The effect of open and short circuit of piezoelectric element towards the resonance frequency of cantilever beam bonded with piezoelectric element

圧電素子を貼り付けた片持ち梁の共振周波数に対する圧電素子の開放と短絡の効果

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ABSTRACT

In this paper, an idea of semi-active damper coupling for 2-inetia torsional vibrating system is proposed where the concept of Dynamic vibration absorber (DVA) using piezoelectric-bonded plate is applied. An experiment to determine ability for the piezoelectric-bonded plate to tune its mechanical characteristic which is the resonance frequency by controlling the open and close circuit configuration in the form of piezoelectric-bonded cantilever system is introduced. Result for the difference of resonance frequency theoretically in open circuit and short circuit is approximately 29.31Hz and 29.03Hz respectively. While, experimentally response in open and short circuit is around 29.51Hz and 29.17Hz either in constant controlled circuit configuration or in an alternate order of open and short circuit configuration. This show clear difference of resonance frequency which is lower value in short circuit than in open circuit. It concludes that the application of piezoelectric-bonded plate can be considered for semi-active control in DVA for SADC.

INTRODUCTION

There is large range of application of piezoelectric material, especially in vibration control and noise suppression due to their good mechanical-electrical coupling characteristics. In the recent years, vibration control using piezoelectric materials has received much attention.

The method of vibration control can be mainly divided into 3 categories which is passive, active and semi-active. Passive control systems, which use R-L shunting, are simplest among three categories, but their control performance is sensitive to the variations of the system parameters. Moreover, the passive control systems usually need large inductance in low frequency domain, which is difficult to realize. Active control systems require high-performance digital signal processors and bulky power amplifiers to drive actuators, which are not suitable for many practical applications. In order to overcome these disadvantages, semi-active approaches, also called semi-passive approaches, have been proposed.

In this thesis, semi-active control using piezoelectric element in a device for disturbance suppression in 2-inertia torsional vibration system which is known as Semi-active damper coupling (SADC) is proposed. As a method of disturbance suppression, the concept of dynamic vibration absorber (DVA) that tuned to counteracts the force from the vibration imbalance also being suggested into the proposed SADC model.

An experiment to identify the effect of different open and short circuit configuration of piezoelectric-bonded cantilever towards the resonance frequency is carried out. In The displacement characteristic of resonance frequency for open and close circuit had been examine experimentally in the field of energy harvesting that resulted in higher resonance frequency in short circuit than in open-circuit in the case of using one patch of piezoelectric-bonded cantilever [1]. The purpose of this experiment is to find out the ability of the piezoelectric plate in tuning the resonance frequency as examined in [1] so that it can be applied in developing DVA in SADC.

CHAPPTER1: THE PROPOSED MODEL

1.1. SEMI-ACTIVE DAMPER COUPLING(SADC) MODEL

2-inertia torsional vibrating system is a system that consist of Load and Motor that is connected by a shaft. The example of 2 inertia torsional vibrating system figure is as shown in Figure 1.

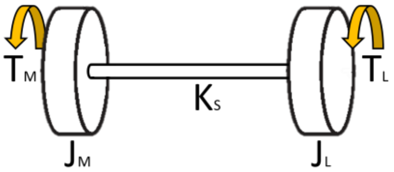


Figure 1 2-Inertia torsional vibrating system

In this system, due to disturbance, undesirable mechanical power is generated. Thus, disturbance suppression is important. From the previous experiment, Semi Active Damper Coupling (SADC) that can vary the damping characteristic of shaft has been created [2].

However, it only can generate small different of damping characteristic. As a new method of disturbance suppression, Dynamic Vibration Absorber (DVA) is suggested to be installed in the SADC. DVA is an additional system that is tuned to counteracts the force from the vibration imbalance.

Figure 2 is one of the basic schematic diagrams of DVA referred from a previous research [3] . The objective of adding the DVA is to decrease the oscillation speed caused by the disturbance torque, T_L. DVA can be fixed to the rotating machine and tuned to oscillate in such a way that exactly counteracts the force from the disturbance. This reduces the possibility that a resonance condition will occur. This means that, when there are disturbance torque T_L, the DVA will reduce the oscillation speed ω_L causes by the T_L because the DVA oscillate instead of it.

