Bolt looseness detection using Spectral Kurtosis analysis for structural health monitoring

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Abstract

Bolt looseness is a major problem for high valued infrastructure assets such as bridges. Historical data indicates failure in the operating bridges is related to bolted joints. This reveals defects generated by small components can leads to major problem thus early detection is required. In this paper, a novel methodology to characterize the bolt looseness using optimal filtering of vibration data is proposed. A Spectral Kurtosis (SK) based optimal filter is designed to extract frequencies that are generated by bolt looseness. The filter is capable of extracting weak signatures (hidden in acceleration data) that are generated by bolt looseness. The proposed approach is demonstrated through experiments. Results have indicated that the proposed approach can be reliable and effective in detecting loose bolts of a structure subjected to fluctuating loads.

1 Introduction

For many civil infrastructures such as building and bridges, bolted joints are commonly preferred as they enable modular construction methods. Owing to its practicality for easy replacement and less disruption during the construction stage, bolting has always been a popular option. According to the Korean Expressway Corporation, historical data shows 33% of failure in the operating bridge are related to bolted joints [1]. This finding clearly identifies the need for efficient planning of scheduled maintenance operations. Previous root cause analysis has also revealed that the majority of the bolt defects are caused by insufficient preload and large vibrations.

Bridge vibration behaviour by nature can be categorized as a random vibration phenomenon with stationary frequencies arising as a result of pacing traffic. Ensembles of the vibration data may contain a pattern, which can be represented or modelled in a deterministic sense. This vibration pattern can be modelled as a combination of the stationary and non-stationary signals. Bolted joints are prone to lose their tensile strength due to the high level of vibration. Monitoring the change in looseness along the axial direction of the bolt can convey the structural health condition[2].

Bolt looseness by definition is a condition in which, the tension or the axial force is inadequate to hold the structure. This can be due to the self-loosening of the nut as an effect of transverse movement produced by vibration under normal operation. Apart from vibration, there are other root causes of bolt looseness; for instance, under-tightening, embedding, gasket creep, differential thermal expansion and shock. As a result, measurement and estimation of this force can contribute to health performance of the structure. Bolt looseness detection is one of the Structural Health Monitoring (SHM) application used to monitor structural integrity. The vibration-based method is a popular choice to implement SHM due to its effectiveness and outstanding performance. For instance, this can be achieved by using a displacement sensor to monitor joint conditions [3], accelerometer with forced excitation for modal analysis [4] and output-only signal processing algorithm using ambient excitation [5].

Conventional signal processing techniques for SHM can be classified as time series, frequency and time-frequency analysis. In time series analysis, it is normally based on observation of variance in statistical features such as standard deviation, peak, mean and root mean square of signal. A bolt looseness detection application is implemented base on the residual error of an autoregression model from its standard deviation as damage sensitive feature [3][6]. Frequency domain analysis is performed by converting time series data to the frequency domain to extract features that are more sensitive in frequency bandwidth but not in time. Time-Frequency analysis is a technique that provides signal resolution in both the time and frequency domain. This allows to show the frequency location of feature and when it happens in time, Wavelet Transform is one of the examples.

Pnevmatikos et al have developed a damage localisation technique based on wavelet analysis for bolted connection [7]; however, they failed to quantify the energy distribution to the actual remaining torque of the bolts. This is essential in evaluating the severity of damage caused by looseness, owing to only a specific spectrum is analysed, therefore, events occurred in other bandwidth will be missed to detect.

In this paper, a novel methodology to characterize the bolt looseness using optimal filtering of vibration data is proposed. The proposed methodology is described in section 2 and in the following sections, details of the experiments are presented. The performance of the signal processing technique to classify loose and tight bolts is presented in section 3. A summary of the results along with recommended future work is presented in section 4.

