TIDC Transportation Infrastructure Durability Center
AT THE UNIVERSITY OF MAINE

Semi-Annual Progress Report

Project Number and Title: 1.6 Progressive fault identification and prognosis of railway tracks based on intelligent inference
Research Area: #1 Transportation infrastructure monitoring and assessment for enhanced life
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Reporting Period: October 01, 2018 – March 31, 2019
Date: March 31, 2019

Overview:

Summary of activities performed

In this first phase of the project, we perform preliminary investigation on sensing mechanism development (Task 1 in the proposal). Specifically, we explore new piezoelectric-based active sensing through high-frequency impedance measurement. Our emphasis is on actuation/sensing performance enhancement by means of circuitry integration. Experimental testbed is established to benchmark impedance sensing and its performance improvement. Analytical model of sensor-structure interaction is developed and validated by experiment. Op-amp based tunable inductance is synthesized, which forms resonant circuit with respect to the inherent capacitance of the piezoelectric transducer to amplify both the signal-to-noise ratio and impedance measurement as well as the fault induced impedance change.

How these activities are helping achieve the overarching goal of the project

The piezoelectric transducers possess two-way electro-mechanical coupling (i.e., deforming when subject to electrical excitation, and generating voltage/current when subject to deformation) and behave electrically as capacitors. Owing to these features, when we integrate (bond/embed) a piezoelectric transducer to a structure, the electrical impedance/admittance of the transducer is directly related to the impedance of the underlying structure. This has led to the recent interest in developing the piezoelectric impedance/admittance-based methods for real-time structural health monitoring. These methods have been examined for a variety of structural faults including crack, corrosion, debonding, joint degradation, etc. In such an approach, the piezoelectric transducer is driven by a frequency-sweeping sinusoidal voltage, and the electrical response (i.e., the resulted current) is measured to extract the impedance/admittance information. The change of piezoelectric impedance or admittance signature with respect to that under the undamaged baseline can be used as the damage indicator. This approach is based upon self-sensing interrogation, i.e., the piezoelectric transducer serves as the actuator and sensor simultaneously.

While promising, currently there exist major challenges in piezoelectric impedance/admittance sensing. Although the piezoelectric impedance/admittance can be measured at high frequency and may possess the necessary wavelength resolution to detect small-sized damage, the actual detection sensitivity hinges upon the scale of difference in the measurements upon the occurrence of damage. As different damage profiles affect the responses differently, the response anomaly can still be buried in the measurement noise. Moreover, in the high-frequency range, the damping effect (i.e., structural damping and circuitry resistance) may easily flatten the response resonant peaks (around which the damage effect is most significant, and will also severely limit the coverage area of the sensor.

The preliminary investigation carried out can effectively address the aforementioned challenges. Specifically, through circuitry integration and tunable resonance, we can greatly enhance the impedance/admittance measurement quality and also enrich the measurement information. This work lays down a foundation for the subsequent tunable sensor design and the fault detection/identification algorithmic investigation.

Describe any accomplishments achieved under the project goals…

We consider a generic structure bonded with a piezoelectric transducer. For simple illustration, we first assume perfect bonding between the structure and the transducer. After certain derivations we may obtain the piezoelectric impedance, or its inverse, the piezoelectric admittance, respectively as [43]

$$\hat{Z}_p = \frac{\hat{V}}{\hat{I}} = \frac{\hat{V}}{i\omega\hat{Q}} = \frac{1}{i\omega C_p\left(1 - \frac{d_{31}^2}{s_{11}^E \varepsilon_{33}^T}\frac{\hat{Z}_m}{\hat{Z}_m + \hat{Z}_e}\right)}, \qquad \hat{Y}_p = \frac{\hat{I}}{\hat{V}} = i\omega C_p\left(1 - \frac{d_{31}^2}{s_{11}^E \varepsilon_{33}^T}\frac{\hat{Z}_m}{\hat{Z}_m + \hat{Z}_e}\right) \qquad \text{(1a, b)}$$

where ω is the frequency of the excitation voltage applied to the piezoelectric transducer, and C_p is the piezoelectric capacitance. $\hat{Z}_m$ and $\hat{Z}_e$ are, respectively, the impedances of the structure and the transducer (before it is bonded to the structure). All other symbols are material constants of the transducer. Hereafter the hat notation is used to indicate

