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Short Communication

Early contact detection between two components

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Abstract

There are several structural components in industries and plants that come in contact with adjacent components over a period of their functional use, for example, the use of coaxial tubes for carrying hot fluid through inner tube. The early detection of such contacts between two components is important for the system performance and safety considerations in many cases. The detection based on the change in the natural frequencies may not be practical in many cases as the shift in frequencies is often found to be insignificant during contact. However, they interact nonlinearly when excited either by the external aid like shaker or through their service loads. Here, the experimentally measured responses in a simple laboratory setup simulating nonlinear interaction between two components were processed to identify the feature for the early contact detection. It has been observed that the higher order coherences (Bicoherence and Tricoherence) of the responses are the most effective parameters for such contact detection, which is presented here.

1. Introduction

There are several types of nonlinear systems in structural dynamics. The most common nonlinear systems observed in practice are of two types—structures with nonlinear cubic stiffness and/or damping models [1–5] and structures with bilinear stiffness in system like breathing of crack particularly seen in rotating shafts [6–11]. Several researchers have suggested methods to identify the nonlinear systems in the structural systems [1–5] and in rotating machinery, specially the breathing of crack in a cracked shaft during its rotation is detected by the shaft responses during the machine normal operation and run up/run down [6–9]. Sinha and Friswell [12] have simulated the presence of the $2\times$ component in the response of a free–free beam with the breathing of a crack when excited at half the beam natural frequency. However, there are many stationary structural components used in power plants and process industries, which may come in contact with neighbouring components over an extended period of operation, for example, two coaxial tubes generally used in plants [13]. In most of these cases the detection of such contacts at an early stage is important for the safety concern. The change in the natural frequency may be insignificant at this early stage of the contact. Balla et al. [14] demonstrated the detection of such an early stage contact between two components using an ordinary

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coherence in a simple laboratory setup consisting of two components separated by a small gap. The estimation of the ordinary coherence needs both input excitation force and response measurements [15]. Here, only measured responses have been used for the contact detection so that the dependency of the input force measurement can be removed. This would be an added advantage for many industrial applications.

The higher-order coherences (normalised higher order spectra (HOS))—Bicoherence and Tricoherence are the tools for the detection of relation among different harmonics (both amplitudes and phases) of any frequency component in a signal [16–18]. The nonlinear behaviour in structures also generates higher harmonic components of the exciting frequency in their responses. So these higher-order coherences and spectra would be useful for such nonlinear behaviour detection. In fact, the earlier studies give some applications of these methods, for example–detection of transient signal [19], looseness at the support [17,20], breathing of a crack [21], a cubical (nonlinear) stiffness in the system [18,22], faults in the anti-friction bearings, cracks and gears, etc. [23,24], and monitoring the quality of the machining process in manufacturing [25], etc. Recently, Sinha [26] has demonstrated the advantage of the bispectrum in distinguishing the dynamic behaviour of the crack and the misalignment in a shaft. Collis et al. [18] gave the detailed concept on the higher order coherences. Hence, the higher-order coherences are computed for the measured responses [14] as a detection tool. The observations made on the higher-order coherences are discussed here.

2. The higher-order coherences

A brief concept of the higher-order coherences is discussed here.

2.1. The bi-coherence

The conventional power spectrum density (PSD) provides information on the second-order properties (i.e., energy) of a signal whereas the bi-spectrum can provide information on the signal's third-order properties. In a physical sense, the bi-spectrum provides insight into nonlinear coupling between frequencies (as it involves both amplitudes and phases) of a signal compared to the traditional PSD that gives only the content of different frequencies and their amplitudes in a signal. The power spectrum of a time series $\mathbf{x}(t)$ is computed by the discrete Fourier transform (DFT) of the signal as

$$\text{PSD, } \mathbf{S}_{xx}(f_k) = E[\mathbf{X}(f_k)\mathbf{X}^*(f_k)], \quad k = 1, 2, 3, \ldots, N, \tag{1}$$

where $\mathbf{S}_{xx}(f_k)$ is the power density, $\mathbf{X}(f_k)$ and $\mathbf{X}^*(f_k)$ is the DFT and its complex conjugate at frequency f_k for the time series $\mathbf{x}(t)$. N is the number of the frequency points. The bi-spectrum is computed by the signal DFT as [18]

$$\text{Bispectrum, } \mathbf{B}_{xxx}(f_l,f_m) = E[\mathbf{X}(f_l)\mathbf{X}(f_m)\mathbf{X}^*(f_l+f_m)], \quad l+m \leqslant N. \tag{2}$$

