Mechanical Systems and Signal Processing 116 (2019) 787–795

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Using impact modulation to quantify nonlinearities associated with bolt loosening with applications to satellite structures

Janette J. Meyer *, Douglas E. Adams

Laboratory for Systems Integrity & Reliability (LASIR), Vanderbilt University, 566 Mainstream Dr., Suite 700, Nashville, TN 37228, United States

ARTICLE INFO

Article history:
Received 21 December 2017
Received in revised form 12 June 2018
Accepted 23 June 2018
Available online 25 July 2018

Keywords:
Impact modulation
Bolted joints
Nonlinear dynamics

ABSTRACT

Recent advancements in satellite technology have resulted in the development of quickly-built, modular satellites that can be designed, built, tested, and launched within days of when their need is established. One consequence of the short time frame during which these satellites are prepared for launch is the increased possibility of having loose bolts within the assembly. Loose bolts are undesirable because they increase the risk of damage during launch and, therefore, a method for identifying the presence of loose bolts within the satellite structure is required. In this paper, the effectiveness of using impact modulation (IM) testing to detect loose bolts within a structure is investigated. Four structures with increasing geometric complexity are tested: a three-beam, two-bolt assembly; a four-beam, three-bolt assembly; a satellite panel; and a full satellite structure. IM results are quantified using an integration-based metric. The value of the metric is shown to increase as the torque on one or more of the bolts within each structure decreases. Results from all four test cases showed that torque loss of 50% or more with respect to the fully tightened, baseline torque level resulted in a change in the metric value of at least 20% from its baseline value.

1. Introduction

In [1], theoretical and experimental evidence for using impact modulation testing and analysis to assess bolted joints was presented. In that work, a two-beam, one-bolt setup was used to demonstrate the effectiveness of the method and its sensitivity to different test parameters. In this paper, impact modulation testing is performed on a series of test specimens of increasing complexity in order to determine whether the method is effective on structures more likely to be seen in the field. In particular, the goal of this work is to demonstrate the ability of impact modulation to assess the bolted joints on quickly-built satellites. These modular-type satellites are being developed to accomplish a wide range of tasks while being ready for launch within days of when their need is established [2]. Evaluating the status of the bolted joints within these structures is important in order to assure the structural integrity of the satellites. Under-torqued bolts reduce the stiffness of the satellite and make its external components more susceptible to damage during launch. One challenging aspect of the evaluation of these satellites is their quick assembly processes and short testing times, which do not allow for traditional methods of structural assurance. Unlike the evaluation of traditional satellites, which are typically designed to perform specific tasks and can take months, even years, to develop, assemble, test, and launch [3], assessing these modular satellites must be accomplished in a short time period. To facilitate quick satellite preparation, the assessment must not rely on

---

[*] Corresponding author.
E-mail address: janette.j.meyer@vanderbilt.edu (J.J. Meyer).

https://doi.org/10.1016/j.ymssp.2018.06.042

time-consuming tasks such as the development and verification of detailed analytical models. In addition, because the configuration of each satellite is mission-dependent, libraries of historical data will be unavailable.

Many different approaches for detecting loose bolts in a structure have been investigated including wave propagation, frequency domain, nonlinear, and numerical modeling analyses. Wave propagation techniques compare the measured response of the structure to a database of measurements taken at various bolt torque levels [4–6]. The location of the loose bolt is determined if the database contains the corresponding reference measurement [7], or by using the time at which the propagating wave first interacts with the loose bolt and the velocity of the wave [8]. In [9], it was shown that the frequency domain based transmittance function can be used to quantify changes in the nonlinearity of a structure due to changes in the torque of the structure's bolts. The transmittance function of a healthy structure is required as a baseline to determine if a structure's transmittance function indicates that loose bolts are present. Bolt loosening is detected in [10] by statistically identifying fluctuations of the high frequency portion of the frequency response function of the bolted structure. To be effective, the method requires response measurements near the bolt of interest. In [11], the sideband amplitudes that result from the nonlinear analysis method called Vibro-Acoustic Modulation (VAM) were compared to a probing force response amplitude to quantify the amount of nonlinearity present in the structure. A threshold value is required for this method to determine the torque level of the bolts. The threshold value is unique to the specimen and to the sensor and actuator placements because the structure's linear vibration characteristics affect the test results [1]. More recently, VAM was used to detect bolt loosening in both metallic and composite beams [12]. Methods based on an analytical model are less prevalent because of the difficulty of modeling the dynamics of a bolted joint. In [13,14], methods which use numerical models to determine a relationship between the loosening of bolts to changes in the structure's properties are developed.

In this paper, impact modulation testing is used to determine the status of the bolts within a structure. In past works, impact modulation and the aforementioned VAM method have mainly been used to detect cracks in various materials including glass [15], sandstone [16], and steel [17], as well as in specimens with more complex geometry such as steel pipes [18] and carbon filament wound canisters [19]. This paper extends the application of impact modulation to loose bolt detection. Impact modulation belongs to a class of nondestructive evaluation techniques based on the measurement and analysis of nonlinear interactions within the specimen due to the presence of damage. Non-linear Elastic Wave Spectroscopy (NEWS) [16] is one methodology that employs high frequency excitations as opposed to the relatively low excitations employed in this paper. Both impact modulation and NEWS methods are based on the premise that waves traveling through a nonlinear system are distorted and mixed, creating harmonics, changes in resonant frequencies, and other phenomena not present in linear systems. The underlying assumption made when using these methods is that damage (i.e. cracks, bolt torque loss, etc.) introduced to the structure increases the amount of nonlinearity present. Impact modulation testing and analysis attempts to quantify this nonlinearity in order to assess the structure. In this paper, impact modulation is used to identify the presence of loose bolts in a three-beam, two-bolt assembly; a four-beam, three-bolt assembly; a satellite panel; and a full satellite structure.

2. Approach

Impact modulation (IM) testing creates waves in a structure with the combination of an impact (via modal impact hammer) and a high frequency input, called a probing signal. The purpose of the impact is to excite the structure's low frequency modes, which in the case of a bolted joint, varies the contact interface area and generates nonlinear contact forces. As the high frequency probing wave passes through this nonlinear area, it is modulated by the modal response [17]. In the frequency domain, the result of the interactions between the modal response and the high frequency response are peaks, called sidebands, at frequencies that are linear combinations of the probing signal and the natural frequencies. For example, if a system with a quadratic stiffness nonlinearity whose equation of motion is written as

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) + \mu x(t)^2 = f(t) \tag{1}$$

with mass, m, damping coefficient, c, stiffness coefficient, k, and a quadratic stiffness coefficient, μ, is excited by a forcing function of the form

$$f(t) = cos(\Omega t) + cos(\omega t) \tag{2}$$

where $\omega \ll \Omega$, then the response, $x(t)$, will contain terms of the form

$$cos(\Omega t)cos(\omega t) = \frac{1}{2}cos(\Omega + \omega) + cos(\Omega - \omega). \tag{3}$$

In IM testing, multiple natural frequencies are typically excited by the impact, and therefore, multiple sidebands are present on either side of the probing frequency. For example, Fig. 1c shows a response spectrum obtained from a nonlinear structure subject to IM testing. Multiple sidebands are present on both sides of the probing frequency (10 kHz).

Fig. 1 also shows the response spectrum of the nonlinear structure to excitation by (a) an impact only and (b) a high frequency (10 kHz) actuator signal only. The response to both the impact and the actuator signal shown in (c) is unlike that of a linear system, whose response to the combination of an impact and an actuator signal would be the superposition of the system's response to each individual excitation. It is clear that the IM results for this nonlinear structure are not merely a