RECOGNITION OF VIBRATION MODE SHAPES USING 3D COMPUTER VISUALISATION

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Abstract

One of the major problems in experimental vibration analysis is to determine location of transducers. It is important to place the transducers on locations with largest vibration amplitude and to avoid locations with zero-movement (nodal lines). These locations are best seen from vibration mode shapes.

Finite element analysis (FEA) provides numerical values for natural frequencies, which are sorted by size and not by mode shapes. Computer visualization can be used to recognize mode shapes and to perform proper classification of FEA results.

1. Introduction

Vibration analysis of complex geometric shapes, such as centrifugal pump impeller, is usually performed by means of finite element method. Finite element method is eigenvalue problem in matrix form; therefore the results obtained are coordinates of points in finite element nodes (mode shapes) and list of natural frequencies sorted by size. Identification of these vibration modes requires fair knowledge on analytical solution for similar shapes. Centrifugal pump impeller natural frequencies can be calculated using similar procedure as the one used in plate vibration, since impeller acts similarly to circular plate [3]. Structures with more complex geometry cannot be analyzed analytically, but require measurements. To relate experimental results with results of finite element analysis, it is necessary to recognize and to classify mode shapes.

2. Experimental vibration analysis

Experimental vibration analysis of structures consists of excitation (by shaker of impact hammer) and measurement of response (by transducers for displacement, velocity or acceleration). Variations in the vibration frequency have influence on the mode shapes – each mode shape has its unique natural frequency. The location of measurement transducers is very important, since there are areas on each structure that have zero-displacement. These areas are known as nodal lines, and transducers should not be placed in them.

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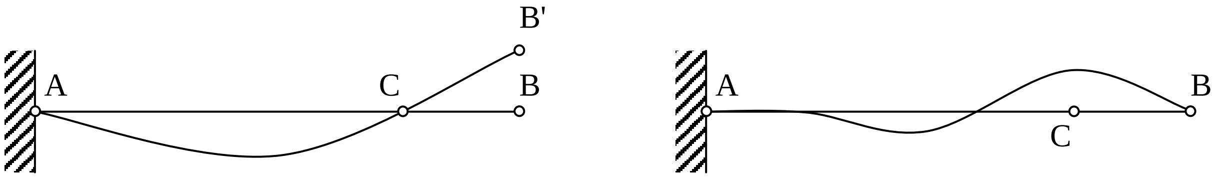


Figure 2.1. Location of transducers for vibration measurement with two different mode shapes

Figure 2.1. shows simple structure (cantilever beam). In stationary state, the structure is straight line between points A and B. One of the mode shapes is curve containing points A, C and B'. If transducer is placed in the point C (nodal point), it will show zero-displacement, and lead to the wrong conclusion that the structure does not vibrate at all. But if the transducer is placed in the point B, it will show maximum displacement. For another mode shape, the point B is the nodal point, and it is not suitable to be the location of transducer. Therefore, it is obvious that mode shape should be known before the measurement to choose proper location for transducers. It is even more important for complex structures, where these mode shapes are not easy to be identified. This paper will focus on circular plates and likewise structures (pump impellers).

3. Mode shapes and nodal lines

Vibration mode shapes of circular plates can be represented using nodal lines and nodal circles. Nodal lines and nodal circles consist of stationary points for specific mode shape, and they form geometric patterns known as "Chladni figures". It was proved in [2] that fluid remains attached to white (vibrating) areas of Chladni figures, and it separates from black areas (non-vibrating nodal lines). The shape of these patterns depends only on frequency, and amplitude depends on intensity of turbulence and velocity by which materials moves on the plate.

