ELSEVIER

Measurement 24 (1998) 43–54

Measurement

Vibration measurements on blades of a naval propeller rotating in water with tracking laser vibrometer

P. Castellini, C. Santolini

Department of Mechanics, University of Ancona, via Brecce Bianche, I-60131 Ancona, Italy

Abstract

The application of laser Doppler vibration measurements is a powerful technique for monitoring and analysing mechanical systems. Frequently experiments in operative conditions may be a useful tool for analysing the real behaviour of an object. However, in several applications we may find that the object is rotating during its work and in these conditions the measurement with traditional techniques becomes difficult. For these reasons a system for the tracking of rotating objects has been developed in order to perform vibration measurements.

In the present work the application of the tracking laser scanning vibrometer on an operative condition problem is shown. A tracking laser scanning vibrometer has been used for measuring the vibration of a map of points on the object surface during a complete circular motion. The analysed object was a model of a naval propeller working in water. A comparison has been found with the static analysis, in water and air, of the same propeller. Some results are shown.

Keywords: Laser vibrometry; Naval propeller; Rotating machinery; Speckle noise

1. Introduction

In machinery, the continuous trend is to generate more power per pound of equipment with a lower consumption. In recent years, the interest of the mechanical engineer has been oriented towards the development of devices with reduced acoustic emissions for low acoustic pollution. In order to obtain these results, the machines must work with closer tolerances at higher speeds.

Another important task for the researcher is to improve the reliability of machines. This study determines the need for control of static and dynamic deformation of moving parts, i.e. analysis of the vibration behaviour of the machine in operative conditions. In a number of cases, component failures are caused principally by vibration-related fatigue stresses. Monitoring of component vibration can play an important role in preventing failures due to fatigue. The resolution of this kind of problem is of significant economic importance, linked to the availability and service life of such equipment [1].

In mechanical applications, the rotating machinery represents a large part of interest in mechanical systems. The rotating "disk" is a fundamental component of modern rotating machinery: a disk is a good model of many different elements of complex systems such as magnetic and optical computer memory units, automotive components, propellers, fans, etc. In the case of naval propellers, the problems are also correlated to the behaviour of water where high variation of pressure is induced. Cavitation is a very important problem affecting the reliability and acoustic emission of propulsion systems in

0263-2241/98/$ – see front matter
PII: S0263-2241(98)00044-X

civil and military ships, where comfort and "stealth" capabilities are respectively requested.

Several important sources of vibration transmitted to the hull are due to the propulsion system. The propeller produces an excitation of the boat, principally by the passage of each blade in front to sternpost and by transmission, through shaft and bearing, of vibration of blades. Dynamic and hydrodynamic effects, i.e. due to solid or liquid masses, can generate vibrations.

A knowledge of the pressure field on blades could allow us to calculate the excitation forces on the propulsion system, and this should be very important in order to analyse the vibrational behaviour of the propeller.

If the effects of solid masses (shaft and blades) can be scheduled and analysed through analytical techniques, the vibrations induced by the hydrodynamic effect are very difficult to predict. In fact, the effects of the water are linked to the real position of blades with respect to the hull and small differences in project parameters can induce large problems.

Hydrodynamic excitation sources are mainly the variation of wake upstream, the cavitation and the turbulence in the abaft of the propeller. The first is due to the non-stationary condition of flow around the propeller. It induces low frequency vibrations and very often a transient response of the propeller due to the passage of a crest in the wake.

Cavitation occurs when a large pressure variation on the blade surface is present, due to the high-speed water flow, determining a separation between water and steam or gases dissolved in them.

The abrupt variation of pressure, due to the generation and collapse of bubble clouds in the proximity of the blade surface, induces a very intensive excitation at the highest frequencies. The separation and attachment of flow cause a large variation of load at lower frequencies, too. In particular, when the speed of the hull is increasing, the propeller cavitation can become a big problem.

