NOVEL MONITORING TECHNOLOGY FOR ROTATING MACHINERY AND STRUCTURES

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ABSTRACT

For monitoring of rotating machinery and structures we need to excite the machinery/structure in question and structure resonance oscillations are processed by the higher order spectra (HOS). The vibration excitation produced by exciters normally consists of the main harmonic at the excitation frequency and phase coupled higher harmonics of the excitation frequency due to exciter non-linearities. These higher harmonics are interferences which are transferred to the structure resonance oscillations. The main disadvantage of the HOS in the considered case is that the HOS estimates are increased for both undamaged and damaged structures due to these phase coupled interferences of an excitation. Therefore, these interferences reduce the effectiveness of damage detection/diagnosis of structure. These interferences also reduce the effectiveness of estimation of signal non-Gaussianity due to damage and the harmonic phase coupling of signals. In the paper it is created new techniques for monitoring of machinery/structure non-linearity suitable for cases of the phase coupled interferences of a structure excitation. It is important to solve this problem for machinery and concrete, metal and composite structures.

1. Introduction

For monitoring of machinery/structure non-linearity due to damage and non-Gaussianity of signals from structures due to damage and estimation of the harmonic phase coupling of signals from structures, an input signal (e.g. vibration excitation, acoustical excitation, etc.) excites the structure in question and structure resonance oscillations are processed by the higher order spectra (HOS) [1]. This approach has been widely investigated for stationary and non-stationary signals [1-13]. The vibration excitation produced by exciters (e.g. electro-dynamical shakers, rotating eccentric mass (REM) exciters, etc.) normally consists of the main harmonic at the excitation frequency and phase coupled higher harmonics of the excitation frequency (e.g. the quadratic coupled, the cubic coupled, etc.) due to exciter non-linearities. These higher harmonics are interferences which are transferred to the structure resonance oscillations. The main disadvantage of the HOS in the considered case is that the HOS estimates are increased for both undamaged and damaged structures due to these phase coupled interferences of an excitation. Therefore, these interferences reduce the effectiveness of damage detection/diagnosis of structure. These interferences also reduce the effectiveness of estimation of signal non-Gaussianity due to damage and the harmonic phase coupling of signals. The traditional approaches for eliminating of interferences from the excitation are based on the classical frequency response function [14] and higher order frequency response functions [15-
However, these important and effective approaches are not suitable for structure monitoring by the HOS.

2. The new frequency response functions based on the HOS

To overcome the above mentioned disadvantage of the classical HOS, novel monitoring techniques are proposed here by the author: the frequency response functions based on the HOS. For estimating the proposed functions, the following step should be undertaken: synchronous time domain output and input (i.e. excitation) signals should be divided into overlapping segments by the internal time window, \( m = 1, \ldots, M \), \( M \) defines the total number of overlapping segments in the signals; the number of segments and level of overlapping should be the same for output and input signals. The generic expression of the proposed frequency response functions based on the classical HOS (i.e. using the Fourier transform) for \( m \)th segment is as follows:

\[
FRF_m(f_1, f_2, \ldots, f_{n-1}) = \frac{H_{om}(f_1, f_2, \ldots, f_{n-1})}{H_{im}(f_1, f_2, \ldots, f_{n-1})},
\]

where \( H_{pm} \) are the non-averaged HOS of order \( n \) of output (\( p = o \)) and input (\( p = i \)) signals respectively, \( n = 3, 4, \ldots \), \( H_{pm}(f_1, f_2, \ldots, f_{n-1}) = X_{pm}(f_1)X_{pm}(f_2)\ldots X_{pm}(f_{n-1})X_{pm}^*(f_{n\Sigma}) \), \( X_{pm}(f_j) \) is the Fourier transform at frequency \( f_j \) and segment duration \( \Delta m \) for output and input signals, \( j = 1, n-1 \), \( f_{n\Sigma} \) is the accumulated frequency, \( f_{n\Sigma} = \sum_{j=1}^{n-1} f_j \), * is a symbol of the complex conjugate. Normally, the HOS related techniques should be averaged over time [1]. The time averaging of the new techniques is proposed as follows:

\[
FRF_a(f_1, f_2, \ldots, f_{n-1}) = \frac{1}{M} \sum_{m=1}^{M} H_{om}(f_1, f_2, \ldots, f_{n-1}) \frac{1}{M} \sum_{m=1}^{M} H_{im}(f_1, f_2, \ldots, f_{n-1}),
\]

