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Characterization of Piezoelectric Stack Actuators for Vibrothermography

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Abstract

Vibrothermography, also known as Sonic IR and thermosonics, is an NDE technique for finding cracks and flaws based on vibration-induced frictional rubbing of unbonded surfaces. The vibration is usually generated by a piezoelectric stack actuator which transduces electrical energy into large amplitude mechanical vibrations. The amplitude and impedance transfer characteristics of the transducer system control the vibration of the sample. Within a linear contact (no tip chatter) model, the interaction between the transducer system and the specimen can be characterized using the theory of linear time-invariant (LTI) systems and electro-mechanical Norton equivalence. We present quantitative measurements of the performance of piezoelectric stack actuators in a vibrothermography excitation system and investigate the effect of actuator performance and specimen characteristics on the induced vibration in the specimen. We show that the system resonances generated because of metal-metal contact of specimen and actuator are broken by adding a couplant between specimen and actuator. Finally, we give criteria for actuator and couplant selection for vibrothermography.

Keywords

thermography, cracks, piezoelectric transducers, vibrations, nondestructive testing, nondestructive evaluation

Disciplines

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CHARACTERIZATION OF PIEZOELECTRIC STACK ACTUATORS FOR VIBROTHERMOGRAPHY

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ABSTRACT. Vibrothermography, also known as Sonic IR and thermosonics, is an NDE technique for finding cracks and flaws based on vibration-induced frictional rubbing of unbonded surfaces. The vibration is usually generated by a piezoelectric stack actuator which transduces electrical energy into large amplitude mechanical vibrations. The amplitude and impedance transfer characteristics of the transducer system control the vibration of the sample. Within a linear contact (no tip chatter) model, the interaction between the transducer system and the specimen can be characterized using the theory of linear time-invariant (LTI) systems and electro-mechanical Norton equivalence. We present quantitative measurements of the performance of piezoelectric stack actuators in a vibrothermography excitation system and investigate the effect of actuator performance and specimen characteristics on the induced vibration in the specimen. We show that the system resonances generated because of metal-metal contact of specimen and actuator are broken by adding a couplant between specimen and actuator. Finally, we give criteria for actuator and couplant selection for vibrothermography.

Keywords: Vibrothermography, Piezoelectric Actuator, LTI Twoport, Sonic IR
PACS: 43.20.Ks, 43.20.Wd, 43.38.Fx, 43.40.Le, 43.40.Yq

INTRODUCTION

Vibrothermography is a nondestructive evaluation technique for finding cracks and delaminations in materials by vibration induced crack heating. First, a specimen with a crack is vibrated. Friction between rubbing crack surfaces generates heat and this heat is imaged with an infrared camera. A key aspect in this technique is the vibration generation. Effective actuation of the specimen is required for successful defect detection. The common methods of vibration generation are using ultrasonic welders and piezoelectric stack actuators.

Ultrasonic welders generate high amplitude vibrations but they operate at specific frequencies (20 KHz, 30 KHz, 40 KHz) only. The selection parameters for ultrasonic welders are operating frequency and horn geometry. With this type of actuation, it is difficult to generate vibrations if the actuation frequency is at a node of the specimen. Piezo stack actuators, on the other hand operate in a much broader range of frequencies (DC to 50 KHz). Because of their wide bandwidth, they can be used to vibrate the specimen at its resonant frequency and therefore it is possible to achieve high vibration amplitude and heating [1] without the nonlinear impacts required to convert a fixed frequency source to broad spectrum of excitation frequencies. The selection parameters for piezostack actuators are stack length and stack diameter. Length of the stack determines the natural resonances of actuator. Stack diameter

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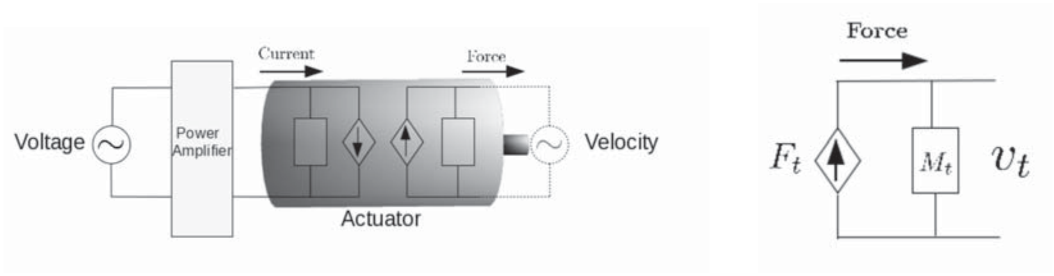