Laplace/frequency domain quantities. Eq. (1) indicates that the change in the structural impedance $\hat{Z}_m$ due to damage occurrence will be reflected in the change of the overall piezoelectric impedance $\hat{Z}_p$ or its inverse, the admittance $\hat{Y}_p$. In this type of detection approach, the piezoelectric transducer serves as the actuator (exciting the structure) and the sensor (sensing the structural property) at the same time. This can fully utilize the high bandwidth of the piezoelectric transducer and lead to high-frequency interrogation.

Although commercial impedance analyzers can be used to measure the piezoelectric impedance curve (impedance versus excitation frequency), they cannot be used for online monitoring due to their bulky size and high cost. Here we start from adopting a low-cost impedance measurement scheme. By measuring the voltage drop across a resistor connected serially with the piezoelectric transducer, the electrical current due to the voltage excitation can be obtained, leading to the impedance/admittance information. This allows the online implementation of the piezoelectric impedance sensing, as the signal generation and FFT algorithm can be embedded into a small-sized digital signal processing unit.

One foundational idea in this phase of the research is to integrate tunable circuitry with the piezoelectric transducer to realize dynamical tailoring of the sensing system to fundamentally enhance the sensitivity and robustness. The underlying idea of this new concept is highlighted in the following paragraphs through a simplified case investigation. It should be noted that this simplified case study involving a tunable inductor is the basic configuration. Throughout this research, a variety of circuitry elements will be integrated into the new sensing system for performance optimization. For simplicity in discussion, here we use a one degree-of-freedom (DOF) model to represent the interested mode of the mechanical structure. The dynamic equations of the structure coupled with the piezoelectric transducer without and with the inductance can be derived as

$$m\ddot{q} + c\dot{q} + kq + k_1 Q = 0\,, \qquad R\dot{Q} + k_2 Q + k_1 q = V_i \qquad \text{(without inductance)} \qquad (2a,b)$$

$$m\ddot{q} + c\dot{q} + kq + k_1 Q = 0\,, \qquad L\ddot{Q} + R\dot{Q} + k_2 Q + k_1 q = V_i \qquad \text{(with inductance)} \qquad (3a,b)$$

where q is the mechanical displacement, Q is the electrical charge in the circuit, m, c, and k are the mass, damping, and stiffness, respectively; $k_2 = 1/C_p$ is the inverse of the piezoelectric capacitance, and V_i is the excitation voltage. Both systems include a resistor that enables the direct measurement of current resulted from the voltage excitation. The piezoelectric admittances can be expressed as, respectively,

$$\hat{Y}_p = \frac{\hat{I}}{\hat{V}_i} = \frac{i\omega\left(-m\omega^2 + ic\omega + k\right)}{\left(iR\omega + k_2\right)\left(-m\omega^2 + ic\omega + k\right) - k_1^{\,2}} \qquad \text{(without inductance)} \qquad (4)$$

$$\hat{Y}_p = \frac{\hat{I}}{\hat{V}_i} = \frac{i\omega\left(-m\omega^2 + ic\omega + k\right)}{\left(-L\omega^2 + iR\omega + k_2\right)\left(-m\omega^2 + ic\omega + k\right) - k_1^{\,2}} \qquad \text{(with inductance)} \qquad (5)$$

Here, one can see that Eq. (5) is a fourth-order system with *two* resonances, while Eq. (4) is essentially a second-order system with one resonance since, compared to k_2, $R\omega$ is very small. Obviously, one major difference between the new sensor with the inductance (Eq. (5)) and the traditional approach (Eq. (4)) is that the inductive circuitry introduces an additional DOF, which leads to *a new resonant effect* in the *admittance* curve. It is well known that the damage-induced changes are most significant around the resonant peaks.

