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

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Outline

- Terminology note
- Motivation
- Transducers & Signal Processing Methods
- Principle of phase demodulation using Hilbert transform
- Accuracy of Incremental Rotary Encoders
- Comparison of Measurements Done with Laser and IRC
- Conclusion
Terminology Note: Nominal vs. Actual Angle of Rotation

It is assumed rotation at the steady-state rotational speed. In fact it is a time axis.

Nominal rotation:
- $\phi$ is the nominal angle of rotation, deg
- $0^\circ$ to $360^\circ$

Non-uniform (irregular) rotation:
- $\Delta \phi$ is the angle variation
- $0^\circ$ to $360^\circ$
Angular vibration as one of the important machine vibration and noise source.

- Angular vibration of a gear versus linear vibration on the gearbox housing (geared axis systems)
- Transmission error measurement of a gear train
- Measuring and analyzing car engine crankshaft rotational irregularities, caused by dynamic changes in torque
Gear Angular Vibration

Difference between actual and nominal rotation angle

Double differentiation

Angular acceleration

Linear acceleration on the gearbox housing
Test Stand for Transmission Error (TE) Measurements

Back-to-back test rig

\[ TE(m) = \left( \Theta_2 - \frac{n_2}{n_1} \Theta_1 \right) r_2 \]

Measurement range: ± 10 μm (microns)
Rotational irregularities of a car engine evaluated using an impulse signal for ECU

Crankshaft angular acceleration

Two complete revolutions

Engine idle speed: 800 RPM
Transducers & Signal Processing Methods for Angular Vibration Measurements

Transducers
- Tangentially mounted accelerometers
- Torsiograf
- Laser Torsional Vibration Meter (Doppler effect)
- Incremental rotary encoders (several hundreds of pulses per revolution)

How to process impulse signals?
- Time interval length measurements
  - Sample number & Interpolation
  - High frequency oscillator (10 GHz) & Impulse counter (Rotec)
- Quadrature mixing
- Phase demodulation
Transducers

Laser Torsional Vibration Meter, Brüel & Kjær Type 2523
- Dual-beam laser transducer based on the Doppler effect
- Laser: Ga-Al-As diode, 780 nm light
- Instantaneous changes in angular velocity
- Measurement ranges: 10, 100, 1000, 10000°/s
- Frequency range: 0.3 to 1000 Hz
- Accuracy: ±1% of full scale

Heidenhain Incremental Rotary Encoders
ERN 460-1024 type, 1024 impulses per revolution
ERN 460-500 type, 500 impulses per revolution
The maximum directional deviation is within ± 1/20 grating period.
Signal Analyzers for impulse signals

PULSE, the BK Signal Analyzers

Frequency range $F_R$:
- 25.6 kHz (65536 kHz samp freq)
- 102.4 kHz (256 kHz sampl freq)

Phase demodulation, including possible signal resampling for order analysis, requires 5 or 6 samples per impulse period at least.
Principle of Phase Demodulation

How to evaluate the instantaneous phase or frequency of a phase modulated harmonic signal?

Instantaneous phase may be evaluated for given sample $y_i$ and envelope $E_i$ using a formula

$$\varphi_i = \arcsin\left(\frac{y_i}{E_i}\right)$$

Problems: estimation of instantaneous envelope, measurement noise.

**Solution**: The creation of an analytic signal to evaluate phase and envelope.
Analytic Signal

\[ f_p = \omega_p^2 \]

Real harmonic signal

Complex analytic signal

\[ H(t) = X_p + jX_n \]

\( \omega_p = 2\pi f \)

\[ Z = 2X_p \]

Time signal + j Hilbert transform = Analytic signal

Envelope

\[ E(t) = \sqrt{x(t)^2 + y(t)^2} \]

Wrapped Phase

\[ \varphi(t) = \text{atan}(y(t)/x(t)) \]

Unwrapped Phase

\[ \varphi(t) = +\pi, +2\pi, +3\pi, \ldots \]

Wrapped Phase

\[ \varphi(t) = -\pi, -2\pi, -3\pi, \ldots \]
Phase demodulation based on the Hilbert transform

- Using FFT and Inverse FFT
  \[ X(j\omega) = FFT\{x(k)\} \]
  \[ y(k) = IFFT\{Y(j\omega)\} \]

- Using digital filters as the Hilbert transformer

\[ x(t) \rightarrow \text{Delay} \rightarrow \text{Hilbert Transformer} \rightarrow y(t) \]

Impulse Response

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Accuracy of Incremental Rotary Encoders

Gear train transmission error measurement

Wheel
Pinion

Two incremental rotary encoders

Required error is less than \(10^{-4} \text{ deg}\) (0.0001 deg) for a mesh cycle
Comparison of two encoders of the Heidenhain ERN 460-500 type

500 impulses per revolution

\[ F_s = 65536 \, \text{Hz} \]

Both encoders rotate at the same rotational speed

Global uniformity of rotation

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Order of Averaging Operation and Phase Demodulation

A - Impulse time signals
B - Averaging in time domain
C - Phase demodulation
D - Phase difference
E - Frequency spectrum
F - Inst frequency spectrum

(Signal Enhancement in BK Signal Analyzers)
Phase difference frequency spectra

16 phase differences

Averaging of impulse signals (A) and phase differences (B)

Averaged spectrum of phase differences (F)
spectrum of averaged phase differences (E)

Spectrum of the averaged impulse signals (D)
Phase Difference between Two Encoders of the ERN 460-500 Type

Averaged spectrum of phase differences

Wave length

Tooth-by-tooth rotation

Teeth

Maximum directional deviation

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Comparison of Measurements Done with Laser Torsional Vibration Meter and Incremental Rotary Encoder

Instrumentation

- Laser Torsional Vibration Meter
  Brüel & Kjær Type 2523
- Incremental Rotary Encoder
  Heidenhain ERN 460-1024 type
- PULSE, the Brüel & Kjær Signal Analyzer
- Sampling frequency 65536 Hz
Signal Processing Procedure

Laser Torsional Vibration Meter
- Sensor output signal is proportional to the instantaneous angular velocity

Incremental rotary encoder
- Band pass filtration with the centre frequency equal to the mean frequency of the impulse signal
- Computation of the Hilbert transform of the phase modulated harmonic signal using the Hilbert Transformer
- Computation of the wrapped phase using ATAN function for real and imaginary coordinates in the complex plane
- Unwrapping phase
- Computation of the first derivative of the phase with respect to time to obtain a signal proportional to the instantaneous angular frequency
Band Pass Filtration

Impulse signal

Phase modulated harmonic signal
Differentiation with Respect to Time

- Impulse signal
  - Band pass filtration
  - Harmonic signal
    - Phase demodulation
      - Phase (Angle)
        - Differentiation with respect to time
          - Angular velocity

Impulse response

Frequency Response: Ideal Diff FIR Filter

Magnitude in dB

Time, s

Frequency, Hz
Averaged Time Signal

Mean rotational speed
390 RPM
6.5 Hz
40.8 rad/s
2340 deg/s

15.4 ms
Averaged Frequency Spectrum

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Conclusion

- The paper describes two methods for angular vibration measurement during rotation.
- The first one is based on the phase demodulation of impulse signals and the second one employs a two-beam Doppler laser vibrometer.
- The measurement method, which is based on using the phase demodulation, was demonstrated on the incremental rotary encoder accuracy testing and measurement of the hand drill rotation uniformity.
- The second presented measurement demonstrates employing the laser vibrometer. Both angular vibration measurements result in almost the same time history and frequency spectrum.
Thank you for your attention