LASER DOPPLER VIBROMETER AND IMPULSE SIGNAL PHASE DEMODULATION IN ROTATION UNIFORMITY MEASUREMENTS

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Abstract

The paper deals with two methods for measurements of angular vibration during rotation, which is a source of machine vibration and consequently emitting noise. Characteristics of the angular vibration allow studying noise and vibration problems at its very source. The first mentioned method for angular vibration measurements is based on using a two-beam laser Doppler vibrometer and the second one on employing the phase demodulation of impulse signals produced by incremental rotary encoders (IRC) or by the teeth of a toothed wheel. The phase demodulation requires using some post-processing to get a result in the form of the phase variations. The laser output signal is proportional to the instantaneous angular velocity while the phase signal has to be converted in angular frequency by the phase differentiation with respect to time. To obtain the angular acceleration, which is proportional to the driving moment or braking torque, the velocity signal has to be converted to the acceleration signal using the angular frequency differentiation with respect to time again. The accuracy of the phase demodulation is depending on the errors in the IRC impulse grating period. Encoder error analysis is an important part of the paper.

1. INTRODUCTION

The main sources of rotating machine vibrations are rotor unbalance, misalignment of shafts and non-uniform driving torque. All these excitations result in a dynamic force acting the bearing supports. Bearing vibration excites vibration of the machine housing, which increases the noise level. This paper is focused on the shaft angular vibration as a consequence of the non-uniformity of a driving torque.

Rotational speed is measured in terms of the number of revolutions per minute (RPM) while the angular vibration is measured in terms of the angle, angular velocity or angular acceleration. The uniform rotational speed at the constant RPM corresponds to an increase in the shaft rotation angle proportionally to the elapsed time. The angle time history, having the form of the sum of a term that is depending linearly on time and a term that is randomly or regularly varying in time around zero, results from the angular vibration during rotation. The angular velocity is obtained as the first derivative of the angle while the angular acceleration is computed as the second derivative of the angle.

There are many possible approaches to measuring angular vibration during rotation
- Tangentially mounted accelerometers
- Laser torsional vibration meters based on the Doppler effect
- Incremental rotary encoders (several hundreds of pulses per revolution).

In practice, measurements based on the use of encoders dominate. Instantaneous angular velocity is proportional to the reciprocal value of the time interval, which elapses between consecutive impulses. The measurement methods for the length of the time interval are as follows:

- Sample number & Interpolation
- High frequency oscillator (100 MHz) & Impulse counter
- Phase demodulation.

The simplest method for evaluation of the instantaneous rotational speed is the reciprocal value of the time interval between two consecutive pulses. If the impulse signal is sampled then the time interval between the adjacent impulses is determined by the count of samples and interpolation of some values, which results in 50 times more accuracy of the time interval length than is indicated by the actual sampling interval. The accuracy is satisfying for the RPM measurement based on only one pulse per shaft rotation. This method is not suitable if a large number of pulses per revolution is generated, which results in a few samples in between successive impulses and the time interval length is impossible to estimate at a satisfying accuracy. If the strings of encoder impulses, as an analogue signal, controls a gate for the high frequency clock signal (up to 10 GHz) that is an input of an impulse counter, then this method works properly. This principle is implemented in the signal analysers produced by Rotec. The primary output of these analysers is angular velocity.

This paper is dealing with the angular vibration measurements based on impulse signal phase demodulation using the theory of complex analytic signals, an imaginary part of which is the Hilbert transform of its real part. The angular vibration measurement using the phase demodulation is compared with this measurement using the laser Doppler vibrometer.

2. PRINCIPLE OF THE PHASE DEMODULATION

The phase demodulation carried out the B"uel & Kjær signal analyser of the 3550 type, which has been produced since 1991. It seems that this signal processing method is marginalized now. In view of the paper’s author, there are two main approaches to the phase demodulation, namely the analytic signal, which is created using the Hilbert transform [1], and quadrature mixing. This paper is focused on the analytic signals. The signal containing information on the instantaneous angular velocity is an impulse signal produced by an encoder attached to the free end of the shaft. The encoders produce a train of impulses rather then a sinusoid. As the spectrum of the impulse signal consists of several harmonics of the basic impulse frequency, the first step in the phase demodulation procedure is to separate the frequency band containing a carrier component including sideband components by using a band-pass filter.