Vibrations are the turbulence in the abaft of the propeller, which determine a geometrical distortion of the wake. The excitation obtained is in a medium range of frequency.

Another type of vibration is that induced by clearance, i.e. a reduced space between the hull and the propeller. This problem, very evident in hulls with heavy displacement, is due to the generation of pulses by the water flow, which is forced to pass in a reduced space. These pulses are transmitted to the poop of the hull.

Traditional contact sensors, such as accelerometers, are not able to resolve this kind of problem. In fact, solid sensors alter the fluid-dynamic field around the object and are subjected to centrifugal loads. The mass of these devices can change the behaviour of analysed blades and their volume the flow around. The extraction of a signal from a rotating device can be difficult, and the use of telemetry or other techniques can be necessary.

In order to study the axial vibration pattern on a rotating disk, two non-contact approaches can be used, the Lagrangian or the Eulerian one, i.e. either with the measurement point following the moving point or with the measurement point steady and the surface moving in front of it. In both cases, it is possible to extract modal information on the vibrating structures.

In Reinhard et al.'s work [1], the measurement is obtained using a stationary laser interferometer observing different points at different times. The rotational speed can be about 7000 rpm, but a good finishing of the surface of the analysed object is requested to avoid speckle effects. A complex data analysis in the post-processing step is necessary to extract modal information [2] from these measurements when the shape of the rotating device is complex. In any case it is not possible to extract the time history of the vibration in a single point of the structure.

Moreover, if laser interferometry is used, the Eulerian approach shows some problems; the "in-plane" component of the surface velocity generates a very tedious noise due to the laser speckle. When component wavelets of an incident laser beam are dephased on scattering from an optically rough target, a speckle pattern is generated. When the target motion causes changes in the speckle pattern on the photodetector, the resulting noise cannot be distinguished from genuine vibration and it represents a "pseudo-vibration" [3]. The scattered light pattern due to the interaction between the laser and the surface roughness moves while the surfaces are moving and gives a signal which is not correlated to the vibration, while it is correlated to rotational speed. It is not possible to separate the component that hides the vibration signal.

For the solution of this kind of problem, Felske [4] and Fieldhouse and Newcomb [5] proposed the use of a laser Doppler interferometer, or a holographic interferometer, used with an image derotator, i.e. a device which is capable of freezing the rotation of a component. A derotator is based on the observation of the rotating object through a roof edge prism that is rotating at half the angular speed of the component. This condition makes the image of the component stationary, regardless of its rotational velocity. With this solution, a very complex and high-cost measurement system is obtained. In the practical application of this technique it is difficult to obtain a good alignment of different components, and then the application on the field becomes difficult, too.

In the work carried out by Bucher et al. [6], a technique for the Lagrangian approach to the vibration measurements of a disk is presented. The measurement laser spot is steady in the disk fixed co-ordinate system. Some analytical considerations about the experimental results obtained are shown.

The present work shows the application of a system for the acquisition of vibration with the tracking of each rotating point [7], in a grid in the disk fixed co-ordinate system. The performances of this system have been tested on a vibration analysis of a model of a naval propeller rotating in water.

2. The measurement system

The measurement system consists of a Polytec OFV 050 optical scanning head, an OFV 3000 vibrometer controller and a PC (Fig. 1). On the vibrometer head two oscillating mirrors are mounted, used in the standard configuration to obtain scanning of a steady surface over a regular grid.

In this arrangement, the mirrors are driven respectively by a sine and cosine signal: this causes the laser to trace a circle on the surface of the projection. The signal generation clock is controlled by the pulse-train signal from the encoder. An incremental encoder measures the instantaneous angle of the shaft. The resolution in the angle determination is 0.5°.

The measurement and control system consists of the PC with a National Instruments AT-MIO 16E-10 board. This board generates the signal to drive the scanning mirror of the vibrometer head and to acquire the signal of the instantaneous position of the laser beam, a reference signal and the vibration signal. The signal drives the mirrors through a closed loop control circuit, which allows us to improve the dynamic response of the mirrors.

