Instantaneous Detection of the Occurrence of Mechanical Resonances

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ABSTRACT

In this paper, the kurtosis of time-domain signal is suggested as a detector of a mechanical resonance (MR). The statistical quantity is dependent on the shape of the statistical distribution of a given signal. Mechanical structures under environment noise vibrate in random pattern. If an eigenmode of the structure is stimulated, the sinusoidal pattern starts to develop in the vibration signal. Once MR occurs, near-resonance fluctuation becomes prominent in the time trace of the signal and alters the noisy signal of unimodal distribution into a near-sinusoidal oscillation of bimodal distribution. The value of kurtosis of the time-domain signal drops from around 3.0, then approaches close to 1.5 as MR progresses. The feasibility of kurtosis as an indicator of MR was tested with the piezoelectric responses obtained from microfabricated beams under acoustic stimulations. The test showed that the statistical parameter instantaneously detected the occurrence of MR elapsing quickly in this case. Investigation with the experimental data justified the use of the parameter as an instantaneous indicator of MR.

1. INTRODUCTION

Mechanical resonance (MR) occurs when an eigenmode of a structure is excited. It typically accompanies violent structural vibrations and may lead to catastrophic failure of the structure unless proper countermeasures are taken.

The kurtosis, known as a quantity describing the statistical distribution of a given signal, has been widely used in mechanical researches such as the detection of failure of a tool (Jemielniak & Otman, 1998a, 1998b), tooth crack of a planetary gear (Barszcz & Randall, 2009), gear fault (Zakrajsek, Townsend, & Decker, 1993), damage in a bearing (Williams, Ribadeneira, Billington, & Kurfess, 2001) and so forth. In bio-medical or occupational safety researches, the statistical quantity has been implemented for assessing the auditory risks of a noise which may induce hearing loss (Davis, Qiu, & Hamernik, 2009; Goley, Song, & Kim, 2011; Hamernik, Qiu, & Davis, 2003; Henderson, Morata, & Hamernik, 2001; Lei, Ahroon, & Hamernik, 1994, 1996; Qiu, Hamernik, & Davis, 2006; Zhao et al., 2010).
In this work, the intrinsic meaning of time-domain kurtosis of a signal was interpreted with regard to MR. The feasibility of the parameter as a simple but efficient indicator of MR was tested with experimental data.

2. KURTOSIS AS A MECHANICAL RESONANCE DETECTOR

Kurtosis of a signal defines the ratio of fourth moment to the squared second moment of the signal values (DeCarlo, 1997). For a discrete signal, kurtosis evaluated for a specific duration T can be represented as:

$$K = \frac{\frac{1}{N}\sum_{i=1}^{N}\left[x_i - \overline{x}_N\right]^4}{\left[\frac{1}{N}\sum_{i=1}^{N}\left[x_i - \overline{x}_N\right]^2\right]^2} \tag{1}$$

where N is the number of the data within the duration, x_i is i-th signal value $(i = 1, 2, \cdots, N)$, and $\overline{x}_N$ is the mean value of the signal over the duration. With T small enough, it represents instantaneous kurtosis of the signal.

2.1. Statistical Distribution of a Signal and Kurtosis

Kurtosis means the relative “peakedness” and “tailedness” of a signal distribution to the Gaussian distribution whose kurtosis is 3.0 (DeCarlo, 1997). A distribution with kurtosis greater than 3.0 generally exhibits a higher peak and/or heavier tails than the normal distribution. Kurtosis less than 3.0 implies that the statistical distribution of the signal may display a flatter peak and/or lighter tails than normal distribution (DeCarlo, 1997). The kurtosis of a sinusoid is 1.5 (Brandt, 2011). The reference value for a sinusoid is independent of its frequency and amplitude.

The statistical distribution of signal values is described by the probability density function (PDF). For Gaussian white noise and a sinusoid, the PDF is given respectively as:

$$\frac{1}{\sigma\sqrt{2\pi}}e^{-(x-\mu)^2/2\sigma^2} \text{ : Gaussian noise} \quad (2)$$

$$\frac{1}{\pi\sqrt{A^2-x^2}} \text{ : sinusoid} \quad (3)$$

where A is the amplitude of the sinusoid, μ is the mean value, and σ is the standard deviation of the signal x (Bendat & Piersol, 2011). The signal values of a Gaussian noise are highly concentrated around the mean value (i.e., 0), whereas those of a sinusoid are heavily populated at two extreme values.