The second step in the process of demodulation is creating an analytic signal of the phase-modulated harmonic signal. The analytic signal is obtained from the original signal by extending this real signal by the imaginary part, which is the Hilbert transform of the real part.
There are two methods how to evaluate the Hilbert transform for sampled signals. The first one is based on using the Fourier transform [1] and the second one employs digital filters approximating the Hilbert transform as a non-causal digital filter [2,3].

The Fourier transform (FT) of real signals is composed from complex conjugate pairs of components with a positive and negative frequency (greater than the Nyquist frequency). The Hilbert transform in the frequency domain can be expressed as a frequency transfer function shifting the phase of each mentioned component by $-\pi/2$ or $+\pi/2$, which means multiplying them by either $-j$ or $+j$. The frequency range of the sampled real signals is limited to half the sampling frequency, $f_s/2$ (Nyquist frequency). Therefore, the argument of the transfer function is limited to the interval $(-\pi,+\pi)$.

$$G_{HT}(\exp(j\omega)) = \begin{cases} j, & +\pi > \omega \geq 0 \\ -j, & -\pi < \omega < 0 \end{cases}. \quad (1)$$

Let $x_n$ be a sample sequence, which is a real part of the analytic signal. The first step of the analytic signal imaginary part computation consists in shifting the phase of the FT components $X_k$, which are corresponding to the sample sequence $x_n$, to become the FT components $Y_k$, which are corresponding to a sample sequence $y_n$. The inverse Fourier transform of the FT components $Y_k$ results in the Hilbert transform of the sample sequence $x_n$, which is corresponding to the analytic signal imaginary part $y_n$. The analytic signal is a sequence of the complex quantities $x_n + j y_n$, where the index $n = 0,1,...,N-1$ designates the order of the samples in the input vector for the FT ($N = 2^n$).

The digital filter performing the Hilbert transform is called the Hilbert transformer. The ideal impulse response of this digital filter is as follows

$$g_{HT}(n) = \frac{1}{2\pi} \int_{-\pi}^{\pi} G_{HT}(\exp(j\omega))\exp(j\omega n) d\omega = \begin{cases} 0, & n = 2k \\ 2/\pi n, & n = 2k + 1. \end{cases} \quad (2)$$

The Hilbert transformer is a low pass, high-pass, or band-pass filter of the FIR (Finite Impulse Response) or IIR (Infinite Impulse Response) filter types. The order of the FIR filter is limited and turns to the causal filter while the filter linear phase is preserved. The phase-modulated harmonic signal $x_n$ is put into the Hilbert transformer to obtain the Hilbert transform $y_n$ giving the imaginary part of the analytic signal $x_n + j y_n$. The group delay of the Hilbert transformer, which is created using the FIR filter, is equal to half the digital filter order; therefore the real part of the analytic signal $x_n$ is delayed by the corresponding number of samples.

The angle $\phi_n = \arctan(y_n/x_n)$ for the complex values $x_n + j y_n$ ranges from $-\pi$ to $+\pi$ and contains jumps at $-\pi$ or at $+\pi$. The true phase $\phi_n$ of the analytical signal as the time function has to be unwrapped. The unwrapping algorithm is based on the fact that the absolute value of the phase difference $\Delta\phi_n = \phi_n - \phi_{n-1}$ between two consecutive samples of unwrapped angle sequence is less than $+\pi$.

$$\Delta\phi_n < -\pi \Rightarrow \phi_n + 2\pi \rightarrow \phi_n, \quad \Delta\phi_n > +\pi \Rightarrow \phi_n - 2\pi \rightarrow \phi_n. \quad (3)$$

The unwrapped phase change per one impulse rotation is equal to $2\pi$ radians. The phase
change, which is corresponding to one complete encoder revolution, is equal to the product of $2\pi$ and the number $K$ of the impulses per encoder revolution. To establish the dependence of the shaft rotation angle on the nominal revolution assuming the steady-state rotation, the phase normalization has to be computed is such a way as follows

$$\varphi_n / K \rightarrow \varphi_n, \quad n = 0, 1, \ldots, N - 1.$$  \hfill (4)

The normalised phase as a function of the nominal rotation is composed from a term, which is identical with the nominal rotation, and the phase variation determining the phase-modulation signal. After removing the linear term, the phase-modulation signal is obtained.

