A PZT-Coated Cantilever Transducer for Simultaneous Sensing and Actuating in Dynamic Testing of Structures

Deyang Wang, Shih-Fu Ling*

Centre for Mechanics of Microsystems,
School of Mechanical and Production Engineering,
Nanyang Technological University,
50 Nanyang Avenue, Singapore 639798
*: msfling@ntu.edu.sg (corresponding author)

Abstract

The concept of utilizing a PZT-coated cantilever for simultaneous sensing and actuating (SSA) in dynamic testing of structures was derived and confirmed usable in previous studies. In the theory, the SSA capability was enabled through a 2 by 2 transduction matrix which describes the relationships between the potential and flow variables at the input and output port of this electromechanical transducer. The four elements of the matrix are actually frequency response functions (FRFs) between one of input and output variables in a broader sense. They characterize the forward actuating and backward sensing properties of the transducer concisely and completely. In this paper, using these 4 FRFs, the sensing and actuating capability of such SSA cantilever transducers are indicated by performance index of sensing and actuating respectively. A number of numerical experiments were first performed to confirm the appropriateness of these two indices. An optimization strategy was then formed to obtain the best balance between the sensing and actuating capability of a given SSA cantilever. Through numerical simulations and nonlinear optimization, design of the SSA cantilever was improved and the performance of the optimized cantilever as a SSA transducer was confirmed significantly better than the original design. In addition, the functional behavior of a SSA transducer is made clearer through the simulations and performance analysis.

INTRODUCTION

In literature, many difficulties occur in dynamic testing of miniature or micro systems. Space is limited for sensor installation is one of the problems. Zeng and Borgy [1] in their modal testing of the miniature suspension of the reading arm assembly of hard disk drives were forced to replace force measurement by detecting the input voltage of a magnetic force exciter. Furthermore, the higher working or natural frequencies exhibited the mini- or micro systems often jeopardize the use of conventional load cells such as at a wire bonding interface mentioned earlier. In the past few years, Ling and his groups also reported [2-5] a method for measuring mechanical impedance of structures exploiting a shaker as both sensor and actuator simultaneously. In their approach, a "transduction matrix" was defined to relate the electrical impedance at the input port and the mechanical impedance at the output port of the electro-magnetic transducer. Once the transduction matrix is calibrated, the mechanical impedance experienced at the output port can then be calculated from the measured electrical impedance at the input port of the shaker. The method by Ling, etc. requires no sensors but only an electromechanical actuator for detecting point mechanical impedance of a structure. This sensor-less nature provides advantages in dynamic measurement of mechanical systems under certain circumstances. It eliminates sensors and therefore applicable to cases where space limited for sensor installation or measurand is out of the range of sensors.

The concept of utilizing a PZT-coated cantilever for simultaneous sensing and actuating (SSA) in dynamic testing of structures was derived and confirmed usable in previous studies [6]. In the following the construction of the cantilever actuator and the concept of transduction matrix are briefly reviewed first. After that, performances of cantilever transducer, including sensing and actuating capabilities are studied and based on this study; an optimization strategy is employed to design the cantilever transducer with balanced sensing and actuating capabilities. Comparing performances of optimized cantilever with those of original one is then presented to validate the proposed method.

TRANSDUCTION MATRIX

The configuration of the cantilever actuator is shown in Figure 1. Supplied with electrical power in z-direction, the PZT patch expands and contracts in x-y plane. The mechanical deflection of the PZT, equivalent to an adding moment, actuates the cantilever, whose bending vibration in turn excites the system by the tip. In this process, the cantilever functions as an actuator. At the same time, the response of the system will affect the motion of the cantilever. It results in additional deformation of the PZT patch, whose electrical output will then be changed due to the direct piezoelectric effect. It can be seen that the information on the dynamic behavior of the system is implied in the electrical signals of PZT. Therefore, the cantilever can serve as a sensor simultaneously.