FIGURE 1. Complete Electromechanical model of a PZT actuator. In the left image, input port is electrical and the output port is mechanical. The four parameters fill in to complete the model. The right image shows the mechanical Norton equivalent circuit of the complete model. The important parameters in it are opencircuit velocity, immovable object force and Mobility.

determines the stiffness of actuator. Longer actuators have smaller resonance frequencies and higher stroke lengths than shorter ones. Thicker actuators have more stiffness and can be used with heavier loads. We use a piezoelectric stack actuators to excite the specimen[2].

In a vibrothermographic inspection, first the specimen is vibrated with a broadband sweep excitation and the specimen velocity spectrum is measured at a point. Specimen resonance frequencies are obtained from this velocity spectrum. Then the specimen is again vibrated with a monotone excitation at its resonance frequency. We see a localized heating in the areas that contain a defect (crack, delamination etc) in the specimen. However, if the actuator tip is in direct contact with the specimen, instead of specimen resonances, we see system resonances (i.e., the joint resonances of specimen actuator) in the velocity spectrum. These system resonances are not repeatable and depend heavily on actuator and mounting. To break these system resonances and vibrate the specimen at its resonances, a couplant has to be introduced between the actuator tip and specimen. We observed that the couplant acts as a spring and if it is compliant enough, the system resonances are eliminated.

We model the actuator using an electromechanical analogy and characterize the behavior of actuator, specimen and couplant using this model. Towards the end, we explain the criteria of how to select an actuator and couplant for a given inspection.

ACTUATOR MODEL

A Piezoelectric stack actuator can be modeled as a LTI (Linear Time Invariant) two port network within linear regime with current and voltage as input parameters and force and velocity as output parameters[3]. The mechanical quantities can be mapped to electrical quantities using electromechanical mobility analogy. In this type of analogy, force and velocity map to current and voltage respectively[4].

Figure 1 shows the two port circuit representation of a piezostack actuator and the Norton equivalent model of the same circuit. In electrical terminology, Norton equivalent model is the generalized representation of any electrical circuit in terms of a current source and an equivalent impedance. The characteristics to be measured for an actuator are its Open circuit velocity, Immovable object force and Mobility. Actuator “Open circuit velocity”, v_t is the velocity of the actuator tip when no load is attached to it. It is measured with a laser doppler vibrometer by exciting the actuator without attaching a specimen. Actuator mobility,M_t is the velocity of actuator per unit applied force. This measured from the velocity of a point