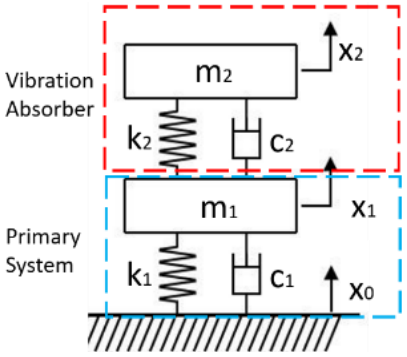
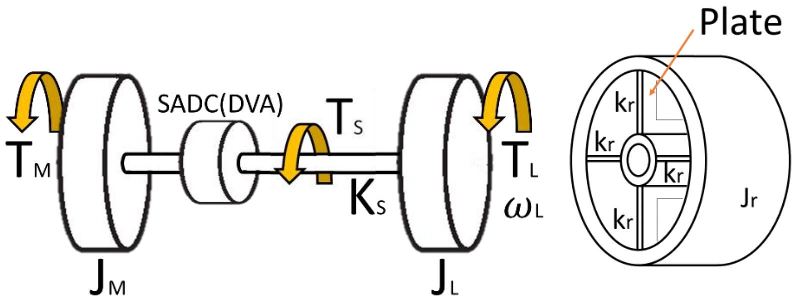


Figure 2 Schematic Diagram for DVA

The idea of installation of DVA in SADC is as shown in Figure 3(Left). Figure 3(Right) shows several piezoelectric-bonded plates placed in the proposed SADC model. These piezoelectric is attached on one side of each plate to introduce semi-active control in the SADC device.



Left: 2-inertia torsional vibration system with installed SADC, Right: The Close-up look for idea of SADC model

Figure 3 Idea of installation of DVA in SADC

$T_M = Motor\ Torque$

$J_M = \text{Motor's inertia}$

$T_L = \text{Load}\ Torque$

$J_M = \text{Load's inertia}$

$T_S = \text{Shaft Torque}$

$J_r = \text{SADC's inertia}$

$K_r = \text{Spring constant of spring plate and piezoelectric actuator}$

$K_S = \text{Spring constant of shaft}$

$\omega_L = Angular\ velocity$

Piezoelectric actuator has a property that enable it to change from electrical energy to mechanical, and vice-versa. Thus, the ability for a piezoelectric-bonded plate to tune the mechanical characteristic which is here identified by the resonance frequency of the device by monitoring the circuit configuration is experimented in this research.

1.2. OVERVIEW OF CHARACTERISTIC OF PIEZOELECTRIC ACTUATOR

The Piezoelectric Effect can be defined as the ability of materials for generating an electric charge in reply toward applied mechanical pressure. In the contrary, the inverse or reverse piezoelectric effect can be defined as, whenever the piezoelectric effect is reversed. Which also can be described as, an applied electric field in a material produces dimensional changes and stresses within a material. This can be formed by applying electrical energy to make a crystal expand. The main function of this effect is to convert electrical energy into mechanical energy.

1.3. PROPOSED EXPERIMENTAL MODEL

Semi-active system for the proposed model is when resonance frequency is tuned by modifying the parameter. In this research, the electrical configuration of the piezoelectric is focused as the monitoring parameter. The purpose of SADC is to suppress the disturbance by tuning the resonance frequency of the 2-inertia torsional vibration system. Thus, the ability for every plate to tune it’s mechanical characteristic by monitoring the parameter continuously is significance for actual application of semi-active control of DVA function of SADC.

In respond to that, an experimental setup to determine the ability of changing the mechanical characteristic of the plate is proposed as in Figure 4 which is a piezoelectric-bonded cantilever system with tip mass. The parameter to check the changing of mechanical characteristic of this proposed model is the resonance frequency.

The piezoelectric cantilever, as shown schematically in Figure 4, mainly consist of a piezoelectric element bonded on a metal beam. The piezoelectric element is attached onto the metal beam using an adhesive that allow electric connection at a position close to the clamped end. This clamped end of the cantilever is fixed on a vibrating base to vibrate along the vertical direction or the thickness direction. While at the other end of cantilever, proof mass M_{tip} is installed, which is used to improve vibration characteristics of the structure for optimal performance in identifying the changes of mechanical characteristic when input electrical energy is converted into output vibration energy.