The bi-spectrum is complex and interpreted as a measure of the amount of coupling between the frequencies at f_l, f_m, and f_l+f_m, and is described by a 'quadratic phase coupling'. The bi-coherence is the normalised bi-spectrum, and is estimated as [18]

$$\text{Bicoherence, } b^2(f_l,f_m) = \frac{\left|\mathbf{B}_{xxx}(f_l,f_m)\right|^2}{E\left[\left|\mathbf{X}(f_l)\mathbf{X}(f_m)\right|^2\right]E\left[\left|\mathbf{X}(f_l+f_m)\right|^2\right]}. \tag{3}$$

2.2. The tri-coherence

As the bispectrum (bicoherence), the trispectrum and the tricoherence are also computed as [18]

$$\text{Trispectrum, } \mathbf{T}_{xxxx}(f_l,f_m,f_n) = E[\mathbf{X}^*(f_l)\mathbf{X}^*(f_m)\mathbf{X}^*(f_n)\mathbf{X}(f_l+f_m+f_n)], \quad l+m+n \leqslant N, \tag{4}$$

$$\text{Tricoherence,}\ t^2(f_l,f_m,f_n) = \frac{\left|\mathbf{T}_{xxxx}(f_l,f_m,f_n)\right|^2}{E\left[\left|\mathbf{X}(f_l)\mathbf{X}(f_m)\mathbf{X}(f_n)\right|^2\right]E\left[\left|\mathbf{X}(f_l+f_m+f_n)\right|^2\right]}. \quad (5)$$

The concept of correlating different harmonic components (both amplitudes and phases) in the higher-order coherences clearly indicates that they are the nonlinear estimators. The nonlinear behaviour in the structural dynamics also generates several harmonics of the exciting frequencies. The normalization process of the HOS limits the scale of the HOC from 0 to 1, where the scale 0 indicates no relation among frequency components and the perfect relations when the scale equals 1.

3. Earlier study

The earlier experimental study by Balla Suryam et al. [14] has been discussed here briefly for the reference of the present study. The schematic of the laboratory experimental set-up used is shown in Fig. 1. The set-up consists of a 2 m long steel tube (outer diameter = 25.4 mm, inner diameter = 22.4 mm, and filled with a number of steel balls), which is mechanically clamped at both the ends and a helical spring of very low stiffness at the centre of the tube. The experiments were conducted using a swept sine signal in the frequency range of 2–10 Hz excitation in 80 s through a shaker to excite the first bending mode of the tube, and the acceleration response and the excitation force were measured for following conditions.

Case (*a*): No interaction of the tube with the spring (the gap (x) was kept large).

Case (*b*): Just *touch and go* contact type interaction of the tube with the spring realizing the beginning of the contact between two stationary components.

Case (*c*): The gap reduced further and the experiment repeated so that the strong *make and break* nonlinear interaction between the tube and the spring was present. This realise the condition of the early stage of the contact.

Case (*d*): The permanent contact of the tube with the spring, and so no make and break nonlinear interaction was present during the test.

