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ORIGINAL ARTICLE

Actuation and dynamic mechanical characteristics of a core free flat dielectric electro-active polymer soft actuator

Abdul Malek Abdul Wahab[1], Emiliano Rustighi[2] and Zainudin A.[3]

[1] Faculty of Mechanical Engineering Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
Phone: +60355436210; Fax: +60355435160
[2] Institute of Sound and Vibration Research University of Southampton, U.K.
[3] Malaysia-Japan International Institute of Technology (MJIIT) Universiti Teknologi Malaysia Kuala Lumpur, Jalan Sultan Yahya Petra 54100 Kuala Lumpur, Malaysia

ABSTRACT – Various complex shapes of dielectric electro-active polymer (DEAP) actuator have been promoted for several types of applications. In this study, the actuation and mechanical dynamics characteristics of a new core free flat DEAP soft actuator were investigated. This actuator was developed by Danfoss PolyPower. DC voltage of up to 2000 V was supplied for identifying the actuation characteristics of the actuator and compare with the existing formula. The operational frequency of the actuator was determined by dynamic testing. Then, the soft actuator has been modelled as a uniform bar rigidly fixed at one end and attached to mass at another end. Results from the theoretical model were compared with the experimental results. It was found that the deformation of the current actuator was quadratic proportional to the voltage supplied. It was found that experimental results and theory were not in good agreement for low and high voltage with average percentage error are 104% and 20.7%, respectively. The resonance frequency of the actuator was near 14 Hz. Mass of load added, inhomogeneity and initial tension significantly affected the resonance frequency of the soft actuator. The experimental results were consistent with the theoretical model at zero load. However, due to inhomogeneity, the frequency response function's plot underlines a poor prediction where the theoretical calculation was far from experimental results as values of load increasing with the average percentage error 15.7%. Hence, it shows the proposed analytical procedure not suitable to provide accurate natural frequency for the DEAP soft actuator.

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dielectric electro-active polymer; soft actuator; actuation; dynamic; theoretical

INTRODUCTION

Dielectric electroactive polymers (DEAPs) have received much attention in recent years to be an adequate replacement for many conventional actuators. It is due to their lightweight, directly actuating structure, fast response, high strain levels with large deformations, high energy convention efficiencies, low-noise and low cost [1–2]. Besides that, DEAP can keep the actuation movement in the given position without additional power [3]. With the exceptional properties, the applications of the DEAP could cover a broad spectrum of actuator engineering-related such as robotics, bioengineering and automation [4–6].

One of the unique properties of this soft DEAP material is that it can provide actuation, although formed into a complex shape. With the different shape configurations, the effect of its actuation is varied. Thus, the researcher has made an effort to fabricate different ways of DE actuators for optimizing the stroke and force for various applications. Li et al. modeled stacked DEAP to find the optimized parameter for the actuator been used in active vibration control [7]. Work by Steffen Hau et al., investigate the influence of geometry on the performance of dynamic stroke and force output for circular membrane DEAP [8]. Work by Berardi modeled the dynamics characteristic of the core-freerolled tubular DE actuator and the actuator successfully control the vibration at a low-frequency range below 10 Hz [9]. Initially, Sarban et al. evaluate the fabrication, characterization and active vibration isolation perform for the core-freerolled tubular DE actuator. Results show that the actuator has a shallow natural frequency at a frequency range of up to 1 kHz [10]. Carpi et al. fabricated DE folded actuator for application in linear contractile equipment and the second type of actuator that operates with out-of-plane unidirectional displacements of an elastomer membrane [11].

Even though all the configuration has been made, fabrication of stacked and freerolled tubular DE actuators has a specific issue in terms of rigidity movement and thickness. For membrane DE actuator, although it is flexible and thin, increasing the force output by adding the thickness will produce a high electric field.

Thus, Danfoss PolyPower A/S invented the sheet of DE that used to make the thin, flexible and soft actuator. This sheet made from thin corrugated silicone elastomer with compliant silver electrodes [12]. The corrugated surface amplitude at 5 μm and 10 μm distance imprinted to ensure the compliance of the elastomer material unidirectional and at maximum elongation as the electric field was applied. Two film sheets placed back to the backside to make two sides of

*CORRESPONDING AUTHOR | Abdul Malek Abdul Wahab | abdmalek@uitm.edu.my

the corrugated pattern and silver electrode compliant [9, 10]. As a result, the DE sheet has different stiffness in the two directions [9].