The additional noise in the measured signals can be reduced by synchronized averaging (filtration or signal enhancement). There are two possible ways how to do it. It is possible to average either the impulse signal or the phase-modulation signal. Both the solutions require to resample an impulse signal according to the rotational frequency in such a way that records, corresponding to the complete revolution, containing the same number of samples (usually power of two). After resampling signals the time unit (second) is replaced by the angle unit (nominal revolution) and the frequency in Hz is replaced by the frequency in order, which is a multiple of the base frequency, usually the shaft rotational frequency. The nominal rotation, which is equal to unity, corresponds to one complete revolution. The effect of the averaging order will be demonstrated in the example.

3. INCREMENTAL ROTARY ENCODER ACCURACY

Using the Fourier transform to compute the phase-modulation signal will be demonstrated by encoder accuracy testing. The encoders under test, shown in Figure 1, are of HEIDENHAIN origin, the ERN 460-500 type. To compute error in pulse distribution against the angle of rotation, both the encoders were mounted on a shaft what ensured their same rotational speed (see Figure 2). Accuracy was assessed at the rotational speed of 1040 RPM. The pulse string generated by the encoders was sampled at the frequency of 65536 Hz.

![Figure 1. Heidenhain encoders of the ERN 460-500 type (500 pulses per revolution)](image1)

![Figure 2. Arrangement of encoders to be tested](image2)

![Figure 3. Autospectrum of phase modulated signal generated by the encoders E1 and E2](image3)
As the running was not perfectly uniform, both the impulse signals were under the influence of the same phase modulation. The encoder speed variation results in the phase modulation of the impulse signal base frequency. As noticed above the phase-modulated signal contains sideband components around the carrying component. The frequency of the carrying component is equal to 500 orders as it is shown in Figure 3.

Using the method described above, the phase difference between modulation signals of both the encoders gives the error in the distribution of impulses. The individual phase differences versus the nominal revolution are shown in Figure 4. The synchronously averaged phase difference of the 16 mentioned phase differences is shown as the blue line in Figure 5. The phase difference computed for the synchronous average of 16 resampled impulse signal records, which are corresponding to 16 successive revolutions, is shown in Figure 5 as the red line.

Figure 4. Individual phase difference for 16 complete revolutions vs. nominal revolution

Figure 5. Average of 16 phase differences (blue line) and phase difference for average of the impulse signal (red line)

Figure 6. Averaged spectrum of phase differences (blue line) and spectrum of averaged phase differences (red line)

Figure 7. Spectrum of the averaged impulse signals

The order spectra of the phase differences can be computed either for the signals shown in
Figure 4 or for the signals shown in Figure 5. It means that synchronous averaging is carried out in either the frequency or angle domain. The averaged spectrum in the frequency domain for the 16 individual phase differences is shown in Figure 6 (blue line). In the same figure the spectrum for the averaged phase differences in the angle domain is shown as well. The spectrum of the phase differences based on the averaged impulse signals is shown in Figure 7.

The order spectra in Figure 6 and 7 have the frequency axis in orders. The quantity “order” determines a part of a circle related to the error level. For instance, the order 20 means the circle arc of the length, which is the twentieth part of the circle circumference. The corresponding spectrum value determines the RMS of the impulse-pair distance error. For incremental rotary encoders with line counts up to 5000, the maximum directional deviation at 20 °C ambient temperature and slow speed (scanning frequency between 1 kHz and 2 kHz), lies within ± 1/20 grating period. The encoder producing 500 impulses works with the maximum error in impulses distribution of 0.036 degree. The distance error for a pair of impulses at the twentieth part of the circle circumference is a value less than 0.0001 degree.

It is evident that the error level in Figure 6 in relation to the error level in Figure 7 is a little bit less. It can be recommended to prefer the computation of the phase-modulation signal for each rotation to the computation of the average impulse signal before the phase demodulation.