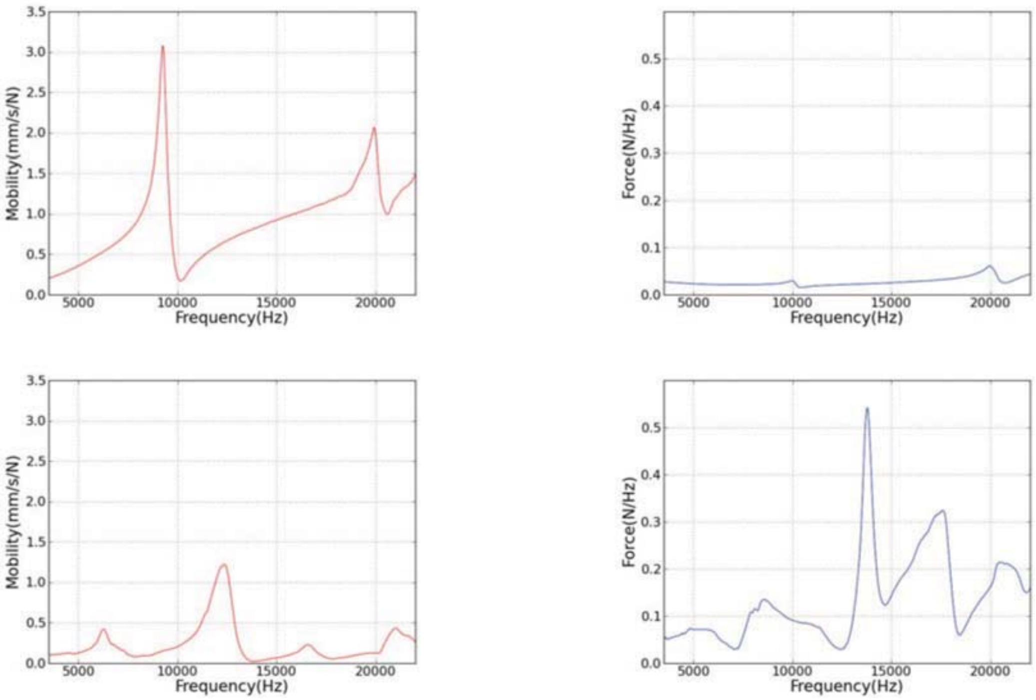

FIGURE 2. Actuator characteristics calculated from the Norton equivalent model. The top left plot shows mobility of an actuator with 16mm stack diameter and 20 mm length. The top right plot shows the immovable object force of the same actuator. The bottom left plot shows mobility of actuator with 25 mm stack diameter and 40 mm length. The bottom right plot shows the immovable object force of this actuator. The immovable object force of actuators is relatively flat compared to the mobility.

mass,m attached to the actuator and solving the equation,

$$F = (j\omega m)v_m = \frac{v_t}{M_t} \tag{1}$$

where F is the force on actuator tip by the point mass. “Immovable object force”,F_t is the force on the actuator tip when an infinite load is attached to it. It is the open circuit velocity divided by the mobility of actuator. Figure 2 shows the plots of mobility and immovable object force of two different actuators plotted against frequency. The actuator has high open circuit velocity at its resonance frequencies. The reason for using immovable object force of actuator is that it is relatively flatter than other characteristics of the actuator and so,it would be simpler to describe specimen behavior in terms of force although its the open circuit velocity that is measured directly. This model,however is not accurate at high excitation amplitude and high frequencies where the system becomes highly non linear.

SPECIMEN CHARACTERIZATION

Specimen characteristics (velocity and mobility) can be measured when the Norton equivalent circuit of the actuator is known. Once we have the actuator and specimen characteristics, we can choose the right actuator to use for a particular specimen/inspection. The top left image of Fig. 3 shows the Norton actuator model with specimen attached. Specimen Velocity, v_s is the velocity of vibrations of the specimen excited with an actuator. This is measured using a laser doppler vibrometer pointed at the vibrating specimen. Specimen mobility, M_s is the velocity of specimen per unit applied force. It is calculated from specimen

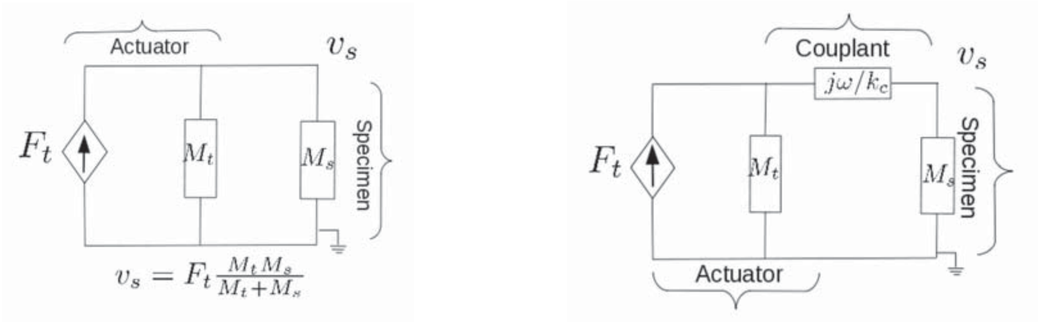

FIGURE 3. Norton equivalent mechanical model of actuator with specimen attached as the load. The left image shows the equivalent circuit when the specimen is directly attached to the actuator tip with metal-metal contact between them. The image on right shows the same equivalent circuit but with a couplant between actuator tip and specimen. The couplant, in this context acts like a spring whose electromechanical analogue is an inductor.