CADA-X software, from LMS International, is also used for the modal analysis of a propeller in air and in water.

3. The test performed

The aim of the work is to perform an analysis of the vibration behaviour of a propeller rotating in water. In this case it is not possible to apply a classical modal model in order to analyse the vibration behaviour of the object, since the excitation conditions do not respect the required hypothesis of localised application of input forces. The movement of the blade in the water determines fluid-dynamical forces, varying randomly in time for the presence of turbulence, cavitation and other forces and applied on the whole surface of the propeller.

In the work carried out by Wu and Moslehy [8], the possibility of obtaining some modal information also in distributed excitation conditions is shown. In these cases a complete modal analysis is not possible.

Our work is divided into several steps, to decompose the problem for more accurate analysis. The first step in the analysis of propeller behaviour has been a modal analysis of steady disk in free–free constraint conditions, performed both in air and in water. The excitation is performed with an electrodynamic shaker driven by a narrow band random noise. These results have been used in the following part of the work to understand better

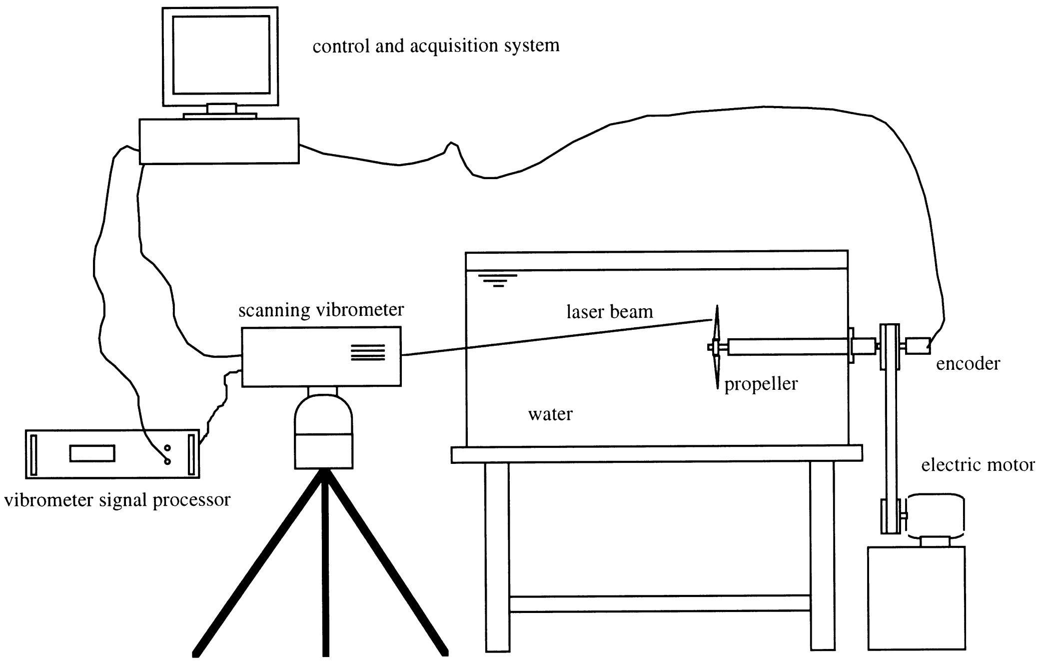


Fig. 1. Experimental set-up.

the vibratory phenomena in more complex conditions. The input forces, applied at a single point, and free–free condition of constraints allow us to perform a classical modal analysis and to compute natural frequencies and modal shapes. The effects of the presence of water are observed and the virtual mass is computed.

