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ANALYSIS AND MODELLINGOF REDUCING TRANSLATIONAL VIBRATION RESPONSEINMAIN SYSTEM AND ELECTRICAL ENERGY GENERATED BY DYNAMIC VIBRATION ABSORBER MECHANISM WITH CANTILEVER PIEZOELECTRIC (CPVA) METHOD

W. Rachma Efendy dan W. Hendrowati
Teknik Mesin, Fakultas Teknologi Industri, Institut Teknologi Sepuluh Nopember Jl. Arief Rahman Hakim, Surabaya, Indonesia
E-Mail: wiwiek@me.its.ac.id

ABSTRACT

Vibrations often occur in industrial machinery. One of solution to reduce excessive vibration is to add Dynamic Vibration Absorber (DVA). The principle of dynamic vibration absorber working is addition mass of absorber and spring in the main system. DVA reduce vibration from main system with resulted vibration which has opposite direction to vibration main system. According to the research by Pachpute [1], Using DVA is proven to reduce main system vibration which operated by natural frequency significantly. This research had been design a mechanism of vibration absorber and energy harvesting with Cantilever Piezoelectric Vibration Absorber (CPVA) method. In this research, the main system is flat plate which supported by four springs. The plate has been received an excitation force from springs below which are connected with eccentric masses on DC motor. Spring used to support flat plate has the same value of spring stiffness 300 N / m. So the excitation that occurs on flat plate is only in translational direction. This research are going to analysis various amplitude of eccentric mass at 0.025 m, 0.030 m, and 0.035 m. Rotational velocity of DC motor is 20.61 rad/s (natural frequency), 22.05 rad/s (harvesting frequency), and 25 rad/s (valley frequency). Various number of cantilever piezoelectric which used are 2600, 2800, and 3000 pieces. The result from simulation process shows that the highest value of power generation and percentage of CPVA reduction is 3.52E-7 watt and 20.36% in natural frequency. Furthermore, the simulation also resulted CPVA characteristic and various number of optimum range piezoelectric in 1400 - 2400 pieces. In that following range, power generation and percentage reduction of main mass displacement that can be reached by CPVA are 5.78E-7 watt and 22.75%.

Keywords: dynamic vibration absorber, cantilever piezoelectric, percentage reduction, amplitude,eccentric mass, frequency, the number of piezoelectric, energy density.

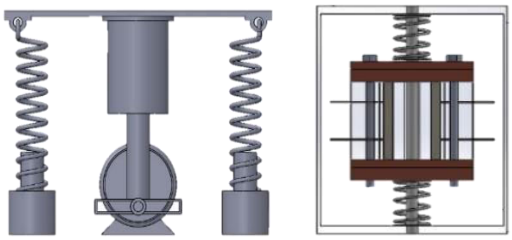
INTRODUCTION

In general, DVA are used to reduce vibration from main system in translational direction vibration from main system which forwarded to mass of absorber is a useful kinetic energy. Cantilever piezoelectric can be used to harvest electrical energy from the vibration. Kinetic energy from the mass displacement absorber can be converted to electrical energy, when the piezoelectric cantilever is deflected and receives tensile or compressive stress. Several studies have shown that using piezoelectric cantilever to harvest kinetic energy from excitation is only produce power at a mill watt capacity. A new mechanism are needed to maximizes the potential deflection of piezoelectric cantilever.

This study discusses about the mechanism of excessive vibration damping and utilization of wasted kinetic energy in laboratory scale. Vibration simulator is designed that to represent simulated vibrations of the main system.

RESEARCH DESCRIPTION

The overall design mechanism begins when the flat plate receives an excitation force from spring bellow is connected with the eccentric mass on DC motor. Furthermore, the excitation of the main mass are absorbed by the mass of absorber which connected by spring. The excitation of mass absorber has potential of kinetic energy, which can be converted by piezoelectric cantilever into electrical energy. This study analysis has been used various number of piezoelectric cantilever, rotation speed of DC motor and eccentric mass amplitude. From this research, the effect of motor rotation speed, amplitude excitation source of main system and number of piezoelectric cantilever on reducing main system vibration and creating energy generation.



(a) (b)

Figure-1. Analysis model (a) Main system as vibration simulator system and (b) CPVA.

