AN APPLICATION OF SPLINES IN SYNCHRONOUS ANALYSIS OF NONSTATIONARY MACHINE RUN

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Summary

As an addition to the order analysis procedures is an approximation of a discrete measurement result by a cubic splines which allows further signal analysis also by analytical means without preliminary large oversampling of a vibration signal. The proposed simple algorithm of conversion from dynamic time scale to momentary cycle time scale of a machine proved itself practically useful by supporting the diagnosis of gearboxes and bearing with use of amplitude spectrum also during the exploitational variations of rotation speed.

Keywords: vibroacoustics, diagnostics, order analysis.

WYKORZYSTANIE FUNKCJI SKLEJANYCH W ANALIZIE SYNCHRONICZNEJ NIESTACJONARNEGO BIEGU MASZYN

Streszczenie

Uzupełnieniem dotychczasowych procedur analizy rzędów jest tu aproksymacja dyskretnego rezultatu pomiaru sklejanymi wielomianami stopnia 3- co umożliwia dalsze badanie sygnału także na drodze analitycznej i pozwala uniknąć wstępnego znacznego nadpróbkowania sygnału drgań. Proponowany, stosunkowo prosty algorytm konwersji skali czasu dynamicznego na skale czasu cyklu chwilowego maszyny sprawdził się w praktyce analizy rzędów wspomagając diagnozowanie przekładni zębatych i łożysk tocznych z wykorzystaniem widm amplitudowych także podczas eksploatacyjnych zmian prędkości obrotowej.

Słowa kluczowe: wibroakustyka, diagnostyka, analiza rzędów.

1. INTRODUCTION

Let us consider objects where repeated interactions of elements or moving medias exist. The sequence of chosen event series of main target completion [4, 6] repeats in time intervals defined as momentary cycle Θ_k. The following appearances Θ_k are not identical even in good technical state and settled conditions of machine run (hence the cyclic movement is not a synonym for periodical movement).The diagnosis of cyclic machines in variable work conditions causes spectrum load which in turn causes the lack of selectivity of stems corresponding to particular harmonics of rotation speed.

As an example the Fig. 1 shows amplitude spectrum of offset vibration of shaft with a disc with speed increase of 0.6% per cycle. The spectrum blur could be seen.

Only one harmonic independent from the rotation speed could be clearly seen (of frequency 100Hz), in a diagnostic sense it is disturbance related to the supply voltage of the drive system. From that example one can state that diagnostics of machines in run-up or run-down state can not be held by means relevant to stationary signals. Nonstationarity causes spectrum load and it seizes to be a state symptom. Even small changes in speed cause the lack of stem selectivity for primary harmonic which impairs making unequivocal diagnostic decisions. The research presented in [3] shows that relative change in run cycle in the range of 0.1% have a negative effect on the diagnosis outcome.

The remedial mean is search for signal changeability definition in another time scale such that:

– changeability definition simplifies
– significant features of informational changeability are preserved
– non-informational changeability reduces

One of them is the order analysis.