The actuation produces in the DEAP material is due to the electrostatic pressure establishes by the existence of voltage potential between the opposing electrodes. The electrostatic pressure causes a compression of the elastomer sheet [13]. It generates an elongation in the axial direction of the DEAP [9, 10, 14] as, shown in a unidirectional extension of PolyPower DEAP in Figure 1.

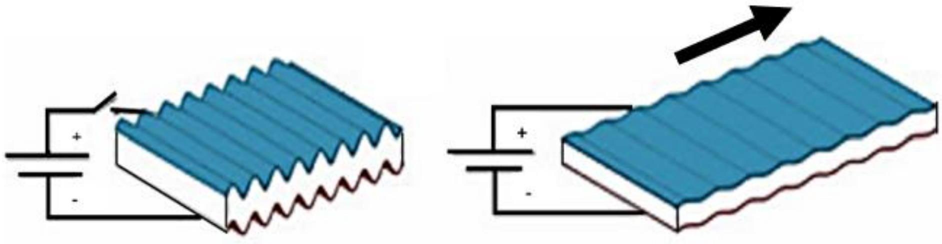


Figure 1. Unidirectional extension of PolyPower DEAP with corrugated silver electrode compliant

Accordingly, the availability of flexible and thin configurations may improve the muscle look like of actuators in practical applications. For this purpose, this paper presents a new structure for a soft contractile actuator. The aims are to investigate the actuation and dynamic characteristics of the original core free flat DEAP soft actuator. For that, this paper examines the linear aspects of the soft actuator. Experimental works were conducted to identify the actuation and dynamic mechanical characteristics of the actuator. A mechanical model of the actuator was then formulated, and, finally, theoretical and experimental results were compared.

METHODS AND MATERIALS

DEAP Soft Actuator

In this work, the actuator was fabricated by rolling the multilayers of the PolyPower DEAP sheet, which then pressed to form a flat structure. This actuator was entirely made-up from the DEAP sheet without any core inside the flat rolling structure resulting in a thin, soft and flexible actuator. A hard-plastic clipper was put at each end of the actuator to ensure the actuator in the flat structure shape. Figure 2 shows the photograph of the flat structure actuator used in this study. Table 1 reports the main geometric and electrical properties of the actuator.

Figure 1. A photograph of the final assembly of Poly Power flat DEAP actuator

Table 1. Actuator specifications and properties [9]

Geometry	Value	Material constants	Value
Actuator's length (m), L	0.28	Permittivity of the actuator (F/m), $\boldsymbol{\varepsilon}$	8.854e^{-12}
Actuator's width (m), w	0.07		
Weight (kg), M	0.0645	Permittivity of vacuum (dimensionless), $\boldsymbol{\varepsilon_0}$	3.1
Clipper's weight (kg), Mc	0.105		
		Elastic Modulus (MPa), $\boldsymbol{Y}$	1.1
		Laminate's thickness ($\boldsymbol{\mu m}$), h	70
		Young's Modulus (MPa), E	1.1
		Density (kg/m^3), ρ	1100

This soft actuator has the capability of pulling and pushing force. Figure 3 shows the simple diagram DEAP operating as pulling and pushing actuator. (K) and (C) is the stiffness and damping of the actuator, respectively. The gravitational force represents by (g) and actuator extension is (x). Figure 3(a) shows the deformation of the DEAP due to the voltage supplied produces the pushing force. As voltage decreases or cuts off, the contraction of the DEAP sheet towards its original shape contributes to the actuator, as shown in Figure 3(b).

