Detection of fastener loosening in simple lap joint based on ultrasonic wavefield imaging

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Abstract. Joints in aero-mechanical structures are critical elements that ensure the structural integrity but they are prone to damages. Inspection of such joints that have no prior baseline data is really challenging but it can be possibly done using the Ultrasonic Propagation Imager (UPI). The feasibility of applying UPI for detection of loosened fastener is investigated in this study. A simple lap joint specimen made by connecting two pieces of 2.5mm thick SAE304 stainless steel plates using five M6 screws and nuts has been used in this study. All fasteners are tightened to 10Nm but one of them is completely loosened to simulate the damage. The wavefield data is processed into ultrasonic wavefield propagation video and a series of spectral amplitude images. The spectral images showed noticeable amplitude difference at the loosened fastener, hence confirmed the feasibility of using UPI for structural joints inspection. A simple contrast maximization method is also introduced to improve the result.

1. Introduction

Joints in aero-mechanical structures are critical elements that ensure the structural integrity. The joints unite and assemble parts to enable them to collectively function as a structural system. Performance and effects of the joints on structural stability and dynamic response are still a concern under active investigation [1]. The inherent material discontinuity at the joints make them a damage hotspot. In general, the joints often suffer from damages such as cracks, corrosion, loosening of fasteners, snap of improperly tightened fasteners, as well as other deviations from original structural condition [2]. The situation is worsened by environmental factors during their service life, which is expected to last for decades due to the high capital cost of respective aero-mechanical structures. Notorious examples of structural failure primarily due to joint damage include the collapse of I-35W Bridge over Mississippi River in the USA [3] and the failure of Nipigon River Bridge in Canada [4]. In fact, the field statistics have shown that 58% of bridge failures are due to fastener loosening and joint failure [5].

Inspection and monitoring of fastened joints is imperatively needed to ensure their good condition and safe continual use. The resonant frequency shift method [6-8] and the ultrasonic time-of-flight (ToF) method [9-11] have been exploited for this purpose. Both methods involve the injection of the acoustoelastic or ultrasonic waves into a fastener, followed by respective measurement of resonant frequency or ToF of the waves in the fastener. Fastener preload could then be calculated by exploiting the linear proportionality of the measurand to the stress in fastener. Major drawback of these methods
is the need of baseline data for previous known states of each fastener, which is difficult to maintain or unavailable. On the other hand, the ultrasound velocity ratio method [12, 13] has circumvented this need and can measure fastener preload without a baseline data. Anyhow, comparison with a baseline is still necessary in order to infer the condition of the fastener. Furthermore, there are also piezoelectric impedance-based methods [14, 15] that generally rely on permanently bonded piezoelectric transducer on the fasteners or structural components being monitored for data acquisition. They exploit linear relationship of the fastener preload with the piezoelectric impedance frequency for result processing. Moreover, a novel optical measurement system known as the Fiber Optic Bolt Loosening Monitoring System has also been previously developed [16]. The system basically consists of one optical fiber strategically fixed to all fasteners under monitoring and an optical time-domain reflectometer (OTDR) to measure the intensity of light transmitted through the fiber. Any loosening of the fastener as small as one degree turn will cause additional bending to the fiber, hence partial loss of optical transmission. The signature of the loss can be associated with the fiber length position in OTDR and this can reveal the loosened fastener.

The methods discussed above have worked excellently under their respective working conditions but generally suffer from one or both of the following issues over a larger perspective. First of all, the methods require either manual attachment of transducers during inspection or permanently bonded transducers for continuous monitoring. Attaching the transducer as needed is a typical task for non-destructive inspection but the work is tedious, especially when the fasteners that require inspection are difficult to access. In the meantime, permanent bonding of transducer is common for structural health monitoring applications but such bonding often suffers from environmental factors and will degrade over time until it adversely affects the result. Secondly, many of the methods require a reference to the baseline data, which is also known as temporal referencing. The baseline is needed either for result processing or loosening inference. Regardless the purpose, the baseline data is difficult to maintain, if not available at all, and also has a low reliability due to susceptibility to the environmental effects such as temperature variation.

An alternative referencing strategy is therefore needed in case of unavailability of baseline data such as for the first inspection of an existing structure with suspected damage. One good strategy is the spatial referencing, which is the intrinsic nature of the ultrasonic propagation imager (UPI). Result processing and conclusion about existence of damage can be done by UPI with reference to data taken from different grid points of the same inspection. This has been applied successfully for detection and evaluation of damages in various structures and materials, including metallic pipelines [17], composite wings and wind turbine blades [18-20]. It should be noted that all of these inspected specimens did not have individual constituent parts that possess strong material discontinuity as in a fastened lap joint. One exception is the inspection of a composite aircraft wing with multiple rivets [21]. However, the focus of that application is the evaluation of skin-spar debond and not the condition of the fasteners.