2 Methodology: Spectral Kurtosis (SK) based optimal filtering

Spectral Kurtosis (SK) is an analysis tool that can be used to detect transients from noisy signals. It is capable of extracting non-stationary frequency components buried in a time waveform. Thanks to its fourth-order cumulant based Kurtosis statistical parameter, which suppresses Gaussian noise and stationary signals but retains the impulsiveness of a signal. This technique has caught many interests in the past decade due to its performance in identifying non-stationary components induced by damage, and most of the applications are focused on the health diagnosis of rotating machines with respect to bearing damage that has a noisy periodic operational effect [8].

SK was originally used to detect random frequency buried in the signal which cannot be displayed by traditional Fourier Transform and also is treated as a supplement to the classical Power Spectral Density (PSD). It was rarely been utilised despite its ability suited to many detection problems until Antoni connected the theory with a mathematical approach and validated with applications in vibration based condition monitoring [9]. The SK estimation is calculated by finding the relationship regards to signal-to-noise ratio (SNR) in detecting transient fused with additive noise. Consider a vibration signal,$x(t)$, SK can be calculated in equation (1) based on the spectral moments of the signal where $S_{2,x}$ and $S_{4,x}$ are the second and fourth moment.

$$SKx(f) \triangleq \frac{S_{4,x}}{S_{2,x}} - 2 \tag{1}$$

The definition of spectral moment is estimated according to equation (2)

$$S_{n,x}(f) = \langle |PS(f)|^n \rangle \tag{2}$$

where $PS(f)$ is Fourier power spectrum of the signal, $x(t)$.

Once the SK estimates are processed, a Wiener filter is extracted by applying a statistical threshold. The threshold is adaptive and the maximum value of the SK is considered for selecting a threshold. The proposed approach eliminates the use of baseline data. Baseline free methods are more preferred in general. In this study a 5% threshold on the maximum value of the SK, estimate is considered. The approach is demonstrated and validated in section 3.

3 Experimental setup

Experiments are carried out to validate the proposed method for detecting bolt looseness. The bolted structured considered in this study has 28 bolts (M10 type) that are arranged in evenly spaced rows. The assembly is made of structural steel and consists of eight components (as shown in Figure 1a). It is assembled using two square lap cover metal plates (150mm×150mm×10mm) to sandwich two rectangle cover metal plates (300mm×200mm×10mm) using two rows of bolts as highlighted in Figure 1a below. This heavy structure is installed on an electro-magnetic vibration testbed (Data Physics GW-V2644 shaker controller) using a pair of elbow brackets (200mm×150mm×75mm) using four columns of bolts (Figure 1b). The weight of the structure is approximately 18.5 kg.

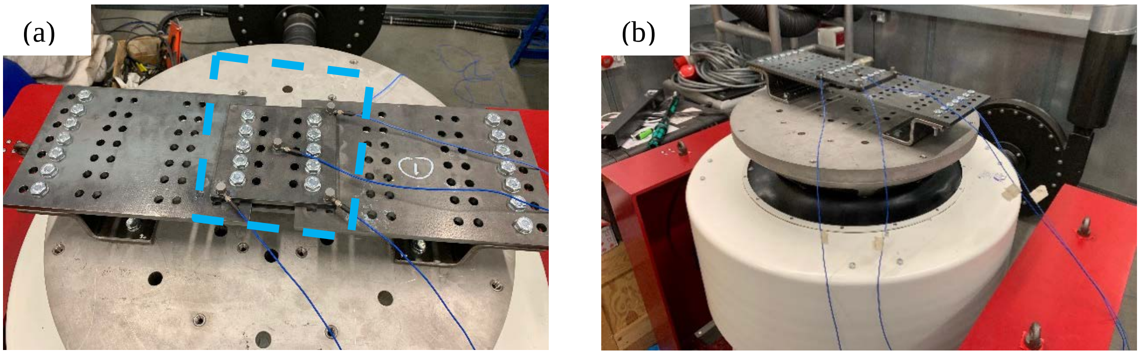

Figure 1: Bolted joint experimental setup (a) Bolt joint (b) Assembly mounted on vibration test-bed