The second step has been analysis with a propeller rotating in air. The test has been performed with a rotational speed variable between 0 and 9 rps. In fact, the naval propeller employed in the research is working at a speed lower than 10 rps and higher frequencies are not of interest in this application. This test has been carried out in order to verify the capabilities of the tracking system to follow each point of the disk fixed grid. The results have shown the good capabilities of the system to analyse the vibration of the propeller during a rotation. This analysis has also been performed to determine and eliminate the effects of the mechanical excitation due to the shaft support, the bearing, the motor and the transmission device. In this case the vibration of the propeller is induced only by this kind of force applied in the propeller support, since the low density of air and the reduced speed of rotation lower the aerodynamic excitation level.

The natural frequencies and the modal shapes obtained in rotation are comparable to the results of steady modal analysis.

To verify the effects of installation of propeller on the shaft and stern tube and of rotation with known input signal, analysis of vibration using an impact hammer and an acoustic excitation was performed. The first is a traditional procedure for structure excitation in modal analysis of a steady structure. This is a powerful technique because it allows us to put structures with a well-known input force in vibration, but shows some limitation in rotating propeller application. In fact, it is possible to operate with this technique when the speed is only about a few revolutions per second.

On the other hand, the acoustic excitation does not allow us to know the excitation level and to measure the frequency transfer functions, but it allows us to directly excite the blades during high-speed rotation, too. With acoustic excitation it is possible to analyse the behaviour of the system at the highest frequency, where forces generated by the rotation do not give enough energy.

The excitation has been performed with an impact hammer with 23 g mass and with a loudspeaker of about 40 W power driven by a narrow band white noise signal between 800 and 1000 Hz.

In Fig. 2 the comparison between FRFs obtained by impact hammer excitation when the propeller is steady and when it is rotating at 1 rps is shown. The low speed of rotation does not induce variations in the behaviour of the structure because the test is performed in air and the centrifugal forces are very low. Therefore, the good correspondence of FRFs and in particular of coherence functions shows a good capability of the tracking system to perform measurements also in operative conditions.

In Fig. 3 the comparison between some results obtained with acoustic excitation of a propeller rotating at 9 rps is shown. In these tests the 798 Hz peak is excited in the modal analysis: in operating conditions, the higher stiffness of the system increases the natural frequency of the propeller.

Finally, the measurement has been performed in operative conditions: the propeller is rotating in water in a tank of Perspex in order to allow optical access for laser acquisition with the test bench shown in Fig. 1.

When water is present, there are several problems in obtaining good measurements. The first problem is due to the refraction index of water. Therefore it is necessary to correct the velocity data and to adapt the grid directly on the blades in the experimental set-up. The laser beam, in fact, is deviated in each interface between the transmission materials on the optical path. Then, during the rotation, the angles between the laser beam and the Perspex surface do not change and no other adjustment is necessary.

The second problem is related to the formation of gas bubbles in water. The low head over the propeller facilitates the cavitation and the absorption of air from the surface, also with low rotational speed. This phenomenon and the high level of turbulence determine the formation of bubbles of gas around the blade surface. When the beam meets a bubble, it is deviated and, for some instants, the measurement is not possible on the analysed surface. The solution in order to avoid this problem at the desired speed is to perform a large number of triggered averages (about 40 in the present tests) in the power spectrum signal, which cancel the effects of signal spikes.