In this study, the feasibility of applying UPI for detection of fastener loosening in a simple lap joint specimen is explored. The data is first processed into an ultrasonic wavefield propagation video to analyze if any change in the wavefield propagation pattern associated to fastener loosening can be identified. Spectral amplitude analysis is then performed by segregating ultrasonic energy into discrete frequency bins and visualizing their amplitude distribution at the fasteners. To improve the visibility of loosened fastener in the final result, a simple contrast maximization method is applied.

2. Materials and Wavefield Data Acquisition

A screw-nut fastened simple lap joint specimen is designed based on the typical engineering practice [22]. Two constituent plates of width 100.5mm and height 201mm are CNC machined from 2.5mm thick SAE304 stainless steel. The plates are then fastened together using five M6 socket head cap screws, and plain washer and nuts on the opposite side. The fasteners are tightened to 10Nm using a torque wrench, except for the second one from the left that is slightly tightened with bare hand only to simulate the loosening case of a fastener. A custom-made diode-pumped solid state Nd:YAG pulsed laser is used for the ultrasonic wave generation through rapid, localized, thermoelastic expansion—
contraction in specimen material. The laser has a wavelength, beam diameter at the laser exit port, divergence and pulse duration of 532nm, 4mm, 0.5m rad and 30ns, respectively. Its output energy is adjusted to approximately 1mJ per pulse in order to keep the wave generation process within non-destructive, linear elastodynamic regime of the specimen material.

Ultrasonic wavefield imaging is performed over 95mm by 100mm area, enclosing all five fasteners of the specimen, is performed. Individual waves are generated over a uniform grid of 0.5mm pitch in both horizontal and vertical directions. This results in a 190 by 200 pixel grid. The 2D grid scanning is realized using a galvanometric optical scanner at 1m standoff and a pulse repetition frequency of 10Hz. Ultrasonic wave generated at each grid point is then measured using a broadband piezoelectric sensor, fixed position at 100mm above the middle fastener. This sensor can be replaced by non-contact sensors such as laser Doppler vibrometer when a remote, on-site measurement is needed. The signals are then sampled using an oscilloscope without any filtering so that they contain all possible ultrasonic modes with as much spectral information as possible. Signal at each spatial point is recorded with 500 samples at a sampling rate of 5 MHz.

Complete ultrasonic wavefield is reconstructed by synchronizing all waves traveling from the laser excitation points and sensed by the fixed sensor in a time-reversal fashion. This is done such that the wavefield can be interpreted as if generated at, and traveled away from, the sensor position. Such a reconstruction is more intuitive and valid as long as the elastodynamic reciprocity holds. It produces high signal-to-noise ratio measurements with broadband frequency contents, facilitating the frequency analysis for evaluation of fastener preload. Visualizing changes of wavefield with time and analyzing variation of its frequency information are realized, respectively, by processing data using Ultrasonic Wavefield Propagation Imaging (UWPI) method [23] and Ultrasonic Spectral Imaging (USI) method [24]. The processes are summarized in a flow diagram given in Figure 1.

Figure 1: Specimen and result processing flow diagram
3. Results and Discussions
The result generated by UWPI method is a video of wavefield propagation over the inspection area. Snapshots captured from this video at selected instances of the wavefield propagation are shown in Figure 2. Snapshot at 20.0μs shows incident wavefield of S0 and A0 modes concentric at the sensing position. The continuation of the S0 mode is broken when the wavefield encounters the fasteners at 23.8μs near the center. Similar discontinuation occurs when the slower A0 mode meets the fasteners at 35.2μs. The fasteners at regular interval caused periodic reflection-transmission of incident wavefield, generating the complex wavefield interference pattern as shown in snapshots at 42.4μs and 47.0μs. On top of that, the strong side reflections of A0 mode further complicate the wavefield until it reaches an indistinguishable complex state as shown in snapshot of 90.2μs. Even though the second fastener has been completely loosened, it did not produce any noticeable difference in the wavefield pattern even for trained eyes. Another result processing method that can extract and present the relevant loosening information, perhaps in a different domain, is needed.

![Figure 2: Snapshots of ultrasonic wavefield propagation video at (a) 20.0μs, (b) 23.8μs, (c) 35.2μs, (d) 42.4μs, (e) 47.0μs and (f) 90.2μs](image)

Analysis in the frequency domain is performed by processing the same set of wavefield data using USI method. The result is a series of images showing the spectral amplitude response of the specimen at discrete frequencies of the periodic interval. Figure 3 depicts three of them at 260kHz, 290kHz and 360kHz, respectively. Five dotted circles are included in Figure 3(a) to indicate actual positions and head size of the fasteners. Figure 3 represents the images with noticeable amplitude difference (using rainbow color scale) between the properly tightened fasteners and the loosened one (second fastener from the left).
Figure 3: Selected images of spectral amplitude response at (a) 260kHz, (b) 290kHz and (c) 360 kHz. The dotted circles in (a) indicate positions and head size of the five fasteners.