Controlled excitation is transferred to the bolted joint using the vibration testbed. A National Instruments cDAQ-9234 module with a NI9171 data acquisition chassis is used to capture the vibration data from three piezoelectric accelerometers mounted on the topmost plate. The accelerometers are stud mounted. Both the shaker controller and DAQ units are connected to a PC for data exchange and computation. A LabVIEW program is deployed to interface with the data acquisition system for sampling the vibration data at 5 kHz. The schematic of the test setup is illustrated in Figure 3. The three channels of the sensors (blue dots, ACC0 – ACC2) and loosened bolt (red bolt at the bottom left) locations on the centre plate are shown in Figure 2.

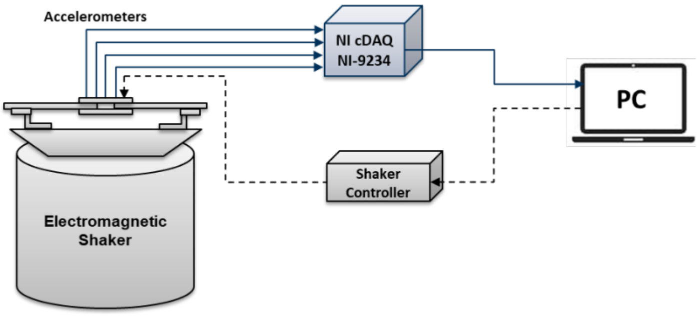

Figure 3: Bolt looseness detection experimental system schematic

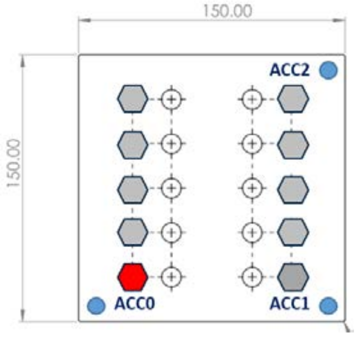

Figure 2: Sensor locations and bolt arrangement

3.1 Multi-Mode input excitation profile

A bridge excitation profile is chosen as a combination of multiple stationary components with a broadband baseline random excitation. The two stationary components represent traffic passing on the bridge. This assumption is proven to be realistic and previously many authors [10][11] have reported the findings. Using FEA numerical simulation modal analysis performed on the bolted assembly revealed, the first three modes are below 500 Hz. This information is utilized to select the bandwidth of the input excitation profile. The profile details are listed in Table 1. The baseline broadband random vibration was matched with the excitation bandwidth with two stationary components with centre frequency located at ~50 Hz and ~110 Hz to simulate excitations received by a bridge. The input excitation model is graphically represented in Figure 4.

Table 1: Multi-mode vibration modelling profile

	Multi-mode vibration components	
Frequency Range	5Hz – 500Hz	
Sinusoidal Stationary Component	48Hz – 60Hz	0.5g^2/Hz
	96Hz – 120Hz	0.25g^2/Hz
Random Broadband	5Hz – 500Hz	
Amplitude	2.4g	

