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Design and Analysis of Piezoelectric Based Cantilever Beam for Level Detection

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Abstract

Piezoelectric materials are frequently used in sensing, actuating, structural health monitoring, and energy harvesting applications due to their excellent coupling between mechanical and electrical energy domains. Therefore, the purpose of this paper is to examine the viability of using a cantilever beam bonded with piezoelectric material as an actuator and sensor to detect the liquid level in a tank. The PZT patch and flexible aluminum substrate make up the rectangular composite sensor structure, and its operating principle is that when liquid comes into contact with the vertically mounted piezoelectric excited cantilever beam, it encounters resistance to its vibratory motion because of the additional liquid mass and the liquid's viscous behavior. The study included Modal and Harmonic analysis with the aid of ANSYS to determine the best location for the PZT patch, formulation of a mathematical model of the cantilever beam structure using Euler-Bernoulli theory, and FFT plot generated using MATLAB to relate resonant frequency and generated voltage signals. A multi-section piezoelectric excited cantilever beam model was developed analytically and yielded a characteristic matrix that can be used to forecast the resonance frequency and vibration wave form of the sensor. The outcome demonstrated that the operating medium (air or liquid) and the depth of immersion have an impact on the dynamic behavior of the piezoelectric excited cantilever beam. For instance, as the depth of immersion (5–50mm) increased, the resonant frequencies of a transverse vibrating beam decreased by 5.48 Hz in water and 7.73 Hz in oil compared to air. A PZT excited cantilever beam structure was theoretically validated as a level-detecting device, in general, according to the thesis work.

Keywords— PZT, sensor, level, liquid, cantilever, beam

Introduction

The majority of scientific and industrial procedures, particularly those involving combustible fuels, foodstuffs, and chemicals in manufacturing and processing facilities, make it hard to gauge the liquid level on the container or tank using a scale. Because of the nature of these liquids—caustic, poisonous, volatile, or the environment in which detection is carried out will be dangerous, possibly explosive, etc. As a result, determining the liquid level when it reaches the desired point requires quite current technology. Practically, there are numerous types of level sensors. Dipsticks, gauge glasses, floats, displacers, and other mechanical-level detecting devices are the least frequently used ones. You may be familiar with the level sensors classified as electrical or modern, such as capacitance type, pressure sensing type, ultrasonic type, radiation absorption type, electrical conductivity type, etc. The same as other sensors, the liquid level sensors operate on the principle that when the liquid level changes, a particular sensor parameter, such as pressure, position, capacitance, inductance, resistance, etc., changes. This change is then converted into a mechanical or electrical signal with the help of an appropriate transducer. For example, in float and displacer-type level sensors, the position of the sensing element changes with the change in liquid level, and this change is transformed into an electrical signal by employing an appropriate transducer (Samik M. et al., 2014).

Piezoelectric materials and piezoelectric-based sensors are more commonly used as electrical energy harvesters, biological sensors (biosensing) and are sensitive enough to be useful for sensing pressure, liquid and gas densities, mass, and other things. Liquid-level detection is one of the many uses for piezoelectric-based sensors. Higher-precision liquid level detection is currently in high demand. For instance, spills of oil are costly, risky, and dangerous at an oil refinery plant. Similarly, mixing activities that are carried out above or below the recommended amount can result in product flaws, health impacts, and higher expenses (unnecessary capital expenses).

Piezoelectric materials as well as piezoelectric-based sensors are more familiar in harvesting electrical energy, as sensor for biological things (bio sensing), and effective for detecting pressure, liquid and gas densities, mass, etc. with sufficient sensitivity. Among the diverse applications of piezoelectric-based sensors is liquid-level detection. Detection of liquid levels with higher accuracy is most wanted by now. For example, in an oil refinery plant, overflows of oil are hazardous, dangerous, and costly. Over- or below-level mixing processes can lead to product defects, health effects, and higher costs (unnecessary expense of capital). Thus, the novel idea of this thesis paper was to conduct research on piezoelectric material-based liquid level sensors to achieve the main requirements of the sensor as a liquid level detecting device. That is, its aim was to demonstrate the superiority of piezoelectric material-based sensors over other material-based sensors in producing high output with very little strain, having a very large natural frequency, excellent linearity over a wide loading range, being insensitive to electromagnetic fields and radiation, enabling their operation in harsh conditions, and having a relatively simple readout circuit that may also give the piezoelectric-based sensors a superiority in detecting the level of liquid. Its' working principle is that when a piezoelectric laminated cantilever beam structure device is immersed from air into a liquid, the cantilever faces more resistance to its vibratory motion. Thus, the added mass contributed by the liquid and the dampening effect of liquid viscosity decrease the resonant frequency and the quality factor (defined as the ratio of the resonance peak frequency relative to the resonance peak width at half peak height) (Oden P.I. et al., 1996). As a result, this change in resonant frequency enables the sensor to detect whether the liquid has reached or not reached the specified level by detecting the vibration of the cantilever beam structure.