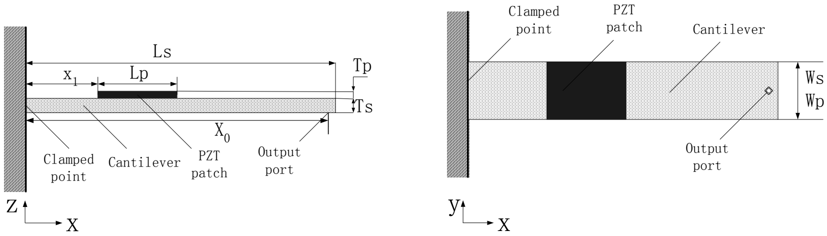

Figure 1- Schematic view of a PZT-Coated cantilever

The PZT driven cantilever is utilized as an electromechanical transducer and viewed as a two-port system, which is like a bridge connecting the mechanical impedance of the system with the input electrical impedance. Since the transducer is linear and reciprocal, the FRFs (frequency response functions) among the voltage and current at the input port and the force and velocity at the output port together forms a two by two matrix,

$$\begin{Bmatrix} E \\ I \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{Bmatrix} F \\ V \end{Bmatrix} = [T] \begin{Bmatrix} F \\ V \end{Bmatrix} \tag{1}$$

Since this transduction matrix provides a well-defined relationship between the mechanical impedance at the output port and the electrical impedance at the input port of the cantilever transducer, the mechanical impedance can be indirectly detected by Eq. (2) if the input electrical impedance is made known.

$$Z_m = \frac{F}{v} = \frac{T_{22} Z_e - T_{12}}{T_{11} - T_{21} Z_e} \tag{2}$$

where $Z_e = \frac{E}{i}$ and $Z_m = \frac{F}{v}$.

Since the PZT-Coated cantilever is utilized as an actuator for sensing simultaneously, performance indices indicating actuating and sensing capabilities will be highlighted in the following section. In this study, a spring-mass-damper (SMD) system, which having mass $m = 100mg$, damping ratio $\zeta = 0.01$, and natural frequency at *50Hz*, is selected as a load added onto the cantilever. As shown in Figure 2, the PZT-Coated cantilever consists of an aluminum cantilever beam 0f 90mm in length, 12mm in width and 1.0mm in thickness. The PZT patch (Fuji C-91) bonded to its top surface is 20mm long, 12mm wide and 0.2mm thick. This PZT patch is 5mm from the root of the beam (x_p=5 mm) and the output port in the two-port model is designated at a point close to the free end of the cantilever ($x_o/L=0.965$).

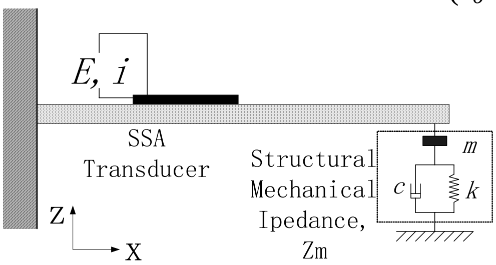

Figure 2- PZT-Coated cantilever driven spring-mass-damper system

PERFORMANCE INDICES OF CANTILEVER TRANSDUCER

SENSITIVITY

For the transducer, the input variable is mechanical impedance of dynamic system and output is electrical impedance. According to the definition of sensitivity, the sensitivity of cantilever transducer, therefore, can be expressed as follows:

$$K = \frac{\partial Z_e}{\partial Z_m} = \frac{T_{11}T_{22} - T_{12}T_{21}}{(T_{21}Z_m + T_{22})^2} = \frac{1}{(T_{21}Z_m + T_{22})^2} \quad (3)$$

Figure 3 shows the numerical results of the PZT-coated cantilever's sensitivity evaluated by using Eq. (3). It is observed that the sensitivity is not constant but a function of frequency. However, in the low frequency range before the first natural frequency, it is regarded as constant. We regard this range as effective dynamic frequency range for sensing and the transducer is feasible for sensing in this range. In the study, both sensitivity and effective dynamic frequency range are utilized as performance indices indicating the sensing capability of cantilever transducer.

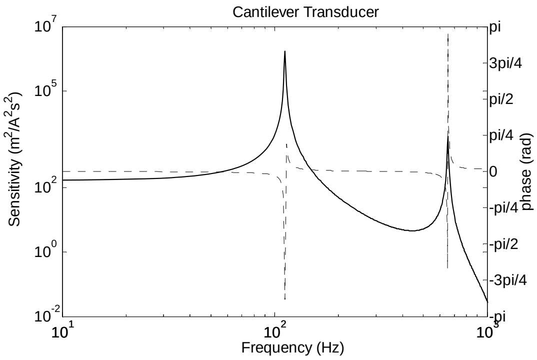

Figure 3- Sensitivity of a PZT-Coated cantilever

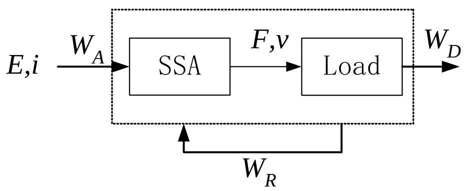

Figure 4- Model of cantilever transducer used as an actuator

ENERGY EFFICIENCY

The model for an actuator is shown in the Figure 4. The input is an apparent power, W_A, and transfers into dissipative power, W_D, and reactive power, W_R. The energy efficiency of the actuator in driving the system is defined as:

$$\psi = \frac{\text{Dissipative Mechanical Power}}{\text{Supplied Electric Power}} = \frac{\text{Re}(Y)}{|Y|} \quad (4)$$

where Y is the coupled electromechanical admittance resulting from the mechanical loss of the mechanical system and is expressed in the equation shown below.

$$Y = \frac{i}{E} = \frac{1}{Z_e} = \frac{t_{21}Z_m + t_{22}}{t_{11}Z_m + t_{12}} = \frac{1}{Z_{ec}} \cdot \frac{Z_m + \frac{t_{22}}{t_{21}}}{Z_m + Z_A} \quad (5)$$

where Z_{ec} is the electrical impedance of the cantilever transducer when it is mechanical clamped, i.e. $Z_{ec} = \frac{E}{I}\big|_{v=0} = \frac{t_{11}}{t_{21}}$; Z_A is the mechanical impedance of the cantilever transducer at the output port when it is electrically short-circuited, which is calculated using $Z_A = \frac{F'}{v} = -\frac{F}{v}\big|_{E=0} = \frac{t_{12}}{t_{11}}$. Note that F by definition refers to the force generated by the cantilever at its tip and to the object being excited. It is opposite in direction to the force *F'* applied to the cantilever having been used in the course of the derivation.

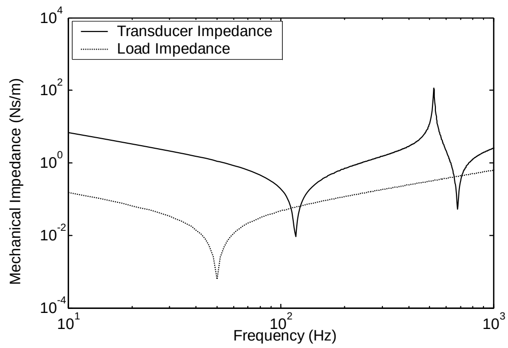

Figure 5- The mechanical impedance of cantilever transducer and SMD system

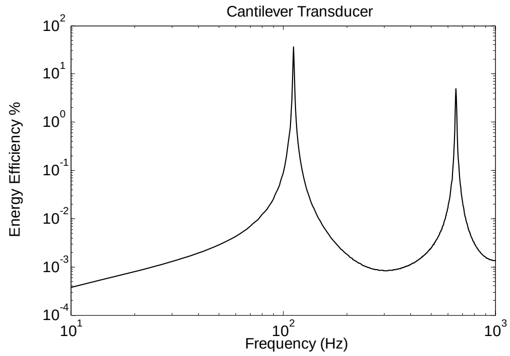

Figure 6- Energy efficiency of cantilever transducer driven SMD system

Figure 5 shows the impedance matching of cantilever transducer and spring-mass-damper system. Figure 6 shows the energy efficiency of the cantilever transducer. It is concluded that the actuator becomes the most efficient when the actuator impedance matches the structural impedance as illustrated in Figures 5 and 6. For a continuous system, there are many peaks corresponding to the natural vibration mode of the system. The height of a peak indicates the effectiveness of the actuator to excite that mode. Therefore, the energy efficiency can be used in the optimal design of actuator configuration and location, and can be used as performance index of actuating capability of cantilever transducer. It is necessary to stat that impedance matching between the actuator and its load means that both impedances are complex conjugate.

OUTPUT FORCE

From the four-pole model of cantilever transducer, the relation can be determined by

$$E = t_{11}F + t_{12}v \tag{6}$$

If the mechanical impedance of the mechanical system is given by Z_m, it means that $v = F / Z_m$. The interactive force can be obtained as

$$F = \frac{Z_m}{Z_m + Z_A} F_b = \frac{Z_m}{Z_m + Z_A} \cdot \frac{E}{t_{11}} \tag{7}$$

where Z_A is the actuator impedance defined above, F_b is the dynamic blocking force by assuming an infinite mechanical impedance, which is $\frac{E}{t_{11}}$. Thus, the characteristic of transduction element t_{11} determines the performance of dynamic blocking force.