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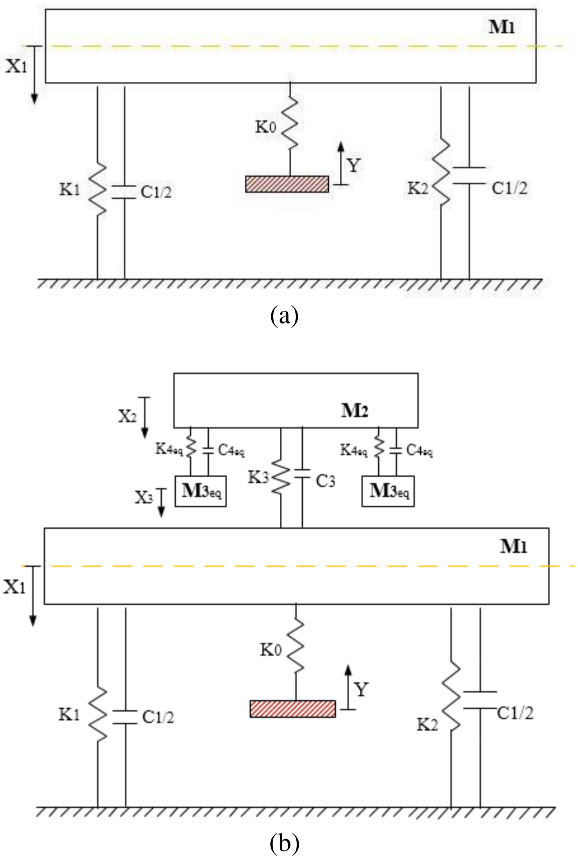

Figure-2. Dynamic model of the main system (a) without CPVA and (b) with CPVA.

Symbols:

M_1	:	Mass of main system	K_0	:	Spring stiffness of eccentric mass
M_2	:	Mass of Absorber	K_1	:	Spring stiffness 1 of mass 1
M_3	:	Mass of Piezoelectric	K_2	:	Spring stiffness 2 of mass 1
X_1	:	Mass of Displacement 1	K_3	:	Spring stiffness of mass 2
X_2	:	Mass of Displacement 2	K_4	:	Spring stiffness of mass 3
X_3	:	Mass of Displacement 3	C_1	:	Damping 1 in mass 1
Y	:	Eccentric mass of Amplitude	C_3	:	Damping 3 in mass 2

In Figure-3 shows free body diagram from mass of main system (M_1). In Figure-3, there are vectors of force that work in M_1. Displacement in mass of main system only happened in translational direction because spring stiffness 1 and 2 has identical value.

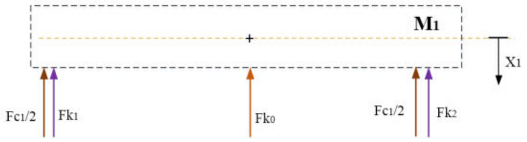

Figure-3. Free body diagram from system without CPVA.

Equation of main system translational force

$\sum F = M_1\ddot{x}_1$

$-Fc_1 - Fk_1 - Fk_2 - Fk_0 = M_1\ddot{x}_1$

$-c_1\dot{x}_1 - k_1x_1 - k_2x_1 - k_0(x_1 - y) = M_1\ddot{x}_1$

$M_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 + k_2x_1 + k_0x_1 - k_0y = 0$

$M_1\ddot{x}_1 + c_1\dot{x}_1 + (k_0 + k_1 + k_2)x_1 = k_0y$

Figure-4 shows free body diagram from main system with Cantilever Piezoelectric Vibration Absorber (CPVA). FBD from main mass (M_1) which affected by spring from mass of absorber (Fk_3) is shown in Figure-4(c). FBD from mass of absorber (M_2), affected by 2 pieces of cantilever piezoelectric have been equivalence is shown in Figure-4(a). Meanwhile FBD from mass of cantilever piezoelectric have been equivalence is shown in Figure-4(b).

