

An Accurate Measurement of Rotation Velocity- Eliminating Measurement Errors Caused by Gear Tooth Shape Unevenness

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ABSTRACT

It is very important to accurately measure rotation frequencies and fluctuations of rotating systems since they cause vibrations and noises, and since they sometimes indicate system malfunctions. Most rotating systems are equipped with electro- or magneto-conductive gears as their components, and rotation pulses are very commonly obtained by installing electromagnetic or electrostatic type sensors closely to target gears, and time dependent (instantaneous) rotation frequencies are obtained from intervals between adjacent pulses. However, since the number of pulses per revolution is relatively small, a method of obtaining instantaneous frequencies from adjacent pulse intervals is not adequate. For these kinds of pulses, instantaneous rotation frequencies are typically derived using the analytic signal (or Hilbert transform) method. In either case, there is an inherent limitation in using rotation pulses obtained from gears. Individual shapes of teeth may slightly differ from each other and this unevenness of the tooth shape causes errors in the instantaneous rotation frequency estimation.

In order to solve the above mentioned problem, this paper proposes a method that uses two sensors closely located to each other. Information regarding the true rotation frequencies of the gear is contained in the two sensor signals without delay. On the other hand, the errors (spurious instantaneous frequencies) caused by the unevenness of the tooth shapes are contained with a time delay corresponding to the angle difference between the sensors. The subtraction of the instantaneous frequencies obtained from the two rotation

pulses gives an instantaneous rotation frequency signal that contains only the spurious instantaneous frequencies. Since the time delay can be known from the phase measurement of the two pulses, the spurious instantaneous frequencies (and then the true instantaneous frequencies) can be calculated. This paper includes numerical discussions of the effectiveness of the method and some experimental results.

INTRODUCTION

It is very important to accurately measure rotation frequencies (velocities) and fluctuations of a rotating system since they are critical for identifying and debugging vibrations and noises, and since they sometimes indicate system malfunctions. One of methods to measure the rotation frequencies including higher order fluctuations with high accuracy is to use rotary encoders which generate as many as several tens of thousands of pulses per revolution. Time dependent (instantaneous) rotation frequencies are obtained from intervals between adjacent pulses. However, measurement systems tend to be expensive and the installation of encoders is sometimes impossible for in-situ measurements.

Since most rotating systems are equipped with electro- or magneto-conductive gears as their components, rotation pulses are very commonly obtained by installing electromagnetic, electrostatic, or eddy-current type sensors close to target gears. Those gears may have several tens to a couple of hundreds of teeth. Since the number of pulses per revolution is relatively small, the direct method to obtain instantaneous frequencies from adjacent pulse intervals is not

adequate. For these kinds of rotation pulses, instantaneous rotation frequencies are typically derived using the analytic signal (or Hilbert transform) method [1, 2, 3, 4, 5]. The original rotation pulse signals obtained by those sensing systems are roughly sinusoidal but sometimes they are converted to rectangular pulse signals for ease of later use. However, reference [5] showed that the former is more suitable than the latter to obtain instantaneous rotation frequencies by the analytic signal method. Applications of the analytic signal method to various signals were discussed in reference [6].

There is an inherent limitation in using gears to generate rotation pulses. Individual shapes of teeth may slightly differ from each other and this unevenness of the tooth shape causes errors in the instantaneous rotation frequency analysis. The authors are unaware of any research published addressing the removal of this type of error. The present paper proposes a method of removing or at least reducing rotation frequency estimation errors caused by unevenness of tooth shapes of a gear using two sensors closely located to each other.

Needless to say, the proposed method is applicable to rotation pulse detecting systems with optoelectric sensors or other types of sensing systems. It is also noted that the proposed method is independent of the measurement method to obtain instantaneous frequencies from two rotation pulse signals.

PROPOSED METHOD

In this section, a method of removing instantaneous rotation frequency estimation errors caused by the unevenness of tooth shapes of a gear is described. The proposed method uses two sensors as shown in Fig. 1.