2.2. Kurtosis and Mechanical Resonance

A mechanical structure excited by low-level background noise would vibrate almost randomly. The vibration signal from the structure would be close to a Gaussian signal which exhibits unimodal distribution. Thus kurtosis of the measured signal would stay around 3.0.

If an eigenmode of the structure is stimulated, the sinusoidal oscillation would grow within the random vibration signal. The occurrence of MR alters the distribution of the signal values from that of Gaussian noise to that of the sinusoid. The alteration leads to the drop of kurtosis of the signal from around 3.0 to around 1.5 as MR progresses. Therefore, the occurrence of MR can be detected by plotting the time evolution of kurtosis.

3. FEASIBILITY STUDY

Piezoelectric signal from a microfabricated cantilever beam was used to test the feasibility of the aforementioned statement. The piezoelectric microbeam was fabricated using microelectromechanical systems (MEMS) technology to construct a mechanical resonator array (Jang, Kim, Sly, O'leary, & Choi, 2013; Kim, Song, Jang, Jang, & Choi, 2013). Details on the fabrication process are available in Refs. 20 and 21. The dimensions of the beam used in this study are 1350µm in length, 400µm in width, and 0.9µm in thickness, respectively.

3.1. Piezoelectric Response from Micro Beams to Acoustic Excitations

The acoustic input and electric output signals and their spectrograms are shown in Figs. 1-3. The spectrograms were plotted with 128 bins of the signal (i.e., subset of 2.5 milliseconds) overlapped by 50% (i.e., 64 bins). The piezoelectric signal generated by the beam and the acoustic excitation of periodic chirp are superimposed in Fig. 1. The chirp signal was presented for 0.32 seconds, during which MR of the beam occurs. Since the beam was excited by the chirp sound, the spectrogram exhibits a bright narrow band as shown in Fig. 2. The spectrogram of the piezoelectric signal is depicted in Fig. 3, which shows the occurrence of the beam resonance at around 10.8 kHz. While the acoustic excitation sweeps the nonresonant frequencies, the piezoelectric signal of the beam remains at a low level. The amplitude of the signal is nearly constant. When the excitation frequency approaches the resonant frequency of the beam, the amplitude of the piezoelectric signal grows abruptly. The peak of the piezoelectric signal disappears soon as the acoustic excitation passed the resonant frequency.

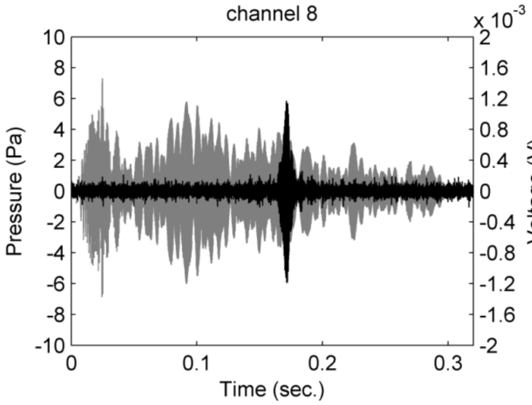

Figure 1. Time trace of the acoustic input (gray) and piezoelectric output (black).

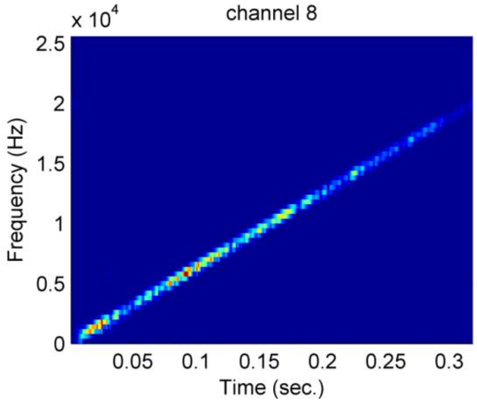

Figure 2. Spectrogram of the acoustic input.