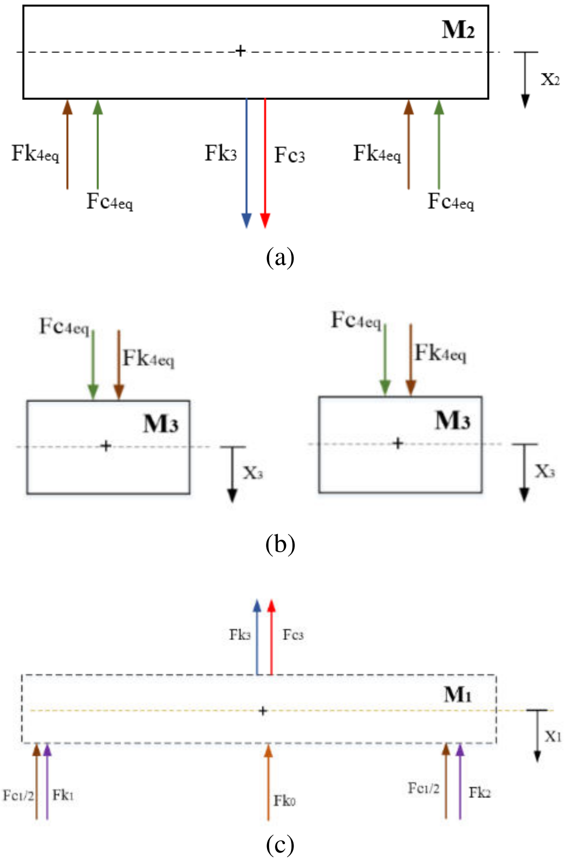

Figure-4. Free body diagram of (a) mass of absorber, (b) mass of piezoelectric, and (c) main mass with CPVA.

From force analysis above, mathematical equations can be made as follows:

a. Equation of main system mass translational

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displacement

$\sum F = M_1\ddot{x}_1$
$-Fc_1 - Fc_3 - Fk_1 - Fk_2 - Fk_0 - Fk_3 = M_1\ddot{x}_1$
$-c_1\dot{x}_1 - c_3(\dot{x}_1 - \dot{x}_2) - k_1x_1 - k_2x_1 - k_0(x_1 - y) - k_3(x_1 - x_2) = M_1\ddot{x}_1$
$M_1\ddot{x}_1 + c_1\dot{x}_1 + c_3\dot{x}_1 - c_3\dot{x}_2 + k_1x_1 + k_2x_1 + k_0x_1 - k_0y + k_3x_1 - k_3x_2 = 0$
$M_1\ddot{x}_1 + (c_1 + c_3)\dot{x}_1 - c_3\dot{x}_2 + (k_0 + k_1 + k_2 + k_3)x_1 - k_3x_2 = k_0y$
$M_1\ddot{x}_1 = -(c_1 + c_3)\dot{x}_1 + c_3\dot{x}_2 - (k_0 + k_1 + k_2 + k_3)x_1 + k_3x_2 + k_0y$

b. Equation of absorber mass translational displacement
$\sum F = M_2\ddot{x}_2$
$Fk_3 + Fc_3 - Fk_{4\,eq} - Fc_4 = M_2\ddot{x}_2$
$M_2\ddot{x}_2 - k_3(x_1 - x_2) - c_3(\dot{x}_1 - \dot{x}_2) + k_{4\,eq}(x_2 - x_3) + \Gamma.n.Vp = 0$
$M_2\ddot{x}_2 - k_3x_1 + k_3x_2 - c_3\dot{x}_1 + c_3\dot{x}_2 + k_{4\,eq}x_2 - k_{4\,eq}x_3 + \Gamma.n.\mathrm{Vp} = 0$
$M_2\ddot{x}_2 = k_3x_1 - (k_3 + k_{4\,eq})x_2 + c_3\dot{x}_1 - c_3\dot{x}_2 + k_{4\,eq}x_3 - \Gamma.n.\mathrm{Vp} = 0$

c. Equation of piezoelectric mass translational displacement
$\sum F = M_{3\,eq}\ddot{x}_3$
$Fk_{4\,eq} + Fc_4 = M_{3\,eq}\ddot{x}_3$
$M_{3\,eq}\ddot{x}_3 - k_{4\,eq}(x_2 - x_3) - \Gamma.n.\mathrm{Vp} = 0$
$M_{3\,eq}\ddot{x}_3 - k_{4\,eq}x_2 + k_{4\,eq}x_3 - \Gamma.n.\mathrm{Vp} = 0$
$M_{3\,eq}\ddot{x}_3 = k_{4\,eq}x_2 - k_{4\,eq}x_3 + \Gamma.n.\mathrm{Vp}$