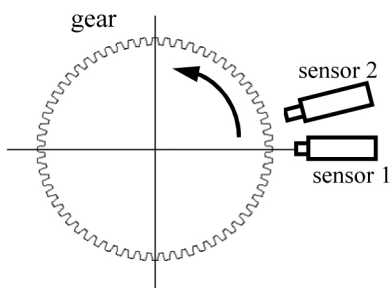


Figure 1. Proposed rotation pulse detecting system.

Sensors 1 and 2 generate rotation pulse signals $x_1(n)$ and $x_2(n)$, respectively, from which two instantaneous rotation frequencies $f_1(n)$ and $f_2(n)$ are obtained.

A method of obtaining $f_1(n)$ and $f_2(n)$ from $x_1(n)$ and $x_2(n)$ needs not be specified to apply the proposed method. The functions $f_1(n)$ and $f_2(n)$ consist of “true” instantaneous frequency $f_{tr}(n)$ and “spurious” instantaneous frequencies f_{sp} ,

$f_1(n)$ and $f_{sp,2}(n)$, respectively. The true instantaneous frequency $f_{tr}(n)$ should appear at the same time in $f_1(n)$ and $f_2(n)$. The spurious instantaneous frequencies represent the errors caused by the unevenness of the tooth shapes of the gear. It is assumed that $f_{sp,2}(n)$ is delayed by M from $f_{sp,1}(n)$. Note that M is not necessarily an integer. Then, $f_1(n)$ and $f_2(n)$ are given, respectively, by

$$f_1(n) = f_{tr}(n) + f_{sp}(n) \quad (1)$$

$$f_2(n) = f_{tr}(n) + f_{sp}(n-M) \quad (2)$$

The subtraction of Eq. (2) from Eq. (1) gives

$$f_{1-2}(n) = f_{sp}(n) - f_{sp}(n-M) \quad (3)$$

Equation (3) is discrete Fourier transformed:

$$F_{1-2}(k) = F_{sp}(k)[1 - e^{-j2\pi kM/N}] \quad (4)$$

In the derivation of Eq. (4), the property that the N -point discrete Fourier transform of $f(n-m)$ is given by $F(k)e^{-j2\pi km/N}$ is used. The spurious instantaneous frequency is then given by

$$f_{sp}(n) = \text{IDFT}[F_{1-2}(k) / \{1 - e^{-j2\pi kM/N}\}] \quad (5)$$

where IDFT indicates the inverse discrete Fourier transform. Then the true instantaneous frequency is given by Eq. (1) and Eq. (5) as

$$f_{tr}(n) = f_1(n) - f_{sp}(n) \quad (6)$$

The above method is very simple and straightforward, but one difficulty of this method is foreseen. There is a division by $\{1 - e^{-j2\pi kM/N}\}$ in Eq. (5), which may become or approach 0 at some frequencies.

ROTATION PULSE GENERATION MODEL

In the papers [4,5], rotation pulse generation models are used that can produce rotation pulse signals with known instantaneous frequencies and phases. These kinds of pulse

signal generation models are a must for the accurate evaluation of rotation frequency analysis methods.

A tooth shape of a gear used for the rotation pulse generation model in the present study is shown in Fig. 2 (only one sensor is shown). The gear of the model has 120 teeth (each tooth width is 3 degrees). An electrostatic sensor has a linear sensing area (length) of 1 degree arc (with uniform sensitivity)-i.e., the average distance from the sensor to the gear teeth within ± 0.5 degrees from the center of the sensing area is output from the sensor. To simplify the calculation of the distance from the sensor to the gear at an arbitrary angle, it is assumed that the sensing arc of the sensor and the circumference of the gear are parallel as shown in Fig. 2. Note that absolute values of r_1 and r_2 are irrelevant since the DC component is removed from the sensor output and gains of the sensors have no effect on the instantaneous frequencies obtained from the pulse signals.