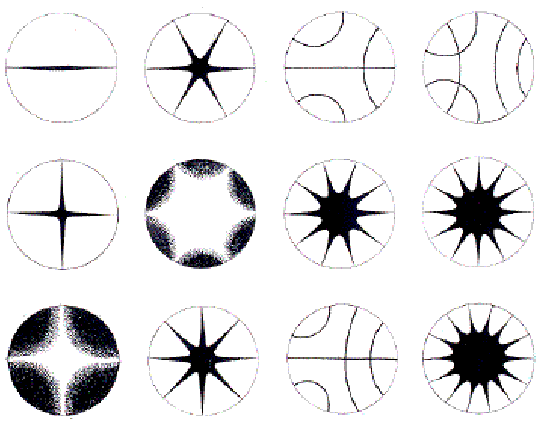


Figure 3.1. Chladni figures – circular plate mode shapes

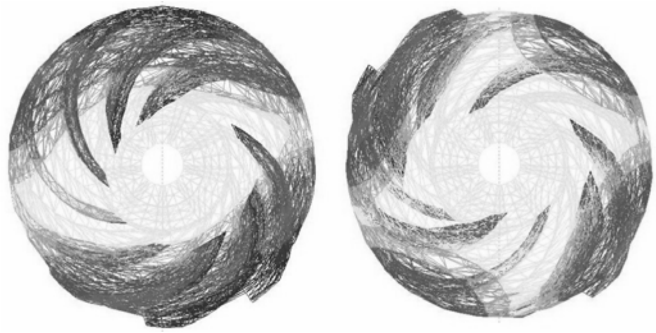


Figure 3.2. Chladni figures formed by vibrating centrifugal pump impeller

4. Finite element analysis

Finite element method is technique used to approximately solve physical or mathematical problems. It is based on continuum discretisation, and it is necessary to solve system of algebraic equations, instead of differential equations. The results of finite element vibration analysis are numerical – sets of natural frequencies and coordinates of points (the points define the mode shapes). These results are usually visualized and this part of analysis is known as post-processing.

Application of finite element method in vibration analysis is based on mathematical eigenvalue problem. The shape of deformed structure is assumed as exponential function. When this function is included in the matrix equation of motion, it is necessary to have non-trivial solution. This means that determinant of the matrix should be zero.

$$\det\left[[K]-\omega^2[M]\right]=0$$

This algebraic equation gives an array of n positive real values ω^2 that represent eigenvalues of the given problem – the natural frequencies of the structure. These results are sorted by size. For plates and more complex structures, there could be more solutions with the same natural frequency, but with different mode shapes (Fig. 4.1.).

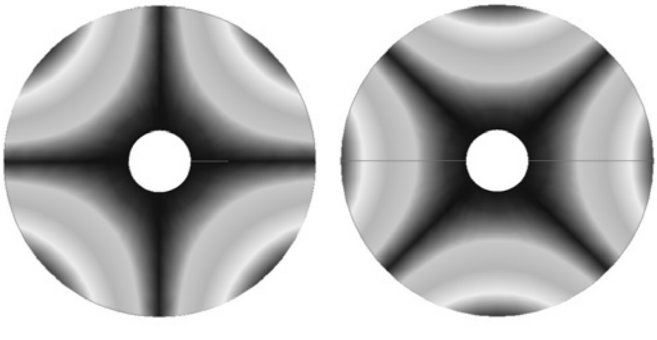


Figure 4.1. Two different mode shapes with the same natural frequency

5. Post processing in finite element analysis

In some cases, to identify mode shapes is not an easy task. Figure 4.1. shows simple circular plate with obvious Chladni figures. Figure 5.1. shows post-processed results of finite element analysis of centrifugal pump impeller [4].

