Experimental modal shape identification of a rotating asymmetric disk subjected to multiple-frequency excitation - Use of FIR filters

Sébastien Berger, Evelyne Aubry, Frédéric Marquet, Guillaume Thomann

TECHNIQUES *by S. Berger, E. Aubry, F. Marquet, G. Thomann*

EXPERIMENTAL MODAL SHAPE IDENTIFICATION OF A ROTATING ASYMMETRIC DISK SUBJECTED TO MULTIPLE-FREQUENCY EXCITATION: USE OF FINITE IMPULSE RESPONSE (FIR) FILTERS

INTRODUCTION

Thin rotating disks are fundamental elements in numerous machines such as turbines, circular saw plates or disk brakes. When the disks rotate, they are often subjected to transverse vibrations. These vibrations decrease the mechanism's capabilities. It is significant to know the disk's vibratory behavior in order to develop a vibration decreasing system. The present paper proposes an experimental method to identify and locate the nodal diameters of a rotating disk. This method can be integrated into a global process to decrease the vibrations.

Methods for the identification of nodal diameters have been developed in a number of studies. Yu[1] has visualized the nodal diameters of a stationary disk with a stroboscope. MacBain *et al.*[2,3] have used holographic interferometry and moiré techniques to identify the nodal diameters of a rotating disk. However, these methods are essentially visual and cannot be used in a process to decrease the vibrations. Berger et al.[4] have perfected an experimental method to identify and locate the nodal diameters of a rotating disk. This method is based on the modulation phenomenon of the signal, which represents the disk's transverse movements. However, this method is only applicable when the excitation has only one frequency. In the case of inputs with multiple frequency components, this method does not allow the nodal diameters to be identified. Indeed, several modes of the disk can be excited simultaneously and the method based on the modulation phenomenon cannot be used to locate the nodal diameters.

This paper proposes an extension of this method: the disks are subjected to an excitation, which can be composed of several frequencies. This method is applied to circular saw blades including radial dilatation slots. Because of these thermal expansion slots, there is no symmetry axis.

METHOD FOR THE IDENTIFICATION OF NODAL DIAMETERS

Natural Frequencies—Modulation Phenomenon

An axisymmetric disk, which is not rotating, has natural frequencies. The mode shapes for each natural frequency are characterized by some nodal diameters and/or some nodal circles. Nevertheless, the disks are rarely symmetric. The disks often have geometric defects (form defects . . .) and/or asymmetries (radial dilatation slots, etc . . .). These asymmetries affect the vibratory behavior of the disk (Tobias & Arnold[5]—Honda et al.[6]—Yu[1]—Shen & Mote[7]). Some modes remain symmetric (repeated modes) whereas the others become asymmetric (split modes). Therefore, because of the asymmetries, some modes are split into two different modes (cosine and sinus modes) with two different frequencies. Thus, for a given mode, an asymmetric disk can have two different natural frequencies.

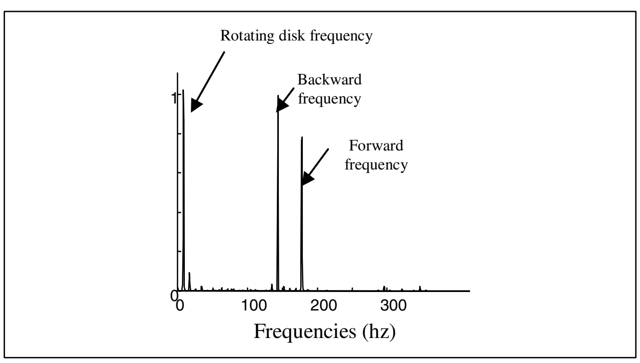

Fig. 1: Frequency response function

When an axisymmetric disk is in motion, some rotation stresses are induced by the centrifugal forces (Hackenberg[8]—Mote[9]). These modify the natural frequencies of the disk: each mode shape is split into two different frequencies. The phenomenon of stationary waves is represented for a given natural frequency by a mode shape. This is due to two different waves around the disk, having the same frequency but travelling with the rotation speed in two opposite directions. When the disk rotates, the rotation speed is added to the propagation speed of the travelling wave in the direction of rotation (forward waves) and is subtracted from the propagation speed of the travelling wave in the opposite direction of rotation (backward waves). So, each mode shape is split into two different frequencies. As only the mode shapes with nodal diameters are affected, the present paper merely considers the nodal diameters.

