Piezoelectric Actuators/Sensors for wavelet Based Failure Detection in Flexible Structures

Li Xinming[1] and Dan Necşulescu[2]
[1] Graduate Student, Department of mechanical Engineering, University of Ottawa, 161 Louis Pasteur, Ottawa, Ontario, Canada
[2] Professor, Department of mechanical Engineering, University of Ottawa, 161 Louis Pasteur, Ottawa, Ontario, Canada

***Abstract* -- This paper presents an analytical and experimental survey of the methods for in-service, in real-time damage detection of bolt connection. The experimental setup is a flexible aluminum beam with one end clamped on a frame and the other end jointed on frame by a bolt. To simulate connection damage, the stress relaxing on the bolt is achieved by the action of loose rotation that is quantified by rotation angle. A piezoelectric actuator produces the exciting signal. The dynamic response of flexible beam system is monitored by a piezoelectric transducer. The voltage output signal is processed offline by a PC and in real-time by an embedded digital signal processor (DSP) chip. Wavelet analysis method investigated in this paper is used to identify early change of beam connection state so as to prevent connection failure. The wavelet analysis results are compared to frequency response analysis (FR) methods in order to identify.**

***Index Terms* – Structural health monitoring, frequency analysis, wavelet analysis, connection failure detection, flexible aluminum beam, and piezoelectric actuator/sensor.**

I. INTRODUCTION

The damage of structural connections is one of the most challenging problems in structural damage detection. In fact, the survey of 61 Boeing 747s showed that 30 percent of structural damages observed are connection damages after three years service period [1]. Connection damage is also more complex than most other damage modes. The damage due to corrosion, fatigue, hole deform or crack on structures as well as looseness, corrosion or crack on fasteners are known causes of connection damage. As the tension on the fastener assembly varies, the joint stiffness is different [2]. The stress on fastener could result in damages of lap joints, for example, when corrosion occurs between layers in a lap-joint. This kind of damage in fuselage structure caused the accident of a Boeing 737 operated by Aloha Airlines in 1988 [3]. To simulate the connection damage, a model of lap joint is built with a bolt that can be rotated from initial tight condition to loose condition.

Non-destructive testing methods have been developed for damage detection. Ultrasonics, eddy current and X-ray photograph are among the most common methods for connection damage detection [3,4]. These methods, however, are less able to detect loose fasteners. Moreover, those methods can be used only manually off service. For an aging structure, like aging aircraft, which is close or beyond designed life-time, the interval of inspection must be shorter and shorter, and the cost of maintenance goes higher and higher. Structural health monitoring is an emerging solution for structural damage detection on the operation of in-service structures and is expected to improve the reliability of the structures and reduce maintenance cost [5].

In this paper, piezoceramic sensors and actuators are chosen due to their high bandwidth, low power consumption and low cost. Statistical techniques on frequency response and wavelet analysis are investigated for connection damage detection. Comparing to the paper [6], here we used a different kind of excitation signal, chirp signal, which covers the interesting frequency domain of vibration for frequency response analysis and optimizing exciting frequency. Moreover, the real time implementation solution for structural failure detection is added.

II. THE EXPERIMENTAL SETUP AND THE MODEL

A structure is made for damage detection with an isotropic aluminum beam 890 mm x 28 mm x 1.2 mm (L x W x T) is level to the ground by clamping one end on a frame and bolting the other end on another frame (Figure 1). Two 37 mm x 17 mm PZT piezoceramic chips were installed on both sides of beam, as shown in Figure 2, so that transverse vibration is excited and monitored. The experiment covered the boundary conditions changing from tight bolt to full loose bolt. The bolt is turned with some angle, step by step, in order to achieve and quantify various levels of damage. A spring washer is installed between the bolt and plain washer so as to extend loose rotation.

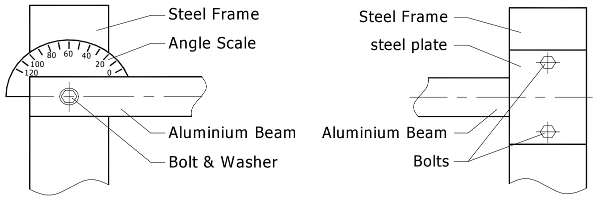
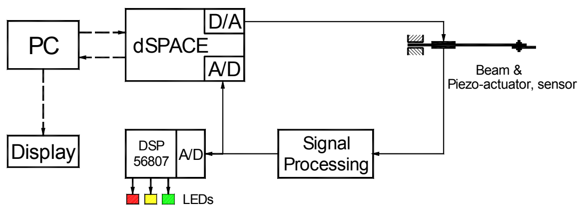