Figure-5 shows electric circuit diagram of piezoelectric material. Piezoelectric material generates electrical energy when the material deflects. Electrical energy consists of voltage, electric current, and power generation. Voltage generation from electrical energy in this mechanism can be written in mathematical equation as follow [4]:

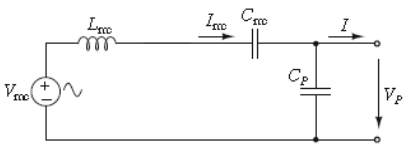

Figure-5. Electric circuit diagram of cantilever piezoelectric.

$$V_p = \frac{3d_{31}E_pw_pt}{4c}x_p$$

Where:

V_p	= Voltage generation of piezoelectric (Volt)
d_{31}	= Voltage constant (C/N)
E_p	= Modulus elasticity (N/m^2)
w_p	= Width of piezoelectric (m)
t	= Thick of piezoelectric (m)
c	= Piezoelectric capacitance (Farad)
x_p	= Piezoelectric deflection(m)

While the current generation of piezoelectric on the mechanism this time can be formulated with:

$$V_{mc} = L_{mc}\frac{dI_{mc}}{dt} + R_{mc}I_{mc} + \frac{1}{C_{mc}}\int I_{mc}\,dt + V_p$$

$$I_{mc} = \frac{1}{L_{mc}}(V_{mc} - R_{mc}I_{mc} - \frac{1}{C_{mc}}\int I_{mc}\,dt - V_p$$

Where:
$V_{mc} = \frac{Fi}{r}$, $L_{mc} = \frac{M}{r^2}$, $R_{mc} = \frac{d_p}{r^2}$, $C_{mc} = \frac{r^2}{k_p}$

with:

M	= Mass (Kg)
d_p	= Damping piezoelectric (Ns/m)
k_p	= Spring stiffness of equivalence piezoelectric (N/m)
C_p	= Piezoelectric capacitance (Farad)

So the power generation of piezoelectric can be formulated with:
$P = V_pI_{mc}$
Where:

P	= Power generation piezoelectric (Watt)
I_{mc}	= Current generation piezoelectric (Ampere)

The parameters for modeling in Figure-2 are obtained from various sources including from the previous reference data.

Table-1. Parameter of main system.

Parameter	Symbol	Value	Unit
Mass Of main system	M_1	4	Kg
Spring stiffness 1 (Equivalence)	K_1	600	N/m
Spring stiffness 2 (Equivalence)	K_2	600	N/m
Spring stiffness Exciter	K_0	500	N/m
Damping Ratio of main system	ζ_1	0.1	-
Damping guiding rod	C_1	17.88	N.s/m

Table-2. Parameter of cantilever piezoelectric vibration absorber (CPVA).

Parameter	Symbol	Value	Unit
Mass of Absorber	M_{abs}	0.02	Kg
Spring stiffness of Absorber	K_3	500	N/m
Damping Ratio Absorber	ζ_2	0.4	-
Damping guiding rod Absorber	C_1	3.577	N.s/m

Table-3. Parameter of Piezoelectric material.

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Parameter	Symbol	Value	Unit
Mass of piezoelectric	M_{pzt}	6×10^{-4}	Kg
Thickness of piezoelectric	t	$1x\ 10^{-3}$	M
Width of piezoelectric	w_{pzt}	6×10^{-4}	m
Length of piezoelectric	Lpzt	12×10^{-3}	m
Piezoelectric capacitance	C_{pzt}	244×10^{-10}	F
Strain of piezoelectric	d_{31}	110×10^{-12}	C/N
Electromechanical coupling factor	k_{31}	12	%
String stiffness piezoelectric	k_{pzt}	$5{,}75 \text{ X } 10^{-1}$	N/m
Modulus Young	E	3×10^{9}	N/m^2

The displacement response of system and energy density are obtained from CPVA modeling simulation. This simulation are used various number of amplitude vibration input, operating frequency, and number of piezoelectric cantilever.

RESULT AND ANALISYS

Based on the calculations that have been done, the natural frequency value of the system with various number of piezoelectric can be seen in Table-4 below. Based on Table-4, the addition of CPVA can shift the natural frequency value of the main system.

Table-4. Parameter of Piezoelectric material.