When an asymmetric disk is in motion, for a given mode, four modes may come up: backward and forward modes respectively for the cosine and sinus modes. (Tobias & Arnold[5]—Honda et al.[6]). Moreover, the backward and forward frequencies of a split or repeated mode are coupled; that is to say, when the forward (or backward) frequency is excited, the backward (or forward) frequency is excited as well. (Ahn[10]).

S. Berger is Maître de Conférences, and E. Aubry is Professor, with MIPS, Mulhouse Cedex, France. F. Marquet is Doctor with LIRMM, Montpellier, France. G. Thomann is Doctor with LAI-INSA, Lyon, France.

EXPERIMENTAL MODAL SHAPE IDENTIFICATION

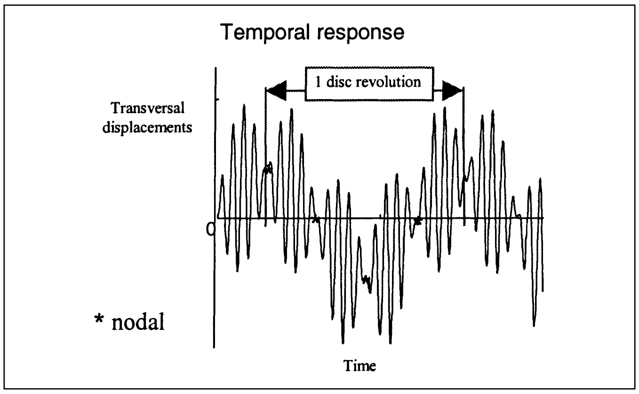

Fig. 2: Transverse disk movements

Assume that an axisymmetric disk is in motion and an outside action excites the forward frequency associated with a mode, so as to study the transverse vibrations of the plate. Figure 1 represents the frequency response function. As the backward and forward frequencies of the mode are coupled, the backward frequency is excited too. In the same way, if the outside action excites the backward frequency, the forward frequency is excited too. Therefore, respectively two peaks appear, associated with the backward and forward waves. A main peak can be observed at the rotation frequency of the disk as well and the frequency is induced by the initial spatial shape of the plate. This shape is induced by a levelness defect. The signal is the sum of the respective waves associated with the initial spatial shape, the backward and forward modes (Fig. 2). The sum of the backward and forward waves is a temporal modulated signal with $f_m/f_r = n$, f_m the modulation frequency and f_r the disk rotation frequency. This temporal modulated signal reaches zero $2n$ times for each disk revolution. Therefore, with the modulated signal measured by the proximity sensor, the nodal diameters can be identified immediately. It must be noticed that this explanation also applies to an asymmetric disk. The mode excited is a split or repeated mode.

Identification Process—Filtering Principle

The modulation phenomenon allows the nodal diameters of an axisymmetric or asymmetric disk to be identified when a single mode is excited. When the plate is subjected to an external action made up of several frequencies, several natural frequencies can be excited simultaneously and the

