ABSTRACT

Finite element analysis is a computer-aided mathematical technique to obtain approximate numerical solution to the abstract equations, which represent models of physical systems, and predict the physical response to the external or internal condition changes.

Bearing vibration measurement is an effective way to monitor the bearing working condition. A piezoceramic sensing module has been designed for acquiring vibration signals. To serve the purpose, harmonic analysis and modal analysis are used to investigate the response of the piezoceramic sensing module when different proof mass is fixed on the top of piezoelectric plate by using ANSYS.

INTRODUCTION

Bearings are widely used in rotating machines, vibration measurement is an effective way to monitor the bearing working condition. Traditionally, accelerometer is usually placed outside a machine. Due to the test bearings are mechanically linked to other structures, such as shafts, and other bearings, an external sensor will pick up all structure-borne vibrations. In addition, the vibration originating from the test bearing will suffer from attenuation when it is traveling from the bearing to the external sensor. By placing the sensor close to or embedding it into the bearing structure, the embedded approach will avoid attenuating the vibration of interest, while the vibrations from other machine parts may be attenuated on the propagation paths to the sensor location. Therefore, embedding the sensor directly into the bearing outer ring is preferred; Figure 1 shows the embedded sensor module in the bearing outer ring. To design the miniaturized sensing module, a piezoceramic plate has been chosen as the sensing element. The piezoceramic plate can be used as an accelerometer to measure acceleration due to the following advantages:

1) It has a rigid structure which enables it to, if used as a load sensor, carry dynamic load of up to 100 MPa in its linear range;
2) Its frequency bandwidth can be up to the 1 MHz, depending on its dimension;
3) It can be used in high temperature environment up to 150°C, which makes it suitable for common bearing applications;
4) The dimension can be customized to be very small to fit in the slot;
5) It converts mechanical vibration or load into a proportional electric charge without requiring any power supply.
The project will use finite element analysis to show the response of the piezoceramic sensing module when different mass is fixed on the top piezoelectric plate and thickness of the piezoelectric plate changes in order to help us design a miniaturized sensing module with high sensitivity, which is shown in Figure 2.

![Figure 2 Pizeoceramic accelerometer](image)

**FINITE ELEMENT ANALYSIS**

The Finite Element Method is a numerical technique for solving any type of equations, which govern the behavior of physical systems. It approximates the complicated problem with acceptable and adjustable accuracy by a collection of simple coupled algebraic problems. This project mentioned above is solved by the following steps:

**STEPS IN FEA METHOD FOR THIS PROJECT**

1) Modal and assumption  
2) Element type selection  
3) Material properties assignment  
4) Meshing the Modal  
5) Boundary conditions  
6) Solve the problem  
7) Results and discussion.

**MODEL AND ASSUMPTION**

1) Due to the structural characteristics of the piezoceramic sensing module, 3D analysis is adopt  
2) The piezoceramic sensing module is fixed on a support block (bearing outer ring)  
3) A one-quarter symmetry sector is modeled with symmetry boundary conditions applied.  
4) The base of the support block is constrained in X, Y, Z direction.

The finite analysis model is shown in Figure 3.

![Figure 3 Structure model for finite element analysis](image)

**ELEMENT TYPE SELECTION**

**SOLID45 3-D STRUCTURAL SOLID ELEMENT**

SODLID45 is used for the three-dimensional modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. (Shown in Figure 4). The proof mass and the support block use this kind of element in this project.

![Figure 4 SOLID45 3-D Structural solid element](image)

**SOLID5 3-D COUPLED-FIELD SOLID ELEMENT**

SOLID5 has a three-dimensional magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. The element has eight nodes with up to six degrees of freedom at each node (shown in Figure 5). Various combinations of nodal loading are available for this element. It is suited to be used in this project for piezoceramic sensing module analysis.
MATERIAL PROPERTIES ASSIGNMENT

Following list the three properties in structure for the finite element analysis.