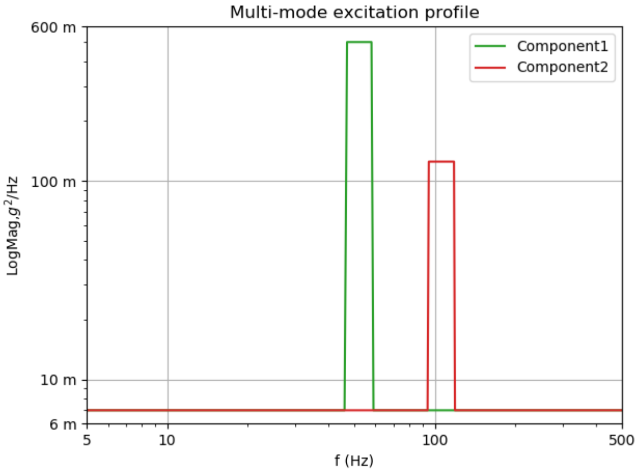

Figure 4: Multi-mode excitation profile

4 Result and discussion

Baseline data for all bolts tight case (45 Nm torque), is acquired multiple times to confirm the repeatability. The input excitation profile considered showed repeatable excitations without any unstable operation. The vibration signals are captured for 40 seconds duration using the controlled excitation. This set of data is labelled to be a tight bolt (or healthy) dataset. Later, the tension in bolt near ACC0 is released until the tension is less than 10 Nm and the same excitation is applied to the structure. This loss of tension caused the onset of a weak rattling effect. It is known from previous investigations that rattling produces non-linear and non-stationary vibration components. This occurs due to a reduction in the local stiffness of the structure. These weak signatures are transferred to the structure through the washers. Traditional signal processing techniques such as Fast-Fourier Transform (FFT) is not suitable for non-linear and non-stationary signals. The aim of this study is to extract these weak signatures using Spectral Kurtosis estimates.

The time-domain data acquired from healthy (all bolts tight) and unhealthy (ACC0 bolt loose) assemblies are presented in Figure 5. The signals show no clear indication of the underlying fault. The PSD estimate as shown in Figure 6, is able to detect slight irregularities in the data after 500 Hz frequency but cannot distinguish the looseness clearly.

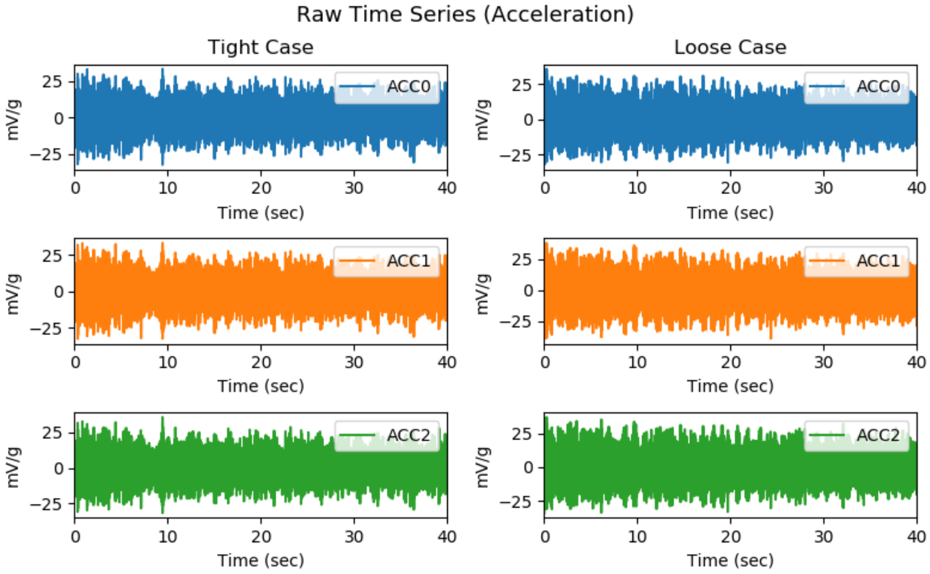

Figure 5: Raw time domain data for tight bolt case (left) and ACC0 loose bolt case (right)