The two normalised frequency response functions based on the well developed normalisation methods [1, 3] are proposed as follows:

\[
frf_1 = \frac{h_{pl}}{h_{i1}},
\]

\[
frf_2 = \frac{h_{pl}}{h_{i2}},
\]

where \( h_{pl} \) are the normalised averaged HOS of the output and the input signals, \( k = 1, 2 \),

\[
h_{pl} = \sqrt{\frac{\sum_{m=1}^{M} H_{pm}}{\sum_{m=1}^{M} |X(f_1)X(f_2)\ldots X(f_{n-1})|^2 + \sum_{m=1}^{M} |X(f_{n\Sigma})|^2}},
\]
To demonstrate that the proposed techniques can effectively detect structure non-linearity due to fatigue damage in the cases of the phase coupled interferences of the excitation, a shaker test with fatigue damaged and undamaged rectangular beams was performed. The schematic of a shaker test is shown on Fig. 1. Resonance vibrations from beams were captured by the high speed laser vibration measurement system Polytech.

The stationary random sine vibration excitation from a shaker with constant acceleration amplitude 5g, constant frequency tuned to the beam resonance frequency and random initial phase excited the resonance oscillations of the first (i.e. bending) vibration mode of beams. The shaker excitation consists also of the phase coupled higher harmonics of the excitation frequency (i.e. interferences).

Twenty eight signals (i.e. 14 signals from the damaged beam and 14 signals from the undamaged beam) were tested for damage (i.e. non-linearity) detection. The resonance frequencies of the first mode of the damaged and undamaged beams are 373Hz and 279Hz respectively.

The classical bicoherence of the shaker excitation is shown in Fig. 2. Relatively high values of bicoherence components at the fundamental-fundamental harmonics (i.e. component B11), the fundamental-second harmonics (i.e. component B12) and fundamental-third harmonics (i.e. component B13) of the excitation could be seen from this Figure. These values characterize the relatively high level of quadratic phase coupling of the shaker excitation. For example, the mean value of the bicoherence component at the fundamental-second harmonics of the excitation is 0.39.

The following parameters have been used for estimating the frequency response functions (3-4) and the classical bicoherence and skewness: the frequency resolutions is 8Hz (i.e. segment sizes is 0.125s), duration of stationary input (i.e. a system excitation) and output signals is 15s,
segment overlapping is 50%, the internal time domain window is the Hamming window, the sampling frequency is 10kHz.

![Fig. 2: The classical bicoherence of the shaker excitation.](image)

The non-dimensional mean/standard deviation values of the magnitudes of the proposed frequency response functions (3) of order 3 at the fundamental and second harmonics for this test are 0.98/0.002 and 2.54/0.098 for the undamaged and damaged beams respectively. Dependencies of the selected component of new functions vs. signal number are shown in Fig. 3 for damaged and undamaged beams. Relatively stable behaviour of the selected component is observed. The Fisher criteria of detection effectiveness [19] are 255 and 87 for the technique (3) and classical bicoherence. It is known [19] that features with higher values of the Fisher criterion provide better detection effectiveness.

![Fig. 3: The normalised frequency response functions based on the bicoherence vs. signal number; red and blue curves are for the damaged and undamaged beams respectively.](image)

The mean value of the signal/noise ratio for the proposed frequency response function based on the bicoherence at the fundamental and second harmonics is 0.6 for undamaged case. This value is low; therefore, the proposed techniques essentially suppress phase coupled interferences of the excitation. The Fisher criteria of detection effectiveness are 333 and 73 for the technique (4) and classical skewness. Thus, the proposed technique provides essential effectiveness gain (i.e. 2.9
and 4.6 times using the proposed frequency response functions based on bicoherence and skewness respectively) in comparison with the classical HOS and, therefore, is more effective for damage (i.e. non-linearity) detection in the cases of the phase coupled interferences of machinery/structure excitation.

3. Conclusions

1. New monitoring techniques, the frequency response functions based on the HOS, are proposed and developed for monitoring of machinery and structure non-linearity and signal non-Gaussianity due to damage and estimation of the harmonic phase coupling of signals from structures for the cases of the phase coupled interferences of a structure excitation.
2. It is shown by experiments that the proposed techniques provide essential effectiveness gain (i.e. 2.9 and 4.6 times) for detection of non-linearity due to fatigue damage in comparison with the classical HOS for the case of the phase coupled interferences of a structure excitation.

The proposed techniques could be used in mechanical and electrical engineering, telecommunication, underwater acoustics, ultrasonic NDT etc. for the cases of interferences of a structure/system excitation.

6. References