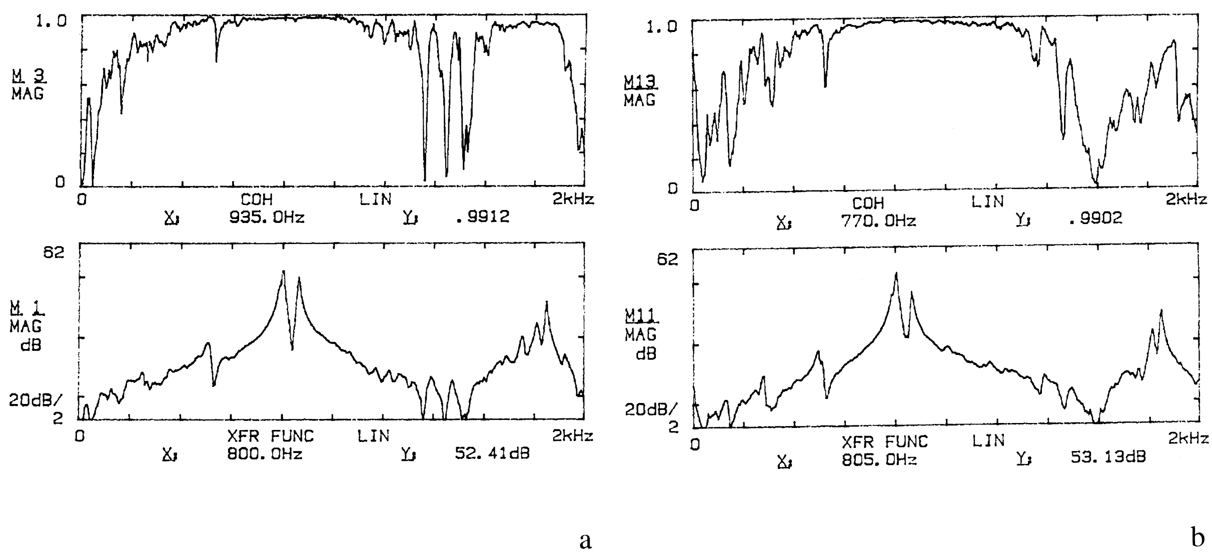


Fig. 2. Comparison between FRF obtained with impact hammer excitation on blade 1: (a) propeller steady; (b) propeller rotating at 1 rps.

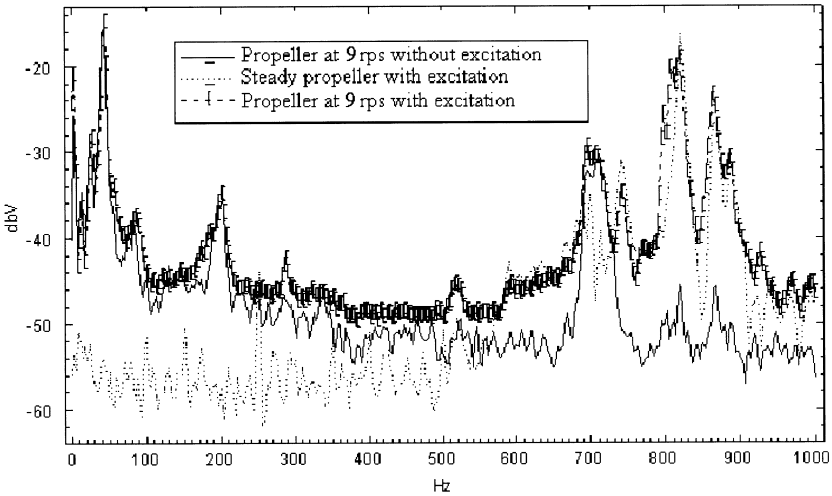


Fig. 3. Comparison between FRF obtained with acoustic excitation.

The last problem is due to absorption of the light due to the presence of particles and impurities in water. In our case, the good quality of water and the short distance in water allow very little signal decay.

4. Discussion and conclusion

In the measurements performed, the main problem observed is the misalignment between rotational axis and laser vibrometer, as shown in Fig. 4. In fact, this causes, during one turn of the propeller, a variation of the optical path from the laser head. This is mistakenly understood as a "vibration" of the surface, and then a sinusoidal signal is detected with a frequency equal to the rotation frequency. This phenomenon imposes to reduce the gain and the resolution of the acquisition system and makes the observation of low amplitude vibrations difficult.

