AVERAGING OF THE VIBRATION SIGNAL WITH THE SYNCHRONIZING IMPULSE LOCATION CORRECTION IN TOOTH GEAR DIAGNOSTICS

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Summary

One of the methods applied to detect pinion or gear wheel damage is an analysis of a signal synchronously averaged by the rotation period of a pinion shaft or gear shaft, respectively. For technical reasons, it is often impossible to record the reference signal directly connected with the diagnosed wheel in industrial conditions. The signal is then connected with a rotating element available outside the gear. As a result of torsional vibration in a system of shafts or gear casing vibration in a place where the shaft's angular position sensor is fixed, or in consequence of a too slowly rising reference signal edge, a synchronizing impulse occurs at wheel's angular positions varying by an insignificant value. This paper presents the usefulness of time-delay estimation methods in the process of vibration signals' synchronous averaging.

Keywords: signal averaging, time-delay estimation, diagnostics, toothed gear.

WYKORZYSTANIE UŚREDNIANIA SYGNAŁU DRGANIOWEGO Z KOREKCJĄ POŁOŻENIA IMPULSU SYNCHRONIZUJĄCEGO W DIAGNOSTYCE PRZEKŁADNI ZĘBATYCH

Streszczenie

Jednym ze sposobów wykrywania uszkodzeń zębnika lub koła jest analiza sygnału uśrednionego synchronicznie odpowiednio okresem obrotu wału zębnika lub koła. W warunkach przemysłowych ze względów technicznych często nie jest możliwe rejestrowanie sygnału odniesienia związanego bezpośrednio z diagnozowanym kołem. Wtedy sygnał ten wiąże się z dostępnym na zewnątrz przekładni elementem wirującym. Na skutek drgań skrętnych w układzie wałów, drgań korpusu przekładni w miejscu mocowania czujnika położenia kątowego wału i często zbyt wolno narastającego zbocza sygnału referencyjnego impuls synchronizujący występuje przy położeniach kątowych koła różniących się o niewielką wartość. W niniejszym artykule przedstawiono przydatność metod estymacji przesunięcia czasowego w procesie uśredniania synchronicznego sygnałów drganiowych.

Słowa kluczowe: uśrednianie synchroniczne, estymacja opóźnienia czasowego, diagnostyka.

1. INTRODUCTION

In rotor machines, some processes repeat in cycles. For toothed gears with permanent axles, the processes are: the period of entering into contact by the same teeth couple, the pinion or wheel shaft rotation period, and the meshing period connected with the frequency of meshing. In the diagnostics of machinery and appliances containing rotating components, synchronous averaging is applied to improve the signal-to-noise ratio and eliminate constituents not connected with the rotation period of a selected element [1, 4, 5]. Attempts are often made to detect damage of selected elements of the diagnosed object. In such case, it is necessary to determine the diagnosed element's rotation period as well as the period in which the damage will generate disturbance of the measured vibration signal. Application of synchronous averaging in the right period will reduce in that case the impact of disturbance not connected with the damage. Drawing conclusions about the occurrence of damage based on the averaged signal will be thereby more effective. However, one should bear in mind that by applying synchronous averaging connected with the pinion shaft rotation period, e.g. in a toothed gear with permanents axles, the information connected with the wheel shaft rotation period gets lost, and vice versa, except for a case where the gear ratio equals 1.

In industrial toothed gears, for constructional reasons, the reference signal used in the averaging process connected with the rotating element can be most easily recorded on the shaft running outside the gear. A remote distance of the signal recording place from the diagnosed wheel, torsional vibration in the gear shaft system, as well as a too slowly rising synchronizing signal edge, make the synchronizing impulse occur at wheel’s angular positions varying by an insignificant value. The differences are particularly important for constituents of a high frequency signal and when diagnosing local damage of wheels generating impulse disturbance, whose duration is comparable to the synchronizing impulse deviation.

2. EXPERIMENTAL RESEARCH

Experimental research was conducted, whose aim was to detect local chipping of a pinion’ or gear’s tooth. The damage was modelled by shortening the tooth’ tip [6, 8]. Both the vibration accelerations of selected points of the gear casing and the velocity of its shafts' transverse vibration were measured. The reference signals corresponding to the shafts' rotation were also synchronously recorded. During testing, the gear was loaded with the moment M_h=207 Nm, with the pinion's rotational speed amounting to 2700 rpm.