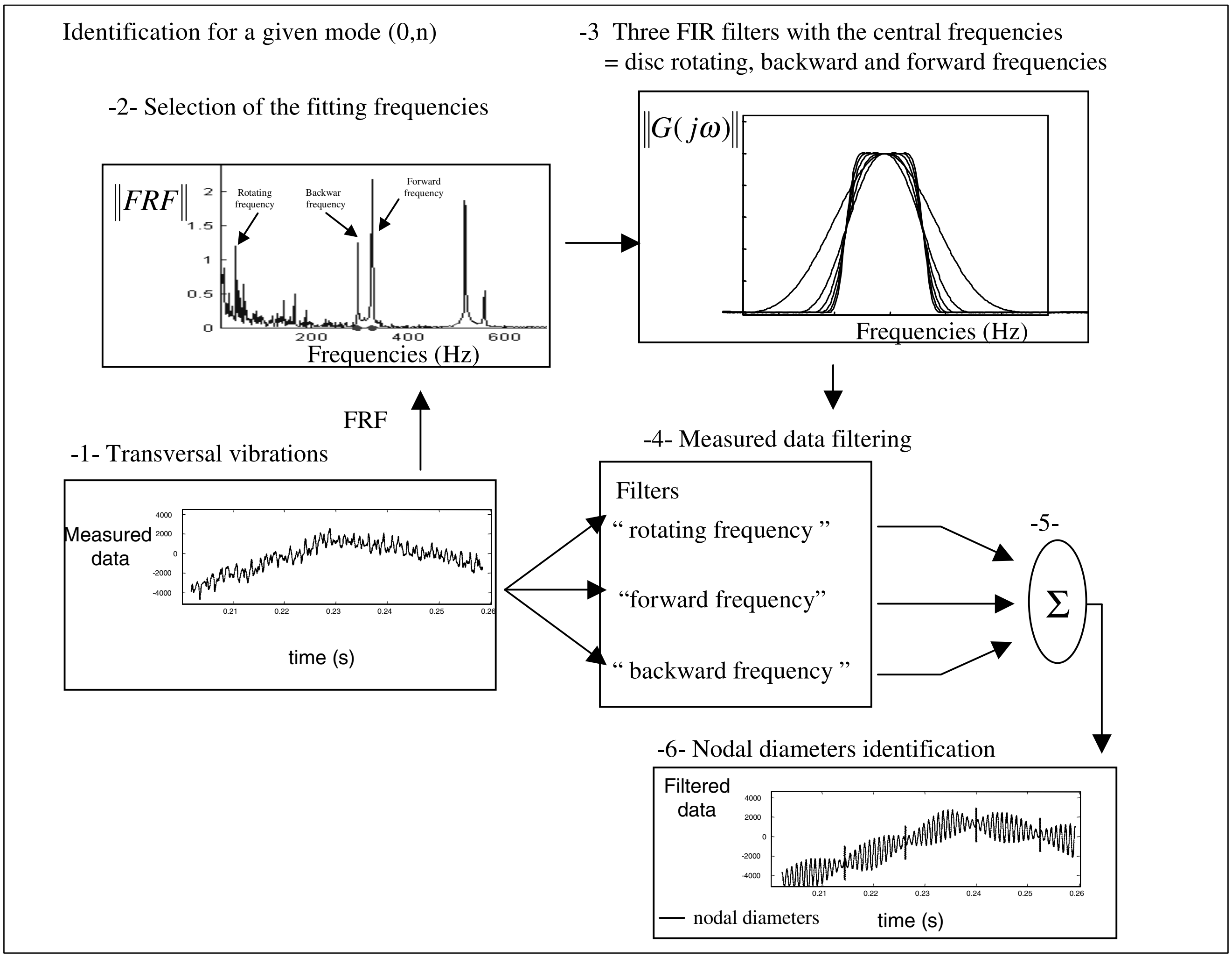

Fig. 3: Identification process for a given mode (0,*n*)