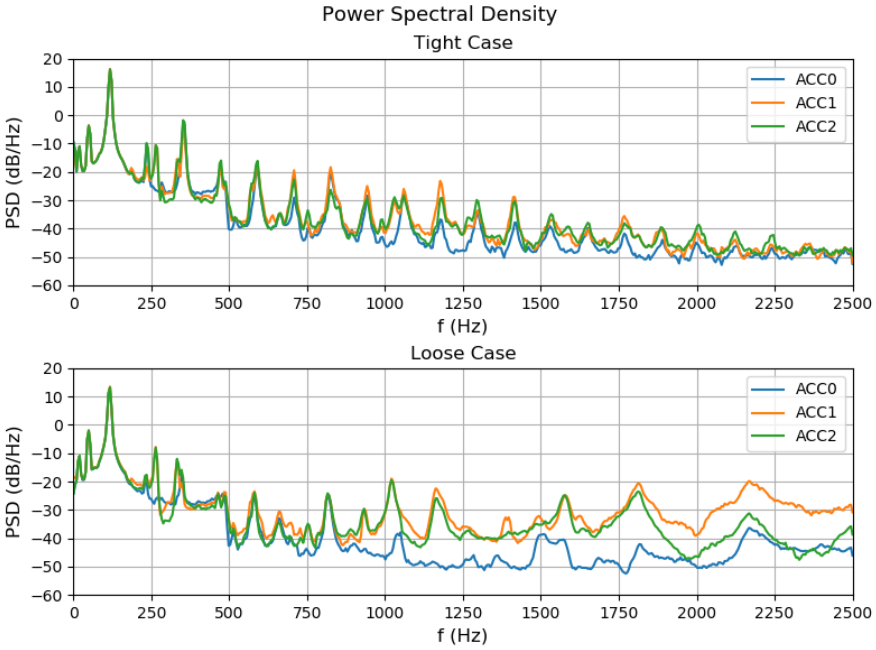

Figure 6: PSD graph of tight and loose case

The Spectral Kurtosis estimate for three individual bolts is presented in Figure 7. It indicates the presence of multiple non-stationary components. All non-stationary components are non-linear and these non-linear and non-stationary components can be leached using a Wiener filter with a 5% statistical threshold. The Wiener filters corresponding to each accelerometer is presented inFigure 8. This is used as a bandpass filter on the raw vibration data to extract the vibration corresponding to the rattling phenomenon. The Hilbert envelope of these non-stationary components as shown in Figure 9 clearly indicates that looseness can be diagnosed using the proposed technique.

A simple peak tracking operation performed on the Hilbert envelope is illustrated in Figure 10 below. Clearly, for ACC0 the presence of the non-stationary behaviour is captured distinctively. The next accelerometer ACC1 is 135 mm away from the loosened bolt. Thus, a weaker peak appeared in the filtered signal. Meanwhile, ACC2 is diagonally opposite to the ACC0 location and thus we see even weaker signature. Even though the peak diminished gradually as we move far away from the loose case, the tight case for the bolts indicated a negligible peak. The proposed approach can be implemented without the use of baseline data (tight case data) to diagnose the looseness defect.