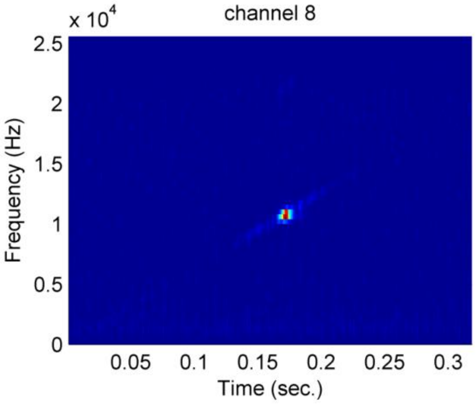

Figure 3. Spectrogram of the piezoelectric output.

3.2. Mechanical Resonance Detection by Kurtosis

In Fig. 4, the occurrence of MR by the fast sweeping acoustic excitation was identified by time-domain kurtosis. The same subset of the piezoelectric signal was used for the calculation of instantaneous kurtosis as for the spectrograms shown in Figs. 2 and 3. Kurtosis values in Fig. 4 oscillate around 3.0 for the low level signals without dropping down to less than 2.0 in this case, which implicates that Gaussian random noise is predominant. Kurtosis beyond 3.0 is mainly due to the intermittent impulsive outliers. The chirp excitation sweeping non-resonant frequency range would induce a weak sinusoid in the random noise thus may lead to small decrease of kurtosis value. As the excitation frequency approaches the natural frequency of the micro beam, the signal grows and kurtosis starts to fall below 2.0. The piezoelectric signal peaked at around 0.17 seconds when the instantaneous kurtosis reached the red line representing the kurtosis of 1.5. The calculated kurtosis is 1.55 at the moment, which means that the piezoelectric signal closely resembles a sinusoid at the moment. Once the acoustic excitation passes the resonance frequency, the signal immediately diminishes and finally returns to its background level. During the transition, kurtosis increases from the minimum then varies irregularly around 3.0.

The feasibility study showed that kurtosis is capable of detecting the occurrence of MR. The resonance elapsed quickly in this case, but instantaneous kurtosis could identify the onset of MR in real time. The test also revealed that impending resonance can be predicted by tracking down the variation of kurtosis. Thus it justifies the use of the statistical parameter as a real time detector as well as a precursor of MR.

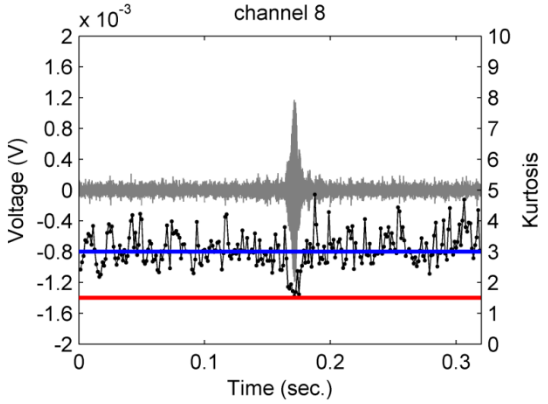

Figure 4. Time trace of kurtosis (black solid line with dots) of piezoelectric signal (gray line) from channel 8, where the blue line and red line represent the kurtosis of 3.0 for Gaussian distribution and 1.5 for a sinusoid, respectively.

4. CONCLUSION

In this study, a new signal processing technique to detect the occurrence of MR is suggested. The technique involves the simple time-domain evaluation of kurtosis of a given signal. The feasibility of the suggested technique was tested with the piezoelectric response of a micro cantilever beam to an acoustic excitation. Kurtosis could detect the fast-passing MR in real time. The variation of kurtosis provided an efficient tool to predict an impending resonance. The test confirmed that kurtosis is a simple but an efficient parameter in detecting MR in real time.

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BIOGRAPHIES

Won Joon Song is currently a professor of the Department of Mechanical Systems Engineering for Energy Convergence (MSEEC) of Dongshin University, Naju, Korea. He received his B.S. and M.S. degrees from Hanyang University, Seoul, Korea, in 1995 and 1997, respectively. He received his Ph.D. degree from University of Cincinnati (UC), OH, USA in 2010. He worked at BOSCH, Sejong, Korea from 1997 to 2003 as an R&D engineer. He served as a researcher at KIMM, Daejeon, Korea from 2010 to 2011. He also worked as a research scholar at IFTP in Hanbat National University, Daejeon, Korea from 2011 to 2016. His research interests include auditory system modeling, signal processing for artificial cochlea, hearing loss assessment, online monitoring of combustion stability, and image processing of combustion flame.