3. SYNCHRONOUS AVERAGING OF VIBRATION SIGNALS

Any deviations in the workmanship of gear components, in particular toothed wheels, make it difficult to detect gear damage [8], since a tooth couple with a considerable resultant deviation of pitch, when coming into contact, generates a force impulse similar to that generated during the wheels’ interaction with the damaged tooth. The impulse maximum value is influenced by both the damage scale and the deviations in the workmanship of the interacting teeth. Therefore, the course of the vibration recorded when the pinion enters into contact with a damaged wheel tooth, where the total deviation in the workmanship of such couple is relatively small, differs from the vibration course where the deviation is greater. Figure 1 presents the course of pinion shaft’s transverse vibration velocity averaged with the teeth couples’ repetition period in the case of considerable chipping of a wheel tooth to a depth of 3 mm. As a result of chipping, the contact ratio CR for the damaged tooth reduced locally from 1.33 to 0.71. Two local increases in the vibration amplitude are visible here, caused by chipping of a tooth in a wheel interacting with different pinion’s teeth, varying in amplitude and duration.

In diagnosing, the acceleration of selected points of gear casing is measured most often. The differences between changes in the signal, caused by local damage, may be even greater. In such case, detection of damage will be much easier when based on an analysis of a signal synchronously averaged by the wheel revolution period.

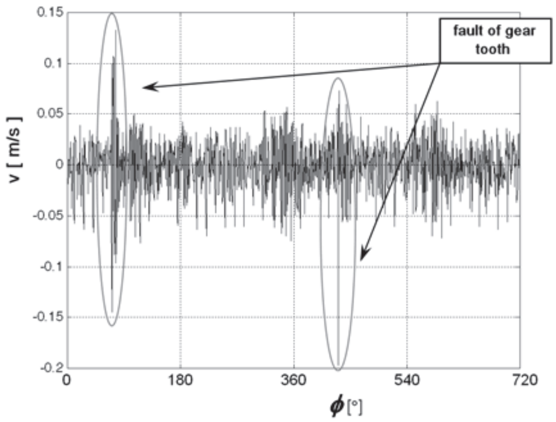

Fig. 1. Pinion shaft vibration velocity signal averaged by the repetition period of teeth couples presented as a function of the wheel rotation angle

As a result of torsional vibration in a system of shafts or gear casing vibration in a place where the shaft’s angular position sensor is fixed, some shifts of the synchronizing impulse take place in relation to the wheel. The shifts may increase as the distance between the reference signal recording place and the investigated wheel grows. For technical reasons, it is often impossible to record the reference signal directly connected with the diagnosed wheel in industrial conditions. The signal is then connected with a rotating element available outside the gear.

By analyzing the overlapping averaged time signals of pinion shaft's transverse vibration (Fig. 2) when the synchronizing impulse location was not initially corrected, it was found that the impulse location deviation equaled ±2 sampling periods, i.e. ca. $\pm 1^{o}$ of shaft’s revolution. To minimize the impact of the deviation, a computational correction of the synchronizing impulse location was made by utilizing time-delay estimation between the successive recorded periods of averaged time signals. It was significant, since the duration of impulse coming from a damaged tooth amounted to $0.12 \div 0.16 \cdot 10^{-3}$[s], i.e. 3÷4 of the sampling periods with the sampling frequency applied. For this reason, the averaging synchronization impulse should be very accurately correlated with the wheel’s angular position, since any deviation in its position may lead to removal of the information about the appearing damage from the averaged signal.

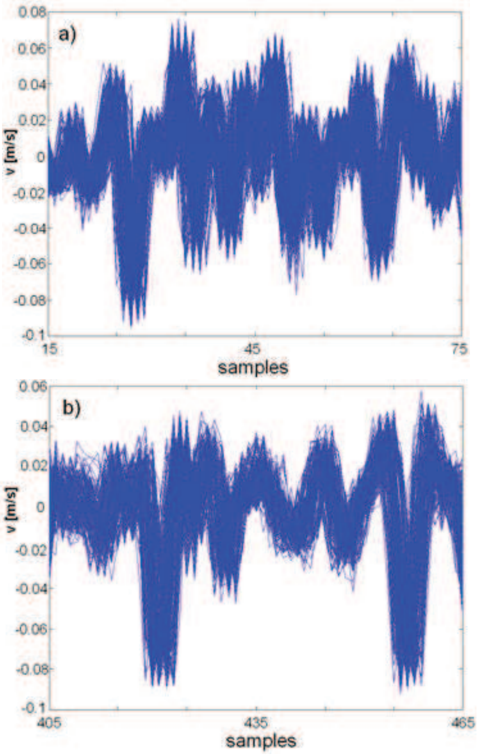

Fig. 2. Overlapping of averaged time signals of pinion shaft's transverse vibration velocity – uncorrected location of synchronizing impulse, a) signal fragment from 15th to 75th sample, b) signal fragment from 405th to 465th sample, pinion's rotation period – 572 samples

