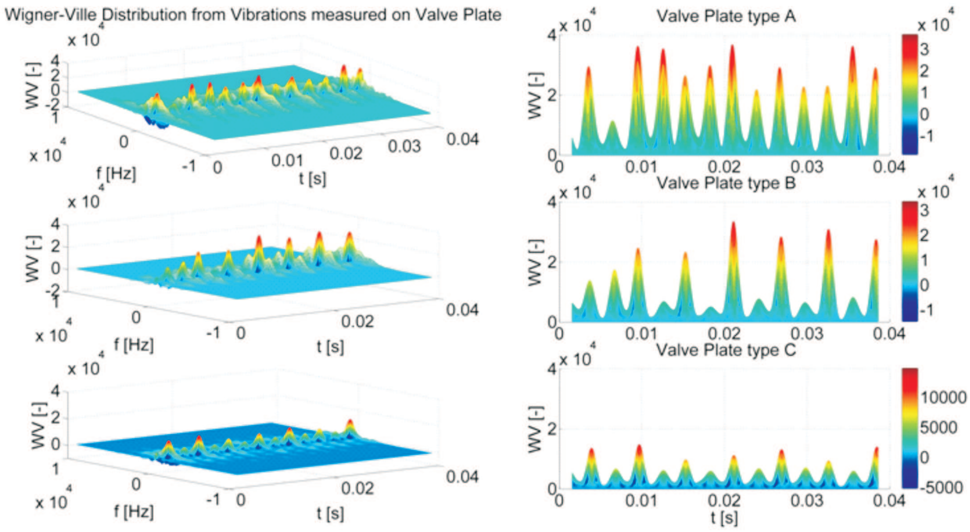

Fig. 10. Representation of time-frequency WVD of vibration signals measured along axis Z for a) unworn valve plate, b) worn valve plate - depth = 0.01mm, c) worn valve plate - depth = 0.05mm

of changes of spectrum amplitude factors STFT, calculated from whole signal time range t, with targeted frequency f_i:

$$rmsX(t, f_i) = \sqrt{\frac{\sum_{j=0}^{N} X\left(t_j, f_i\right)^2}{N}} \tag{4}$$

where:

$X(t_j, f_i)$ – spectrum amplitude factor *STFT*,

N – length of time course corresponding to single rotation of the pump shaft.

Based on the performed quantitative tests of time-frequency representations *STFT* and *WVD* determined for the measured signals, we can conclude:

- The analysis of *STFT* courses (Fig. 5) obtained in the axis *X* indicates that the increase in valve plate wear is accompanied by a shift of the signal spectrum towards lower frequencies, with simultaneous decrease in its amplitude. This effect has also been proven by the analysis of *WVD* representation (Fig. 8). Quantitative analysis of distribution of the root mean square of the *STFT* spectra (Fig. 11) indicates that the assessments of valve plate wear was somehow imprecise within the frequency range up to 2 kHz, but already in the range from 4 to 6 kHz we can observe evident tendency of a decrease in the spectrum amplitude and its shift towards lower frequencies.

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

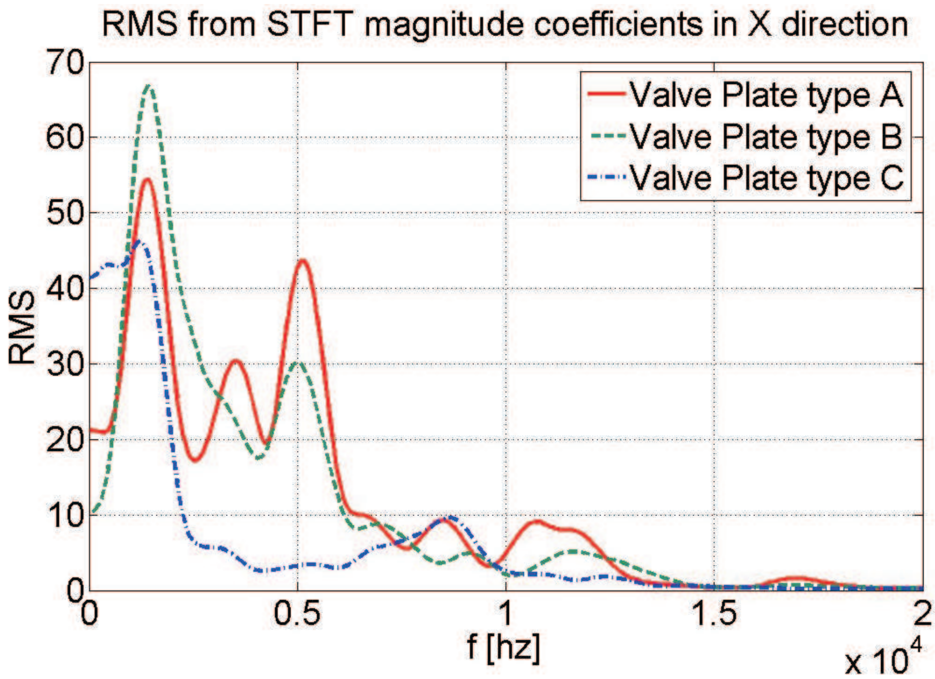

Fig. 11. Course of root mean square of amplitude spectra *STFT* determined from signals measured in axis X for tested valve plates