Current Applications of Piezoelectric as a Sensor

The piezoelectric effect is generated when a pressure is applied to a piezoelectric material, it causes a mechanical deformation and a displacement of charges. That's why an electric field will generate and thus voltage can be detected on the upper and lower surface of the piezoelectric materials. Piezoelectric materials have two properties, Direct effect: is the property of some materials to develop electric change on their surface when mechanical stress is exerted on them, while converse effect: is the property of some materials to develop mechanical stress when an electric charge is induced. Piezoelectric devices fit into four general categories, depending of what type of physical effect is used: generators, sensors, actuators, and transducers. Generators and sensors make use of the direct piezoelectric effect, Actuators work vice-versa when transforming electrical energy into mechanical by means of the inverse piezoelectric effect. And transducers both effects are used within one and the same device. The property of piezoelectric materials to withstand harsh environmental conditions made it a candidate material for application in different branches. Especially, PVDF, PZT and Piezo ceramic ceramics have attracted researcher's attention for sensing different parameters.

For instance (B. MIKA, 2007, Jaynat S. and N. Chopra, 2005, M.Umapathy et al., 2000, Rongjie I., 2014, and W.Zhou et al., 2005) are the scholars that proposed and developed a model to show the feasibility of a piezoelectric based sensors for sensing pressure, strain, bio effect, chemical, displacement and Dc current respectively.

Even though most of the scholars investigate the application of a piezoelectric material for sensing mass, chemical, pressure and so on. But, researchers like (Campbell.GA and Mutharasan R., 2005) fabricated a composite resonant millimeter sized piezoelectric device for measuring micro-level liquid level changes. Thus, obtained a result the piezoelectric based cantilever beam structure sensor can sense the liquid change in small level.

Many researchers have been present papers on piezoelectric material due to piezoelectric materials as a smart material offers many different application even piezoelectric liquid level measure sensors were addressed with the purpose of measuring the liquid change at micron level according the mass change. Whereas, the aim of this thesis paper was to indicate whether the liquid reaches on the specified level or not in addition by interfacing with microcontroller and smart valves it can used as a switch. Thus, this thesis paper proposed to justify a piezoelectric based liquid level sensing device perform equally comparing with the other methods of level detecting.

Methods, Techniques, Studied Material and Area Descriptions

The scope of the study was to design and analysis of a piezoelectric excited cantilever beam theoretically, to justify the application of a PZT based cantilever beam structure as a level detection. The study addresses two major parts of the proposed sensor, knowing the maximum strain generated on the cantilever beam structure and investigating the dynamic behavior of a piezoelectric based cantilever beam structure when it excite in air and liquid (water and oil). According the following methodologies,

i. **Dynamic analysis of the cantilever beam structure:** Modal and harmonic analysis is conducted using ANSYS software to know the the optimal position position of PZT material on the surface of the aluminum cantilever beam structure.

ii. **Formulation of mathematical modeling of the piezoelectric laminated cantilever beam structure:** A mathematical equation developed using equation of motion for flexible Euler-Bernoulli beam with non-uniform cross section and vibrating transversely in air and in side less viscous (water) and more viscous (SAE 50w oil) liquids is derived.

iii. **Dynamic analysis of the piezoelectric based cantilever beam vibrating in, air and liquid (water):** This can be used to find the dynamic characteristics of a PZT excited cantilever beam and to investigate the characteristics change when vibrating in air and liquid (water,oil).