Before applying time-shift estimation, a fragment was selected of the vibration time signal, equal to the averaging period in relation to which the time-shift was determined. It was the time signal fragment best correlated with the other periods. Usefulness of the time-shift methods available in the Matlab system [7] was checked. First, the time delay was determined using a method based on the third-order cumulants (TDE). The method will be presented using an example with the signals: *x* and *y*.

$$x(t) = s(t) + \varpi_x(t), \quad (1)$$

$$y(t) = A_m \cdot s(t - D_t) + \varpi_y(t). \quad (2)$$

The signals can be also presented in a form useful for a digital analysis:

$$x(n) = s(n) + \varpi_x(n), \quad (3)$$

$$y(n) = A_m \cdot s(n - D) + \varpi_y(n), \quad (4)$$

where:

s - stationary process,

A_m – relative amplitude multiplier,

D_t - signal y shift in relation to signal x,

D - signal y shift in relation to signal x, expressed in sampling periods,

ϖ_x and ϖ_y – noise.

The third-order cumulants of signal $s(t)$ according to [2] are described by the dependence:

$$C_{sss}(\tau_1, \tau_2) = E\{s(t)s(t+\tau_1)s(t+\tau_2)\} = \frac{1}{T}\int_0^T s(t)s(t+\tau_1)s(t+\tau_2)dt, \quad (5)$$

where:

T – observation time of signal $s(t)$.

The third-order cumulants in a form useful for a digital analysis are described by the dependencies [7]:

$$C_{xxx}(q,\rho) = E\{x(n)\, x(n+q)x(n+\rho)\}, \quad (6)$$

$$C_{yxx}(q,\rho) = E\{y(n)x(n+q)x(n+\rho)\}. \quad (7)$$

If signal $s(t)$ is not a Gaussian signal and noises $\varpi_x(t)$ and $\varpi_y(t)$ are non-Gaussian noises, the third-order cumulants can be used even where the noises are correlated. If *P* is the maximum expected shift and assuming that shift *D* is an integer, we obtain [7].

$$y(n) = \sum_{i=-P}^{P} a(i)x(n-i) + \varpi(n), \quad (8)$$

where:

$a(n)=0,\ n \neq D,\ i\ a(D)= A.$

By utilizing (8) and (7), we obtain:

$$C_{yxx}(q,\rho) = \sum_{i=-P}^{P} a(i)C_{xxx}(q+i, \rho+i). \quad (9)$$

By applying this equation for different values of ρ and q, we will obtain a system of linear equations $a(i)$:

$$\mathbf{C}_{xxx}\mathbf{a} = \mathbf{c}_{yxx}. \quad (10)$$

The estimated delay is marked with index *n,* at which $|a(n)|$ reaches its maximum.

It is important that the allowable signal shift *P* cannot be too large. In particular, *P* must always be smaller than the number of samples falling on a shaft's rotation by one meshing pitch, otherwise, the signals may get completely desynchronized.

In order to obtain the best results, the following numbers of samples were used to calculate the third-order cumulants: n_{samp} = 256, 128, 64, 32, 16. The best results were obtained where n_{samp} = 32 samples (Fig. 3). Compared to Fig. 2, improvement was visible.