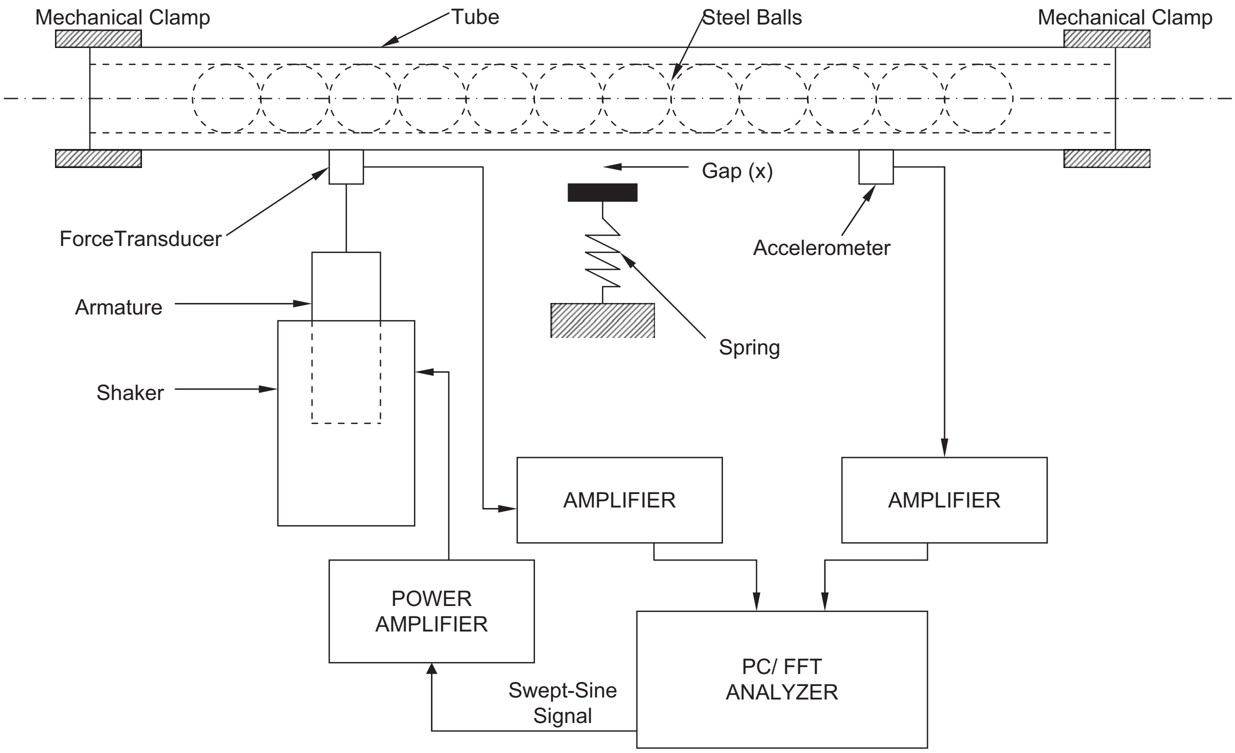

Fig. 1. Schematic of a simple experimental set-up.

The amplitude spectra for the *Cases* (*a*)–(*d*) are shown in Fig. 2. The change in the natural frequency of the primary component (the tube) is not significant (just 6.25 from 6 Hz) for the early stages of contact (*Cases* (*b*) and (*c*)). But it was demonstrated experimentally in the earlier study [14] that the drop in the ordinary coherence from 1 was significant for these two cases, and so it was suggested earlier [14] to use the ordinary coherence for such contact detection. However, this ordinary coherence [14,15] requires the measurement of both the force and response. Now the same measured acceleration responses only for the *Cases* (*b*) and (*c*), where the nonlinear interactions were present, are used again for the computation of the bicoherence and tricoherence, and their behaviours are compared with the *Cases* (*a*) and (*d*) which is a linear system. Since the computation of the coherences requires large number of averages, the swept sine excitation experiments were repeated 50 times.

4. Observations on the bicoherence and tricoherence

Fig. 3 shows the amplitude spectra (amplitude normalised to unity at the resonance) for the different conditions. No higher harmonics components of the natural frequency for the conditions (a) and (d) indicate