Along with the vibration at the vibrating base, the point loading also-called proof mass M_{tip} will also have velocity along the direction of the point loading. And the plate will deflect into curve. When the velocity goes to zero, the deflection reaches to maximum. The cantilever will be in resonance frequency at this point. The deflection of the cantilever plate induces the deflection of the piezoelectric actuator, which result in the strain of the piezoelectric actuator.

A piezoelectric actuator attached on the top surface of the flexible beam, is switched between open and short circuit configurations. This switching introduces a change in stiffness, which, in turn, can remove energy from the overall system by directly affecting the stored potential energy in the flexible beam.

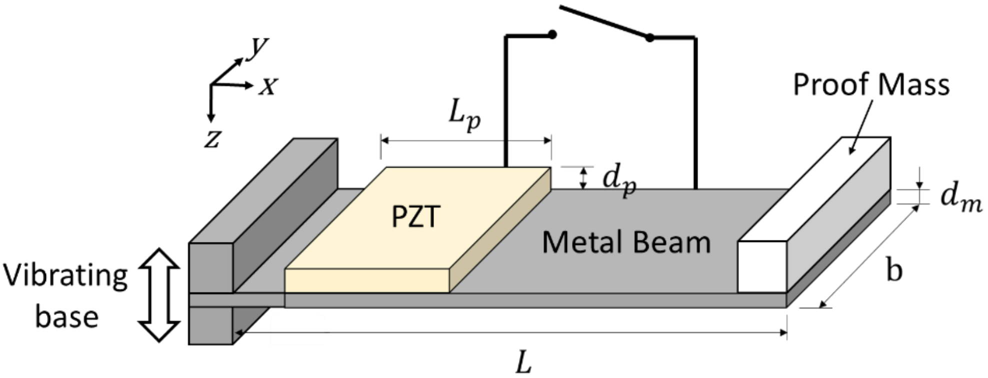


Figure 4 PZT-Layered Cantilever System

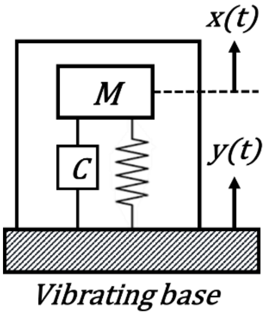


Figure 5 Equivalent Single Degree of Freedom (SDOF) system

1.4. CALCULATION FOR ESTIMATED RESONANCE FREQUENCY

Table 1 Specification of cantilever

	Metal Beam SUS430	PZT $Pb(Zr \cdot Ti)O_3$
Density $[kg/m^3]$	$\rho_m = 7.8 \times 10^3$	$\rho_p = 7.65 \times 10^3$
Young ratio [Pa]	$E_m = 2 \times 10^{11}$	$E_{p\_open} = 6.2 \times 10^{10}$ $E_{p\_short} = 7.3 \times 10^{10}$
Poisson's ratio	$\nu_m = 0.275$	-
Size $[mm^3]$	$L \times d_m \times b$ $115 \times 0.3 \times 40$	$L_p \times d_p \times b$ $45 \times 0.5 \times 40$

The mechanical part consists of a seismic mass with M, a spring with constant K, a dashpot with damping coefficient C, and a vibrating base, as shown in Figure 5. Here, x(t) and y(t) are the motions of seismic mass and vibrating base along the z-axis, respectively. The equivalent Single Degree of Freedom (SDOF) system can be generally described as [4]

$$\ddot{z} + 2\zeta\omega_n\dot{z} + {\omega_n}^2 z = -\ddot{y} \tag{1}$$

Where z=x(t)-y(t) is the relative motion between the mass and the vibrating base and is the damping ratio. For the piezoelectric cantilever in Figure 4, the angular frequency is given as

$$\omega_n = \sqrt{\frac{K}{M}} \tag{2}$$

Where Seismic Mass, M can be defined as

$$M = M_{tip} + \frac{33}{140} M_{beam} \tag{3}$$

Here, M-tip is the proof mass, and the $M_{\text{beam,}}$is the beam mass defined as

$$M_{beam} = \rho_m L b d_m + \rho_p L_p b d_p \tag{4}$$

Where the spring constant, K is given by

$$\mathrm{K} = \frac{9\,EI\,E_m I_m}{2\,EI\,(L - L_p)^3 + 5\,E_m I_m\,{L_p}^3 + 9\,E_m I_m\,{L_p}^2 (L - L_p)} \qquad (5)$$