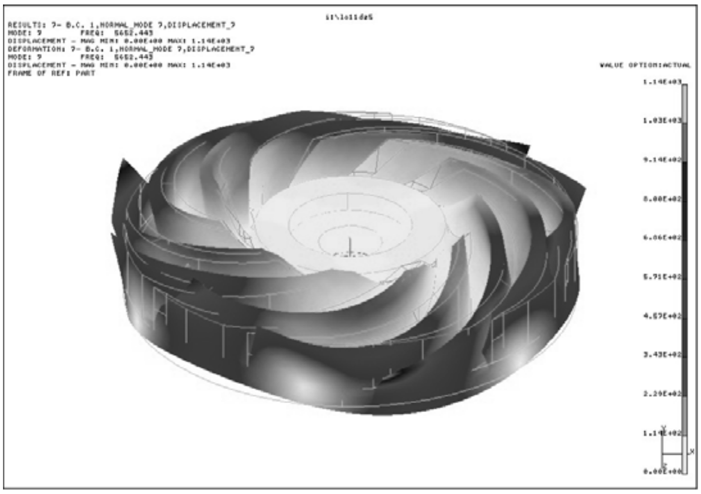


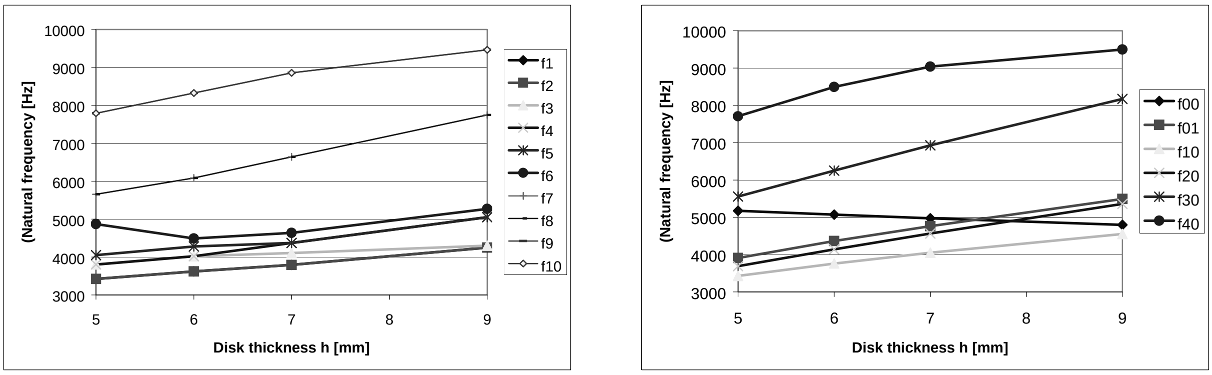
Figure 5.1. Mode shape of centrifugal pump impeller

In [4] detailed analysis of influence of constructive parameters to vibration behavior on one type of centrifugal pump was performed. Natural frequencies were calculated by means of finite element software "I-deas Master Series(c)" for various constructional parameters, such as disk thickness, number of vanes, vane thickness, etc.

Natural frequencies sorted by size					Natural frequencies sorted by vibration modes				
Disk thickness	5 mm	6 mm	7 mm	9 mm	Disk thickness	5 mm	6 mm	7 mm	9 mm
f1	3422	3619	3793	4249	f00	4870	4488	4106	4301
f2	3422	3619	3793	4249	f01	4052	4279	4636	5270
f3	3806	4021	4106	4301	f10	3422	3619	3793	4249
f4	3806	4021	4372	5051	f20	3806	4021	4372	5051
f5	4052	4279	4372	5051	f30	5652	6086	6642	7742
f6	4870	4488	4636	5270	f40	7792	8324	8856	9461
f7	5652	6086	6642	7742					
f8	5652	6086	6642	7742					
f9	7792	8324	8856	9461					
f10	7792	8324	8856	9461					

Table 1. Natural frequencies calculated using finite element method

Table 1 shows results of calculated natural frequencies for various disk thicknesses, as they are given by finite element method software. These results are sorted only by size, and there is no distinction between torsional and lateral vibrations. First ten natural frequencies are calculated, and some values are repeated.



a) *Sorted by size* b) *Sorted by vibration mode shapes*

Figure 5.2. Natural frequencies calculated using finite element method

Figure 5.2.a. shows diagram with false dependence between disk thickness and natural frequencies, since it does not involve vibration classification according to vibration modes. Figure 5.2.b. shows diagram according to results sorted by vibration modes (right-hand half of table 1). Natural frequencies are not denominated with ordinal numbers, but they have two indexes. First index represents number of nodal diameters, and second one number of nodal circles. Index "00" represents torsional vibration. To perform such classification, it is necessary to compare mode shapes of the impeller with Chladni figures of circular plates, identifying nodal diameters and nodal circles. Figure 5.3. shows results of finite element analysis with appropriate Chladni figures of circular plates.