Number of PZT (n)	M_3 = (n x 0.0006) Kg	M_2 = (0.02 + M_3) Kg	Natural frequency main system without CPVA (rad/s)	Natural frequency system with CPVA (rad/s)		
				ω_{n1}	ω_{n2}	ω_{n3}
2600	1.56	1.58	20.61	5.6	21.2	87
2800	1.68	1.7		7.9	21.4	102
3000	1.8	1.82		9.7	21.5	115

Modeling of the main system with CPVA (fixed number of piezoelectric)

This modeling simulation is used various number of excitation amplitude, operating frequency variation, and piezoelectric variation. Various number of amplitude excitation which used in this simulation are 0.025 m, 0.030 m, and 0.035 m. The frequency that used in this simulation is the natural frequency of the main system 20.61 rad / s. The next frequency is the harvest frequency sourced from the Galal research [2], where the value of harvest frequency in operating DVA frequency (ω_f / ω_{abs}) is 1.07, so the harvest frequency that obtained is 22.05 rad / s. The last frequency is valley frequency; this frequency is outside from the ratio resonance frequency range. Based on the resonance transmissibility graph from the book "Mechanical Vibrations" by Rao [6], range of resonance frequency is 0.9 - 1.1, so the frequency that obtained is 25 rad/s. The number of piezoelectric that used is 2600, 2800, and 3000 pieces.

Response of displacement main mass with CPVA in various frequency

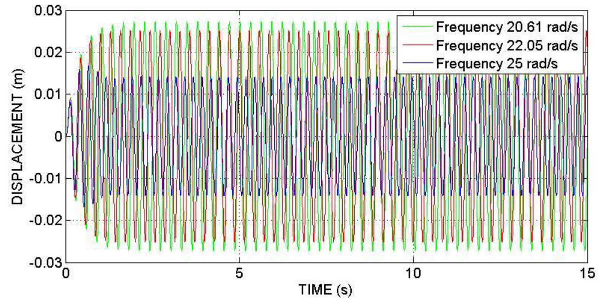

Figure-5. Response from displacement of main mass with CPVA in various frequency

Figure-6 shows graph response from displacement of main mass with CPVA. The simulation uses 0.025 m of amplitude and 2600 pieces of piezoelectric. The green line represents the response of main mass transfer which operated at frequency 20.61 rad/s. The red line shows displacement of main mass displacement which operated at frequency 22.05 rad/s. Meanwhile blue line represents displacement of main mass displacement which operated at frequency 25 rad/s. The graph shows that response of main mass displacement decrease when operating frequency is further away from natural frequency of the system in 21.2 rad/s.

Response of main mass displacement with CPVA in various amplitude

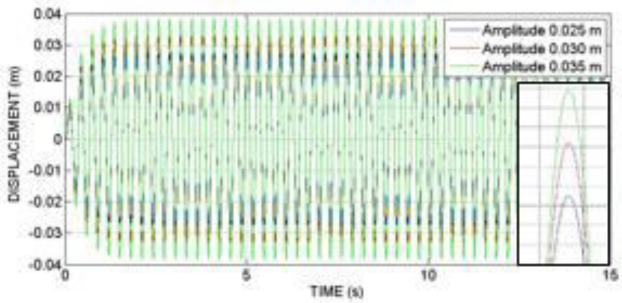

Figure-6. Response of main mass displacement with CPVAin various amplitude.

Figure-7 shows graph response of main mass displacement with CPVA. The simulation uses frequency20.61 rad/s and 2600 pieces of piezoelectric the blue line represents response of main mass displacement in amplitude 0.025 m. The red line represents response of main mass displacement in amplitude 0.030 m. Meanwhile green line represents response of main mass displacement

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in amplitude 0.035 m. The graph shows that response of main mass displacement decrease when excitation amplitude is reduced.

Electrical energy generation from Piezoelectric in various frequency

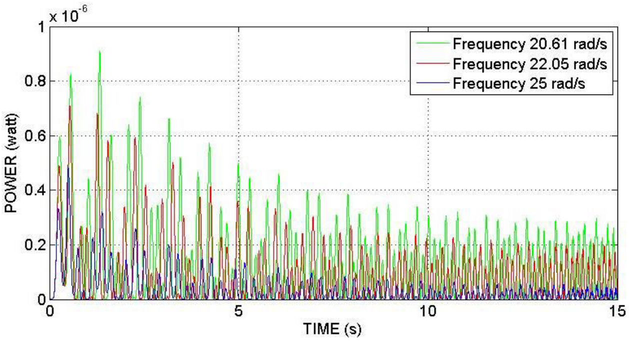

Figure-7. Energy generation from piezoelectric in various operating frequency.