This effect is shown in Figs. 5 and 6, obtained in different alignment conditions. In the vibration map, obtained with shaft rotating in water at a speed of 9 rps, it is possible to see the typical pattern of a rigid oscillation at the rotation frequency. The "steady" misalignment in the laser co-ordinate system is observed, in the disk-fixed co-ordinate system, as a "dynamic" flexion, because the measuring spot is travelling between points at different distances from the interferometer.

In order to measure the vibration of the surface, it is necessary to align the scanning head axis with the rotational axis. The effect observed is a spurious signal due to the change of distance from the

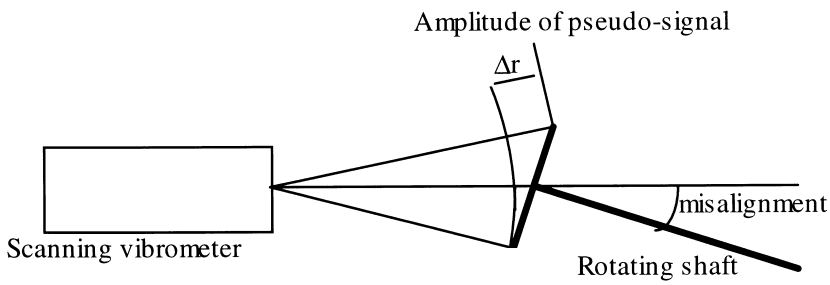


Fig. 4. Misalignment of scanning and shaft axes.

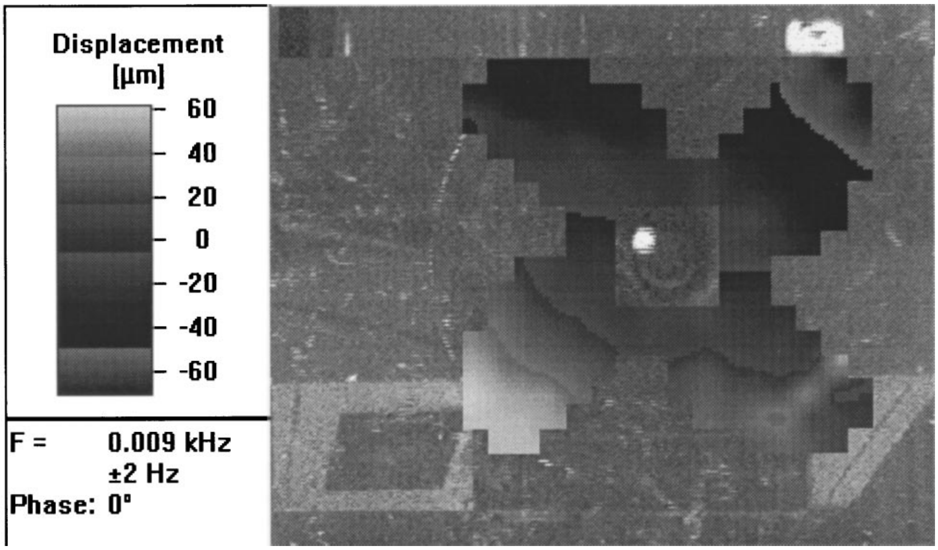


Fig. 5. Pseudo-vibrations effect of misalignment of scanning and shaft axes.

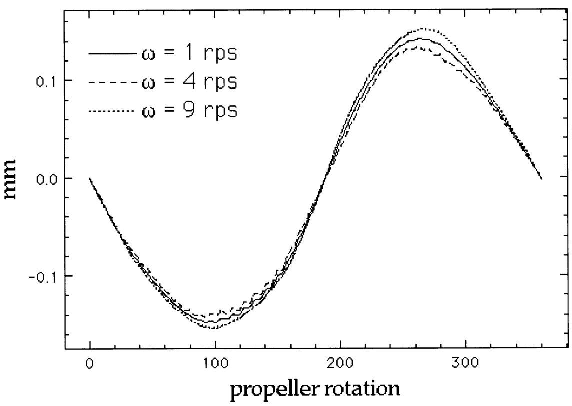


Fig. 6. Time histories of vibrations: effects of misalignment at different rotational speeds.

