Computer Aided Design of Tine of Tuning Fork Densitometer
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Abstract. In order to assist the structural design of the tine part of the tuning fork densitometer, the parameters of the material used in the simulation should be effectively selected. First of all, the model is established according to the real tine, and the inherent frequencies and the vibration modes are obtained by modal analysis. The inherent frequency of the real tine is calculated through collecting the voltage signal of detection circuit. Then, the elastic modulus \( E \) and the Poisson's ratio \( \lambda \) parameters for simulation are adjusted finely to make sure that the inherent frequency of the simulation model is the same as the actual tine’s so as to determine the material parameters. Further, the thickness of the root beam on tine model is changed to analyze the influence of beam thickness on the inherent frequency and vibration modes by simulation.

Introduction
Tuning fork densitometer is widely used in petroleum, chemical, brewing, food and other industries due to its accuracy and stability, which is designed according to the principle of resonance [1,2]. The structure of the tuning fork densitometer is so complex that the simulation analysis for design and manufacture is essential to meet the higher requirements on the material properties and machining. This paper has built the entity model of the tine of the tuning fork densitometer by AIP and analyzed the modal of the tuning fork using ANSYS finite element analysis software. The inherent frequency and vibration modes of the tuning fork can be obtained and the relationships of the parameters and inherent frequency can be determined. The material parameters for simulation can be known certainly by making the inherent frequency of the simulation consistent with the real tine.

AIP Visual Modeling
AIP software is used to build the tine model of tuning fork densitometer for the advantages that it’s simpler and more convenient. AIP is designed for manufacturing industry development, with a strong mechanical drawing function, including the integrity of the standard parts library and automation tools library, who has accelerated 2D mechanical design. Using AIP software could create a stunning 2D and 3D design, to make the creative design of all kinds of formal practical works for amazing, and design easily two-dimensional into digital 3D objects, then change the design of your mind into the actual shape of full size annotation.

ANSYS Modal Extraction Analysis
In ANSYS there are several methods of extraction mode: block Lanczos method, subspace method, power dynamics method, reduction method, asymmetric method and damping method. Which kind of modal extraction method is adopted mainly depends on the size of the model (with respect to the computing ability of computer) and for the specific applications. This paper mainly uses the method of block Lanczos as modal extraction analysis method of the tine.

Modal Analysis
The so-called modal means the inherent vibration characteristics of the mechanical structure. Modal analysis is a technique used to determine the vibration characteristics of the structure, it can
determine the inherent frequency, vibration mode and vibration mode participation coefficient. Modal analysis is the basis of all kinetic studies.

The modal analysis for mechanical structure is mainly to find the inherent frequency of the structure, analysis of structure resonance, to avoid resonance effect. While the modal analysis for tuning fork densitometer is to design optimal resonance structure, get the stable inherent frequency, and analyze the impact of the change of environmental medium on the inherent frequency[3].

**Modeling and Modal Analysis**

The tine of tuning fork densitometer is carried on modal analysis whose physical diagram is shown in Figure 1. Firstly, according to the actual size of the tine, the entity model of the tine is built by AIP 2015 software and the modeling steps can be summarized as follows[3]: (1) analysis of the form; (2) create a sketch; (3) add features; (4) repeat the above operation gradually completed all the results of modeling other, and generate as *.iges file. And then, with the model file imported into ANSYS, the modal analysis is carried out by ANSYS finite element analysis software. First, doing preprocessing operation, including setting unit type, material type, mesh, applying the constraints, and then analyze the solution[4,5]. Finally, postprocessing will be done. Solid186 is selected as element type, and the material parameters of 316L steel are: the elastic modulus $E=1.9\times 10^{11} \text{Pa} ~ 2.1\times 10^{11} \text{Pa}$, density $D=8030 \text{kg/m}^3$, Poisson's ratio $\lambda=0.25 ~ 0.3$[6].

![Figure 1. The actual tine.](image)

**Simulation Result**

The first to sixth order inherent frequencies and vibration mode shapes of the tine are obtained and listed in Table 1 by ANSYS modal analysis when the Young's modulus $E=2.1\times 10^{11} \text{Pa}$ and Poisson's ratio $\lambda=0.3$. The first two vibration modes as shown in Figure 2a and 2b respectively.

<table>
<thead>
<tr>
<th>order</th>
<th>frequency /Hz</th>
<th>load step</th>
<th>substep</th>
<th>cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1636.2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1641.1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3663.2</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4070.7</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>9619.5</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>9655.5</td>
<td>1</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

![Table 1. The first to sixth step natural frequencies.](image)

![Figure 2. The vibration mode figures of the actual tine.](image)

From the above analysis results, it can be seen that the vibration of the tine of the tuning fork
densitometer can be clearly seen by the modal analysis of the tine by ANSYS. The analysis is simpler and more intuitive.

**Resonance Frequency Test for Actual Tine**

In order to verify the feasibility of the ANSYS finite element analysis, the inherent frequency of the tine part of the densitometer is measured. The hammering resonance method is used to excite the tine for the tuning fork is not large [7]. The resonant frequency of a tuning fork is also its inherent frequency and is designed in the audio range 1~3kHz. The signal generated from the tine resonating is picked up by the audio detecting circuit, and then converted to digital signal. FFT spectrum analysis is carried out to get the inherent frequency of the actual tine in the MATLAB platform. The test system block diagram is shown in Figure 3.