Table 1, List of the material properties (units in SI_MKS)

<table>
<thead>
<tr>
<th></th>
<th>Young’s Module (E)</th>
<th>Density (ρ)</th>
<th>Poisson’s Ratio (ν)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proof Mass (Lead)</td>
<td>1.379e10</td>
<td>11300</td>
<td>0.44</td>
</tr>
<tr>
<td>Support block</td>
<td>2.0e11</td>
<td>7860</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 2 List of Geometric parameters

<table>
<thead>
<tr>
<th></th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric plate</td>
<td>10e-3</td>
<td>5e-3</td>
<td>2.5e-3</td>
</tr>
<tr>
<td>Proof mass</td>
<td>10e-3</td>
<td>5e-3</td>
<td>0-0.75e-3</td>
</tr>
<tr>
<td>Support block</td>
<td>12.5e-3</td>
<td>5e-3</td>
<td>2.5e-3</td>
</tr>
</tbody>
</table>

To the piezoelectric plate, \( ρ = 7500 \text{ kg/m}^3 \) and Constitutive Matrices are listed below:

Piezoelectric Matrix \([e]\) C/m\(^3\), which relates the electric field to stress:

\[
\begin{bmatrix}
0 & 0 & -4.1 \\
0 & 0 & -4.1 \\
0 & 0 & 14.1 \\
0 & 0 & 0 \\
0 & 10.5 & 0 \\
10.5 & 0 & 0 \\
\end{bmatrix}
\]

Dielectric Matrix \([ε]\) \(×10^9\) F/m

MESHING THE MODAL

Theoretically, the smaller the mesh size, the more accuracy the results can get. However, it will need long run time and more computer resource. In this project, some meshed sizes are used to compare the results. IF two results are nearly the same, then the mesh size is chosen. There are two mesh methods, one is smart mesh and the other is mapped mesh. In this project, mapped mesh us applied due to the simplicity of structure. Figure 6 shows one of mesh results.

BOUDDARY CONDITION

In this project, a one-quarter symmetry sector is modeled with symmetry boundary conditions applied, and the base of the support block is constrained in X, Y, Z direction. The bottom surface of the piezoelectric plate is grounded which means the voltage is set to zero. The top surface of the piezoelectric plate is also set to have the same voltage. This can be seen in Figure 7.
SOLVE THE PROBLEM

COUPLED-FIELD ANALYSIS

A coupled-field analysis is an analysis that takes into account the interaction (coupling) between two or more disciplines (fields) of engineering. There are two distinct methods can be identified: sequential and direct. The sequential method involves two or more sequential analyses, each belonging to a different field, and the direct method usually involves just one analysis that uses a coupled-field element type containing all necessary degrees of freedom. Coupling is handled by calculating element matrices or element load vectors that contain all necessary terms. In this project, the interaction between the structural and electric fields needs to be analyzed for solving the voltage distribution due to applied displacements, or vice versa. Therefore, direct method will be used in this project.

RESULTS AND DISCUSSION

HARMONIC RESPONSE ANALYSIS

Harmonic response analysis is a technique used to determine the steady-state response of a linear structure to loads that vary sinusoidally (harmonically) with time. The idea is to calculate the structure's response at several frequencies and obtain a graph of some response quantity (usually displacements) versus frequency. There are three harmonic response analysis methods: full, reduced, and mode superposition. Full method is used to do the analysis because it has the following advantages:

- It is easy to use, because you don't have to worry about choosing master degrees of freedom or mode shapes.
- It uses full matrices, so no mass matrix approximation is involved.
- It calculates all displacements and stresses in a single pass.
- It accepts all types of loads: nodal forces, imposed (non-zero) displacements, and element loads (pressures and temperatures).

However, this method usually is more expensive than either of the other methods when you use the frontal solver.

Procedure:

After the structural modal is constructed:

1) Define the analysis type as harmonic
2) Apply displacement loads. Here 1e-6 displacement will be applied to the top surface of the support block
3) Solve from current LS and get the result. The results will be the voltage at the top surface of the piezoelectric plate due to the displacement.

Results:

A piezoelectric plate has two major resonant frequencies, one is the transverse mode frequency, and the other is the thickness mode frequency. In this project, we only investigate the thickness mode frequency because the sensing module that we designed is to detect the vibration in one direction. The piezoelectric plate that we have was tested to show that it has a thickness mode resonant frequency at 814 kHz. By using FEA method, we found that the thickness mode resonant frequency decrease with the increasing of the size of proof mass (shown in Table 3). Figure 8 shows thickness mode frequency responses under different sizes of proof mass.