Figure-8 shows the displacement of electrical energy generation from cantilever piezoelectric. The simulation uses amplitude 0.025 m and 2600 pieces of piezoelectric. The green line shows electrical energy when system operated on frequency 20.61 rad/s. The red line shows electrical energy when system operated on frequency 22.05 rad/s. Meanwhile blue line shows electrical energy when system operated on frequency 25 rad/s. The graph shows that electrical energy generation decrease when operating frequency is further away from natural frequency of the system in 21.2 rad/s.

Electrical energy generation from piezoelectric in various amplitude

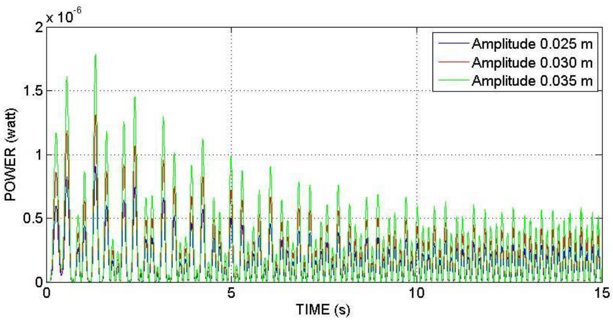

Figure-8. Energy generation from *piezoelectric* in various amplitude.

Figure-9 shows electrical energy generation from cantilever piezoelectric. The simulation uses frequency20.61 rad/s and 2600 pieces of piezoelectric. The blue line shows electrical energy generation on system when operating in amplitude 0.025 m. The red line shows electrical energy generation on system when operating in amplitude0.030 m. Meanwhile green line electrical energy generation on system when operating in amplitude 0.035 m. The graph shows that electrical energy generation decrease when excitation amplitude is reduced.

Main system modelling with CPVA (Various number of Piezoelectric)

Response of main mass in various number of Piezoelectric

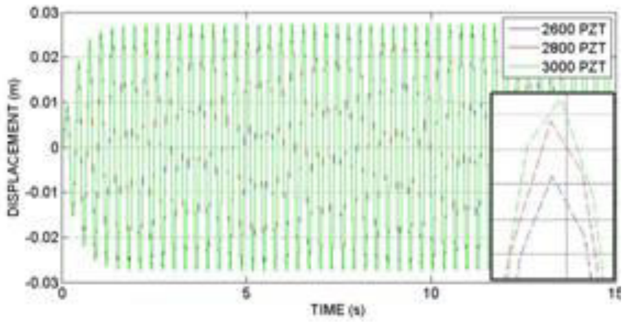

Figure-9. Response of main mass in various number of piezoelectric.

Figure-10 shows graph of main mass displacement with CPVA. The simulation uses frequency 20.61 rad/s and amplitude 0.025 m. The blue line shows response of main mass displacementin2600 pieces of piezoelectric. The red line shows response of main mass displacement in 2800 pieces of piezoelectric. Meanwhile green line shows response of main mass displacement in 3000 pieces of piezoelectric. The graph shows that response of main mass displacement decrease when the number of piezoelectric is reduced.

Electrical energy generation energi bangkitan listrik dengan variasi jumlah Piezoelectric

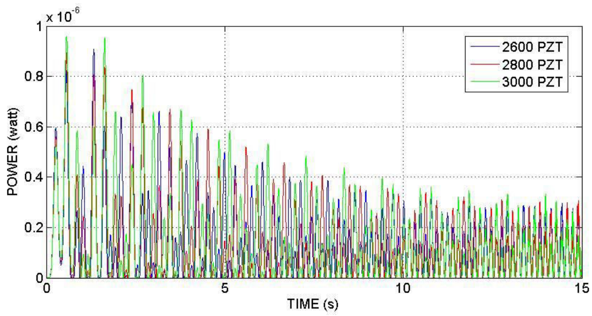

Figure-10. Electrical power generationin various number of *piezoelectric.*

Figure-11 shows electrical power generation from piezoelectric. The simulation uses frequency 20.61 rad/s and amplitude 0.025 m. The blue line represents electrical power generation in 2600 pieces of piezoelectric. The red line shows electrical power generation in 2800 pieces of piezoelectric. Meanwhile green line shows electrical power generation in 3000 pieces of piezoelectric. The graph shows that electrical power generation decrease when the number of piezoelectric is reduced.