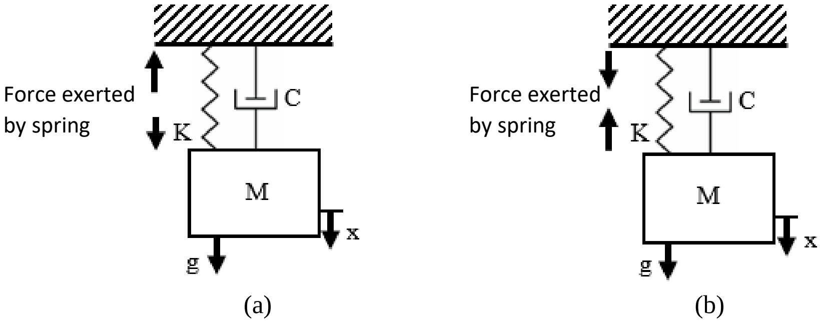


Figure 2. (a) Pushing force due to deformation as the voltage supplied and (b) Pulling force due to contracting as voltage reduce or cut off

Voltage-Strain Testing

In the Voltage-Strain testing, the actuation characteristic of the actuator was discovered. It provides information about the operation behavior either in linear or nonlinear for the actuator. For this purpose, the DEAP actuator with the specification and properties as Table 1 was used. The Voltage-Strain testing was set up with one end of flat DEAP actuator was clamped at the static iron beam and another end was hung freely as shown in Figure 4(a). The pre-stretch condition of flat DEAP actuator due to the mass of caliper (Mc) was assumed as an equilibrium condition. Trek high voltage amplifier supplied the voltage from 0 V to 2000 V in the step of 100 V. The elongation of the actuator was measured and recorded by the Keyence laser displacement sensor with no additional load mass.

Then, the experimental results were compared with the actuating principle of DEAP material that has been modeled by Pelrine [13]. The relationship between strain and voltage for unloaded DEAP actuator can be determined by:

$$s = \frac{\varepsilon \varepsilon_0 \left(\frac{V}{t}\right)^2}{Y} \tag{1}$$

where s is the strain, ε and ε_0 represent the absolute and relative dielectric constants of the elastomer, v is the voltage supplied, t the thickness of the laminated DEAP material and Y is the elastic modulus of the elastomer in the axial direction.

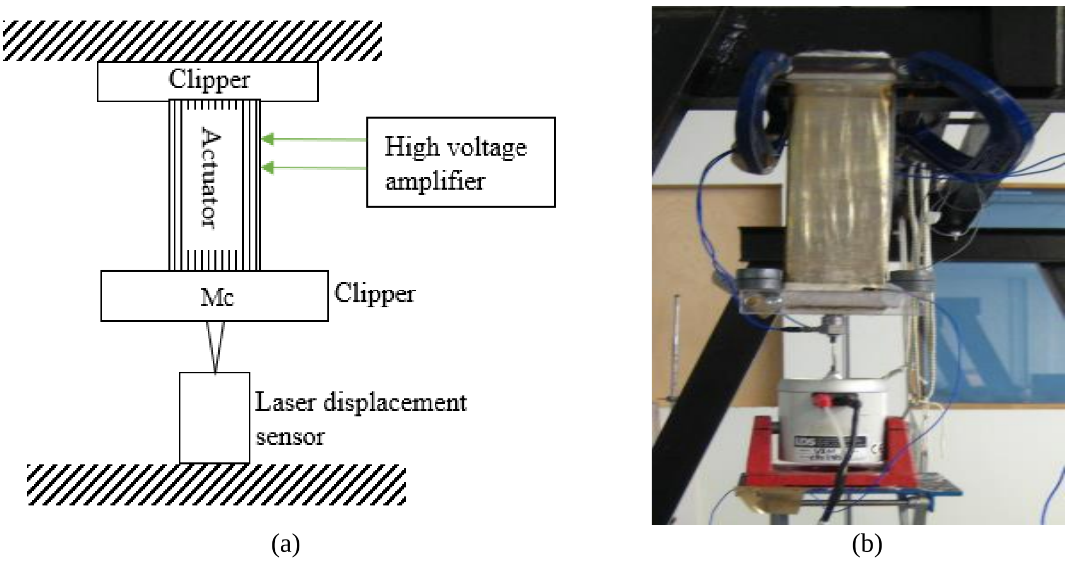


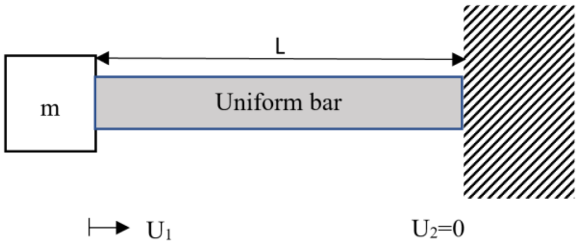
Figure 3. (a) Voltage-Strain setting for the flat DEAP actuator and (b) dynamic testing for the DEAP pull actuator