The flexural rigidity of the metal layer,$E_b I_b$, and composite part of piezoelectric and metal layer,EI are as below,

$$E_m I_m = \frac{1}{12} \times \frac{E_m}{1 - {\mathrm{v}_m}^2} b {d_m}^3 = \frac{1}{12} \times E_M b {d_m}^3 \qquad (6)$$

$$EI = \frac{1}{3} E_M b\left({d_m}^3 + 3 d_m a^2 - 3 {d_m}^2 a\right) + \frac{1}{3} E_p b\left({d_p}^3 + 3 d_p a^2 - 3 {d_p}^2 a\right) \qquad (7)$$

Here, the a is the distance from the interface to the neutral axis (z=0) in the PZT layer, [5]

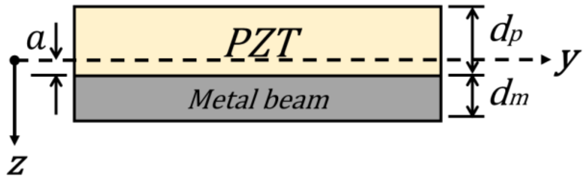


Figure 6 Cross-sectional area of Piezoelectric layer and metal beam in the system

$$a = \frac{bE_M {d_m}^2 - bE_p {d_p}^2}{2(bE_M d_m + bE_p d_p)} \tag{8}$$

Finally, the relation between Young’s Modulus of piezoelectric in open circuit and short circuit is [6]

$$E_{p\_open} = E_{p\_short} \frac{1}{1 - {k_{31}}^2} \tag{9}$$

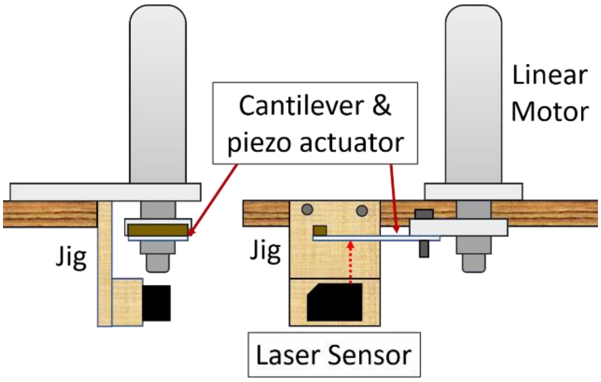
Here, $k_{31}$is the coupling coefficient of the piezoelectric.

By substituting the parameter in

Table 1 into these equations, the resonance frequency in open and close circuit can be calculate theoretically.

CHAPPTER2: EXPERIMENTAL APPARATUS

The main component of the experimental apparatus consists of a linear motor, laser sensor and the cantilever system. The supporting component included a jig for laser sensor and jig for cantilever system. The image of experiment set up is as shown in Figure 8.