EXPERIMENTAL MODAL SHAPE IDENTIFICATION

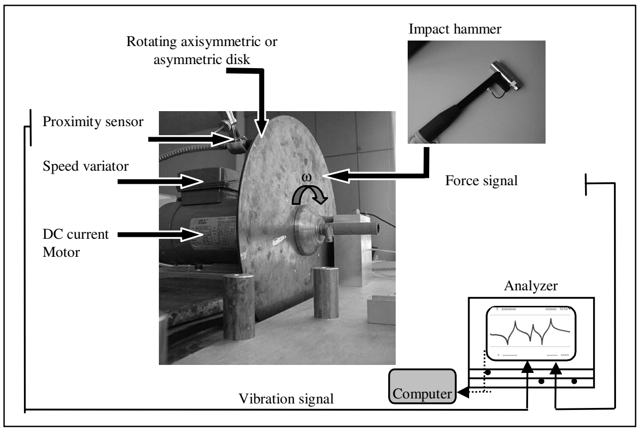

Fig. 4: Description of the test bench

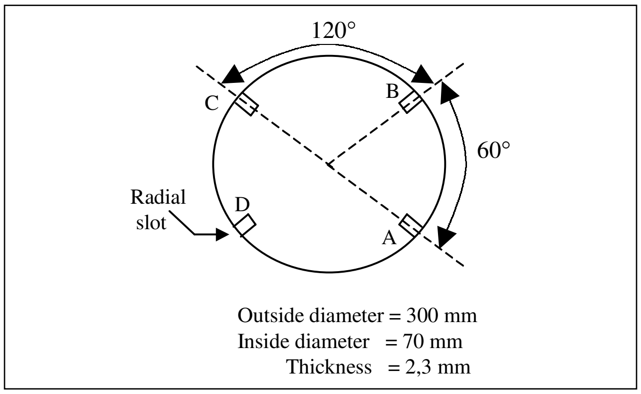

Fig. 5: Circular saw plate

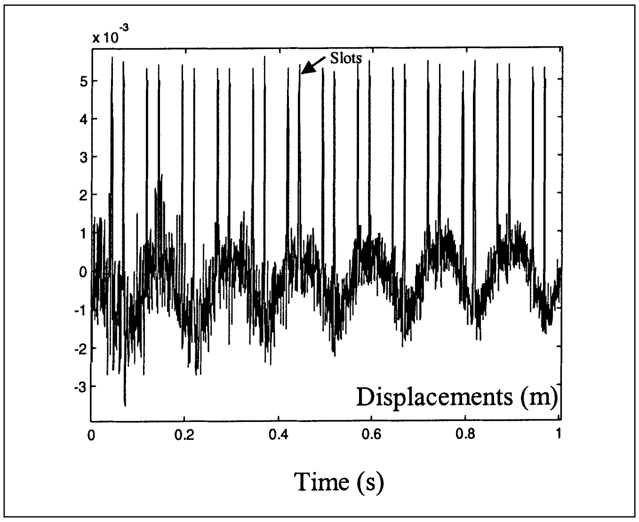

Fig. 6: Time response: transverse disk movements

method based on the modulation phenomenon cannot be used to locate the nodal diameters. The method must be perfected.

In order to identify the nodal diameters with the modulation principle, the signal components of the disk's transverse movements associated with each excited mode must be iso-