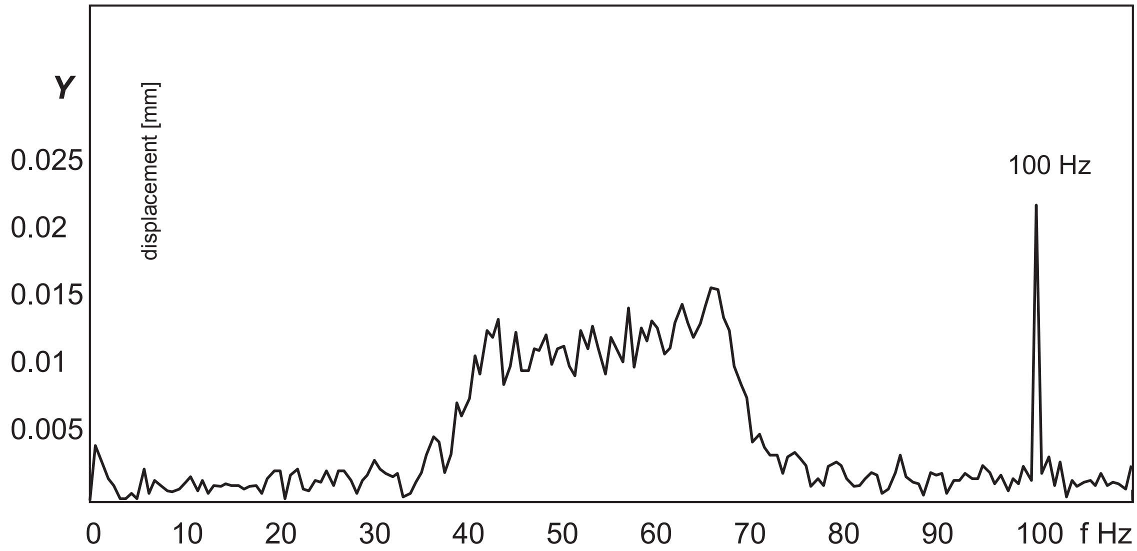

Fig. 1. Amplitude spectrum of offset vibration of shaft with a disc.
Blur of kinematic lobes due to rpm growth

2. TIME SCALE CONVERSION

If assumed [3], that the valuable information transfer is organized through cycle, then its length might be a conditional time unit η. Let us assume that:

- the run η, timed by cycle is uniform and in real-time scale '*t*' it is not (see fig. 2b), since the cycles are not of equal length.
- The scale 'η' might be recreated by non-uniform sampling – such that not only the number of samples per cycle was uniform, but also their distribution throughout of the cycle was similar in each cycle and related to similar events in the range of scale transformation. The number of momentary cycles should be equal in both scales.

For rotating machines the cycle time is conditioned by an rotational movement. The most used tachometric measurement allows simple presentation (see Fig. 2b) and formalizes the rule of dynamic time scale 't' transformation into cycle time scale 'η'.

Let *m* be the number of position markers per 1 rotation *a*, Δφ be the rotation angle increase – thence:

$$m\Delta\varphi = 2\pi = 2\pi\sum_{k=1}^{m}\frac{\Delta t_{tk}}{\Theta_{tk}}$$

$$\Delta\varphi = \text{const},\ \Delta t_k = \text{var} \qquad (1)$$

where Θ_{tk} = momentary values of the cycles in moments t_k,

The set of reference events $\{z_k\}$ is defined by moment t_k of the angle detection markers (Fig. 2b).

Those moments are the reference for the clock counting momentary cycle count Θ,

$$\{z_k\} \Rightarrow \{\eta_k\} = \{k\}$$
$$\Delta\varphi \Rightarrow \Delta\eta \quad \{t_k\} \Rightarrow k\Delta\eta \qquad (2)$$

timed uniformly, as Δφ = const for Δη= const.

For the range *T* including *1…n…M* cycles:

$\eta \in [0, mM]$, $t \in [0, T]$, the number of distinguishable moments η from the beginning of counting defines 'now' according to:

$$\eta_{now} = m(n-1) + k \quad k = 0,\ m-1$$

Δη − unitary range

In case of persistent cycle change $\Theta(t)$ the transformation formula takes the form (3)

$$\frac{d\eta}{dt} = \frac{1}{\Psi\left[\Theta(t)\right]} \qquad (3)$$

$\psi_k(\Theta)$ − characteristic of momentary cycle. The choice of operation ψ - decides of reference event set of clock η, the practical usefulness of that new scale in diagnostics and of completion method and complexity of the transformation procedure [3 4 5].

It is worth to notice that the number of observed moments η is in practice finite. The value of m/2 denotes the expected range of order spectrum [1, 2]). Its increase not always is justified by a need, hinders the measurement and the result processing.

In practice, as the authors research shows, consideration of continuous nature of η by means of interpolation might be advisable, of which we speak later.