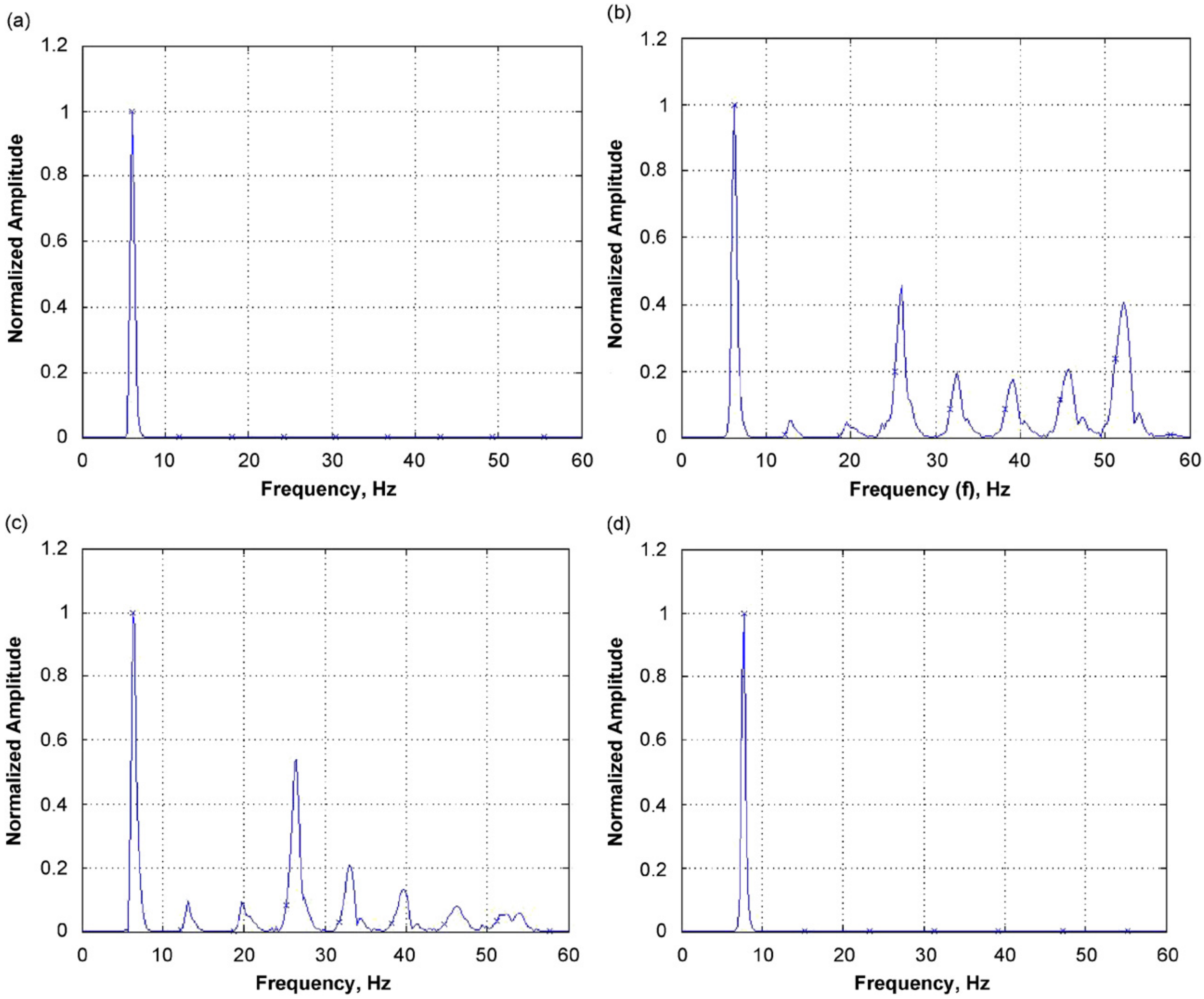

Fig. 2. The amplitude spectra: (a) no contact, (b) just make and break (touch and go), (c) strong make and break, and (d) permanent contact between tube and spring.