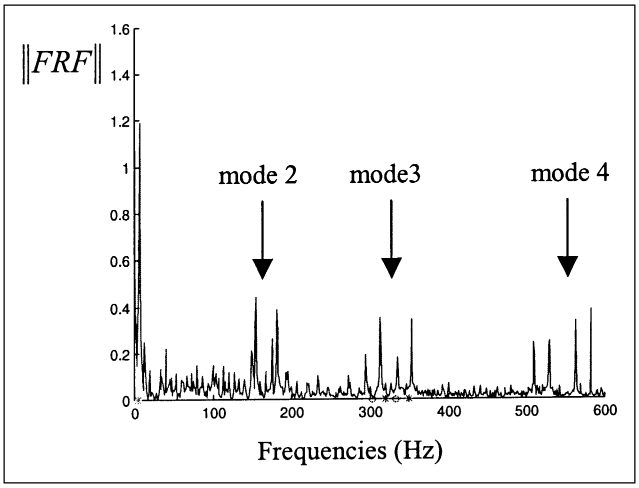

Fig. 7: Frequency response function

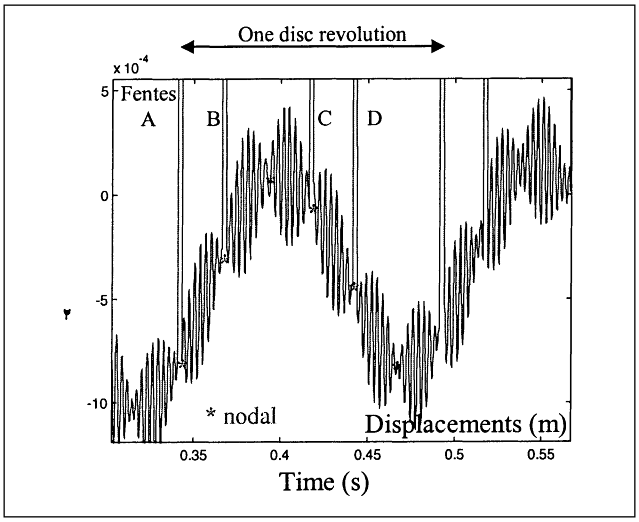

Fig. 8: Sinus mode (0,3)—Filtered time response

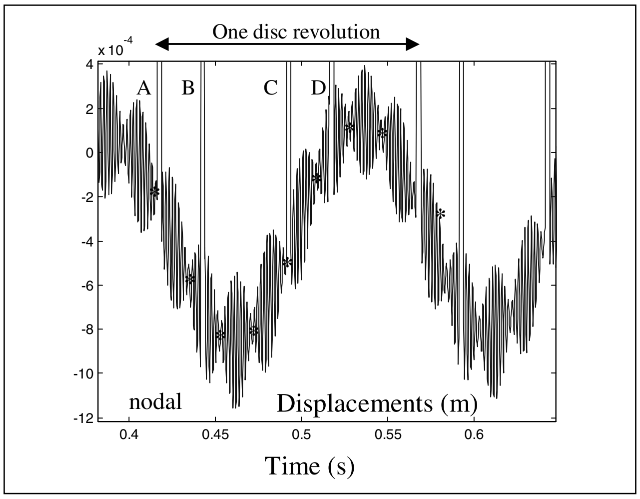

Fig. 9: Sinus mode (0,4)—Filtered time response

EXPERIMENTAL MODAL SHAPE IDENTIFICATION

lated. That is to say, the temporal response of the disk must be filtered and the single mode to be considered must be stored. Bandwidth filters and, in particular, finite impulse response filters are used. These filters have been chosen because of their linear phase. Therefore, the phase difference between the different modes can be compared and the nodal diameters can be located in comparison with the reference (initial spatial shape of the disk). For a given mode, three filters with the central frequency respectively equal to the rotating disk, the forward and backward frequencies will be defined. Each filter is determined from the frequency response function. The temporal response, which represents the transverse movements of the disk is successively filtered by the three filters. So, three filtered signals are obtained and the modulated signal is the sum of the three of them (Fig. 3).

DESCRIPTION OF THE TEST BENCH

The method is applied to circular saw blades. The tests meet the normal working conditions of the tools: a circular rotating steel tool, with a bore, on a shaft with flanges of a given diameter. The blade is subjected to an external action consisting of several frequencies. So, several modes can be excited. An impact hammer fitted with a piezoelectric force sensor provides the excitation and the response is measured by a proximity sensor. This sensor measures the lateral movements around the plate. The spectrum analyzer stores the time signal, carries out the signal analysis (windowing, averaging, Fast Fourier Transform (FFT), etc. . .) and calculates the frequency response function. Then, a Matlab ® script performs the post-analysis (filtering, . . .) and displays the resulting curves. See (Fig. 4).

EXPERIMENTAL RESULTS

This method was successfully tested with axisymmetric and asymmetric circular saw blades. The experiments were carried out at several rotation speeds. In each experiment, several modes were excited. The results of only one experiment are presented here. The tested saw blade was an asymmetric steel disk with four radial slots (Fig. 5). In such a case, asymmetry means there is no axis of symmetry. The rotation speed of the disk was 400 rpm. The modes (0,2), (0,3) and (0,4) were excited. Figure 6 represents the disk transverse movements measured by the proximity sensor. It is obvious that the nodal diameters of the different modes are difficult to identify from this signal. The analyzer computes the frequency response function (Fig. 7). The disk rotation frequency and the four frequencies associated with each mode (0,2), (0,3) and (0,4) appear in this function. The modulated signals are determined for each mode from the time response and the FIR filters.

Figures 8 and 9 represent respectively the filtered signals associated with the sinus modes (0,3) and (0,4). For each excited mode, the nodal diameters can now be directly identified. Figures 10 and 11 show the diameter locations on the disk. The identification of the slots by the proximity sensor allows the nodal diameters on the disk to be located through comparison with the slot locations.