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DISCUSSIONS

Based on the simulation, data and graphs areobtained as follows:

Table-5. Value of RMS displacement, velocity, acceleration from main mass and reduction percentage with CPVA.

Amplitude (m)	**Frequency** (rad/s)	**RMS displacement** (m)	**RMS velocity** (m/s)	**RMS acceleration** (m/s^2)	**Reduction of displacement** (%)
0.025	20.61	0,0191	0,399	8,1083	20,08
	22.05	0,0176	0,392	8,5444	7,85
	25	0,01	0,250	6,2248	-2,04
0.030	20.61	0,0229	0,479	9,7168	19,93
	22.05	0,0211	0,470	10,257	7,86
	25	0,012	0,301	7,4683	-2,56
0.035	20.61	0,0266	0,561	11,307	20,36
	22.05	0,0246	0,548	11,981	7,87
	25	0,0139	0,351	8,7106	-1,46

The above data can be made a graph in the following figure.

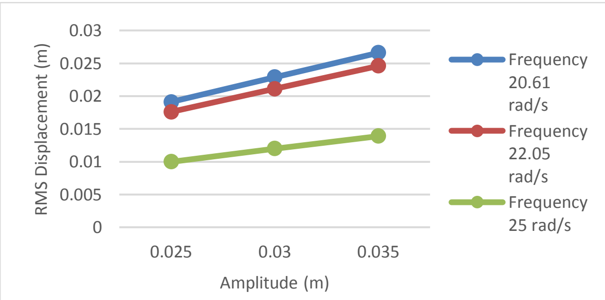

Figure-11. Response of RMS main mass displacement (X1) with CPVA in various amplitude.

Figure-12 represent the response of main mass displacement (X1) with CPVA and amplitude effect. This simulation uses 2600 pieces of piezoelectric. The chart has a rising trend line. When operating frequency 20.61 rad/s and amplitude 0.025 m, the response value of $X_1$is 0.0191 m. In the same frequency and amplitude 0.03 m, the response value of X1 is 0.0229 m; mean while in amplitude 0.035 m the response value of X1 is 0.0266 m. The graph shows that increasing number of amplitude effected to higher response value of main mass displacement. The higher number of excitation amplitude increase input force value of main mass, and rise the value of main mass displacement.

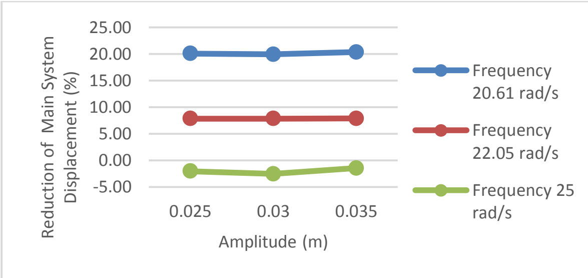

Figure-12. Reduction response of main mass displacement (X1) in various amplitude.

Figure-13 shows reduction response of main mass displacement which effected by amplitude and frequency. This simulation uses 2600 pieces of piezoelectric. The chart has a straight trend line with a very small deviation value. The graph shows that the magnitude amplitude does not affect by reduction of main mass transfer response.

As the increment of excitation amplitude, the value of the input force received by the main mass becomes higher. But this has resulted in an enlarged opposing force from the absorber system, so the reduction percentage of main mass transfers becomes constant. Base on the theory, reduction percentage of main mass displacement is not determined by input force, but determined by operating frequency of the system. The percentage of reduction increases as the system operates approach to natural frequencies.

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Table-6. Electrical energy generation value from *piezoelectric* depend on amplitudo and frequency value.

Amplitude (m)	**Frequency** (rad/s)	**RMS of Vp** (volt)	**RMS of Imc** (ampere)	**RMS of power** (watt)
0.025	20.61	0,1811	1,30E-06	2,08E-07
	22.05	0,1494	1,04E-06	1,57E-07
	25	0,0738	1,06E-06	6,80E-08
0.030	20.61	0,2161	1,12E-06	2,76E-07
	22.05	0,1793	1,13E-06	2,08E-07
	25	0,0885	9,56E-07	8,73E-08
0.035	20.61	0,2501	1,19E-06	3,52E-07
	22.05	0,211	1,12E-06	2,69E-07
	25	0,1042	9,75E-07	1,08E-07

The above data can be made a graph in the following figure.

