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Time–frequency analysis of nonstationary vibration signals for deployable structures by using the constant-Q nonstationary gabor transform

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ABSTRACT

Deployable structures have been widely used in on-orbit servicing spacecrafts, and the vibration properties of such structures have become increasingly important in the aerospace industry. The constant-Q nonstationary Gabor transform (CQ-NSGT) is introduced in this paper to accurately evaluate the variation in the frequency and amplitude of vibration signals along with time. First, an example signal is constructed on the basis of the vibration properties of deployable structures and is processed by the short-time Fourier transform, Wigner–Ville distribution, Hilbert–Huang transform, and CQ-NSGT. Results show that time and frequency resolutions are simultaneously fine only by employing CQ-NSGT. Subsequently, a zero padding operation is conducted to correct the calculation error at the end of the transform results. Finally, a set of experimental devices is constructed. The vibration signal of the experimental mode is processed by CQ-NSGT. On this basis, the experimental signal properties are discussed. This time–frequency method may be useful for formulating the dynamics for complex deployable structures.

1. Introduction

Space deployable mechanisms have been widely employed in aerospace vehicles because they are an effective solution for improving space utility rates. A number of works have been conducted over the past decades for the simulation analyses and experimental tests of deployable structures (e.g., antennas, booms, solar arrays, and other scientific instruments) to analyze their dynamic properties in working situations [1–7].

As a type of deployable structure, solar cell arrays are an important part of satellites. However, vibrations may occur during operations, and damping is minimal in space. Therefore, suppressing the vibration caused by disturbances is difficult. Vibrations can lead to the abnormal operation of satellites and may lead to accidents. In the 1960s, the US OGO_IV swift spacecraft failed a mission because of the thermal vibrations of solar arrays [8]. In 1991, while the US UARS worked in the path way, the thermal vibrations of the solar array caused a severe disturbance phenomenon in satellite attitude [9]. In 2001, the Chinese DFH-3 satellite also experienced thermal vibrations because of the clearances of hinge joints [10].

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Many researchers have conducted investigations to eliminate the harmful effects of the vibrations of deployable mechanisms [11–24]. Thornton et al. [11–15] conducted considerable research to obtain the thermal vibration of the solar array of the Hubble Space Telescope. By comparing flight data with the computer simulation results of the solar array of the Hubble Space Telescope, Foster [19] found that the disturbance source was the thermally driven deformation of the solar array. Tsai [20] proposed simplified governing equations to study thermal vibrations. Mahaney and Thornton [21] investigated the thermal-structural vibrations of solar arrays by an analytical approach. Baturkin [22] surveyed current tendencies in the thermal control of a micro-satellite. The aforementioned studies have provided significant foundations for further research on the dynamic properties of deployable mechanisms.

Owing to the flexibility of structures, clearances of joints, and other nonlinear factors such as friction and damping, vibration signals present vivid nonlinearity and nonstationary [8]. Formulating nonlinear joints and simulating the nonlinear dynamics of the deployment process of deployable structures are the focus of many researchers [25–26]. However, establishing an accurate formulation of the dynamics of complex deployable structures is difficult because of several undecided parameters, such as the friction coefficients and precision description of the contact forces of two parts in a clearance connection. Furthermore, solving the formulation of the system presents considerable mathematical difficulties that mainly result from the fact that the formulation involves particular differential equations with time-variable coefficients and boundary conditions. Therefore, experiments have to be conducted to reveal the phenomena of the nonlinear dynamics of solar arrays. Experimental data should be processed for the dynamic analysis of solar arrays [27], and the time–frequency distribution is an important foundation for analyzing vibration signals.

A time–frequency analysis technique with an ideal time–frequency resolution should be employed to accurately obtain vibration properties. The Gabor transform was proposed in 1946 [28]. Since then, a great number of scholars have conducted studies for time–frequency analysis techniques. The short-time Fourier transform (STFT), which is similar to the Gabor transform, was presented in 1947 [29]. Given that introducing window functions that successively slide along the time axis enable the method to obtain the frequency and corresponding amplitude variation along with time, the frequency and time resolutions may not be ideal at the same time because of the restriction of Heisenberg uncertainty principle.

The Wigner–Ville distribution, which is from the quantum mechanics field, was introduced in 1948 [30]. Given that the resolution of the method reaches the downside of Heisenberg uncertainty principle, the time–frequency resolution is greatly improved. As indicated by the existence of negative power for certain frequency ranges, the cross term is unavoidable in this technique [31] and hinders the selection of the true time–frequency distribution of the analyzed signals.

In 1984, Morlet [32] proposed wavelet transform, which probably poses a considerable ideal resolution because the basic wavelet function can be modified according to the specific needs of specific applications. Considering that the wavelet analysis is versatile, significant theory and application research has been conducted about wavelet transform, such as the continuous wavelet transform [33–37], discrete wavelet transform [38–40], wavelet packet [41–44], and second generation wavelet transform [45–49]. At present, many publications suggest that several classes of wavelets, such as B-spline wavelets, pose fine general applicability [50–52]. However, selecting a suitable wavelet basis that can match the signal structure remains an open issue [53].

In 1998, Huang [54] proposed a self-adapting decomposition algorithm called empirical mode decomposition (EMD). Extensive studies and applications for this adaptive decomposition algorithm have been conducted since then [55–67]. In 2008, Xun [5] employed the technique to perform a time–frequency analysis for the vibration characteristics of solar cell arrays. Although several valuable conclusions were obtained, mode mixing may occur in EMD. In this paper, the limitations of several of the methods mentioned above are specifically presented with an example signal.

STFT features uniform time and frequency resolutions and a linear spacing of time–frequency bins, which are limited by the fixed length of the window function. Therefore, promising results may not be obtained by employing this technique. In 1978, Youngberg and Boll [68] introduced a variable-length window function into the transform process of STFT and proposed the constant-Q transform (CQT). In 1991, Brown [69] presented a calculation algorithm of CQT, thus making CQT easy to achieve. In 2011, Holighaus, Velasco, and Dörflerb et al. [70–74] extensively investigated the nonstationary Gabor transform and proposed a high-efficiency calculation algorithm called the constant-Q nonstationary Gabor transform (CQ-NSGT), which overcomes the problems of the classical implementations of the CQT, particularly the computational intensity and lack of invertibility. Moreover, adaptive time and frequency resolutions can be realized in the algorithm; therefore, time and frequency resolutions may be concurrently promising. CQ-NSGT is introduced in this paper. To obtain the vibration signals of deployable structures and stimulate the natural frequencies of an experimental mode, the hammer impact method is used. CQ-NSGT is then applied to analyze the vibration signals to obtain the vibration properties of the experimental mode.

The rest of this paper is organized as follows. Section 2 briefly explains the limitations of several time–frequency techniques, with an example signal constructed on the basis of the properties of the vibration signals of a deployable structure. Section 3 illustrates the principle of CQ-NSGT and presents the result of the CQ-NSGT of the example signal. Section 4 provides the description of experimental devices and presents the CQ-NSGT result of the experiment signal and corresponding analysis. Finally, Section 5 concludes.

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