For clearer results, contrast maximization based on the mean amplitude analysis is performed. First of all, five regions of interest (ROI) having the same relative position and size of the dotted circles in Figure 3(a) are established on all spectral amplitude images. The data within these ROI at respective frequency, $f$, are isolated as $v_{\text{ROI, } f}$. The mean amplitude of all data within the respective ROIs is calculated, giving five values of mean amplitude for each frequency as $\bar{v}_{\text{ROI, } f}$. The values at some selected frequencies are plotted and shown in Figure 4, after self-normalization against the amplitude range of all values used in the plot. They exhibit a high amplitude for properly tightened fasteners but a low amplitude for the loosened fastener. This trend is consistent with the lower transmissibility of ultrasound across the fastener-plate interface at the loosened fastener. Specifically, the interface looks flat and smooth but contains many surface asperities at the microscopic scale. The transmissibility of ultrasound across the interface depends on the true contact area of the asperities, which in turn has direct proportionality with the stress at interface and hence the tightness of fastener [25]. Figure 4 also shows high amplitude consistency for the first and second fasteners but the values are quite disperse for the other fasteners. The inconsistency could be caused by inaccurate machining, although unlikely for CNC machining, subjected to further investigation.

Figure 4: Mean spectral amplitude for the fasteners at selected frequencies

In order to improve the consistency, the contrast of the mean amplitude at respective frequency are calculated using Equation 1, where $C[f]$ represents the contrast at frequency, $f$, and $\bar{v}_{\text{ROI}=i}$ represents mean amplitude at ROI number $i$.

$$C[f] = \min |\bar{v}_{\text{ROI}=i} - \bar{v}_{\text{ROI}=2}|, \; i = 1, 3, 4, 5$$ (1)
Images corresponding to the five frequencies that provide the highest contrast $C[f]$ are selected for a pixel-wise averaging. The result is an averaged image $v_{AVE}[x,y]$ as shown in Figure 5, in which more consistent amplitude distribution could be observed, making the specimen features such as fasteners, upper plate and plate boundary highly distinguishable. First of all, a significant lower amplitude could be observed (using rainbow-coloured scale with red as the highest amplitude) at the loosened fastener as compared to the other four intact fasteners. The loosening causes poorer contact at the fastener-plate interface, resulting in a higher loss of wave amplitude. The lower stress level at the loosened fastener and plate material at close proximity will change their natural frequency. Nonetheless, this effect is indistinguishable in this result. Perhaps, a new result processing method that can map the natural frequency or dominant frequency of the wavefield data should be developed for this purpose. Other observations include high spectral amplitude over the upper plate, which provides material continuity with minimal loss for the waves to reach the sensor bonded on it. Much lower amplitude is shown on the lower plate that is due primarily to the material discontinuity of the plate and the wave reflection by the fasteners. Apparently, 20.1 mm overlapping of the plates does not provide a sufficient continuity for the waves to travel across the joint.

**Figure 5: Averaged spectral amplitude image after contrast maximization**

4. Summary and Future Works

The joints in aero-mechanical structures are critical elements that ensure structural integrity but they are prone to damages like fastener loosening. Various inspection methods have been proven effective and reported in the literatures. However, they are not readily applicable for inspection of an existing structure that has no baseline data taken at previous known good condition. UPI that does not need any baseline data could be the solution under such circumstances. The feasibility of applying the UPI for detection of fastener loosening in a simple lap joint specimen has been investigated in this study. All fasteners in the specimen are tightened to 10Nm but one of them has been slightly tightened with bare hand only to simulate the loosening case of a fastener. The wavefield data acquired from the specimen is reconstructed as an ultrasonic wavefield propagation video. The video has shown the propagation of wavefield across the fastened joint but it does not show any abnormal wavefield pattern that can be associated with the loosened fastener. The same set of data is then processed into a series of images that show the spectral amplitude response of the specimen at discrete frequencies of periodic interval. Some of the images at specific frequencies show noticeable amplitude difference between the properly tightened fasteners and the loosened one. This confirms feasibility of using UPI for structural joints inspection. Lastly, a contrast maximization method is introduced to improve the visibility of loosened fastener and the consistency in the final result.

There are many opportunities to expand or improve this work. For example, inspection of fastened specimen with various levels of loosening should be done in order to understand the sensitivity of the method. The incident wavefield can be also removed and the wavefield related to fasteners only can be
highlighted, facilitating an easier interpretation of the wavefield changes due to the fastener loosening. Furthermore, the wavefield data can be processed into natural or dominant frequency map such that the changes of frequency due to different stress-strain level at the loosened fastener can be identified. Perhaps with such type of frequency analysis, direct measurement of axial stress in the fastener could be done in the future. In addition, investigation on how this method can be expanded for evaluation of joints and fasteners that have been damaged by corrosion is also interesting.

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