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Angular and temporal determinism of rotating machine signals: The diesel engine case

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The aim of this work is to highlight theoretically and experimentally the effect of cyclic speed fluctuations on the temporal and angular deterministic parts of signals recorded on rotating machines operating in steady state conditions. The deterministic parts of such cyclostationary signals are defined by their periodic components, or their CS1 part (order 1 of cyclostationarity). It can be assessed by using cyclic averaging, using a time or angle sampling, leading to an estimation of the temporal or angular deterministic part. If the instantaneous speed of the machine is not purely periodic, the temporal and angular deterministic parts will be different. These differences are firstly theoretically considered, and then experimentally assessed in the case of a diesel engine.

0. Introduction

Acoustic or vibration signals acquired on rotating machines operating in steady-state conditions are said to be cyclostationary [1]. Cyclostationarity is the general framework to treat signals exhibiting periodical properties. The deterministic part of a cyclostationary signal is commonly defined by its purely periodic component, i.e. the expected value of the signal during a cycle, also called CS1 part (first order of cyclostationarity). This part can be estimated by averaging the signal over a large number of cycles [2]. The random part of the signal is defined relatively to the deterministic part: it is the residual part resulting from the subtraction of the deterministic part from the total signal. This definition of the deterministic/random decomposition of a cyclostationary signal is attractive because of its simplicity. It can, however, be ambiguous when dealing with signals acquired on rotating machines running in steady-state conditions. The determinism of vibration or acoustic signals acquired on rotating machines is dual: firstly the occurrence of mechanical events (mechanical shocks, combustions in reciprocating engines…) is guided by the position of the main shaft of the machine: this is an angular determinism. Secondly, the response of the structure to excitations results from a convolution product in the time domain: it is a temporal determinism. This construction of signals in temporal and angular domains brings out the concept of fuzzy cyclostationarity [3]. The duality of the determinism is not a problem if the instantaneous speed is purely periodic (or constant). In this case, a signal purely periodic in angle will be purely periodic in time [3,4]. Difficulties appear when the instantaneous rotation speed exhibits fluctuations from cycle to cycle, i.e. if the instantaneous speed is not purely periodic. In this case, the relation between temporal and angular domains is not deterministic. Cycle averaging operations, that are necessary to estimate deterministic parts of signals, will thus lead to different results in time or angle. The deterministic part of the signal in angle (resp. in time) will exhibit a random part in time (resp. in angle).

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The aim of this paper is to assess theoretically and experimentally the effect of speed fluctuations on angular and temporal deterministic parts of signals acquired on rotating machines. Sections 1 and 2 concern, respectively, the temporal and angular deterministic part. Simple and general considerations about sources in rotating machines lead to the expression of low pass filters and damping effects on deterministic parts. The last section is an experimental illustration in the case of a diesel engine operating at cold idle.

In all the following, "time signals" or "angular signals" will stand for signals sampled with a constant step, respectively, in time or angle.

1. Extraction of the temporal deterministic part

1.1. Synchronous averaging

The temporal deterministic part of a rotating machine signal corresponds to its expected value during one cycle in the time domain. It can be estimated by averaging it over a large number of cycles. The main difficulty of this averaging process is that consecutive cycles do not have the same number of samples because of cyclic speed variations. In fact, two cycle events separated by a constant value in angle will be separated by a varying delay in the time domain. It means that the resulting average does not correspond exactly to a cycle as defined relatively to the angle, but to a time portion of the signal corresponding approximately to the mean duration of a cycle. However, an angle reference corresponding to a given position of the main shaft is necessary to align those time portions before the averaging operation (position-locking in [2]). A given time portion will thus be defined as the m points preceding the chosen angle reference together with the p points following it, $T=(m+p)/f_s$ corresponding approximately to a cycle duration (with f_s the sampling frequency in Hz). Because of cyclic speed variations, the temporal deterministic part of a signal is necessarily defined together with a chosen angle reference. The choice of different angle references for the synchronization will lead to different results.

1.2. Effects of the synchronization error

Unfortunately, time portions corresponding to successive cycles cannot be exactly synchronized because of the discrete nature of acquired signals. The chosen angle reference is indeed localized between two time samples. Without resampling or interpolation techniques, a synchronization error is unavoidable, and corresponds to the delay between the reference and the nearest sample of the time portion. This error can be described by a random variable Δ uniformly distributed between $-1/(2f_s)$ and $1/(2f_s)$ (assuming the rotation speed and the sampling frequency are non-commensurable). The effect of this error on the synchronous average can be obtained by considering its expected value. The Fourier decomposition of the deterministic part of the signal is expressed as follows:

$$d(t)=\sum_n D_n e^{j2\pi f_n t} \quad \text{with } f_n=\frac{n}{T}=\frac{n}{m+p}f_s \tag{1}$$

Considering the synchronization error, the expected value of the synchronous average is given by

$$\tilde{d}(t)=E[d(t+\Delta)]=\sum_n D_n E[e^{j2\pi f_n(t+\Delta)}]$$

$$\tilde{d}(t)=\sum_n D_n e^{j2\pi f_n t}E[e^{j2\pi f_n \Delta}]$$

$$\tilde{d}(t)=\sum_n E[\cos(2\pi f_n \Delta)]D_n e^{j2\pi f_n t} \tag{2}$$

Eq. (2) brings out a frequency dependent bias factor, whose value is easily calculated considering the law of Δ:

$$b(f)=E[\cos(2\pi f\Delta)]=\frac{f_s}{\pi f}\sin\left(\frac{\pi f}{f_s}\right) \tag{3}$$

It means that the synchronous average will give a biased estimation of the deterministic part. The bias factor is a function of the ratio f/f_s, and varies between 1 (no bias) for f=0 and 0.64 for f/f_s = 1/2 (Nyquist frequency). The bias factor is drawn in Fig. 1.

It can be noted that it is possible to use upsampling procedures to artificially increase f_s. No information is created: the frequency content of the upsampled signals will remain zero above the original Nyquist frequency. However, it permits to align more precisely time portions before the averaging process by decreasing the synchronization error Δ.

1.3. Effects of cyclic speed variations

The dynamic response of the structure and its acoustic radiation are defined in the time domain. Thus, the temporal synchronous averaging is theoretically optimal to extract the response of the structure to an impact excitation occurring in