iv. **Generate voltage signals to resonant frequency of the model relation analyzed theoretically (Signal analysis):**

Results

A cantilever beam structure element has modeled and analyzed in ANSYS software. The mechanical properties of the selected aluminum material (Al6061) is given in Table (3.1). As stated the type of material used as non-piezoelectric

Table 1: properties and dimensions of the aluminum cantilever beam structure

Length ()		0.3048
Width ()		0.0127
Thickness()		0.00318
Young's modulus ()		71
Density $K_3\left(—\right)$		2700
Posson's ratio	0.33	

A harmonic analysis conducted at resonance frequency to identify and verify the location of maximum strain/ stress and to deduce where the PZT patch bond in the cantilever beam structure. Where, resonance frequency obtained by substituting the selected material properties and dimension on $= 2^{2-}$ or using modal analysis with support of ANSYS software.

Table 2: Natural Frequency by Analytical and FEA Approach

Mode shape	Analytical Frequency	FEA Frequency	Difference Analytical & FEA
1	28.366	28.433	0.067

Therefore, from the harmonic analysis conducted the maximum strain was around the clamped end (see Figure 1). Thus, in order to sense and actuate the piezoelectric patch appropriately it must be placed on the clamped end of the cantilever beam structure where a maximum strain occur. However, due to the brittle property of the PZT it cannot be fixed at the clamped end. Therefore, the location of the PZT patch must deduced by taking in to account the property of piezoelectric as the same time the location of the maximum strain.

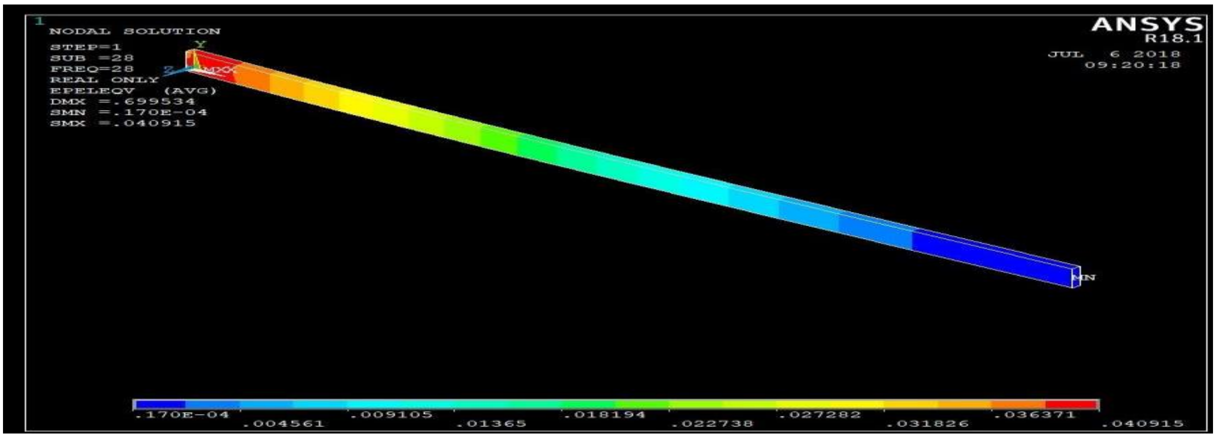


Figure 1: First mode beam contour plot

A numerical analysis conducted using ANSYS (Apdl) to verify the resonant frequencies of the PZT based cantilever beam when vibrating in air with the analytically obtained using equation