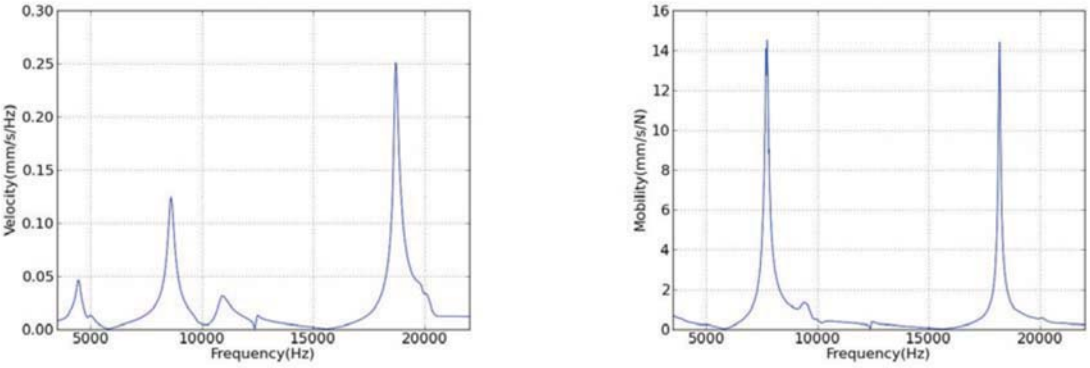

FIGURE 4. Specimen characteristics calculated from the Norton equivalent model of the actuator. Plot on the left shows the velocity profile of the specimen measured by a Laser Doppler Vibrometer. Plot on the right shows the calculated value of specimen mobility from the model. Clearly, the peaks in velocity profile do not match those in the mobility profile which represent the natural resonances of specimen. This is because of the actuator-specimen system resonances. Adding a couplant breaks these system resonances.

velocity and actuator characteristics as given in equation (2).

$$v_s = F_t \frac{M_t M_s}{M_t + M_s} \tag{2}$$

The left and right plots in Fig 4. show the measured velocity and calculated mobility of the specimen from the model respectively.

However, the limitation in this experiment is that the peaks in the specimen velocity do not match those of its actual resonances as shown in the mobility. This is because, the resonances seen in the velocity plot are actuator-specimen system resonances and not specimen resonances alone. Since system resonances depend on actuator and mounting, they are not repeatable across actuators. Hence it is important to separate specimen resonances from the system resonances. In conventional vibrothermographic testing, a couplant is often used between actuator tip and specimen. The reason for using a couplant in vibrothermography has not been to date, completely understood. When we used a layer of card stock as couplant between actuator tip and specimen, it broke the system resonances and the specimen vibrated at its own natural resonances and not at system resonances. The top left plot in Fig 5. shows the