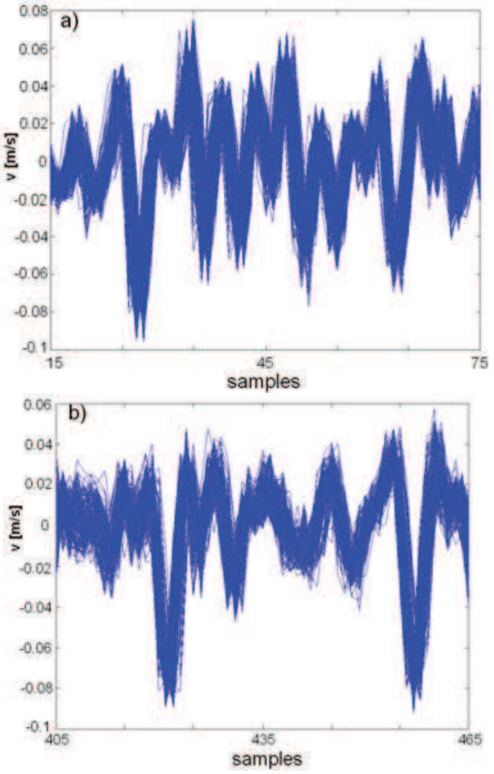

Fig. 3. Overlapping of averaged time signals of pinion shaft's transverse vibration velocity – location of synchronizing impulse corrected by means of the TDE method, $n_{samp} = 32$, a) signal fragment from 15th to 75th sample, b) signal fragment from 405th to 465th sample

The next method applied was the time-delay estimation using cross-bispectrum (TDEB). The auto- and cross-bispectra are defined as follows [7]:

$$B_{xxx}(f_{B1}, f_{B2})=E\{X(f_{B1})\ X(f_{B2})X^*(f_{B1}+f_{B2})\}, \quad (11)$$

$$B_{xyx}(f_{B1}, f_{B2})=E\{X(f_{B1})\ Y(f_{B2})X^*(f_{B1}+f_{B2})\}. \quad (12)$$

The absolute value $h(\tau)$ determined from dependence [7]:

$$h(\tau)=\int d f_{B1}\int df_{B2}\ exp(j2\pi f_{B2}\tau)\frac{B_{xyx}(f_{B1}, f_{B2})}{B_{xxx}(f_{B1}, f_2)}, \quad (13)$$

reaches its maximum at τ equal to the real shift D_t of signal y in relation to signal x.

Fig. 4 shows the overlapping of signals where the location of synchronizing impulse was corrected by means of the TDEB method and where the number of samples FFT (n_{FFT}) equalled the number of samples corresponding to the pinion rotation period. The calculation time was then much longer than where the TDE method was applied.

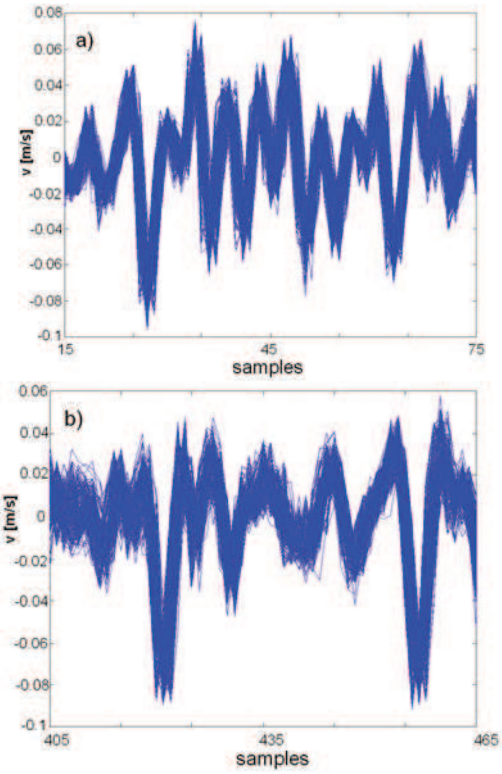

Fig. 4. Overlapping of averaged time signals of pinion shaft's transverse vibration velocity – location of synchronizing impulse corrected by means of the TDEB method: a) signal fragment from 15th to 75th sample, b) signal fragment from 405th to 465th sample

Fig. 5a presents the pinion shaft's vibration velocity signal averaged by the pinion's rotation period, obtained by applying a correction of the synchronizing impulse location. The arrow shows the local maximum coming from the damaged pinion tooth; also, the time intervals are marked, in which the overlapping time signals were presented before averaging – Fig. 2÷4.

Fig. 5b shows the pinion shaft's transverse vibration velocity signal averaged by the pinion's rotation period, where the location of synchronizing impulse was not corrected. When compared to the signal presented in Fig. 5, a reduction of the signal amplitude is visible.

In the spectra of those signals, as shown in Fig. 6, differences in the values of constituent amplitudes are also visible. The differences grow as the frequency increases.