From Eq. (7), if the impedance of the mechanical system is at its lowest, which corresponds to its resonance, the force provided by the actuator is at its lowest. If the structural impedance, Z_m, matches the actuator impedance, Z_A, the actuator provides the maximum force and power. In the above study, it is also concluded that when the actuator impedance matches the structural impedance, the actuator becomes more efficient, which has higher energy efficiency. The remained important factor, which also influences the characteristic of output force, is dynamic blocking force, F_b. This performance measure is just the force at the actuator output when the output is prevented from moving, which is assumed an infinite mechanical impedance, when a drive signal is applied [7]. It is commonly described in terms of output force per input voltage. Figure 7 shows the numerical results of output force when the selected cantilever transducer is clamped. It is found that the output force is very low and an improvement of cantilever transducer for a higher output force is essential.

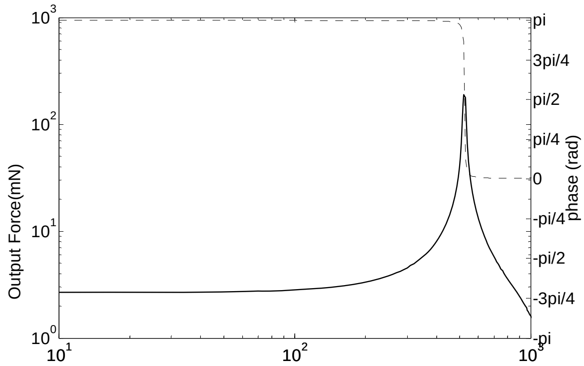

Figure 7- Output force of cantilever transducer

OPTIMIZATION OF THE CANTILEVER TRANSDUCER

As described in previous sections, we know that the actuating capability of cantilever transducer is very weak. The objective function of the optimization for cantilever transducer design, therefore, is mainly to improve the output force of cantilever transducer, while the other capabilities, including effective dynamic frequency range, sensitivity and energy efficiency, are also considered in the terms of constraints shown in the following equations.

$$\min : f(x) = -\overline{F} \tag{8}$$

$$\begin{cases} c_1(x) : \text{first natural frequency} : f_1 > f^* \\ c_2(x) : \text{sensitivity} : \mathrm{K} > k^* \\ c_3(x) : \text{energy efficiency} : \psi > \psi^* \end{cases} \tag{9}$$

where $\overline{F}$ is the mean value of output force in the effective dynamic frequency range, * means a specified value.

The design variables of the optimization include length, width and thickness of cantilever beam and PZT patches, position of PZT patches bonded on the beam. Finally, the dimensions and parameters of optimized cantilever transducer have been obtained using software program (MATLAB software) and results are shown in Table 1.

Table 1: Dimensions of cantilever transducer (L'=90mm; L=190mm)

Design Variables	Symbol	Original	New
Length of beam	L_s	L'	L
Width of beam	W_s	*0.133 L'*	*0.092L*
Thickness of beam	T_s	*0.011 L'*	*0.092L*
Length of PZT	L_p	*0.222 L'*	*0.965L*
Width of PZT	W_p	*0.133 L'*	*0.092L*
Thickness of PZT	T_p	*0.002 L'*	*0.043L*
Position of PZT	x_1	*0.056 L'*	0

Figure 8 shows the comparison results of sensitivity between original (dot line) and new cantilever transducer (solid line). The effective frequency range of new cantilever transducer greatly increases while the sensitivity reduces as illustrated in Figure 8. In the previous investigation, we know that the sensitivity of original transducer is very high, which is not necessary. After the optimization, the sensitivity of new transducer greatly reduces but is still more than 1. Hence, the new cantilever transducer is still good enough in sensing the load. A comparison result of output force between the original and new cantilever transducer is also shown in Figure 9. It is observed that the force at the output port of new transducer is much higher and more stable than the original one. It means that the actuating capability of new transducer is increase greatly. Thus, from Figures 8 and 9, it is concluded that the sensing and actuating capability of new cantilever transducer have been balanced. From the above numerical simulation, it is demonstrated that the performances of new cantilever transducer are better than those of original transducer and the optimization strategy is feasible to design a cantilever transducer for best simultaneous sensing and actuating.