1 + 1 4

2 = 1 3 = 1

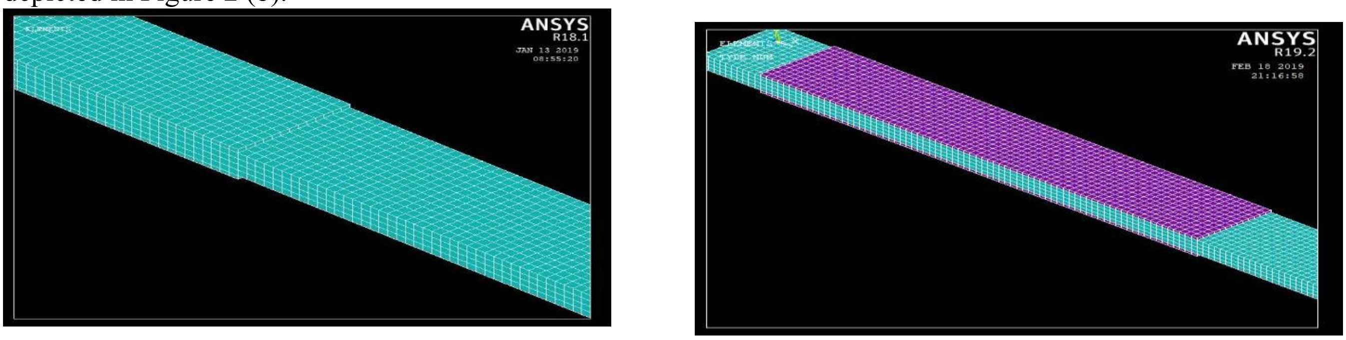
2

[( )( )] / ( )

Table 3: exhibits th]e beam and the PZT dimensions and properties used in numerical simulation.

Symbol	Definition	Cantilever (Al6061)	Piezoelectric (PZT5H4E)
L_1 (mm)	1^{st} section cantilever length	10	-
L_2 (mm)	1^{st} and 2^{nd} section cantilever length	86.5	-
L_3 (mm)	Total length	300	76.5
E_b/E_p (Gpa)	Young's modulus	71	47.62
ρ_b/ρ_p ($\frac{kg}{m^3}$)	Volumetric mass density	2700	7500
w_b/w_p (mm)	Width	12.7	12.7
t_b/t_p (mm)	Thickness	3.18	0.5
d_{31} ($\frac{pC}{N}$)	PZT strain constant	-	-247

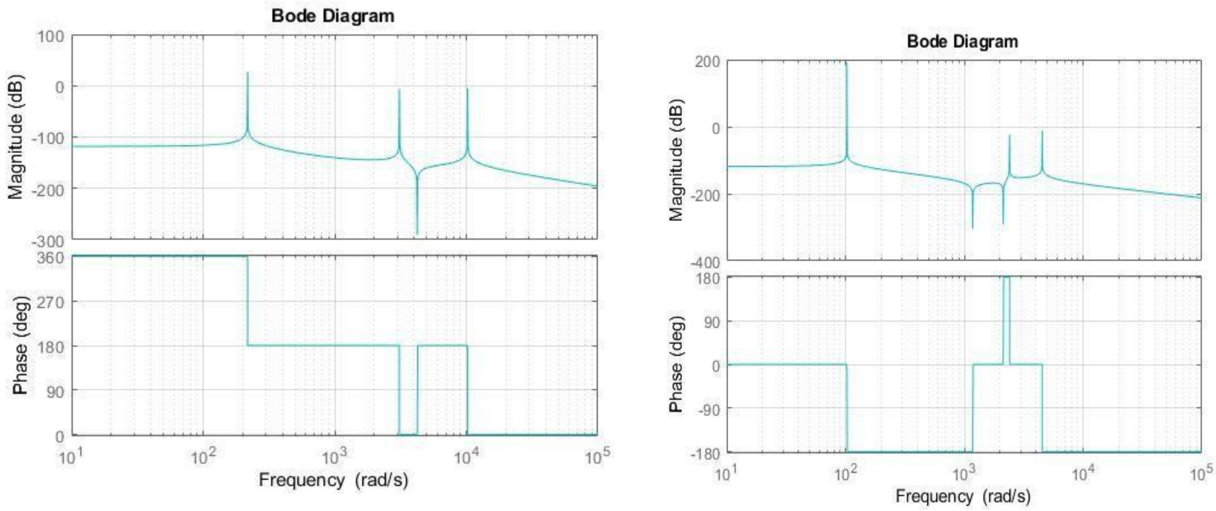
To validate PZT excited cantilever beam as a sensor, numerically the PZT excited cantilever beam modeled on ANSYS Apdl and discrete (meshed) the system into small elements as shown in Figure 2 (a). Using the coupling DOF's the PZT material and aluminum beam combined each other to act as a single element as depicted in Figure 2 (b).