Passive Dynamic Testing

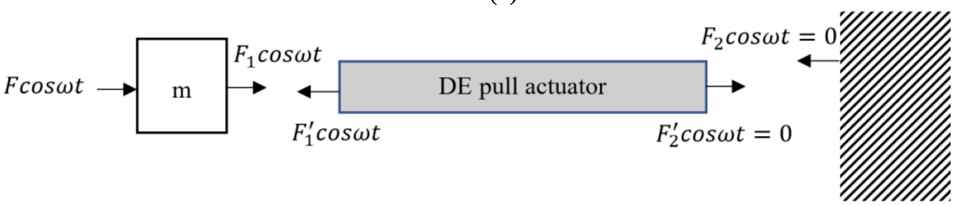
While the dynamic characteristic provides an indication of the frequency range for the active vibration isolation to work successfully [10]. In dynamic testing, a similar setting as the Voltage-Strain experiment has been done. The electrodynamic shaker was attached at one end of the actuator so that the excitation was only one direction as shown in Figure 4(b). This procedure was done to ensure that the modal response in just that direction can be obtained. The force transducer was used to measure the force applied. Meanwhile, the accelerometer was used to measure the dynamic response of the actuator in acceleration. The tests were conducted by adding load m1 from 0 g to 200 g in the step of 20 g. The signal used to drive the shaker in the experiments was set as pseudo-random. The transfer function of acceleration per unit force has been acquired by spectrum analyzer in the frequency range from 0 to 200 Hz. Physics software recorded the signal for 30 sec using rectangular windowed with a frequency resolution of 3200 lines and over an average of 75 times.

Theoretical Modeling of the Actuator

In this section, the dynamic response of the DEAP actuator was calculated analytically by simplifying the actuator into a uniform bar rigidly fixed at one end and attached to mass at another end as shown in Figure 5(a). The force was applied at the end attached to mass as shown in the illustration of the actuator model in Figure 5(b). In this study, the source of force applied was harmonic excitation. Masses were added to investigate the effect of mass on the dynamic characteristics of the actuator. In the figure, (m) represents the mass added, U is the displacement, t is time, ω is the frequency of the force and F is the force.



(a)



(b)

Figure 5. Mass rigidly attached to the uniform bar at one end and rigidly fixed at another end: (a) steady-state and (b) the force was applied

The relationship between displacement and force for uniform bar rigidly fixed at one end was derived using Newton's law, which led to the equation of motion for the particle at any point on the cross-section of the bar as below;

For excited mass, m:

$$(F + F_1)cos\omega t = -m\omega^2 U_1 cos\omega t \tag{2}$$

For DEAP actuator:

$$\begin{bmatrix} F_1' \\ F_2' \end{bmatrix} cos\omega t = EAk \begin{bmatrix} cotkL & -coseckl \\ -coseckl & cotkl \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} cos\omega t \tag{3}$$

where,

$$k = \omega \sqrt{\frac{\rho}{E}} \tag{4}$$

The equilibrium of the junction between the parts is given by:

$$F_1 + F_1' = 0 \text{ and } F_2 + F_2' = 0 \tag{5}$$

Since U_2, F_2 and F_2' are zeroes at fix end, substituting Eq. (2) and Eq. (3) into Eq. (4) gives:

$$F = (-\omega^2 m + AEkcotkL)U_1 \tag{6}$$

For acceleration:

$$\ddot{U} = -\omega^2 U \tag{7}$$

Hence, the accelerant equation can be written as;

$$\frac{\ddot{U}}{F} = -\frac{-\omega^2}{(-\omega^2 m + AEkcotkL)} \tag{8}$$

Thus, the accelerant in Eq. (8) was solved using Matlab soft code and was compared with the experimental findings. In this paper, the creep's effect [4] and hysteresis [6] were not considered since only short dynamic tests were performed. The loss factor (η) from dynamic testing were used to construct the equation of motion. The values for the actuator geometry and properties are shown in Table 1. From Eq. (8), m was the summation of the mass of the clipper (Mc) and additional mass (m1).