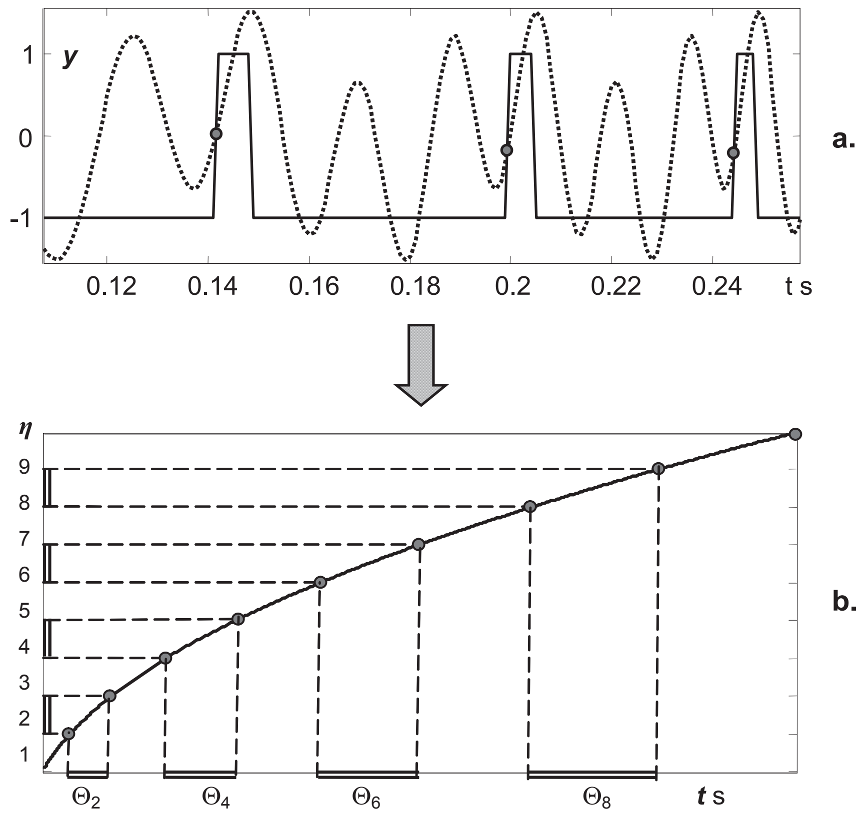

Fig. 2. The principle of order time clock synchronization
a) synchronizing impulse series b) curve ψ of time scale conversion ' t '⇒ 'η'

3. ORDER TRANSFORMATION

In the fig. 3a the set m of rotation angle markers defines the set of reference events (moments) of order time clock, synchronized by momentary cycles. In a new time scale the subsequent synchronizing cycles are of equal length and the description of signal changeability simplifies. Then the trend and the work cycle fluctuations might be reduced to allow usage of analysis methods relevant to stationary signals [2, 4].

Simultaneous ranges Θ_k of dynamic time t correspond to non-uniform sampling in the scale 't', since Δt_k = var. But the measured signal is sampled uniformly and the demand of constant number of samples per cycle is not met.

How to handle this?

Large preliminary oversampling of the signal y allows improvement of synchronization through choice of samples proportional to linear approximation of work cycle changes – that is how linear decimation procedure PLD works [3]. Such an estimation well recreates the spectrum of rotation harmonics and the angle modulation in the range of monotonic cycle changes. In case of standard measurement equipment the demand of 50-100 fold oversampling might be impossible to be met.

For such conditions it is possible to resample the signal by means of cubic splines interpolation.

The method described below uses splines for inter-sample approximation of signal $\boldsymbol{y}$. The stages of such a order analysis are presented by Fig. 3. and following is the short description:

– normalized synchronizing pulses of phase marker signal (Fig. 3b) split the analyzed signal $\boldsymbol{y}$ to particular cycles Θ_k corresponding to rotation angle $\varphi = 2\pi$;
– by synchonization with m under-multiplicity of the 2π angle the sample subsets correspond to equal values of $\Delta\varphi_k = \Delta\varphi$, but not equal to $\Delta\Theta_k$ (Fig. 3b);
– for such subset in ranges of Θ_k (or $\Delta\Theta_k$) interpolated continuous function is created. In presented algorithm such function is build from cubic splines [2] (Fig. 3c)
– resulting continuous function is split into equal time sections $\Delta\eta$. A mean value is calculated for each section creating data vectors $\boldsymbol{u}_k$ of the same length corresponding to subsequent $\Delta\varphi$ (Fig. 3c);
– the resulting data vector $\boldsymbol{u} = [\boldsymbol{u}_k]$ describes the signal $\boldsymbol{y}$ changeability in scale 'η' of order time.