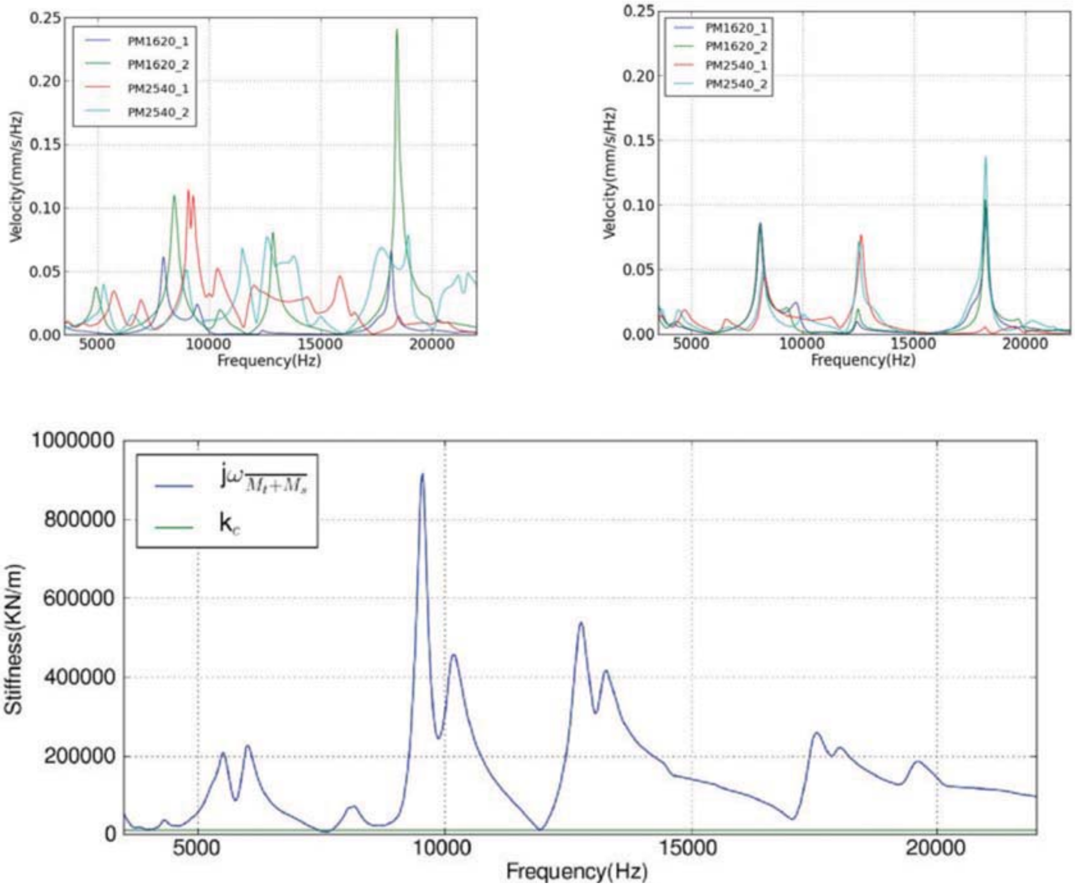

FIGURE 5. Effect of adding a couplant on specimen behavior. The top left image shows the velocity response of a specimen with four different actuators with metal-metal contact. The resonances in the specimen velocity are not repeatable. The top left image shows the same but with a couplant in between actuator tip and the specimen. In this case, the system resonances are broken and we only see the specimen resonances which are very repeatable across actuators. The bottom image shows the reason for this behavior. If the compliance of the couplant is small enough to dominate, the system resonances are eliminated.

velocity plot of a single specimen excited with different actuators without using a couplant (metal-metal contact) under identical mounting conditions. Clearly, the system resonances are actuator dependent and hence not repeatable. With a couplant, the specimen vibrates at its natural resonances which are independent of actuator used and this is shown in the top right plot of Fig 5.

ACTUATOR AND COUPLANT SELECTION

According to our preliminary observations, the reason for using a couplant in vibrothermography is two-fold. First, the tip of a piezostack actuator is not flat and hence the actuator does not sit well on the specimen. This may result in tip-specimen contact being broken and effect the specimen vibrations. The second and more important issue is generation of non repeatable system resonances which depend on the actuator and mounting. A couplant effectively breaks system resonances leaving just the specimen resonances and thus it makes the experiment more repeatable. A Couplant can be thought of as an elastic spring (stiffness k_c) between actuator tip and specimen. The equivalent electromechanical analogue of spring is an inductor (according to Mobility analogy). We included this inductor in our Norton model as shown on the right image of Fig 3. and calculated the specimen mobility as given in equation (3).

$$M_s = \frac{v_s(M_t + M_s + \frac{j\omega}{k_c})}{F_t M_t} \tag{3}$$

where k_c is the stiffness of couplant. For the case of a single layer of card stock, the k_c measured was about 10000 KN/m. From equation (3), the system resonances are effectively eliminated if the following condition holds.

$$k_c \ll \frac{j\omega}{M_t + M_s} \tag{4}$$

In this case, the specimen velocity can be approximated as follows:

$$v_s \approx \frac{k_c}{j\omega} F_t M_t M_s \tag{5}$$

Since the product $F_t M_t$ is the actuator open circuit velocity, the specimen velocity depends on the product of actuator open circuit velocity and specimen mobility and not on the joint mobility of specimen and actuator ($M_s + M_t$). In the bottom plot in Fig. 4, the horizontal line in green shows the stiffness of the couplant we used. From this plot, we verified that the condition in equation (4) indeed holds for our couplant (a layer of card stock). If a card stock is used as a couplant, its compliance can be increased by increasing the thickness of the stock. However, specimen velocity decreases as couplant becomes more compliant. Hence, a couplant whose compliance is small enough to eliminate the system resonances is ideal to use in vibrothermography. Common choices for couplant are layers of card stock, teflon tape, etc.

Since the specimen velocity is proportional to actuator open circuit velocity with sufficient coupling, an actuator with high open circuit velocities at or near the specimen resonances increases the specimen vibrational velocity. Some resonances of actuator are actually small. So, it is important to select an actuator that has a large resonance closer to the specimen resonance frequency being tested at.

CONCLUSION

Defect detection in vibrothermography depends on the actuator used for exciting the specimen. At a given excitation mode, one actuator may result in heat generation while another may not. By modeling the actuator and specimen, we can predict the behavior of actuator and the specimen. Actuator-specimen system resonances can be eliminated if a couplant is introduced between actuator tip and specimen. A simple linear model is used to calculate the actuator and specimen characteristics. An actuator with high velocities at or near specimen resonances of operation generates high vibrational velocities in specimen. A couplant that is compliant enough that it breaks the system resonances from specimen resonances should be used.

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