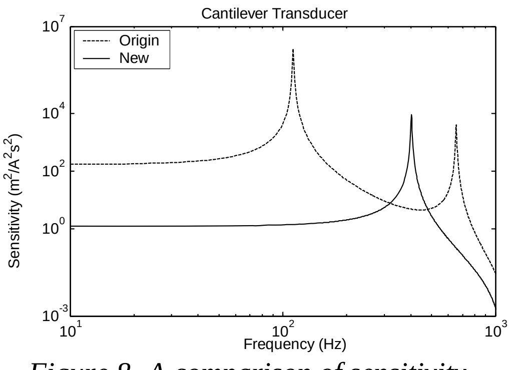

Figure 8- A comparison of sensitivity between origin (dash) and new cantilever transducer (solid)

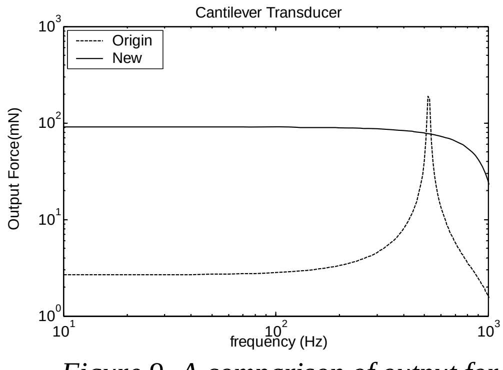

Figure 9- A comparison of output force between origin (dash) and new cantilever transducer (solid)

DISCUSSION AND CONCLUSIONS

In the paper, sensitivity and effective range of transducer, which indicating sensing capabilities of the transducer, are studied firstly. After that, energy efficiency of cantilever transducer has been studied and numerical results show that energy efficiency is an important performance index for design of our cantilever. It is known that the actuator becomes the most efficient when the actuator impedance matches the structural impedance. The resonance of the electro-mechanical system occurs when the actuator impedance and structural impedance match. Output force is a most important index of actuating capability of transducer, equation for numerical calculation of output force is derived and numerical study is also done. From the results, it's known that the original PZT coated cantilever is not a good actuator to drive the spring-mass-damper system, though its sensitivity is very high.

Based on this investigation and results, an optimization strategy is employed to design the cantilever transducer as a good actuator with proper sensing capability to drive the given spring-mass-damper system. The objective function of the optimization is to improve the output force of cantilever transducer and the other capabilities, including effective frequency range, sensitivity and energy efficiency, are also considered in the forms of constraints. By comparing new cantilever with original cantilever, it can be seen that the effective frequency range is greatly increased and sensitivity is relative high to sense the load. Moreover, the actuating capability of transducer is strongly emphasized. Thus, the new cantilever is a good actuator with balanced sensing capabilities and the optimization method is successful to optimal design of cantilever transducer for simultaneously sensing and actuating.

REFERENCES

[1] Zeng, Q.H. and Bogy, D.B., "Dynamic characteristics of a suspension assembly part 1: modal experiment", *Advances in Information Storage Systems*, **vol. 8** (1998): 105-120.

[2] Ling, S.F. and Xie, Y., "Monitoring structural integrity using a piezoelectric inertial actuator cum sensor", *Journal of Sound and Vibration*, **247**(4) (2001): 731-737.

[3] Ling, S.F. and Xie, Y., "Detecting mechanical impedance of structures using the sensing capability of a piezoceramic inertial actuator", *Sensors and Actuators a-Physical*, **93**(3) (2001): 243-249.

[4] Yin, Y., Ling, S.-F., and Liu, Y., "A dynamic indentation method for characterizing soft incompressible viscoelastic materials", *Materials Science and Engineering A*, **379**(1-2) (2004): 334-340.

[5] Ling, S.-F., Hou, X., and Xie, Y., "Decoupling loading effect in simultaneous sensing and actuating for dynamic measurement", *Sensors and Actuators A: Physical*, **120**(1) (2005): 257-265.

[6] Ling, S.-F., Wang, D., and Lu, B., "Dynamics of a PZT-coated cantilever utilized as a transducer for simultaneous sensing and actuating", *Smart Materials and Structures*, **14** (2005): 1127-1132.

[7] Lesieutre, G.A., Rusovici, R., et al., "Modelling and characterization of a piezoceramic inertial actuator", *Journal of Sound and Vibration*, **261**(1) (2003): 93-107.