- The analysis of *STFT* courses (Fig. 6) obtained in the axis Y shows not quite explicit shift of the signal spectrum towards higher frequencies, which results from a greater wear of the valve plate. The rise in the spectrum amplitude in the case of valve plate with the greatest wear (C type plate) is also observed. However, based on the analysis of *WVD* distributions (Fig. 9), we can notice that, in the result of wear of this element, there appear side lobes in the spectrum, and the amplitude of these side lobes increases with the plate wear. In the case of quantitative analysis of *STFT* distributions, for which the values of root mean square of the *STFT* spectrum were determined in the function of frequency (Fig. 12), one observes a reduction in spectrum amplitude with the plated wear (for f~1.8kHz) accompanied with an evident increase of amplitude of the spectrum. In the case of the most worn plate (C type plate) the whole spectrum is shifted towards higher frequencies.

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

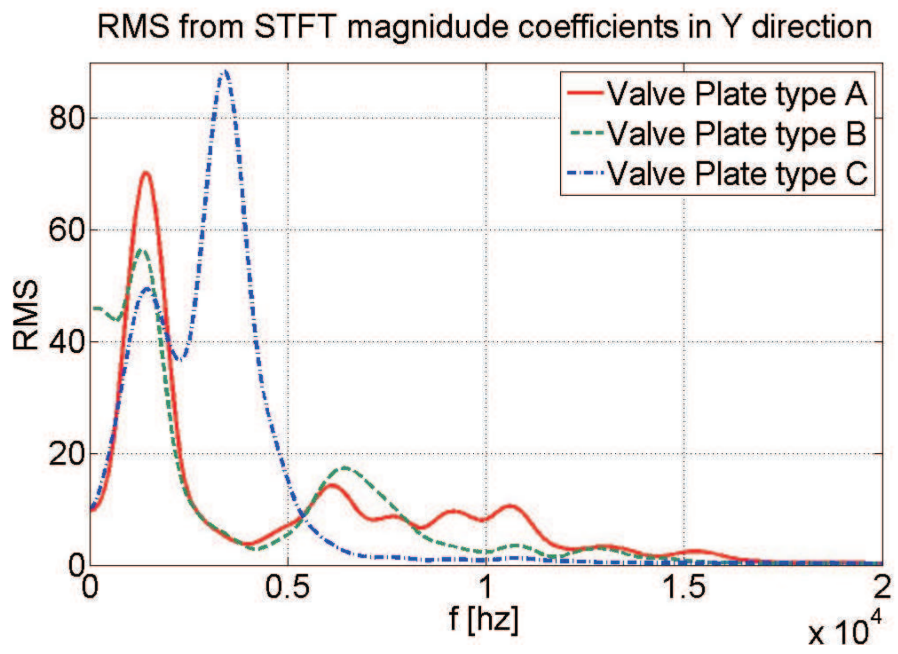

Fig. 12. Course of the root mean square of amplitude spectra determined for signals measured in the axis Y of tested valve plates

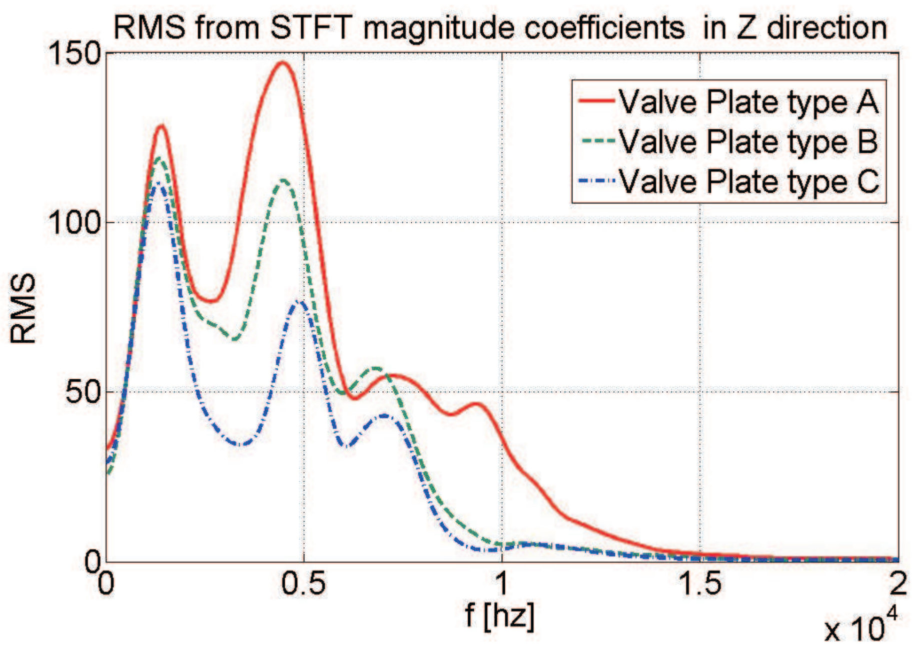

Fig. 13. Course of root mean square of amplitude spectra determined from signals measured in the axis Z of the tested valve plates