Left: Side view, Right: Front view

Figure 7 Image of experimental apparatus

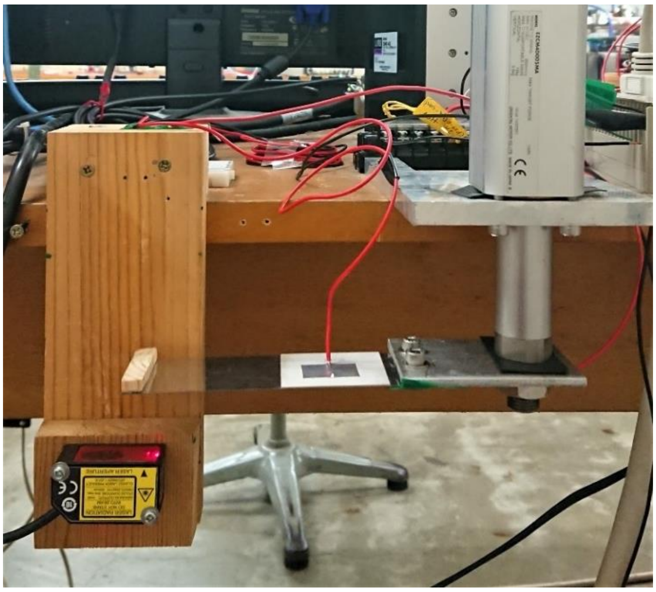


Figure 8 Picture of actual experiment setup apparatus

2.1. LASER SENSOR

The monitoring of the cantilever flexural displacement is performed by HG-C1030 Laser sensor. The vertical displacement is measured close to the cantilever’s mass loading. The output wave of laser sensor is first checked using oscilloscope before beginning the experiment to ensure that it works properly.

The specification of laser sensor used in this experiment is as shown in Table 2. The measurement range was determined according to the displacement range at the proof mass end. The output voltage is connected to an AD Converter and PC so that the output wave detected by the sensor can be observe in the PC.

Table 2 Specification of Laser Sensor

	Laser Sensor HG − C1030
Measurement centre distance	30mm
Measurement range	$\pm 5mm$
Analog voltage ouput	$0\sim 5V$ $110 \times 0.3 \times 40$

2.2. LINEAR MOTOR

Linear motor used in this research is model EZCM4D005MA from Oriental Motor which is monitored from PC. During the frequency response of a cantilever system, few adjustable parameters must be considered. These are, the input amplitude of vibration, the increment of frequency response, and the range of frequency response.

In this research, the input amplitude of linear motor is fixed at 0.006. In the beginning, frequency response experiment with the linear motor is set to vibrate from 10Hz to 50Hz for one cycle to identify the point of resonance frequency. When the peak of resonance frequency has been determined roughly, Frequency response experiment is run in a frequency range near those peak.

2.3. PHOTOSWITCH FOR CIRCUIT MONITORING

Photoswitch is installed to monitor the open and close circuit configuration of piezoelectric-bonded cantilever system. With the installation of photoswitch in the circuit, the circuit can be controlled as programmed in the PC.

2.4. JIG FOR LASER SENSOR AND CANTILEVER

The material for jig for laser sensor and cantilever is steel and wooden block respectively as shown in Figure 8. The laser sensor is fixed on the jig to maintain its position. While, the position of cantilever is set 30mm above the sensor to match the measurement center distance for optimum measurement range.

The jig for cantilever is made up of thick and hard aluminum plate to avoid resonance frequency from the jig itself which can affect the resonance frequency of the cantilever system during frequency response.

CHAPPTER3: METHODOLOGY

3.1. CONDITION CHECK OF EXPERIMENTAL APPARATUS

The experiment carried out using apparatus in Figure 8. To ensure the reproducibility of frequency response experiment using this apparatus, several conditions of apparatus check-up must be taken into considerations seriously. These are included as below

1. The condition of bolt and screw that connect cantilever to jig and the bolt that connect cantilever’s jig to the linear motor.
2. After turning on the power supply, must re-check voltage value of the power supply to ensure no short circuit of power supply occur.
3. Check the wire of circuit connection that connect to piezoelectric plate and metal beam.
4. Always make sure that the cantilever position is in the measurement range.

Despite qualifying the reproducibility of experiment result, these listed acts also important for the throughout the experiment.

3.2. REPEATABILITY OF FREQUENCY RESPONSE EXPERIMENT

After the conditions of experimental apparatus is well checked, Repeatability of resonance frequency is important to qualify the reliability of the obtained result. Thus, the frequency respond is carried out without changing any parameter including the circuit configuration for few cycles.