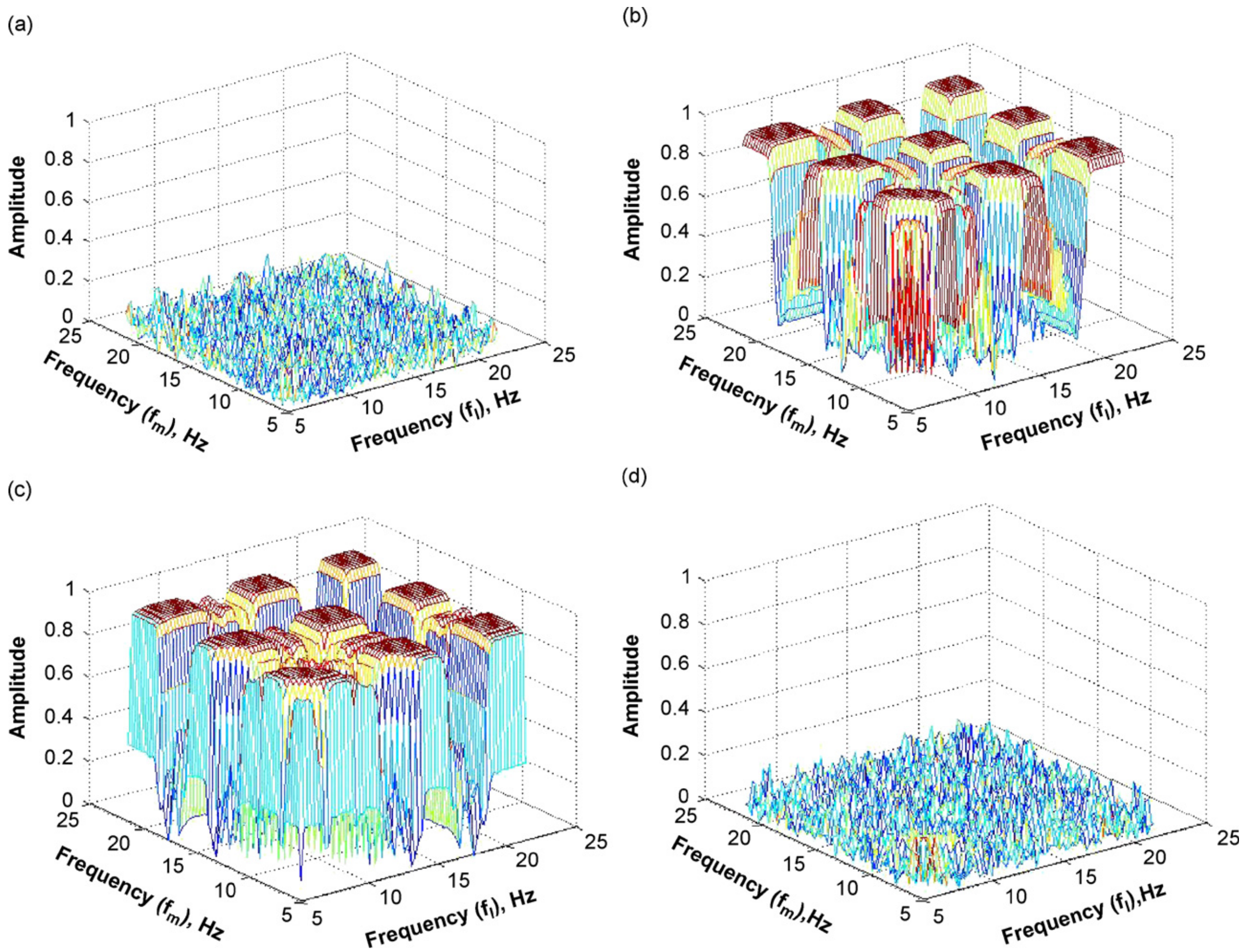

Fig. 3. The bicoherences: (a) no contact, (b) just make and break (touch and go), (c) strong make and break, and (d) permanent contact between tube and spring.

the system behaviour is linear; however, several harmonics are seen for the conditions (b) and (c) together with 2nd mode near 27 Hz and its harmonics. The appearance of the 2nd mode of the tube may be due to the transient excitation (swept sine) by the shaker near to the tube anti-node at the second mode. Moreover, imagine a similar condition in fields where such a detailed dynamic behaviour may not be observed, as the measured responses may be noisy and/or the contact location unknown due to inaccessibility, then an alternate detection methodology will always be highly appreciated and helpful. One such detection method has already been suggested earlier using the ordinary coherence [14]. Now the HOC have been computed for the measured responses for all the experimental conditions and compared. The bicoherences are shown in Fig. 3 and the tricoherences in Fig. 4.

The spheres diameter indicates the value of the tricoherence in Fig. 4 at the intersection of three frequency components. The values of the tricoherence above 0.90 have only been plotted here for the *cases* (*b*) and (*c*), and above 0.2 for other two cases. The observations seen in Figs. 3 and 4 clearly indicate the coupling of many higher harmonics due to the nonlinear interaction. However, in case of (*a*)—no contact, and (*d*)—hard contact, the bicoherences are well below 0.2 at all frequencies and the tricoherences below 0.3 simply indicates the system behaviour in both these cases is linear as expected and the responses at all the frequencies other then the frequency band of excitation contain noise only. Hence, the bicoherence and tricoherence of the measured responses have potential for the detection of early stage contact i.e., when nonlinear interaction is present.