Fig. 1. Boundary condition of the beam



The electro-mechanical model of the actuator is

$$\sigma_x = E_p \varepsilon_x - g_{31} \frac{V}{h_p} \tag{1}$$

where σ_x is the stress, E_p is the Young's modulus of the piezoelectric material, ε_x is the strain, g_{31} is piezoelectric constant, V is the voltage applied, h_p is the thickness and $W_p(x)$ is the variable width of the piezoceramic layer.

$$M = EIw'' + g_{31} V W_p(x) \frac{H}{2} \tag{2}$$

where M is the bending moment, $w(x,t)$ is the vertical displacement of the beam. H is the thickness across the beam, and EI is the bending stiffness of the beam and the piezoelectric film together. Taking into account eq. 2, beam equation of motion gives

$$\rho A \ddot{w} + (EIw'')'' = -g_{31} V W_p{}''(x) \frac{H}{2} \tag{3}$$

For the two ends of the beam, the four boundary conditions are,

1. Clamped end:

$Deflection = 0$, or $w(0) = 0$ and $Slope = w' = 0$

2. Bolt connected end:

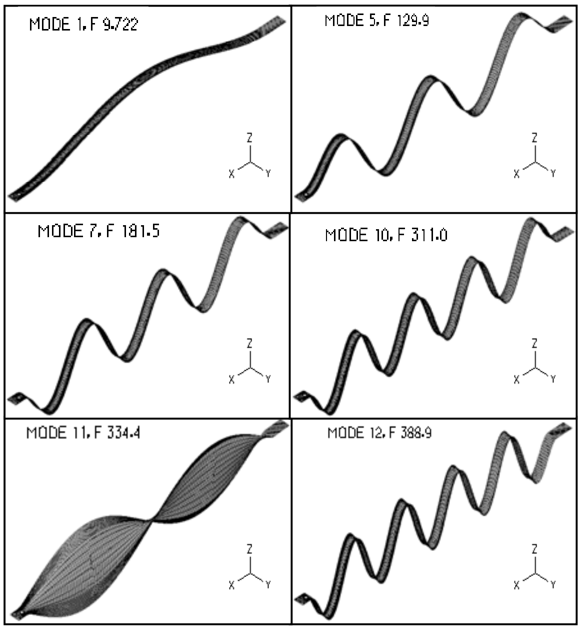
$$Shear\ Force = \frac{\partial}{\partial x}\left(EI \frac{\partial^2 w}{\partial x^2}\right) = kw$$

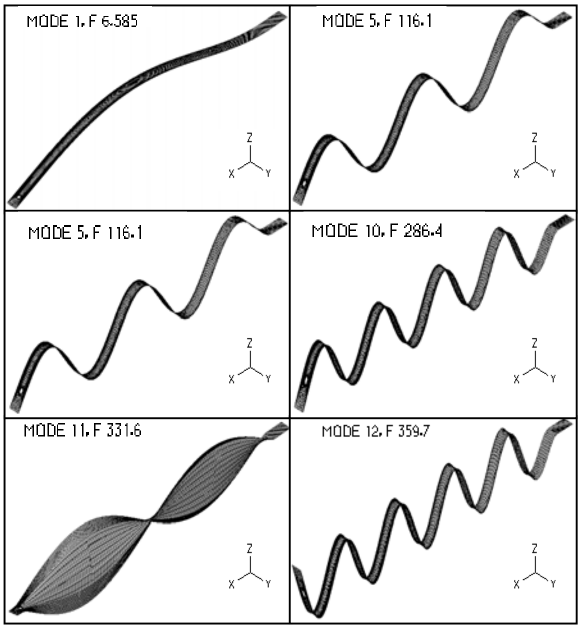
and $Bending\ Moment = EI \dfrac{\partial^2 w}{\partial x^2} = 0$

Turning the bolt changes the frequency response of the beam system.

Based on finite element analysis, for the location of piezo-sensor 100 mm away from the end, the most detectable mode is among mode 9, mode10, mode12 or mode 13 corresponding to a frequency band from 241.9 Hz to 475.6 Hz approximately. The precise mode will be measured by experiment and the natural frequencies of beam will be compared to the results of experiment.

Figure 3 shows some simulating results of finite element analysis of beam vibrating modes vs. natural frequencies obtained on ADINA system: one group is under clamped – tight bolt condition; another is clamped – fully loose bolt condition.