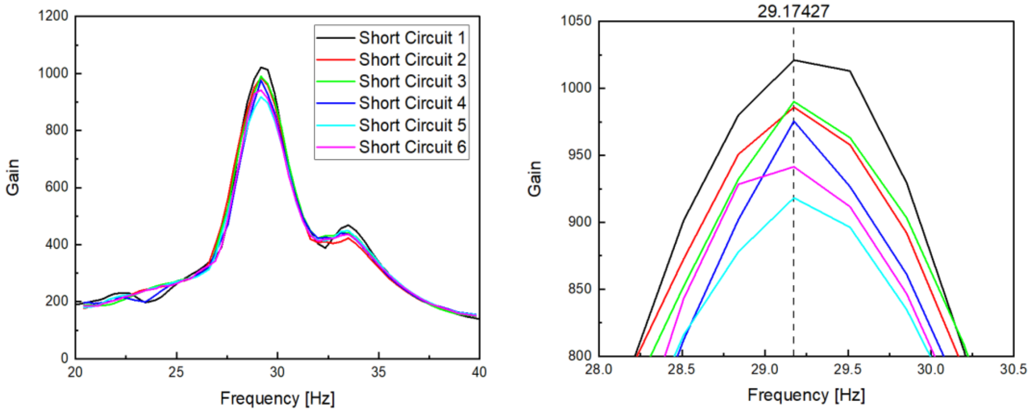
3.3. PARAMETER ADJUSTMENT

As mentioned in 2.2, other than the circuit configuration, there are several other input parameters for the frequency response experiment that is monitored on PC. These are the frequency range of frequency response experiment, the amplitude of and the displacement of the vibrating base.

Last but not least, the frequency response result is then analyze using matlab.

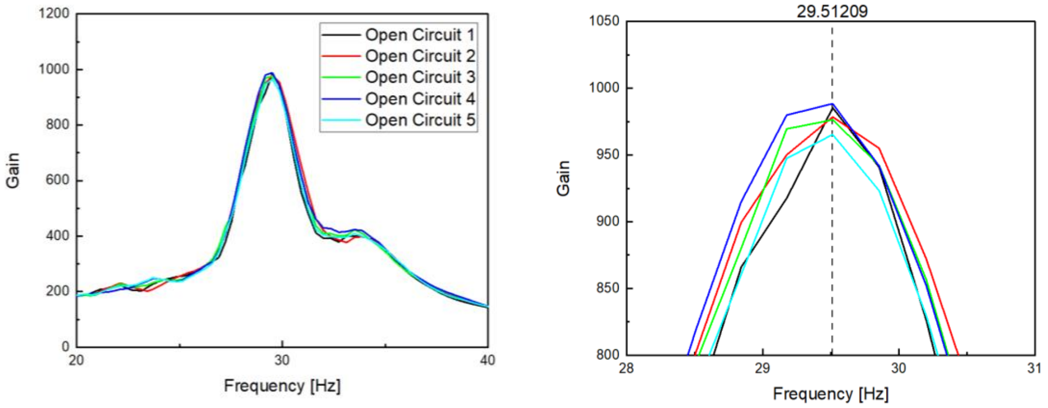
CHAPPTER4: RESULT AND DISCUSSION

The displacement characteristics of open circuit and of short circuit is measured in a frequency band around the first vibration mode which are plotted in Figure 9, Figure 10 and Figure 12.



Left: Overall frequency response graph, Right: Enlarged graph

Figure 9 Frequency response of piezoelectric-bonded cantilever during short circuit without circuit changing



Left: Overall frequency response graph, Right: Enlarged graph

Figure 10 Frequency response of piezoelectric-bonded cantilever during open circuit without changing circuit

Experiment is repeated for a certain circuit configuration (either open or short circuit) without changing the circuit configuration to determine a constant value of resonance frequency. In Figure 9 and Figure 10 shows the frequency response for piezoelectric-bonded cantilever during open and short circuit that had been repeated several times respectively. In both figures, the frequency at first and highest peak is the resonance frequency of the main system which is the piezoelectric-bonded cantilever system.

From calculation mentioned in 1.4, The resonance frequency in short circuit is approximately 32.004Hz and in open circuit is 32.36Hz.The experimental result for resonance frequency of piezoelectric cantilever during short circuit is constant at around 29.17Hz while during open circuit it is around 29.51Hz.