We have performed an experimental feasibility study to examine the measurement performance. We consider a thin aluminum beam (length 607.8mm, width 7.62mm, thickness 3.175mm; fixed-fixed) bonded with a piezoelectric transducer (length 17mm, width 7.62mm, thickness 0.191mm). We target at the structural resonant frequency at 6070 Hz corresponding to the first impedance peak in Figure 1, which originally does not show noticeable change upon damage occurrence. The measurement results (electrical current versus excitation frequency) of the traditional approach without the inductance and of the new concept with the inductance are compared in Figure 1. The current versus frequency curve obtained by the new sensing system has two resonant peaks, and exhibits two orders of magnitude increase in amplitude. This will greatly increase the signal-to-noise ratio in actual practice. In this case study, the inductance is selected as 77 mH, which results in a circuitry resonant frequency equal to the structural natural frequency.

Of more importance is how the admittance signature changes when damage occurs. For the same damage and under the same level of voltage excitation, the larger such change, the more sensitive the sensing system is. Here we use a small added mass (0.33g) placed near the middle of the beam to emulate the damage. The differences in admittance (before and after damage occurrence) versus the excitation frequency of the traditional approach and of the new sensor design are plotted in Figure 2 (in dB scale). It can be seen that the admittance difference (i.e., the damage indicator) is amplified by more than one order of magnitude, which directly indicates that the new design can greatly enhance the damage detection sensitivity.

Moreover, the sensing system is online tunable, i.e., the inductance in the measurement circuit can be tuned to a series of different values, which then yields a family of admittance curves (and their changes upon damage occurrence). This has also been experimentally validated. As shown in Figure 2, under the same damage scenario, by tuning the inductance to two different values, e.g., L=75.6 mH and L=77 mH, we can obtain two different sets of admittance change curves. Although these two inductance values are close to each other, the corresponding admittance change curves are quite different, which means additional information regarding damage has been obtained.

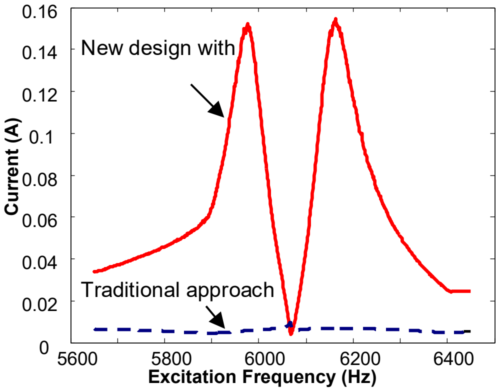

Figure 1. Electrical current: new design greatly amplifies the measurement.

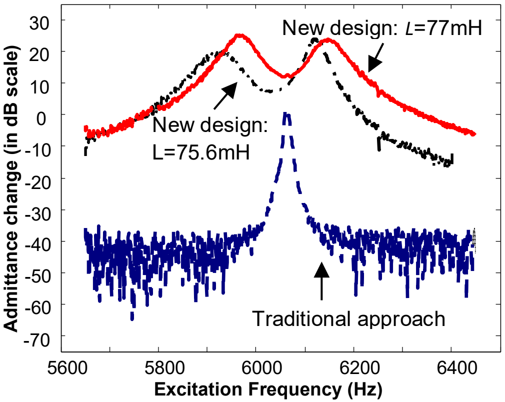

Figure 2. Admittance change due to damage: new design greatly amplifies the change.

Describe any opportunities for training/professional development that have been provided…

This project currently involves on graduate student, Yixin Yao, to carry out the numerical and experimental investigations. This provides opportunity for training. The project progress is being communicated with industry collaborator, Sperry Rail Service, which provides another opportunity for training of state-of-the-art knowledge of active materials and advanced signal processing techniques for working professionals.

Describe any activities involving the dissemination of research results

In this phase of research, research results have been disseminated in the following occasions:

- TIDC workshop held at Portsmouth, NH; Nov. 08-09, 2018
- Working meeting with CT DOT, held at University of Connecticut, Feb 28, 2019
- Working meeting with Sperry Rail Service, held at Sperry, Mar 13, 2019

Participants and Collaborators:

Participants: Dr. Jiong Tang, PI, project lead; Yixin Yao, graduate student, research assistant.
Collaborator: Jan Kocur, Sperry Rail Service, providing technical assessment and industry insights.

Changes: N/A

Planned Activities:

The next phase of the research will focus on tunable sensor optimization, as well as fault identification algorithm development.