III. WAVELET TRANSFORM

Fourier transform provides frequency components existing in a whole signal, but time varying signals requires, STFT (Short-Time-Fourier-Transform) to find the efficient compromise regarding time and frequency resolutions. Wavelet transform decomposes a signal in time-frequency domain using a family of functions ψ^*, based on

$$CWT(\tau,s)=\frac{1}{\sqrt{|s|}}\int x(t)\psi^*(\frac{t-\tau}{s})dt \qquad (4)$$

where $x(t)$ is time domain signal to be transformed, τ is the translation parameter which is related to time, s is the scale parameter which is reciprocal of frequency, the function $\psi^* \in L^2(\Re)$ is mother wavelet, $CWT(\tau,s)$ is the wavelet coefficient [6-8].

The mother wavelet represents the window functions with different regions of support that are used in the transformation process and which are derived from a main function. The calculated wavelet coefficients refer to the closeness of the signal to the wavelet at the current scale. The mother wavelet used for the analysis in this paper is the Gaussian (gausN) wavelet

$$Gaus(x,n)=C_p e^{-x^2} \qquad (5)$$

where C_p is such that the 2-norm of the P-th derivative of $Gaus(x,n)$ is equal to 1 [9].

IV. EXPERIMENTAL APPROACHES

The experiments were performed using two approaches: one was collecting a time series vibration signals for frequency response and wavelet analysis on a PC; the other was processing vibration signal into frequency domain in real-time by DSP embedded chip [10].

Figure 1 & 2 shows the experimental setup containing dSPACE hardware, D/A port for voltage command signals to the piezoelectric actuator and A/D port for signal acquisition from the piezoelectric sensors. Also, the acquired signals are transmitted to the Motorola DSP56F807 evaluation board for real-time processing through FFT algorithm and for display using LEDs. A LabVIEW™ workstation is used to monitor the vibration signals for DSP chip protection. The resulting data are saved on dSPACE and then processed using MATLAB™ toolboxes for filtering, Hanning windowing and frequency response as well as continuous wavelet transform analysis.

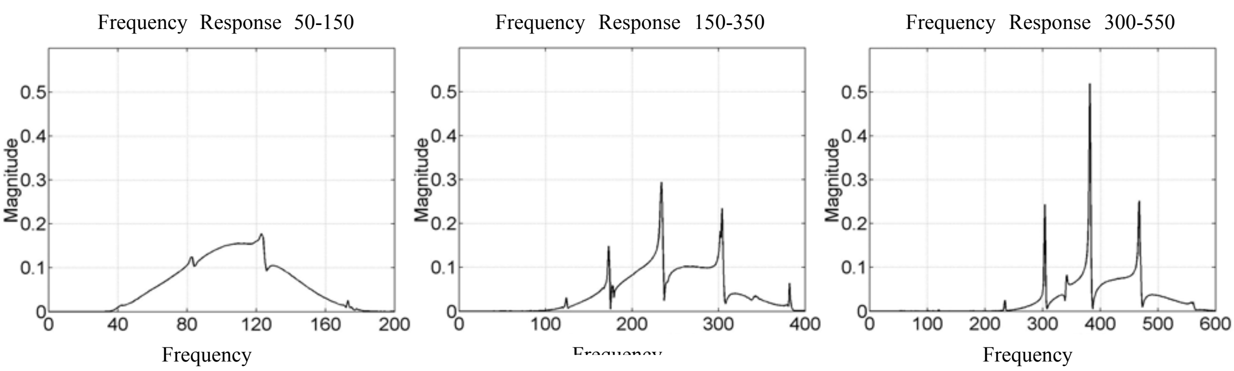
To compare the change of frequency responses for damage detection, continuous dynamic response of the structure is required in some range of frequency. A chirp signal was well designed to sweep a range of frequency in one second in order to obtain the beam frequency responses. The prototype of a chirp signal function used was $\sin(2\pi(a+bt+ct^2))$.

The experiments started from an initial condition of the connection in which the bolt has been fastened by a wrench in 5 ft.lb torque. The tests continued loosening the bolt using a wrench step-by-step, characterized by the corresponding rotation angle. The results were analyzed by frequency response method and wavelet analysis in PC and processed in Motorola DSP chip in real-time. The total loose connection can be regarded as bolt fracture or total failure.

For real-time detection the SDK tool kit called for 2048 samples spectrum computation in DSP. To avoid leakage error, again, each data was multiplied by the factor of Hanning Window, which is 2048-point length.

V. EXPERIMENTAL RESULTS

The determination of frequency of exciting signal is one of critical concern of measurement of active vibration.



