Calibration of Sensors for Angular Vibration Measurements

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Outline

- Motivation
- Calibration problem
- Principle of phase demodulation using Hilbert transform
- Calibration procedure
- Software tools for phase demodulation
- Conclusion
Motivation

Angular vibration as one of the important machine vibration and noise source.

Low noise gear design …

Emitted gearbox noise level is proportional to the transmission error (TE) level resulting from the gear angular vibration.
Transducers & Signal Processing Methods for Angular Vibration Measurements

Transducers
- Tangentially mounted accelerometers
- 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)
- Phase demodulation
Test Stand for Transmission Error (TE) Measurements

Simple gear train, tooth numbers $n_1$, $n_2$

Wheel

Pinion

Two incremental rotary encoders

Measurement range: ± 10 µm (microns)
Calibration problem

Requirements for Measurements

- Rotational speed up to 6000 RPM
- Sampling frequency less than 65 kHz (or 256 kHz)
- Low price encoders (IRC)
- Easy to use, measurements in situ

It was needed to prove that

- Phase demodulation of impulse signals is reliable to use
- Both the encoders for TE measurements are enough accurate
Heidenhain Incremental Rotary Encoders

ERN 460-500 type

500 impulses per revolution

ERN 460-1024 type

1024 impulses per revolution

The maximum directional deviation is within ± 1/20 grating period.

Price less than 300 €
Laser Torsional Vibration Meter

- Dual-beam laser transducer based on the Doppler effect
- Laser: Ga-Al-As diode producing 780 nm light
- Output: instantaneous changes in angular velocity
- Measurement ranges: 10, 100, 1000, 100000/s
- Frequency range: 0.3 to 1000 Hz
- Accuracy: ±1% of full scale
Signal Analyzers for measurements

9/2 channel PULSE
65 kHz sampling frequency

9/2 and 2/1-channel PULSE Analyzers
65 kHz and 256 kHz
Principle of Phase Demodulation

How to evaluate the instantaneous phase of the harmonic signal?

\[
\varphi_i = \arcsin \left( \frac{y_i}{E_i} \right) \quad \text{Instantaneous envelope } E_i = ?
\]
Phase Modulation

Real phase modulated signal

\[ x(t) = A \cos(\omega_p t + \Delta \varphi_M(t)) \]

Modulation signal

Phase

Analytic signal

Carrying component

Sideband components

Nominal Revolution
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

Real part

Imaginary part

Impulse Response

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Phase Unwrapping and Linear Trend Removing

Discontinuities removing \( (2f \leq f_{\text{sampl}} \Rightarrow |\Delta \varphi| \leq \pi) \)

\( \Delta \varphi < -\pi \Rightarrow \varphi + 2\pi \rightarrow \varphi, \Delta \varphi > +\pi \Rightarrow \varphi - 2\pi \rightarrow \varphi \)
Calibration Procedure

- Verifying the method of the phase demodulation by comparing simultaneous encoder and laser angular vibration measurements
- Comparing of two identical encoders mounted on the common shaft
Comparison of Laser and Encoder Angular Velocity Measurements

1188 RPM

Impulse signal 65536 Smps/s

Frequency spectrum
Differentiation with Respect to Time

Impulse signal

Phase demodulation

Phase (Angle)

Differentiation with respect to time

Angular velocity

Impulse Response: Ideal Diff FIR Filter

Frequency Response: Ideal Diff FIR Filter

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Averaged Time Signal and Frequency Spectrum

![Graphs showing averaged time signal and frequency spectrum with data points labeled as Laser and Encoder.](image)
Comparison of two encoders of the ERN 460-500 type

500 impulses per revolution

![Graph showing comparison of E1 and E2 encoders.](attachment:image.png)
Accuracy of Position Measurement

Ideally accurate impulse position

Actual impulse position

Errors in degs $\ldots \varepsilon_i, i = 1, \ldots, N$

Mean value $E\{\varepsilon\} = 0$

Dispersion $E\{\varepsilon^2\} = \sigma^2_{\varepsilon}$

Cumulative errors $\eta = \sum_{i=1}^{N/\text{order}} \varepsilon_i$

Mean value $E\{\eta\} = 0$

If $E\{\varepsilon_i \varepsilon_k\} = 0 \quad (i \neq k)$, then

Dispersion $E\{\eta^2\} = \sigma^2_{\eta} N/\text{order}$

Std deviation $\sigma_{\eta} = \sigma_{\varepsilon} \sqrt{N/\text{order}}$
Phase Difference between Two Encoders of the ERN 460-500 Type

Maximum directional deviation
Uncorrelated errors

Nominal Revolution [-] vs. Phase difference (deg)
RMS deg vs. Order [-]

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Indoor Software Tools for Angular Vibration Measurements
Automation Program for PULSE, the BK Signal Analyser
Signal Analyser
Conclusion

- The paper is focused on the calibration of the angular vibration sensors.
- There are many approaches to angular vibration measurements, e.g. laser vibrometers, encoders.
- Phase demodulation based on the theory of analytical signals gives reliable result of measurements.
- The low impulse number encoders seem to be more accurate at the 1/20-part of a circle than the maximum directional error stated in the Heidenhain brochure.
- The theory is illustrated by the verification and comparison of the encoders.
Thank you for your attention
Measurement Examples
Effect of Phase Modulation on Impulse Signal Frequency Spectrum

Pinion 21 T

Wheel 44 T

Enhanced Spectrum, 21-Tooth Gear

Enhanced Spectrum, 44-Tooth Gear

Scaled in multiples of the rotational frequency

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Angular Vibration of the 21and 44-Tooth Gear in Degs (after Comb Filtration)

Toothmeshing frequency harmonics with some sideband components

[Graphs showing time history for pinion and wheel with deg and revolution values]
An Alternative Procedure

Phase .................. \[ \varphi(t) = \arctan\left( \frac{y(t)}{x(t)} \right) \]

Angular frequency ... \[ \omega(t) = \frac{d\varphi(t)}{dt} = \frac{dx(t)}{dt} \frac{y(t)}{x^2(t) + y^2(t)} - x(t) \frac{dy(t)}{dt} \]

Phase .................. \[ \varphi(t) = \int_{0}^{t} \omega(\tau) d\tau \]

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