3. COMPARISON OF THE LASER TORSIONAL VIBRATION METER AND ENCODER INCREMENTAL ROTARY ENCODER MEASUREMENT

The laser torsional vibration meter of a type 2523 of the BK origin consists of a meter and a dual-beam laser transducer. Without contacting a rotating component, this sensor primary determines the instantaneous changes in angular velocity from the frequency difference of the retroreflected, Doppler-shifted beams. Measurements are independent of the target cross-section. The heart of the system is a low power (less than 1.5 mW) Ga-Al-As laser diode producing 780 nm invisible light. The laser beam is split into two equal-intensity parallel beams separated by a distance of 10 mm. The angular velocity measurement range is ranging from 0.3 to 7000 degrees per second (RMS) and the frequency range from 0.3 to 1000 Hz.

The electric hand drill was employed as a source of the angular vibration during rotation. The measurements were realized while this tool was running at an idle speed of approximately 400 RPM. The encoder of the 460-1024 type, which is producing 1024 impulses per revolution, was attached to the end of the spindle while the other end was fixed by the drill chuck. The plan of the laser beams was perpendicular to the spindle axis and the beams were focused on the cylinder of the 15 mm diameter as it is shown in Figure 8.
The laser and encoder output signals are sampled at the rate of 65536 Hz. It means about ten samples per an impulse as it is shown in Figure 9. The impulse signal contains many harmonics of the impulse base frequency, which is equal to 6656 Hz. As the phase demodulation works only for the phase-modulated harmonic signal, the impulse signal spectrum is limited to the frequency band 6656 ± 3000 Hz. This way of the passband filtration in the frequency domain, using the 65536-point FFT and IFFT, results in the purely phase-modulated signal. The impulse signal is transformed into the analytical signal using the 160-order FIR filter acting as the Hilbert transformer. The real and imaginary part of the analytic signal gives the signal phase limited to an interval from $-\pi$ to $+\pi$ radians. After unwrapping the phase and the phase normalisation to the spindle rotation (division by the number of the encoder impulses per revolution), the rotation angle as a function of time is obtained.

To compare the laser output signal, measuring the angular vibration in unit of degrees per second, with the result of the encoder signal phase demodulation, the phase, as the rotation angle, has to be differentiated with respect to the time to obtain the same unit of the phase demodulation output signal as the laser output signal. Taking into account that the spectrum of the laser output signal is cut down to a frequency of 1000 Hz, the 147-order FIR filter acting as a differentiator is combined with the low pass filter. The impulse and frequency response is shown in Figure 10 and 11.

Two FIR filters, which are used in successive steps, insert in the signal processing the delay, which is given by half the order sum of both the FIR filters. For the mentioned sample frequency, this delay of the angular vibration signal in relation to the laser output signal is equal to 2.288 ms.

To reduce the signal background noise, the synchronous averaging of the records, corresponding to the spindle complete revolution, is computed. The averaged angular velocity in degrees per second is shown in Figure 12 as a function of a nominal revolution, which is assuming the uniform rotation of the spindle. As it is evident, the laser signal is delayed in relation to the encoder signal by 3.296 ms. It can be explained by the internal filters employed in the laser measuring chain. It can be concluded that the laser total delay is about 5.584 ms.

The order spectrum, which is shown in Figure 13, confirms the almost identical results of measurement using the different measurement methods.

All the described algorithms are implemented in Signal Analyzer, the indoor software for supporting signal processing education, training and research.
CONCLUSIONS

The paper describes two methods for angular vibration measurement. The first one is based on the phase demodulation of impulse signals and the second one employs a two-beam Doppler laser vibrometer. The mentioned measurement method, which is based on using the phase demodulation, was demonstrated on the incremental rotary encoder accuracy testing and hand drill rotation uniformity. The second presented measurement demonstrates employing the laser vibrometer for angular vibration measurement and compares both the described measurement methods at the same time.

The comparison of the synchronous averaging in the angle and frequency domain results in recommendation according that it is better to average the modulation signal to average the input impulse signal. The matching of the encoder and laser measurements allows determination of the laser delay.

REFERENCES


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