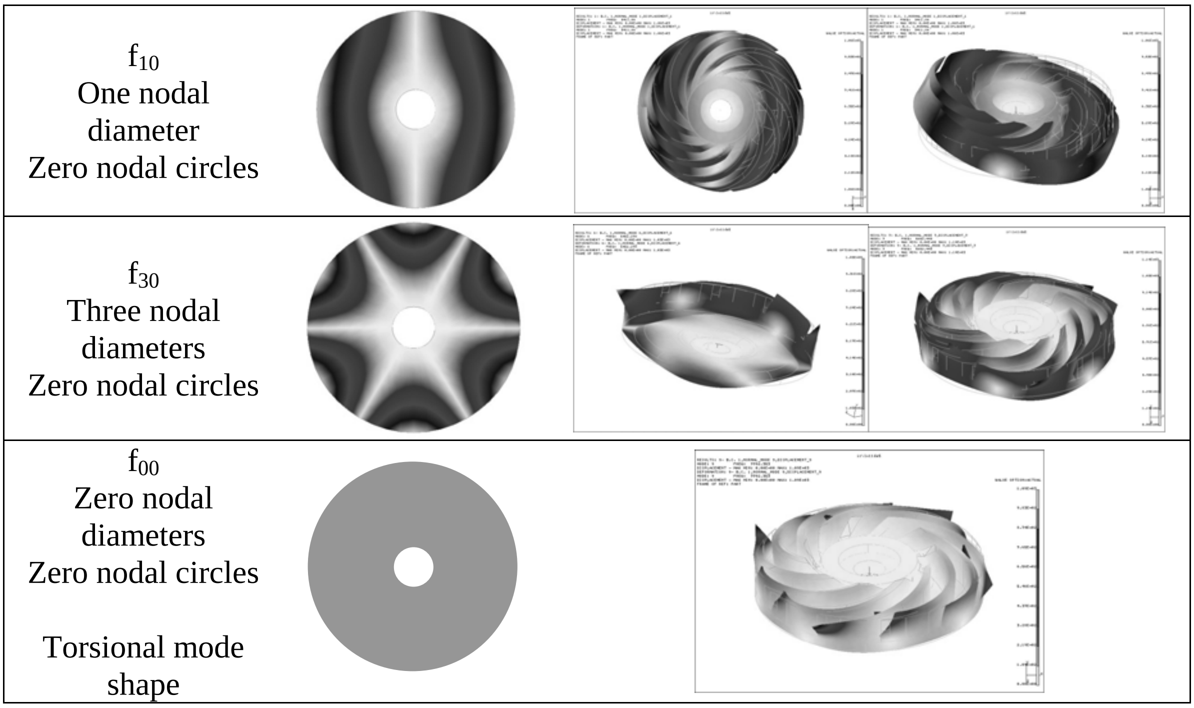


Figure 5.3. Some vibration mode shapes of circular plate and centrifugal pump impeller

6. The need for computer vision in experimental vibration analysis

Chladni figures can be used to determine nodal lines for basic shapes, such as circular or rectangular plates. Figure 6.1. shows how computer vision can be used to determine mode shapes of spinning flexible circular disk. The rotational speed of the disk can be adjusted to be equal to natural frequency. Then the mode shape is acquired by CCD camera, and it can be compared to result of finite element analysis. Similar assembly can be designed for complex shapes, by using shaker instead of motor.

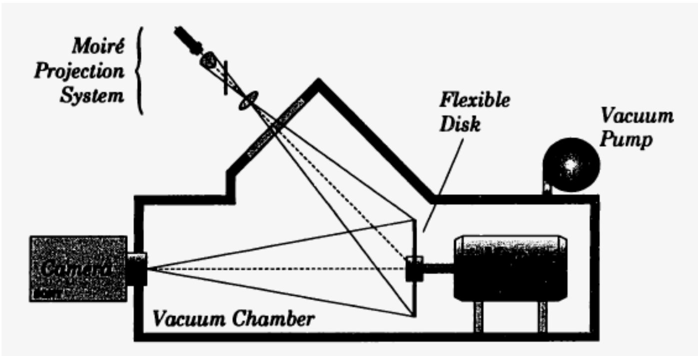


Figure 6.1. Use of Moirre-interferrometry to determine mode shapes of spinning circular plate [1]

7. Conclusion

Finite element method gives fair results in calculation of natural frequencies. Nevertheless, if dependence of some parameters is needed, it is necessary to be familiar with physical character of vibrations of structure being analyzed. Chladni figures can be of great importance as a basis for identification and classification of vibration modes of plate-shaped structures, such as impellers of some centrifugal pump, rail wheels, plates in computer hard disks, etc. For more complex structures, computer vision can be used to obtain nodal lines, which than can be used to recognize mode shapes from finite element analysis results.

8. References

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