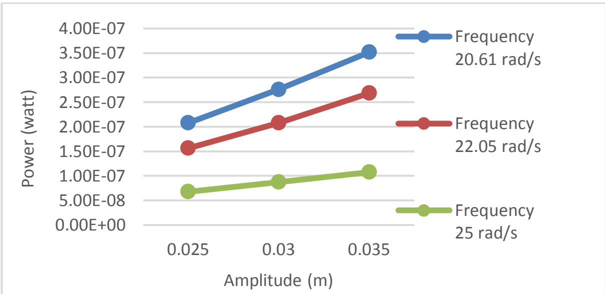

Figure-13. Electrical power generation in various amplitude.

Figure-13 represents electrical power generation from piezoelectric which affected by amplitude. This simulation uses 2600 pieces of piezoelectric. The chart has a rising trend line. When operating frequency 20.61 rad/s and amplitude 0.025, the power is 2.08E-7 watt. In the same frequency and amplitude 0.03 m, the power is 2.76E-7 watt, meanwhile in amplitude 0.035 m; the power is 3.52E-7. The graph shows that increasing number of amplitude effected to higher value electrical power generation.

As the increment of excitation amplitude, the value of the voltage generation piezoelectric becomes from higher this also causes the increment of power generation.

Table-7. Electrical energy generation from piezoelectric depend on the number of piezoelectric.

Numb of PZT	**Power** (watt)		
	Amplitude 0.025 m	**Amplitude 0.030 m**	**Amplitude 0.035 m**
2600	2,08E-07	2,76E-07	3,52E-07
2800	2,00E-07	2,66E-07	3,40E-07
3000	1,97E-07	2,62E-07	3,34E-07

The above data can be made a graphs in the following figure.

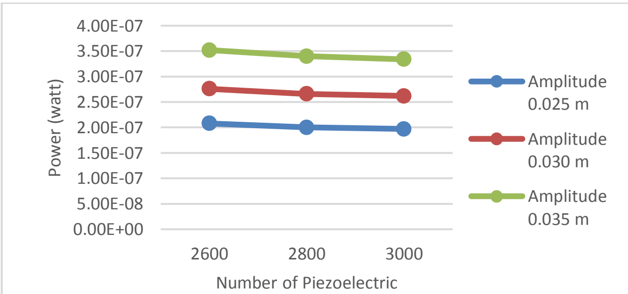

Figure-14. Electrical power generation in various number of piezoelectric.

Figure-14 shows electrical power generation which affected by various number of piezoelectric and amplitude. This simulation uses operating frequency in 20.61 rad/s. The chart has downward trend line. At amplitude0.025 m, the obtained power generation range is 1.97E-7 to 2.08E-7 watts. When the amplitude 0.030 m, the obtained range of power generation is 2.62E-7 to 2.76E-7 watts. Whereas with amplitude of 0.035 m, the range of power generation that can be obtained is 3.34E-7 to 3.52E-7 watts. The graph shows that increasing number of piezoelectric affected to electrical power generation decrease.

The equation (1) that mentioned earlier shows that voltage generation is proportional with the occurring deflection of piezoelectric material. Higher number of piezoelectric affected to the deflection of piezoelectric material reduction, so the electric energy generated is also decreasing.

CONCLUSIONS

Based on the results of simulations and analysis, it can be concluded that:

a) The higher number of excitation amplitude are rising the displacements value of main mass, mass of absorber, and mass of piezoelectric. This increment also rise the number of CPVA voltage and power generation. However, the percentage reduction of main mass has a constant value.

b) Increment of operating frequencies approach to natural frequencies are raising displacement value of main mass, mass of absorber, and mass of piezoelectric. This increment also rise the number of CPVA voltage and power generation. Highest value of power generation that produce by CPVA is 3.52E-7 watt. Furthermore, percentage reduction of main mass displacement also has increasing value. Highest reduction value when it operated in natural frequency is 20.36%.

c) The highest number of piezoelectric occur increment of main mass, but it decrease the percentage reduction of main mass transfer.However, using large number of piezoelectric are decrease the value of displacement absorber mass and piezoelectric mass. This phenomenon also decreases CPVA number of voltage and power generation.

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