Experimental and estimated values of resonance frequency in open circuit and short circuit differ for around 2.83Hz and 2.85Hz respectively where theoretical value is higher than experimental result. This is because of the difference in value of real mass and mass from calculation. In calculation the mass of the wire is not considered. For example, from Eq (4). M_{beam} is 17.649g and the real mass of beam as in Figure 11 is 22.292g. This show that Mass in the calculation lower than the real mass, results in higher estimated value of resonance frequency.

Moreover, In actual system different position of piezoelectric patch also effected the effective stiffness of the whole piezoelectric-bonded cantilever system where the lesser the length between the piezoelectric patch and vibrating base (V=0) resulting higher resonance frequency [7]. In the experimental cantilever system, there is space length between piezoelectric patch and vibrating base (L=0) that is not being considered in the estimated calculation, thus the calculation resonance frequency value is higher than the experimental value.

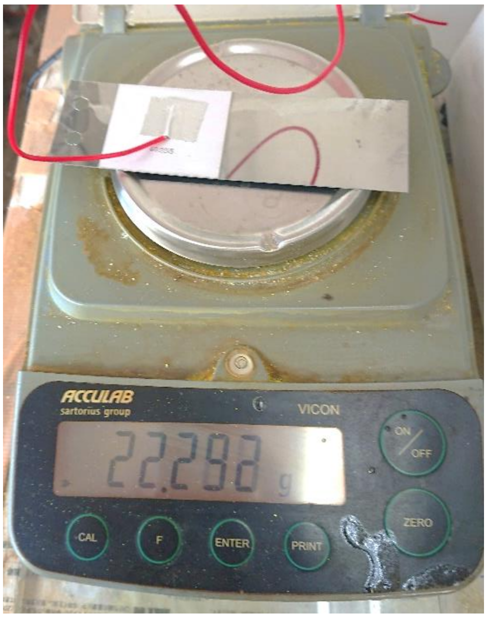
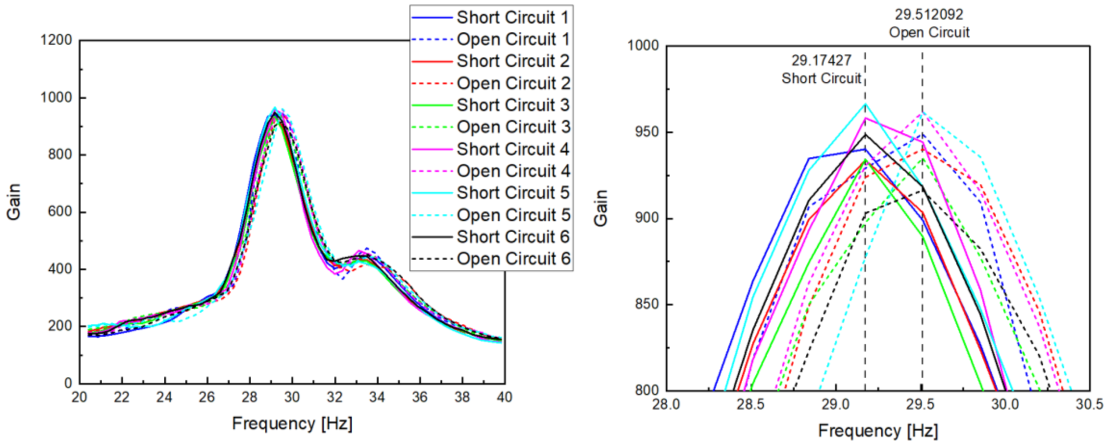


Figure 11 Real mass of Piezoelectric/Metal composite beam

The value of resonance frequency in short circuit is lower than in open circuit in the case of no change of circuit configuration. This is because stiffness of piezoelectric-bonded cantilever change when circuit change. In short circuit, the stiffness is lower than in open circuit and based from Eq. (2), stiffness does affect the resonance frequency of the piezoelectric-bonded cantilever system. Moreover, the reproducibility of frequency response experiment is also confirmed from these result (Figure 9 and Figure 10).

There is also a small peak appear after the resonance frequency very near to the resonance frequency. This peak is not the 2nd mode resonance frequency as the vibration mode shape throughout the experiment does not change.