RESULTS

Actuation Characteristics

In accordance with the actuation test specified, the DEAP actuator exhibited the Voltage-Strain curves as shown in Figure 6. The experiment tested the model of the actuator with manufacturing serial number 1099. Owing to such a typical non-linear trend provide by any rubbery material, the elongation of the actuator was quadratic proportional to the voltage supplied. This result was not good agreement with the predicted theoretical model at a voltage between 100V to 1000V and 1700V to 2000V with the average percentage error 104% and 20.7%, respectively. Between 1100V to 1600V, the result is in line with Pelrine's theory, with an average percentage error of 5.7%.

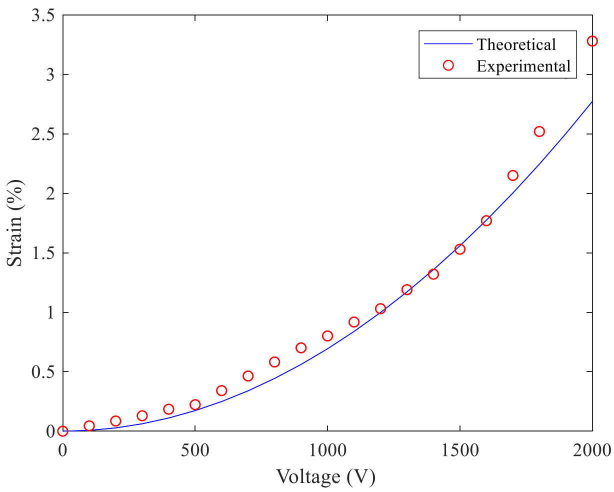


Figure 6. Voltage-Strain curve for DEAP actuator

Passive Dynamic Characteristics

Figure 7 presents the frequency response function (FRF) of the DEAP actuator at zero loads and zero voltage supply. The magnitude and phase angle response shows that only the first-order mode of resonance occurred at a range of 0 to 200 Hz. The first resonance frequency was close to 14 Hz. Natural or resonance frequency is fundamental in applications of actuator because it indicates the bandwidth or the range of operation frequency. Based on the result, the output of the actuator amplified, and the phase angle was no longer being close to zero at the resonance frequency. Therefore, in this study, the natural response of the DEAP actuator was at a low-frequency range.

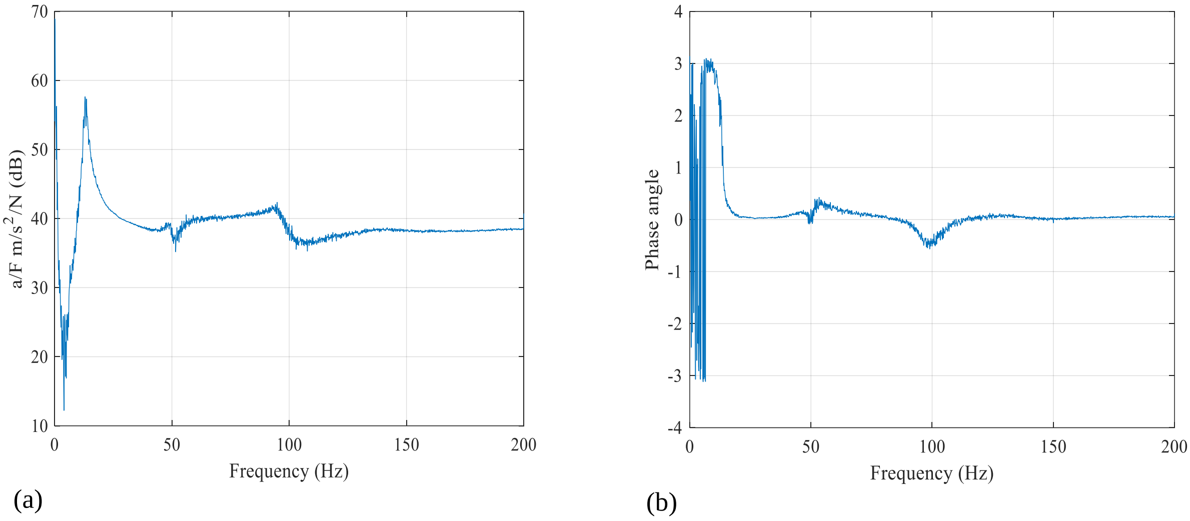


Figure 7. Acceleration per unit force of the flat DEAP actuator: (a) magnitude and (b) phase angle