It depends structure, actuator or sensor type and their location. Preliminary experiments were carried out for selecting the optimal excitation frequency domain. Three chirp signals designed with similar power density level swept frequency band from 50 Hz – 550Hz. Figure 4 shows the results of their responded frequency analysis, which indicate the resonance on 382 Hz and its around are the most detectable area. Table I presents for comparison the finite element method (FEM) results, test results and the relative error. The results show that for mode 12 or 382 Hz is the natural frequency the difference of test and FEM results is 1.8% only [11].

TABLE I
FEM natural frequencies vs. test resonant frequencies

	Mode 5	Mode 7	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
FEM [Hz]	129.9	181.5	241.9	311	334.4	388.9	475.6
Test [Hz]	123	173	234	304	342	382	468
Difference	5.6%	4.9%	3.4%	2.3%	-2.2%	1.8%	1.6%

Based on these results, the chirp signal $\sin(2\pi(40+180t+200t^2))$ was designed for frequency response analysis, which centered on 382 Hz in order to minimize the effect of Hanning Window.

A. Excitation and acquisition for frequency response analysis

Excitation and acquisition lasted 5 seconds, i.e. 5 repeat cycles of chirp signal were sent to actuator while the data were acquired in the same time for total 40960 samples. The average of 5 cycles could be obtained for reducing the zero mean noise effect. The results of FRs for different connection states are shown in Figure 5.

as an effect of bolt loosening. The results prove that the FR method is sensitive to connection damage of bolt loose and even incipient damage can be perceived. Real-time detection results were showing obtained by the combination on-off of three onboard LEDs linked with port B, which can show six variations of mode 12 resonant frequencies (Red, Yellow, Green, Red-Yellow, Yellow-Green and Red-Green) – the resonant frequency tracing field from 382 Hz to 377 Hz, rotation angle up to 2358 (the 8th loose). According the system demand, an alert could be defined, or damage index [12] could be calculated in real-time and results showed by LCD accessory.

B. Wavelet analysis

Wavelet analysis was carried out for 30 cycles of 382 Hz sinusoid excitation for each connection state. The response of transient disturbance and relaxation was recorded by dSPACE. Then, These signals were processed by continuous wavelet transform. The results for three states of the bolt connection (Tight, Medium Loose and Very Loose) are shown in Figure 6. The time variation of dynamic response and relaxation are on the upper left side; 2-D top view shows coefficient contour on the lower left side and 3D plot of Time-Frequency-Coefficient on the right hand side. Since the output and input were configured synchronously on dSPACE, the time abscissa shows the duration starting from just beginning of disturbance. For every step, the time lasted was 25000/19100 = 1.309 s/step. The exciting signal lasted 30 (cycles) x 50 (samples) / 19100 = 0.08 s [11]. The similarity between Gaussian mother wavelet and response signals produced 3D or 2D results of coefficient variations in time-frequency domain. Similar to the results of FR

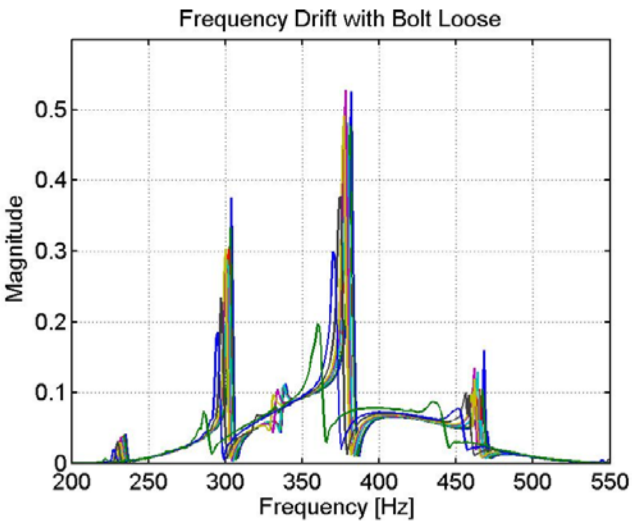


Fig. 5. Frequency responses of different connection

This results show, for each of the four modes of vibration, a reduction of the magnitude and frequency shown in Fig. 6, also shows, for each increase in bolt loosening a reduction of the amplitude versus frequency. Moreover, the results of wavelet analysis in Fig. 6 also show the corresponding time variation wavelet analysis and appear more efficient in distinguishing early damage levels.

From Tight to Very Loose condition, the maximum coefficient is obtained when the excitation stopped. The results show that increasing connection damage indicating that wavelet analysis results are relevant for damage detection. Further investigation will extend these approaches to complex structures.