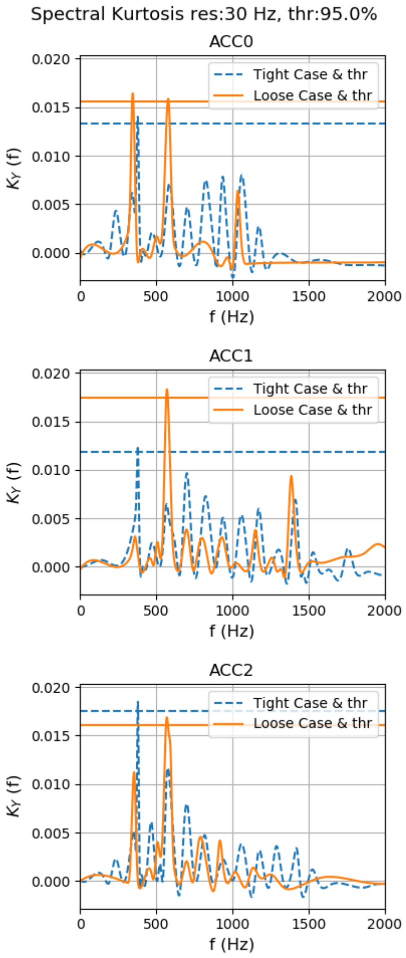

Figure 7: SK estimates

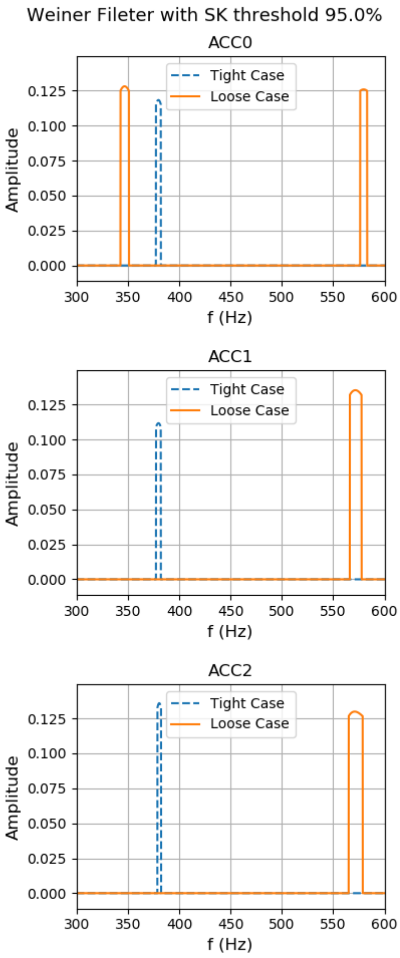

Figure 8: Wiener filter of SK estimates

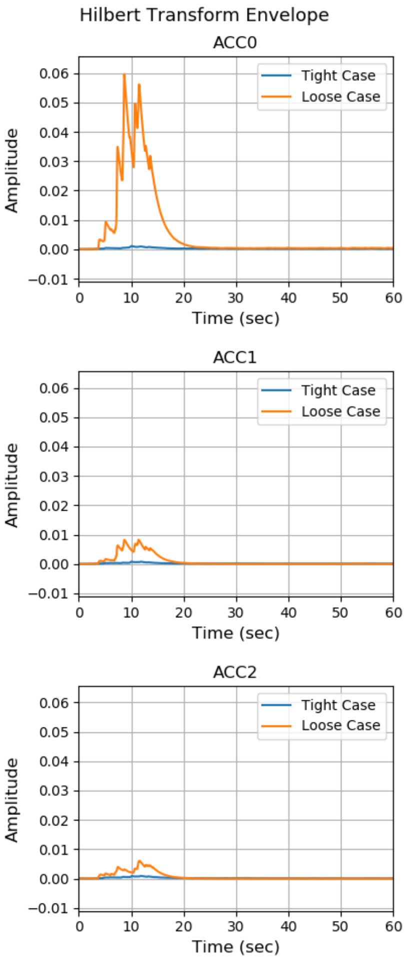

Figure 9: Features: Hilbert Envelope of the filtered signals

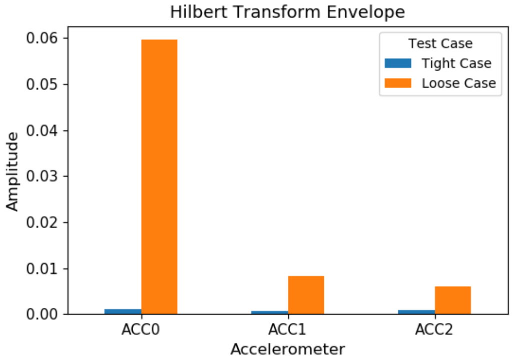

Figure 10: Peak tracking performed on the Hilbert envelope (Figure 9) of the filtered signal

5 Conclusions

Bolt looseness is a major problem for high valued infrastructure assets such as bridges. In this paper, a novel methodology to detect bolt looseness using optimal filtering of vibration data is proposed. A Spectral Kurtosis (SK) based optimal filter is designed to extract frequencies generated by bolt looseness. The filter is capable of extracting weak signatures (hidden in acceleration data) induced by bolt looseness. The proposed approach is validated through experiments. Results have indicated that the proposed approach can be reliable and effective in detecting loose bolts of a structure subjected to fluctuating loads.

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