(a) (b)

Figure 2: Piezoelectric based cantilever beam ANSYS Apdl model

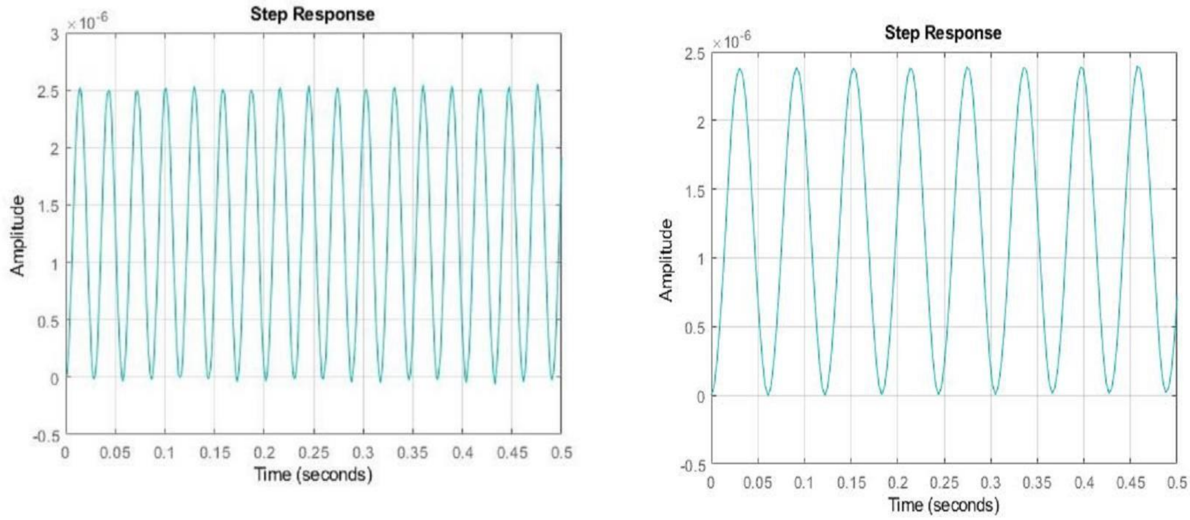
Figure 3 (a) and **Figure 3 (b)** shows the frequency response of a PZT excited cantilever beam structure when vibrating in air and liquid (water) respectively. Where, no damping considered in the system modelling and the piezoelectric patch applies the excitation forces as a concentrated moment at the locations of the piezoelectric layers starts and ends.



(a) (b)

Figure 3: Bode plot of tip displacement (a) vibrating in air, (b) immersed in water

Depending the Bode plots, the time response of Euler-Bernoulli theory due to a unit step input of vibrating in air and vibrating in water with depth of immersion of 50mm are as shown in Figure 4 (a) and 4 (b) respectively. The step response clearly demonstrates that the effect of the liquid on the vibration characteristics of the cantilever beam structure.



(a) (b)

Figure 4: Bode plot of tip displacement (a) vibrating in air, (b) immersed in water

Comparisons of the natural frequency for the first 3 resonant modes of a piezoelectric based cantilever beam by varying the medium of operation (air, less viscous (water) and more viscous (oil) liquids) and varying the depth of immersion was done and given in Table 4. As it can be shown on the table, the natural frequency show significant change when operating media change. Not only has this, the frequency of vibration showed also a change with a change in depth of immersion. This change in natural frequency was a result of change of kinetic energy of the fluid beams system without a corresponding change in strain energy.

Table 4: Comparison of the first 3 Eigen-frequency values between a piezoelectric based cantilever beam vibrating in air and resonant modes from 5 to 50 mm immersion depth in