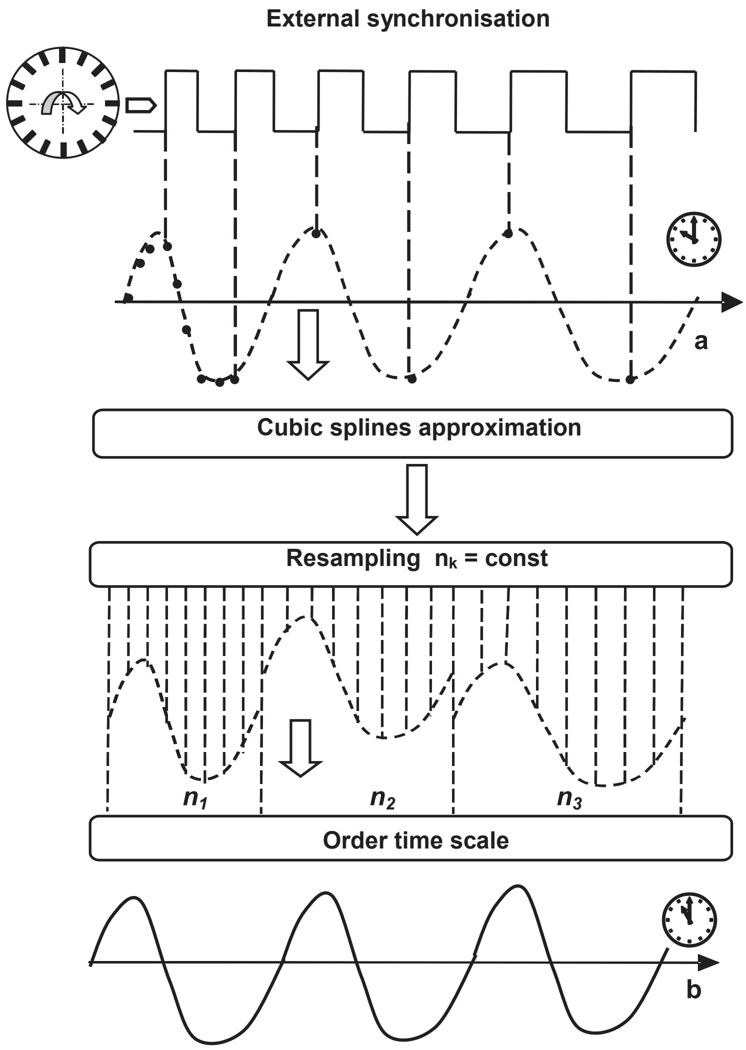

Fig. 3. Order transformation using splines approximation
a) real-time clock, b)order-time clock

5. NOTES ON PRACTICAL USE

Apart from procedure programming the correct synchronization is important which is conditioned by:

The synchronizing cycle choice - the procedure filters the rotation harmonic corresponding to synchronizing cycle transforming it to the stationary signal whereas stationary parts of the signal become nonstationary in order time scale and corresponding spectra diffused and heavily loaded

Synchronizing signal forming – mean square error of order spectrum component and its number depends on the resolution and measurement accuracy of encoder disc

Normalization – the aim of this operation is precise definition of beginnings of subsequent $\Delta\varphi_k$ (see Fig. 2a). In given case normalization means the calculation of i-th derivative of phase marker signal and zeros detection with considerations of function monotonicity and signal level variation hysteresis.

Scaling – necessary for whole measurement and processing channel of ***y***, ***u*** if the values of spectrum stem have the diagnostic interpretation. It is also important to define the conversion range 't' $\Rightarrow$ 'η' considered as satisfying.

An example

Here the result presentation as RMS spectra of a gearbox in the range of rotation harmonic serves only as a mean to compare the effects of order transformation to the original signal spectrum, thence the scaling is omitted with the scale similarity kept. Both simulated (Fig. 4) and real signal spectra (Fig. 5) has been compared. It's seen that spline approximation provides more details in low frequency domain o kinematic spectra.

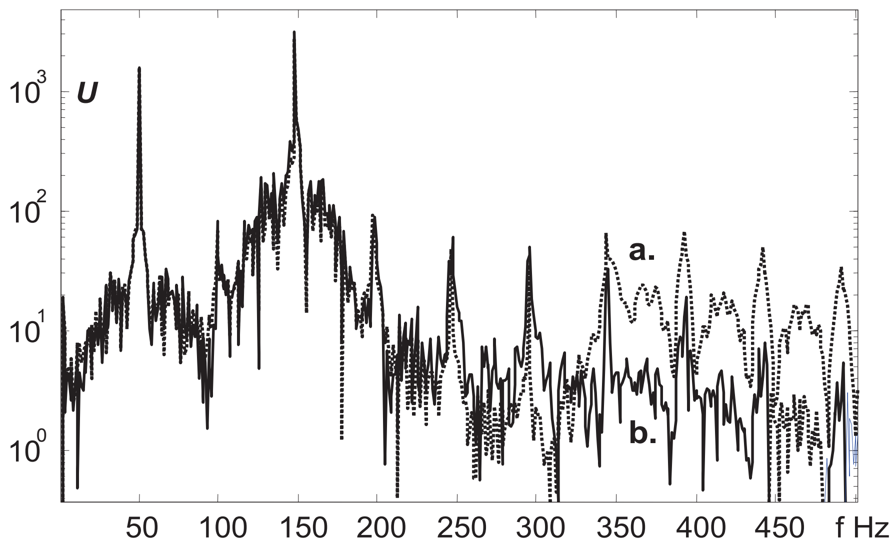

Fig. 4. Order spectra of simulated signals: a) linear approximation, b) 3-rd order spline approximation