Comparison between Theoretical and Experimental Findings

In this section, the natural frequency for theoretical results and experimental are compared and explained. In the experiment, the DEAP actuator was in a passive condition (0V). For FRF model prediction, the values of the DEAP actuator Young's modulus (E), density (ρ), length of the bar (L), and mass of the attached clipper M are shown in actuator properties data in Table 1. Damping is considered to affect the stiffness by substituting the Young' modulus E with the complex expression of $E = E\ (1 + \eta i)$, where η is the measured damping.

Figure 9 shows the comparison between theoretical and experimental work for load at M which was the mass of the clipper. Results for the natural frequency are in good agreement between theoretical and empirical with a percentage error of 1.4%. However, the theoretical model underestimates the experiment results as the additional load $m1$ at 200g as shown in Figure 10. The FRF's plot underlined a poor prediction for the natural frequency with percentage error at 16.6%. The percentage error for the natural frequency between theoretical and experimental is below 10% for the first 100g additional loading as shown in Table 2. The theoretical model is not good agreement with the experiment results as the additional load $m1$ increased starting from 140g and noticeable at 200g with the average percentage error 15.7%.

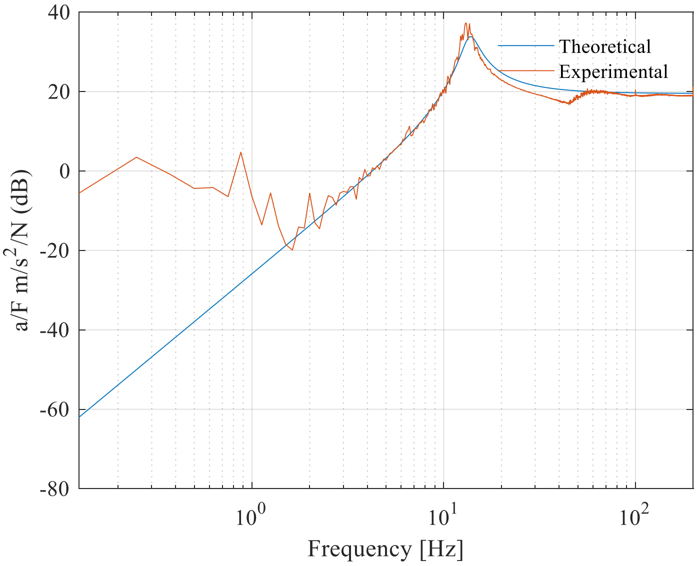


Figure 9. 0 mass (pre-stretch due to clipper mass of 105 g)

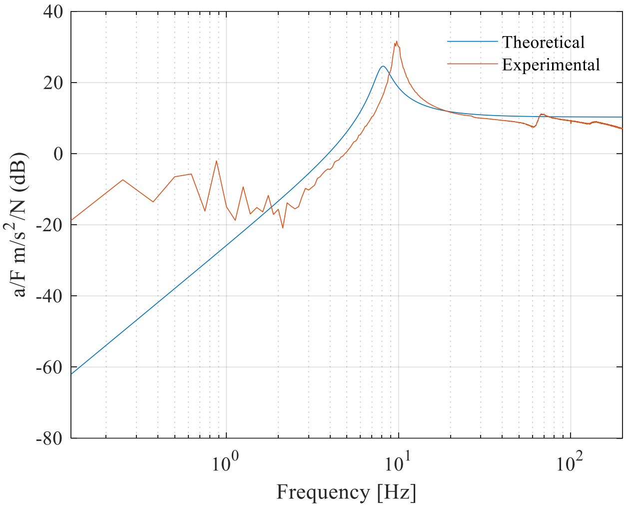


Figure 10. 200 g mass (pre-stretch due to clipper mass of 105 g)