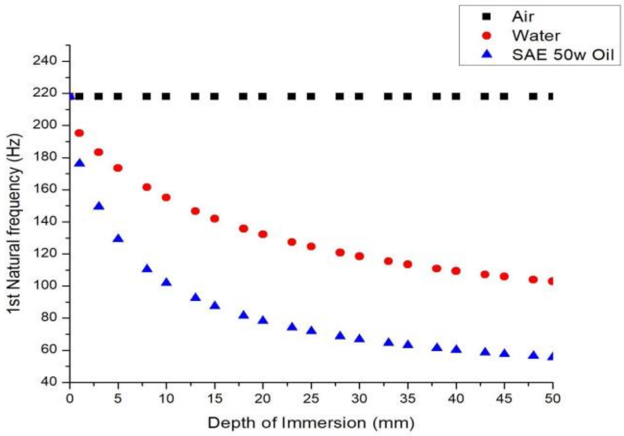
	Medium of Vibration										
	Air	Liquid									
Modes		5	10	15	20	25	30	35	40	45	50
First	218	173.5	155.1	141.9	132.2	124.6	118.5	113.5	109.4	105.9	102.9
		129.2	101.9	87.4	78.2	71.8	66.9	63.2	60.2	57.7	55.66
Second	3101	2644.5	2588.5	2574.7	2573.2	2572	2564.4	2545.6	2512.5	2464.7	2404.6
		926.8	904	900.3	900.1	898.4	892.4	880.1	860.1	832.3	797.496
Third	10232	5299.5	5246.4	5242.2	5232.8	5194.6	5109.8	4977.5	4819.5	4665	4538.1
		2614.3	2600	2597.2	2574.1	2514.9	2411.7	2276.8	2136	2012.5	1916.4

water and SAE 50w oil respectively.

Discussion

Comparing the obtained frequency of vibration of the piezoelectric excited cantilever beam when it excite in air medium and liquid medium (water, oil), the frequencies found at air medium were maximum as depicted in Table 4. This is because the frequency of vibration () and the equivalent mass have indirect relationship. $^{2} = ^{4}$ ( )

Depending on the above equation when the PZT based cantilever beam vibrating in air it is only considered the mass of aluminum beam and PZT material. Where as if it vibrate in liquid (water) in addition to the mass of the beam and PZT material it is also add the mass of the water (the displaced mass due to the immersed cantilever beam).



$$2 = \frac{}{+}$$

$$\frac{}{4}\ {}^{2}\left[\ \left(\frac{}{}\right) + 2.6868\left(\frac{}{}\right)\frac{1}{\sqrt{}}\ \right] \text{ and}$$

$$\frac{}{4}\ {}^{2}\left[2.6883\left(\frac{}{}\right)\frac{1}{\sqrt{}} + 1.3682\left(\frac{}{}\right)\frac{1}{}\ \right]$$

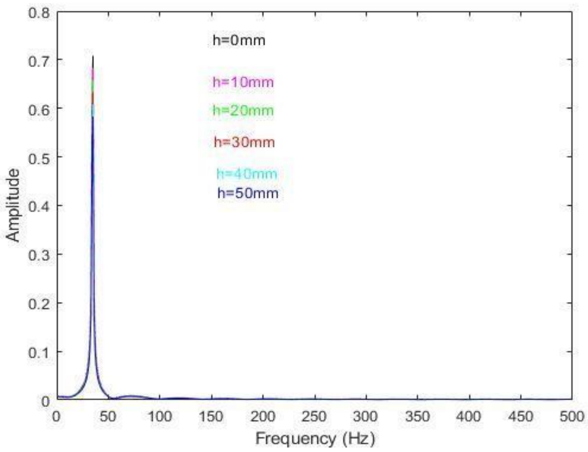
Figure 5: Shows the 1st natural frequency of the PZT based cantilever beam vibrate in air, water and SAE 50w oil

Figure 5 justifies the theoretically modeled PZT based cantilever beam change its' characteristics with a change in liquid medium. In addition, from this we can understand that the PZT excited cantilever beam enable to differentiate the type of liquid. Note that the 1st transverse mode resonance frequency of SAE 50w oil is smaller than in water and air medium this is because the more viscous behavior of oil. The fundamental resonant frequency for the transverse mode drops due to the increased displaced fluid mass and viscous damping averagely by 3.484% or 5.48 in water and by 6.14% or 7.73 in SAE 50w oil. This validate the proposed sensor can sense the level of the liquid and the type of the liquid by sensing the change in added mass or the change in damping when there is a change in depth of immersion. Because as Fig. 6 describes, fluidic mass and fluidic damping increase as liquid medium viscosity increase, since as given in the equation,

Where, $= {}_{2} = \quad 1.0553$

$= {}_{1} =$

The damping ratio depend on the fluidic damping ($_1$) and displaced fluidic mass ($_2$). The fluidic damping and displaced fluidic mass increase (indirectly damping ratio increase) when depth of immersion increase. This in turn applies a force to oppose the motion of the cantilever beam structure and the more viscous liquid the more damping ratio exhibit.
The MATLAB simulated result shown in Fig. 6 is another indicator that relates the amplitude of vibration of the system (piezoelectric excited cantilever beam) and depth of immersion, As the depth of immersion increases the amplitude (cantilever beam tip displacement) reduce. This is because the hydrodynamic loading (liquid effect) resist the beam movement.