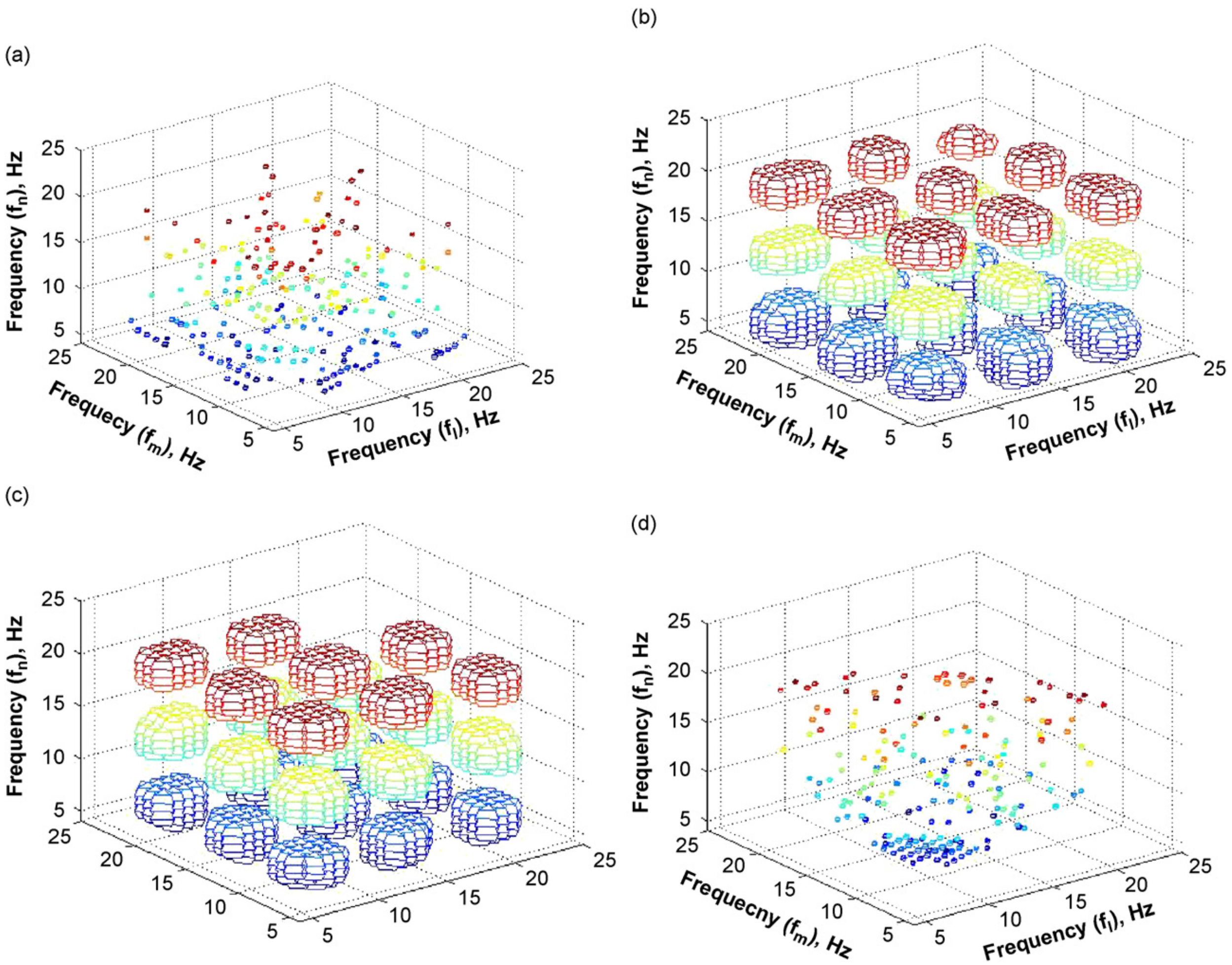

Fig. 4. The tricoherences: (a) no contact, (b) just make and break (touch and go), (c) strong make and break, and (d) permanent contact between tube and spring.

5. Conclusion

The detection of early stage contact between two structural components is presented here when the change in the system natural frequency due to contact is insignificant. The higher-order coherences were used to demonstrate their usefulness in contact detection through an experimental example. The advantage of the bicoherence and tricoherence is that they use only measured responses for contact detection and hence eliminate the need of the measurement of the force. It would be useful for field applications.

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