![Figure 3. Test system block diagram.](image)

**Detecting Circuit**

The detecting circuit is mainly composed of the electret condenser MIC and the single power supply amplifier TLC2252 chip, as shown in Figure 4. Tuning fork resonance audio signal through the MIC is connected with the detecting circuit, after TLC2252 two-stage operational amplifier converted into the voltage signal. The circuit is supplied by single power VCC, the bias of MIC is provided by the partial voltage circuit of R1 and R2, and the direct current is blocked by capacitor C1. The VCC=5V and the static circuit works in 2.5V. The magnification times of the two stage amplifiers are respectively 2 and about 15 ~ 161.

![Figure 4. Detecting circuit.](image)

**Test Results**

The output signal from detecting circuit is sampled in a sampling interval 0.1ms which is sampling frequency $f_s=10$kHz. A total of 2478 sample points with several complete cycle are used in FFT frequency analysis in order to ensure the frequency resolution. Figure 5a shows the sampled waveform of the output signal from the detecting circuit, and the corresponding amplitude-frequency characteristics are shown in Figure 5b. The frequency resolution is $(10000/2478)$Hz by the time sampling length 247.8ms. The inherent frequency of tuning fork is nearly 1594.0274Hz through FFT analysis by MATLAB.

**Correction of the Resonant Frequency of the Tine in ANSYS Model**

The elastic modulus, one of the most important and the most characteristic mechanical properties of elastic material, can be regarded as an index to measure the difficulty degree of elastic deformation of materials. It is only related to the chemical composition of the material and the temperature. It has nothing to do with neither the organizational changes nor the heat treatment [6].
Poisson's ratio is the ratio of the transverse positive strain to the axial absolute strain when the material is subjected to uniaxial tension or compression. It is also called the transverse deformation coefficient. It is the elastic constant reflecting the transverse deformation of the material.

The first-order inherent frequency of the tine by above ANSYS simulation is 1636.2Hz while the actual measured inherent frequency is 1594.0274Hz. In order to make the both consistent, with the error is less than 0.1%, then the modal analysis is carried out again, changing the values of elastic modulus $E$ and the Poisson's ratio $\lambda$, with other parameters remaining unchanged.

Firstly, the Poisson’s ratio $\lambda=0.3$ remain unchanged, the elastic modulus $E$ is changed from 1.90e11Pa to 2.10e11Pa interval with a step interval 1e9Pa, and the corresponding first-order inherent frequency is obtained through modal analysis. The approximate relationship between the first order inherent frequency $f$ and the elastic modulus $E$ is obtained by using the MATLAB curve fitting:

$$f = 15E^3 - 140E^2 + 780E + 480$$  \hspace{1cm} (1)

Secondly, the elastic modulus $E=1.9e11Pa$ remain unchanged, the Poisson's ratio $\lambda$ is changed from 0.25 to 0.3 with a step interval 0.005, and the corresponding first-order inherent frequency is obtained through modal analysis. The approximate relationship between the first order inherent frequency $f$ and the Poisson's ratio $\lambda$ is obtained by using the MATLAB curve fitting:

$$f = -31\lambda^3 + 300\lambda^2 - 64\lambda + 1500$$  \hspace{1cm} (2)

According to the rules of formula (1) and (2), the elastic modulus $E=2.0e11Pa$ and the Poisson's ratio $\lambda=0.275$ are finally determined after several amendments, and the first-order inherent frequency obtained after the modal analysis is 1594.17Hz with an error less than 0.01%. After the correction simulation results is consistent with measured results within allowable error range.
Effect of Beam Thickness on the Vibration Mode and Inherent Frequency

ANSYS is used to calculate and analyze the change of the inherent frequencies (here only the first order frequencies to be concerned) of the tine of the tuning fork versus the thickness of the beam of the tine root beam which is set to 3.0mm, 2.5mm, 2.0mm, 1.5mm, 1.0mm and 0.5mm respectively, and other parameters remain the same. The corresponding analysis results are listed in Table 2.

Table 2. The first order inherent frequencies versus thickness of the beam.

<table>
<thead>
<tr>
<th>thickness of the beam on tine root /mm</th>
<th>the first order inherent frequencies /Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>1594.17</td>
</tr>
<tr>
<td>2.5</td>
<td>1551.95</td>
</tr>
<tr>
<td>2.0</td>
<td>1527.33</td>
</tr>
<tr>
<td>1.5</td>
<td>1503.69</td>
</tr>
<tr>
<td>1.0</td>
<td>1472.16</td>
</tr>
<tr>
<td>0.5</td>
<td>1446.15</td>
</tr>
</tbody>
</table>

The ANSYS analysis results show that it has little effect on the interdigital displacement vibration by the different thickness of the beam. The first order inherent frequencies of the tine decrease with the decrease of the thickness of the beam [8]. We can use this rule to select the proper thickness of the beam and design the tuning fork densitometer so that it can vibrate at the inherent frequency we want.

Conclusions

The AIP software is used to establish the 3D finite element model of tine of the tuning fork densitometer, and the modal analysis of the tine is carried on by ANSYS finite element analysis software. The elastic modulus and the Poisson's ratio parameters for simulation are determined as 2.0e11Pa and 0.275 respectively by making the first order simulated inherent frequency equal to the actual measured inherent frequency with an error less than 0.01%. In addition, the finite element analysis of the tuning fork with different beam thickness shows that there has little influence of the thickness of the different beam on the first order inherent frequency of the tuning fork densitometer.

References