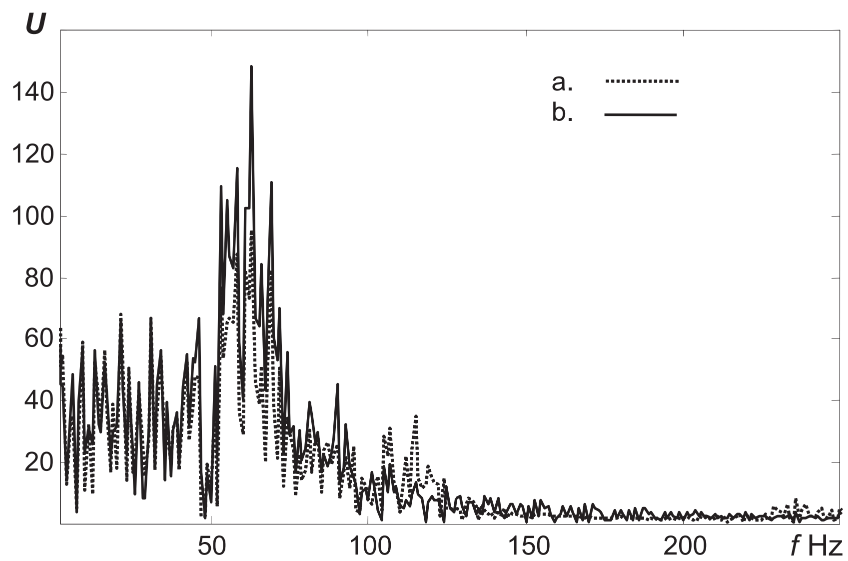

Fig. 5. Order spectra of bevel gear vibrations: a) linear approximation, b) 3-rd order spline approximation

6. CONCLUSION

In recent applications the described method proved to be fairly effective in analysis of vibration of gearboxes and bearing of rotating machines with the exploitational variations of rotation speed.

Calibration with non-stationary modeling signals showed its superiority (at least in the tested range) over the popular algorithm of order analysis using resampling and low-pass filtering.

Main advantages are:

– Harmonic spectrum dynamics < -40dB.
– Square mean error < 5%.
– Possibility of application for classic data analysis methods.
– Fast and simple algorithm.

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8. GLOSSARY OF SYMBOLS

DPR	–	dynamic residual process;
MVS	–	machine vibration signal;
OT	–	Order transform;
PDI	–	Diagnostic identyfication procedure;
PLD	–	linear decimation procedure;
TSC	–	Time scale conversion;
$\psi(\Theta)$	–	synchronizing cycle characteristic;
$\Delta\varphi$	–	angular step of synchronization;
Θ	–	characteristic cycle;
Θ_o	–	Duty cycle;
$\boldsymbol{y}$	–	original measured signal;
$\boldsymbol{u}$	–	final signal after TSC;
'η'	–	order time scale;
'*t*'	–	real time scale;
$\boldsymbol{s}_F$	–	characteristic signal;
T	–	przedział obserwacji sygnału;
η	–	cycle time;
z_k	–	referential event;

Dr inż. **Tomasz KORBIEL** jest adiunktem w Katedrze Mechaniki i Wibroakustyki AGH. Jego zainteresowania związane są z diagnostyką techniczną, analizą sygnałów oraz nowoczesnymi systemami pomiarowymi.

Dr hab. inż. **Piotr KRZYWORZEKA,** prof. AGH pracuje na tej uczelni od ukończenia studiów. Wykładał kilka lat w Algierii. Jest autorem ok. 90 publikacji, głównie o tematyce diagnostycznej, rzeczoznawcą SEP w zakresie elektroakustyki, a także członkiem PTDT od momentu jego powstania. W pracy badawczej preferuje podejście sygnałowe. Interesuje się także psychologią i filozofią. Jako środek transportu preferuje rower.