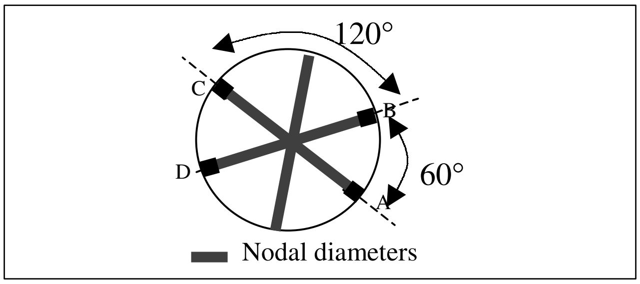

Fig. 10: Sinus mode (0,3)—Nodal diameter locations

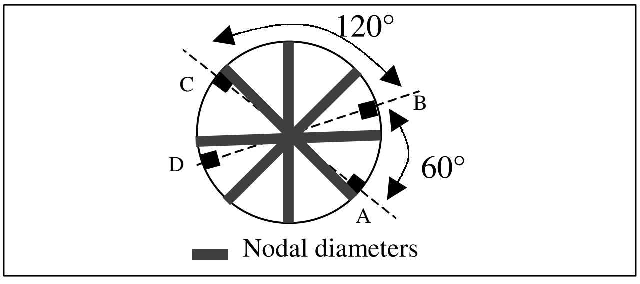

Fig. 11: Sinus mode (0,4)—Nodal diameter locations

CONCLUSION

This paper has presented an experimental method for the identification and location of the nodal diameters of rotating axisymmetric and asymmetric disks. It is based on the modulation phenomenon of the disk transverse movements. To identify the different excited modes, finite impulse response filters are used.

The disk rotation speed covers a wide range and the frequency bandwidth of the considered modes is wide, too. This method is applicable when the disk is excited by several frequencies. The tests met the normal working conditions of the disk in the industry (circular saw blades). To construct the filters, the user must identify manually the excited frequency associated with the mode studied from the frequency response function. It would be interesting to automate this step in order to integrate the method into a vibration decreasing process.

References

1. Yu, R.C., Vibration and Parametric Excitation in Rotating Asymmetric Circular Plates, PhD. Dissertation, University of California, Berkeley, 1986.

2. MacBain, J.C., Stange, W.A., Harding K.G., Real-Time Response of a Rotating Disk Using Image-Derotated Holographic Interferometry, *Experimental Mechanics,* **21**, 1981, pp. 34–40.

3. MacBain, J.C., Stange, W.A., Harding K.G., Analysis of Rotating Structures Using Image Derotation with Multi-Pulsed Pasers and Moiré Techniques, *Optical Engineering,* **21**, 1982, pp. 474–477.

4. Berger, S., Marquet, F., Aubry E., Thomann G., Méthode Expérimentale d'Identification et de Localisation des Diamètres Nodaux d'un Disque en Rotation, XV^{ème} Congrès Français de Mécanique, Nancy, 2001.

5. Tobias, S.A., Arnold, R.N., The Influence of Dynamical Imperfection on the Vibration of Rotating Disks, *Proceedings of Mechanical Engineers,* **171**, 1982, pp. 669–690.

N

6. Honda, Y., Matsuhisa, H., Sato, S., Modal Response of a Disk to a Moving Concentrated Harmonic Force, *Journal of Sound and Vibration,* **102**, 1985, no. 4, pp. 457–472.

7. Shen, I.Y., Mote, C.D., Dynamic Analysis of Finite Linear Elastic Solids Containing Small Elastic Imperfections: Theory with Application to Asymmetric Circular Plates, *Journal of Sound and Vibration,* **155**, 1992, pp. 443–465.

8. Hackenberg, P., Spannungen in Mechanisch und Thermisch Vorgespannten Sägenblättern, Aachen, 1974.

9. Mote, C.D., Free Vibration of Initially Stressed Circular Disks, Transaction of the ASME, *Journal of Engineering for Industry,* **87**, May, 1965, pp. 258–264.

10. Ahn, T.K., Mote, C.D., Mode Identification of a Rotating Disk, *Experimental Mechanics,* **38**, no. 4, December, 1998, pp. 250–254. ■

N