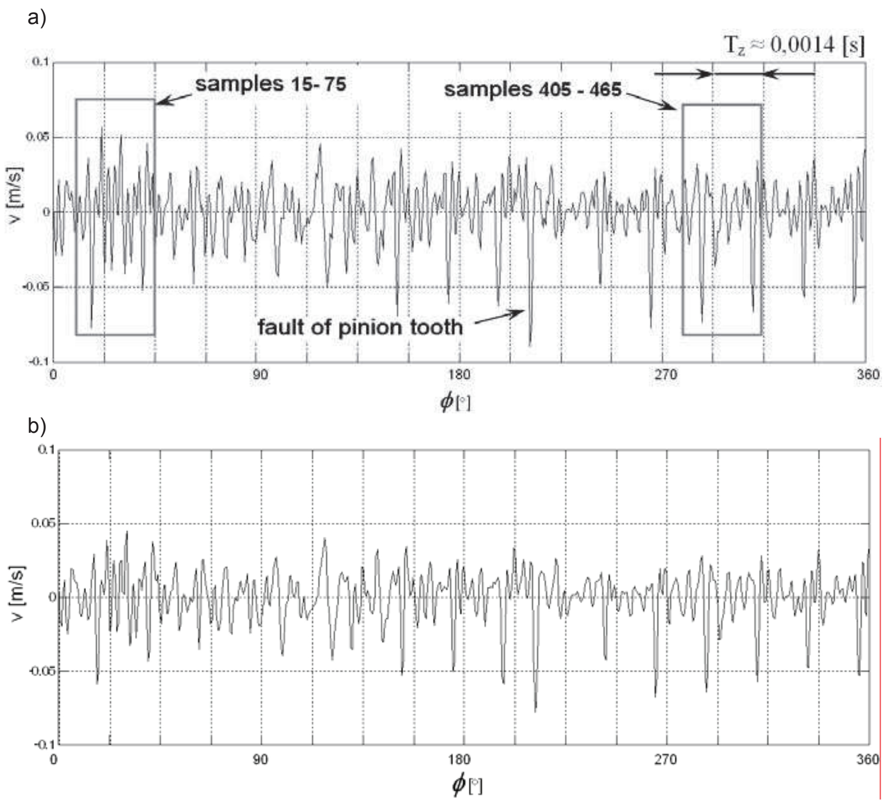

Fig. 5. Course of the pinion shaft's transverse vibration velocity averaged by the pinion's rotation period - chipping of pinion tooth to 3 mm, corresponding to *CR* = 0.96: a) the synchronizing impulse location was corrected, b) the synchronizing impulse location was not corrected

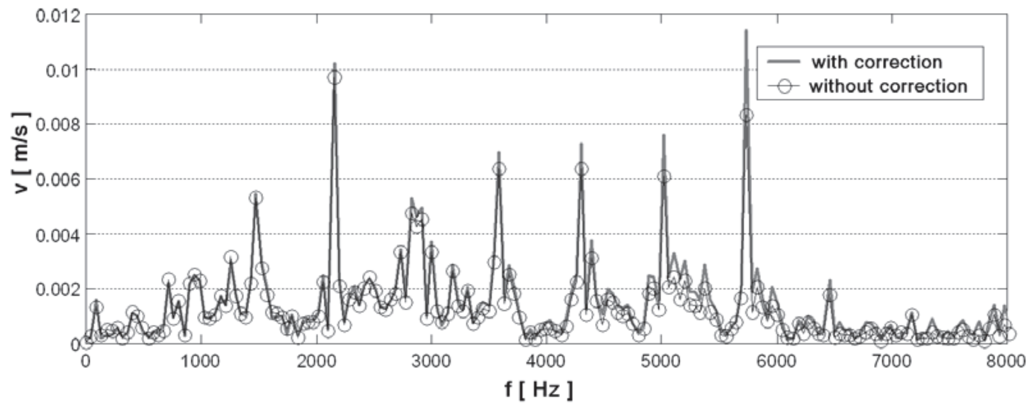

Fig. 6. Averaged signal spectrum before and after correction of the synchronizing impulse location

4. CONCLUSIONS

Based on the research conducted it can be concluded that:

- In the case of averaging the vibration signal when diagnosing toothed gears, it is purposeful to apply correlation of the synchronizing impulse location.
- The time-delay estimation using cross-bispectrum (TDEB) proved to be the best method to determine the correction of the synchronizing signal location for a toothed gear shaft's vibration velocity signal.
- It seems useful to apply this method for averaging the time signals when diagnosing other components of machinery and appliances.

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