Table 3 Thickness mode frequencies under different sizes of proof mass

<table>
<thead>
<tr>
<th>Height</th>
<th>0</th>
<th>0.05H</th>
<th>0.10H</th>
<th>0.15H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response</td>
<td>845624</td>
<td>823987</td>
<td>795986</td>
<td>739665</td>
</tr>
<tr>
<td>Frequency(Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>0.20H</td>
<td>0.25H</td>
<td>0.30H</td>
<td></td>
</tr>
<tr>
<td>Response</td>
<td>686023</td>
<td>652051</td>
<td>622038</td>
<td></td>
</tr>
<tr>
<td>Frequency(Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) No Proof Mass
Figure 8 Thickness mode frequency responses under different sizes of proof mass

b) Proof Mass Height 0.05H

c) Proof Mass Height 0.10H

d) Proof Mass Height 0.15H

e) Proof Mass Height 0.20H

f) Proof Mass Height 0.25H

g) Proof Mass Height 0.30H
Also the relation between the thickness mode resonant frequency and thickness is investigated. Table 4 lists the resonant frequency under different thickness, and Figure 9 shows the curve of response. It can be seen that the thickness mode resonant frequency increases when the thickness of the piezoelectric plate decreases.

Table 4: Resonant frequency under different thickness of piezoelectric plate

<table>
<thead>
<tr>
<th>Thickness</th>
<th>1.00H</th>
<th>0.95H</th>
<th>0.90H</th>
<th>0.85H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant Frequency (kHz)</td>
<td>846</td>
<td>864</td>
<td>964</td>
<td>1014</td>
</tr>
</tbody>
</table>

Figure 9 Frequency responses under different thickness

**MODAL ANALYSIS**

Modal analysis is used to check the modal at the thickness modal frequency under different sizes of proof mass and show the change of the sensitivity when different proof mass is fixed on the top of piezoelectric plate. Figure 10 shows the Modal shape of thickness mode frequency response under different sizes of proof mass. Table 5 lists the modals that can be excited under different proof mass, and Table 6 lists the minimum frequency that can be excited under different proof mass. From Table 5 and Table 6, we can see that the number of excited modals increases and the minimum frequency that can be excited decreases when the size of the proof mass increases, this indicates that the increase of the size of the proof mass (which means the weight of the proof mass will increase) leads to the more excited modes of the piezoceramic sensing module.

Table 5: Excited Modals under different sizes of proof mass

<table>
<thead>
<tr>
<th>Height</th>
<th>0</th>
<th>0.05H</th>
<th>0.10H</th>
<th>0.15H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Modals</td>
<td>32</td>
<td>39</td>
<td>56</td>
<td>80</td>
</tr>
<tr>
<td>Height</td>
<td>0.20H</td>
<td>0.25H</td>
<td>0.30H</td>
<td></td>
</tr>
<tr>
<td>Number of Modals</td>
<td>92</td>
<td>103</td>
<td>113</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: the excited minimum frequency under different sizes of proof mass

<table>
<thead>
<tr>
<th>Height</th>
<th>0</th>
<th>0.05H</th>
<th>0.10H</th>
<th>0.15H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>3181020</td>
<td>3001550</td>
<td>2828260</td>
<td>2658920</td>
</tr>
<tr>
<td>Height</td>
<td>0.20H</td>
<td>0.25H</td>
<td>0.30H</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>2494140</td>
<td>2336060</td>
<td>2187060</td>
<td></td>
</tr>
</tbody>
</table>
a) No Proof Mass  

b) Proof Mass Height 0.05H  

c) Proof Mass Height 0.10H  

d) Proof Mass Height 0.15H  

e) Proof Mass Height 0.20H  

f) Proof Mass Height 0.25H
CONCLUSIONS

From the results of the FEA, we can see that proof mass has a direct affection to the characteristics of the piezoelectric plate. The increase of the size of the proof mass will improve the sensitivity of the sensing of the piezoceramic sensing module due to more modes included in the module are excited. It is useful to guide us to design a miniaturized sensing module and get a good sensitivity at the same time.

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REFERENCES