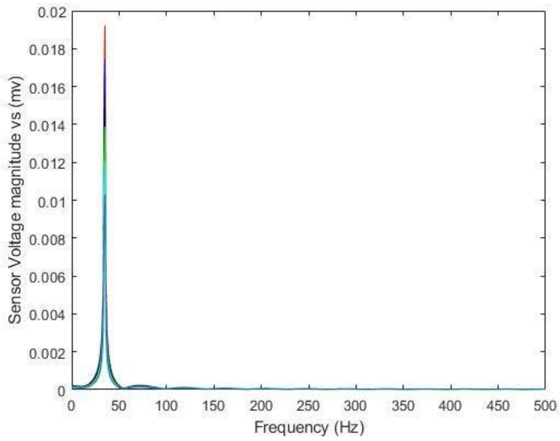


Figure 4**:** FFT plot of the Amplitude vs frequency

Figure 4: FFT plot of the Amplitude vs Sensor voltage

Finally, a MATLAB generated FFT plot (Fig. 7) prepared to show the relation of the depth of immersion and the sensor voltage. Theoretically, it was investigated as depth of immersion increases frequency of vibration decreases. This implies the PZT excited cantilever beam deflection become minimum. The minimum bending of the PZT excited cantilever beam the minimum output voltage generated. Therefore, sensor voltage change with corresponding change in depth of immersion. Thus by sensing the change in sensor voltage it is possible to decide whether it is reached at the specified level or not. Specially, by finding a relation between the depth of immersion and induced sensor voltage it is possible to obtain specific level of the liquid (reading).

Conclusion

The main goal of this thesis is to investigate the feasibility of a PZT laminated cantilever beam for level detection. The sensor structure was designed as a rectangular composite which consist of a PZT patch and flexible aluminum substrate. To fulfil the goal of piezoelectric excited cantilever beam as a level sensor, the study encompassed finding the optimal position of the PZT patch through modal and harmonic analysis and theoretically investigating the dynamic behavior of the sensor when vibrating in air (empty tanker) and partially immersed inside a liquid (water and SAE 50w oil) using Euler-Bernoulli beam theory.
A three section (when vibrating in air) and four section (when operating in liquid) piezoelectric excited cantilever beam model developed analytically and obtained a characteristic matrix that can be used to predict the resonance frequency, vibration wave form ... of the sensor. The result showed the dynamic behavior of the piezoelectric excited cantilever beam depend on the operating media (air or liquid) and the depth of immersion. For instance the first mode resonance frequency in air was obtained 218, in water 173.5 and in oil the resonant frequency decrease to 129.2 when 5 depth of immersion. In general, from the analytically obtained results the resonant frequencies of a transverse vibrating beams in air, liquid (water and oil) decreases by 5.48 in water by 7.73 in oil as the depth of immersion increase ($5 - 50$) due to the increasing of operating medium density and dynamic viscosity.
An analytical equation was derived to show the effect of hydrodynamic loading on the amplitude of vibration and the sensor voltage generated. And a MATLAB simulation was conducted to justify the response of the piezoelectric excited cantilever beam will change with the change in depth of immersion. Hence, because of the fluidic viscosity and fluidic mass, width of vibration (cantilever beam tip

displacement) and generated voltage decrease. With corresponding change in depth of immersion the fluidic damping per unit length increases averagely by 0.0000857 $\_\_\_^{N_2}$ and displaced fluidic mass change by0.00135 $\_\_\_^{K}$. This change was a significant change and enable to change the dynamic characteristics of the PZT excited cantilever beam.

Generally, the conclusion drawn from this paper work is, a PZT excited cantilever beam structure is theoretically validated as a level detecting device.

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