VI. Conclusions

The results of wavelet analysis and the frequency response for structural health monitoring, in structures with bolt joints, investigated experimentally in this paper, indicate that the bolt connection damage causes detectable changes in the frequency responses.In this investigation the optimal frequency band chosen such active excitation is effective. Both wavelet analysis and frequency response method are sensitive to the very early change of bolt connection, while wavelet analysis appears more efficient in discriminating early damage levels. However, different factors and characters of primitive wave convolved in these transforms confine the further discussion of the relation between the results of FFT and Wavelet Analysis. The wavelet analysis provides extreme flexibility to fetch the effective information from signals with the right choice of mother wavelet.

The piezoelectric elements combined with DSP chips represent an interesting and cost effective solution for a minimally intrusive monitoring system.

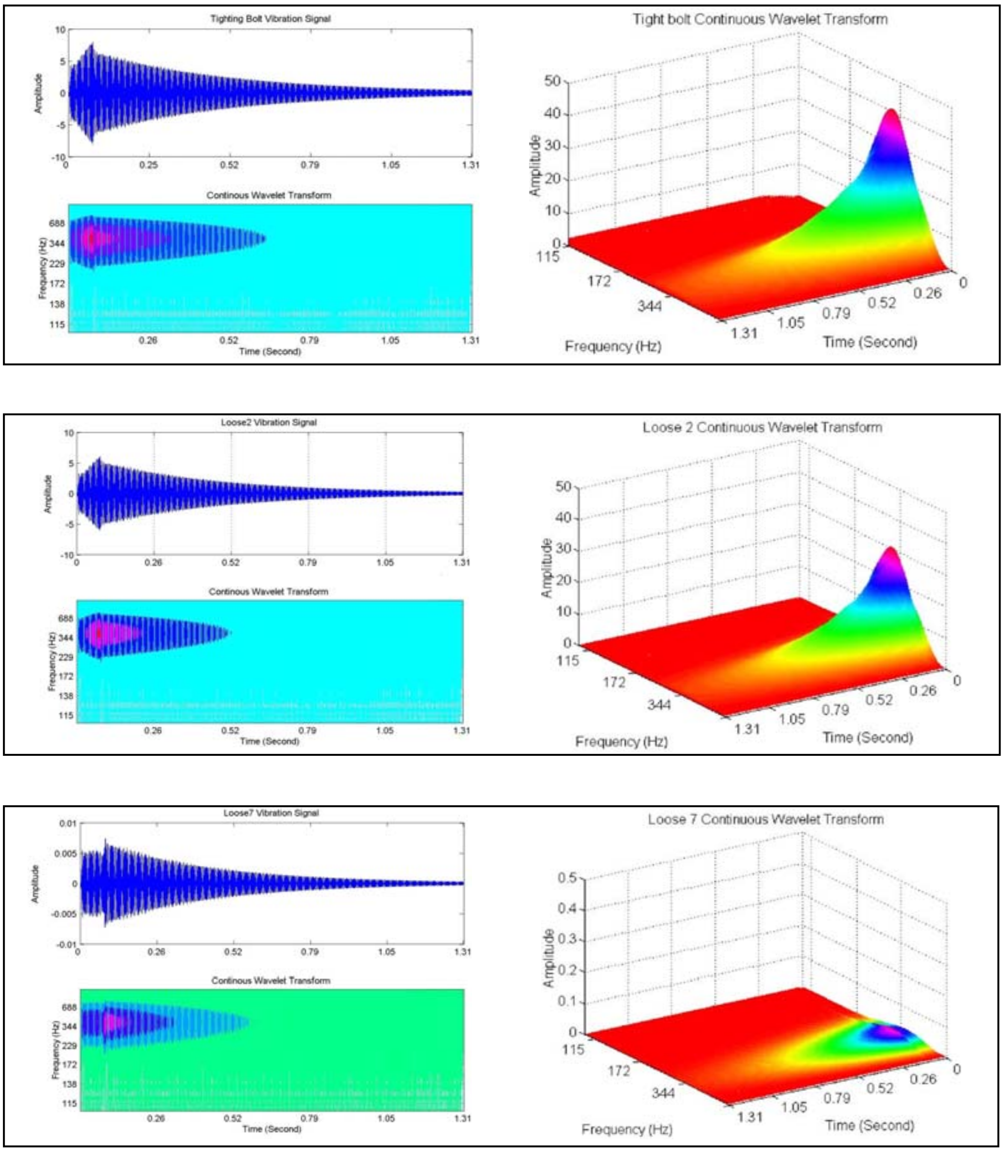


Fig. 6. Transient vibration signals and 3D,

2D contour plots of wavelet analysis

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