In Figure 12, the value of resonance frequency in open and short circuit remain the same although the order of circuit configuration alternate from short circuit to open circuit continuously. This means that semi-active monitoring or control of piezoelectric-bonded plate is applicable for SADC.



Left: Overall frequency response graph, Right: Enlarged graph

Figure 12 Frequency response for experiment with arrangement of switching from short to open circuit simultaneously for 6 set

CHAPPTER5:   CONCLUSION

An idea to develop an SADC to suppress disturbance by substituting DVA so that it can tune the resonance frequency of 2-inertia torsional vibration system is proposed in this research. A piezoelectric-bonded plate which has properties that can change electrical energy into mechanical is implemented as the DVA in the SADC. The difference of resonance frequency in open and short circuit is calculated theoretically and experimentally. A frequency response experiment to determine the ability of the piezoelectric-bonded plate to change its resonance frequency by adjusting circuit configuration is done in the form of a cantilever with tip mass.

Estimated result for the difference of resonance frequency in open circuit and short circuit is approximately 32.36Hz and 32.004Hz respectively. The experimental result of resonance frequency obtained from frequency response in open and short circuit is around 29.51Hz and 29.17Hz either in constant controlled circuit configuration or in an alternate order of open and short circuit configuration. This prove that the inverse-piezoelectric effect of the piezoelectric-bonded plate is reproducible and can be considered to be implemented in the application of SADC as semi-active control by monitoring the circuit configuration.

In actual performance of 2-inertia torsional vibration system, the motor will run continuously which means that the controlled of circuit change cannot be handled manually. Thus, the implementation of photoswitch in the electrical circuit configuration of piezoelectric-bonded plate as stated 2.3 in is a significant way for automatic monitoring in tuning the resonance frequency of the device. Moreover, this experimental result also shows that different of resistance value, R which is R=0 (short circuit) and R=∞(open circuit) affect the resonance frequency. Thus, as further improvement, deriving resistor in the circuit can allow better parameter control in tuning the resonance frequency of the piezoelectric-bonded plate.

Moreover, although the effect of circuit changes of piezoelectric-bonded plate in the form of basic cantilever with tip mass has been proved, there are also several outer factor that can affect the difference of resonance frequency which also should be considered such as the effect of surrounding or device temperature.

BIBLIOGRAPHY

[1] Hui Shena; Jinhao Qiua; Hongli Ji ; Kongjun Zhua; Marco Balsi ; Ivan Giorgio; Francesco Dell’Isola , "A low-power circuit for piezoelectric vibration control by synchronized switching on voltage sources," *Sensors and Actuators A: Physical,* vol. 161, no. 1-2, pp. 245-255, 2010.

[2] R. Kobayashi, "Development of a semi-active-damper coupling for variable damping characteristics of two-inertia system," Nagaoka University of Technology, Mechanical Engineering Department Poster Presentation 2018, Nagaoka, Japan, 2018.

[3] I. Chikishi, "Control of vibration amplitude by generation and regeneration," Bachelor of Master Degree Thesis 2018, Mechanical Engineeering Department, Nagaoka University of Technology, Nagaoka,Japan, 2018.

[4] Zhoua, L. Suna, Zhenga, S. Denga, J. Zhaoa, S. Penga, Y. Zhanga, X. Wangb and H. Chengb, "A model for the energy harvesting performance of shear mode piezoelectric cantilever,," *Sensors and Actuators A: Physical,* vol. 179, pp. 185-192, 2012.

[5] S. CHENGLIANG, L. QIN, F. LI and Q.-M. WANG, "Piezoelectric Energy Harvesting using Single Crystal Pb(Mg1/3Nb2/3)O3-xPbTiO3 (PMN-PT) Device," *Journal of Intelligent Material Systems and Structures,* vol. 0, 2008.

[6] O. Guillon, F. Thiebaud, P. Delobelle and D. Perreux, "Tensile behavior of PZT in short and open-circuit conditions," *Materials Letters,* vol. 58, p. 986–990, 2004.

[7] Yabin Liao; Henry A Sodano, "OptimalPlacement of piezoelectric maaterial on a cantilever beam fofr maximum piezoelectric damping and power harvesting efficiency," *SMART MATERIALS AND STRUCTURES,* vol. 21, 2012.