www.czasopisma.pan.pl www.journals.pan.pl

- Based on the quality analysis of *STFT* and *WVD* distributions obtained in the *Z* axis, one can note that the increase in the valve plate wear does not cause any significant shift of the signal spectrum toward lower or higher frequencies (Fig. 7 and 10). The tendency of the spectrum amplitude to drop, resulting from the plate wear, is also noticeable (it is particularly well seen in the case of *WVD* distributions). The performed quantitative analysis of root mean square of the *STFT* spectra (Fig. 13) evidently confirms that the spectrum shifts toward higher frequencies (f from the range of 4 to 6 kHZ), which is associated with a reduction in spectrum amplitude increasing with the plate's wear.

7. Summary

Summarizing the analysis of the obtained time-frequency distributions, we can state that it is possible to get diagnostic information about the valve plate wear by quantitative analyses of distributions of *STFT* and *WVD* spectra of the tested signals. Additionally, quantitative assessment of parameters of the time-frequency distributions of root mean square of the *STFT* spectrum facilitates interpretation of the spectra, and can be useful for tracking the plate's wear. On the basis of the analysis of the courses of $rmsX = F(f)$ functions one can also assume an appropriate value of the critical plate wear (with respect to the pump exploitation conditions), plan the date of pump overhaul and replacement of the worn-out element. Selection of the location of the measurement transducer on the pump body (axis X, Y, Z) influences quality of the obtained diagnostic information. In the performed tests, unambiguous results of measurements were acquired from the transducer located in the pump axis (axis Z).

Research supported by KBN project no. N501325135

Manuscript received by Editorial Board, February 22, 2010;
final version, August 17, 2010.

REFERENCES

[1] Gao Y., Kong X., Zhang Q.: Wavelet Analysis for Piston Pump Fault Diagnosis. National Conference on Fluid Power, Las Vegas 2002.

[2] Murrenhoff H., Scharft S.: Wear and Friction of ZRCG-Coated Pistons of Axial Piston Pumps. International Journal of Fluid Power. Vol. 7, no. 3, November 2006.

[3] Ql Zhuge, Yongxiang Lu.: Vibration Source Transmission Path Response Analysis and Condition Monitoring of Hydraulic Pump. The Journal of Fluid Control. Vol. 21 no 1.

[4] Guillon M.: Teoria i Obliczanie Układów Hydraulicznych. Wydawnictwo Naukowo Techniczne, Warszawa 1966.

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

[5] Lyons R.G.: Wprowadzenie do cyfrowego przetwarzania sygnałów. Wydawnictwo Komunikacji i Łączności, Warszawa 2006.
[6] Stryczek S.: Napęd hydrostatyczny. Wydawnictwo Naukowo Techniczne, Warszawa 1995.
[7] Zieliński T.: Od teorii do cyfrowego przetwarzania sygnałów. Wydawnictwo Komunikacji i Łączności, Warszawa 2009.
[8] Żółtowski B., Cempel C.: Inżynieria diagnostyki maszyn. Praca zbiorowa. Wydawnictwo PTDT, Radom 2004.

Wykorzystanie analizy czasowo-częstotliwościowej w diagnostyce zużycia tarczy rozrządczej pompy tłokowej

S t r e s z c z e n i e

Zadanie jakie spełnia rozrząd tarczowy w pompach tłokowych to doprowadzenie czynnika roboczego ze strefy ssawnej pompy do komór wyporowych współpracującego z nią wirnika i odprowadzenie go do przewodu tłocznego pompy. Właściwe ukształtowanie konstrukcji tarczy rozrządczej jest jednym z najtrudniejszych zadań w procesie projektowania. Od konstrukcji tarczy i jej współpracy z wirnikiem zależą główne parametry pompy takie jak: sprawność objętościowa, hałaśliwość i jej trwałość eksploatacyjna.

W procesie eksploatacyjnym zużycie tarcz rozrządczych związane jest z pojawianiem się mikrokanałów przepływowych pomiędzy otworem ssawnym pompy a jej otworem tłocznym na powierzchniach stref przejściowych tarczy. Powstałe kanały powodują przepływ czynnika roboczego co prowadzi do braku szczelności między strefą ssawną i tłoczną oraz do obniżenia ciśnienia eksploatacji i sprawności ogólnej pompy. W niniejszym artykule przedstawiono możliwość wykrycia stopnia zużycia tarczy rozrządczej tłokowej pompy osiowej, za pomocą czasowo-częstotliwościowych metod analizy sygnałów pomiarowych. Wykorzystano do tego celu krótko-czasową transformatę Fouriera *STFT* oraz uogólniony algorytm Wignera-Villa *WVD*.