DISCUSSION

Effect of Voltage

The high average percentage error at low voltage and high voltage possibly were due to hardness factors and variations of actuator thickness, respectively. In between 100V to 1000V, the homogeneity and perfect bonding between the multi-layered DEAP sheet increases the rigidity that contributes to a decrease in the elongation of the actuator as the low voltage applied [15]. While at a high voltage between 1700V to 2000V, the thickness of the actuator starts to varies due to deformation occurs at the actuator [14]. Thus, causing the present results not align with Pelrine's theory that considers the thickness of the material is constant. A slight reduction in the value of the hardness factor will give a slightly higher stroke for the same voltage that improving the model fit. The results proved that the flat DEAP soft actuator was nonlinear electromechanical devices.

Effect of Mass

The resonance frequency of an actuator is dependent on its stiffness and mass, while the peak values at resonance are dependent on the material's damping coefficients. Besides, for elastomer, the inhomogeneity, particularly in the length direction and the initial (unloaded) tension, can affect the frequencies [16]. As shown in Figure 8, this result shows the resonance frequency inversely proportional to the loading mass. However, the reduction of the resonance frequency was not uniform. This result indicates the inhomogeneity and initial tension can significantly affect the resonance frequency of the DEAP soft actuator.

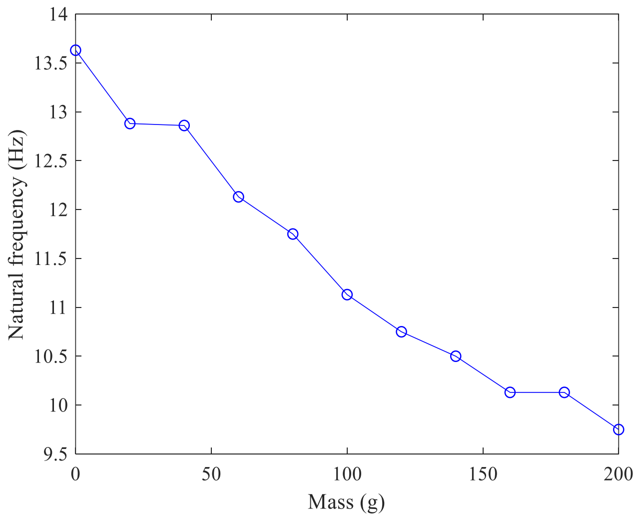


Figure 8. The relationship between resonance frequencies and mass

Theoretical Discrepancies

For both Figure 9 and Figure 10 the significant discrepancies occur at the low frequencies of the experimental data is due to random noise during testing work, which may establish from friction between multilayer DEAP soft actuator. The significant difference as additional *m1* increased as shown in Table 2 could be explained by the variation of actuator stiffness due to its inhomogeneity, particularly in length direction [17]. The inhomogeneity occurred due to the rubber properties of the actuator. The thickness of the DEAP soft actuator reduces as the additional load increased to contribute to varying the stiffness of the actuator. For better results, the actuator can be a model as a composite material.

Table 2. Comparison of resonance frequencies between those of the theoretical model and experiment results

Weight, ml,(g)	0	20	60	100	140	180	200
Model (Hz)	14.3	12.75	11.13	10	9.0	8.5	8.13
Experiment (Hz)	14.1	12.75	11.88	11.13	10.5	10.13	9.75
Differences (%)	1.4	0.0	6.3	10.2	14.3	16.1	16.6

CONCLUSIONS

The actuation and dynamic mechanical characteristics of a new core free flat DEAP soft actuator were investigated. The actuating behavior of the actuator was quadratic proportional to the voltage supplied. It was found that experimental results and Pelrine's theory were not in good agreement for low and high voltage, with average percentage error are 104% and 20.7%, respectively. The resonance frequency of the actuator was 14 Hz and decreasing as load increases. Finally, the DEAP actuator has been modelled as a uniform bar rigidly fixed at one end and attached to mass at another end under zero voltage applied. Results showed a good outcome between theoretical and experimental for the zero loads. However, due to the inhomogeneity of the soft actuator, the FRF's plotted underlines a poor prediction where the average percentage error is 15.7% as load increasing. Further studies are necessary to investigate the active dynamic and electromechanical characteristics of the actuator for application in for active vibration control.

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