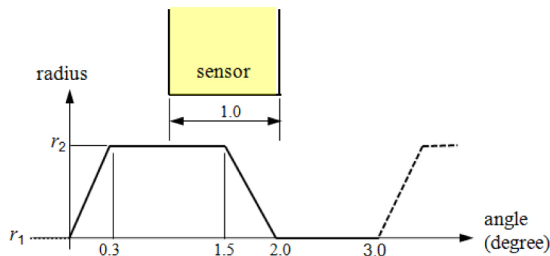


Figure 2. Tooth shape from 0 to 3 degrees of a model gear with 120 teeth.

The instantaneous rotation frequency $f(n)$ of the gear with a rotation fluctuation as a function of time $n\Delta t$ can be expressed by

$$f(n) = f_0 + \Delta f \sin(2\pi f_m n\Delta t) \quad (7)$$

and the phase is given by:

$$\phi(n) = 2\pi\Delta t \sum_{m=0}^n f(m) + \phi_0 \quad (8)$$

where ϕ_0 is an initial phase, which can be assumed to be zero. If the total angle (phase) of the gear rotation is known, the average distance from the sensor to the gear is obtained. In this study, the average distance is obtained by calculating distances at 51 equally spaced points along the sensing area.

An example of waveforms generated by the pulse generation model for the case with $f_0 = 30$, $\Delta f = 0$, $M = 20$, $f_s = 51,200$ is shown in Fig. 3. Since $M_Z = 14.222 (=51,200/(30 \times 120))^\dagger$, the

sensors are separated by approximately 4.22 degrees. As Fig. 3 shows, the sensor 2 output waveform is almost identical with the sensor 1 output.

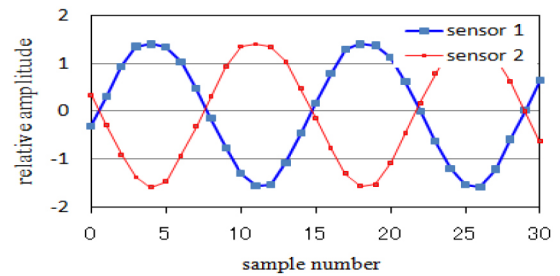


Figure 3. Example of rotation pulse signals obtained by the two sensors for the case with $f_0 = 30$, $\Delta f = 0$, $M = 20$, and $f_s = 51,200$.

If the gear is made perfectly as shown in Fig. 2, it will be referred to as the “ideal gear”. In the present study, the “faulty gear” is defined as follows: Each tooth shape from 0 to 3 degrees shown in Fig. 2 is widened by 0.01 %, and accordingly, the flat portion of the last tooth (originally 1.0 degree width) is shortened to 0.964 degrees. Since the pulse width of the 120th tooth is narrower than other pulses, the instantaneous frequency should increase when this tooth comes under the sensing area. This increase (or decrease) is the rotation frequency estimation error caused by the unevenness of the tooth shapes of the gear.

ANALYTIC SIGNAL METHOD

In the present study, the instantaneous rotation frequency is obtained from rotation pulse signals by the analytic signal method [1, 2, 3, 4, 5, 6]. In this section, the procedure is briefly given using the rotation pulse signals generated by the model described in the previous section. The rotation pulse signals are discrete Fourier transformed and all spectra except for positive frequency components including the tooth frequency component f_Z are removed. In the present study, the low and the high cutoff frequencies of the rectangular filter are set equal to $(1-c_b)f_Z$ and $(1+c_b)f_Z$, respectively, with $c_b = 0.7$. Fig. 4 shows the spectrum of the rotation pulse signal of sensor 1 for the case with $f_m = 300$ and $\Delta f = 1$. The spectral peak is at the tooth frequency f_Z . Note that the carrier frequency of the rotation pulse signal is f_Z instead of f_0 (see [5]). The reason why the high cutoff frequency is set closer to the second harmonic ($2f_Z$) instead of the center between f_Z and $2f_Z$ is that the level of the $2f_Z$ component and its sidelobes are lower than those of the fundamental (f_Z) component. The frequency band from 1080 Hz to 6120 Hz (range within the two vertical lines in Fig. 4) contains the

[†]Please refer to the DEFINITIONS/ABBREVIATIONS section at the end of this document for a definition of M_Z and other terms used throughout this paper.