surface point and the vibrometer head and, if the error is large, to an in-plane velocity of the analysed surface. In fact, if a non-perfect alignment is realised, the distance between the laser interferometer and the target point on the surface of the disk changes with a sinusoidal law with a frequency corresponding to the rotation speed. The laser spot describes a circle on the surface itself, instead of being steady in the disk-fixed co-ordinate system. This effect is quite negligible, whereas the first one is more important: in fact, if the measurement is possible also with this distance variation, this effect has some practical consequences on the choice of the vibrometer resolution and acquisition gain: in other words, the misalignment effect hides the vibration signal.

To eliminate the undesired signal the best solution seems to be the use of a variable filtering of the RF signal, before any processing, in order to avoid the effects on the choice of acquisition parameters. With this solution, gain and resolution can be optimised for the vibration need, and the noise of misalignment is eliminated.

Fig. 7 shows the time history acquired at different radial positions on the same blade rotating in water. The presence of the low frequency sinusoidal signal due to misalignment is clear. The period is coincident with a period of rotation and the amplitude is very large with respect to the vibration displacement. This amplitude changes linearly with the radial position, because the distance variation during a turn decreases with the opening of the cone described by the laser beam.

The high frequency signal of vibration is superimposed on the noise signal. The amplitude varies with position because in these conditions the blade has a simple flexional deformation. The amplitude ratio between vibration and misalignment signal is, sometimes, lower than 0.8.

Fig. 8 shows the time history acquired at

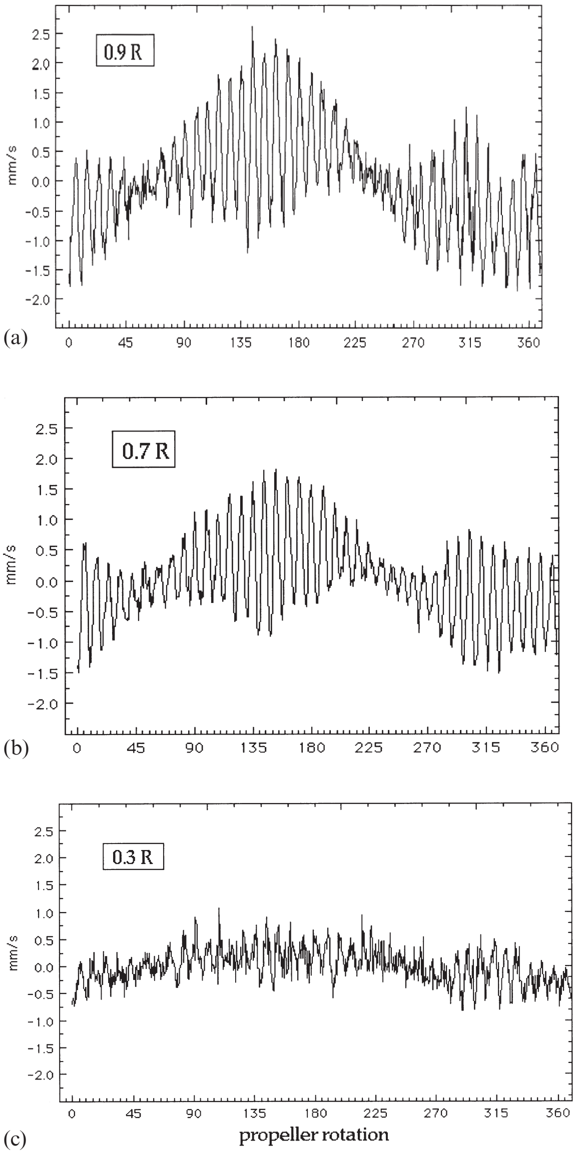


Fig. 7. Velocity vibration signal at different positions.

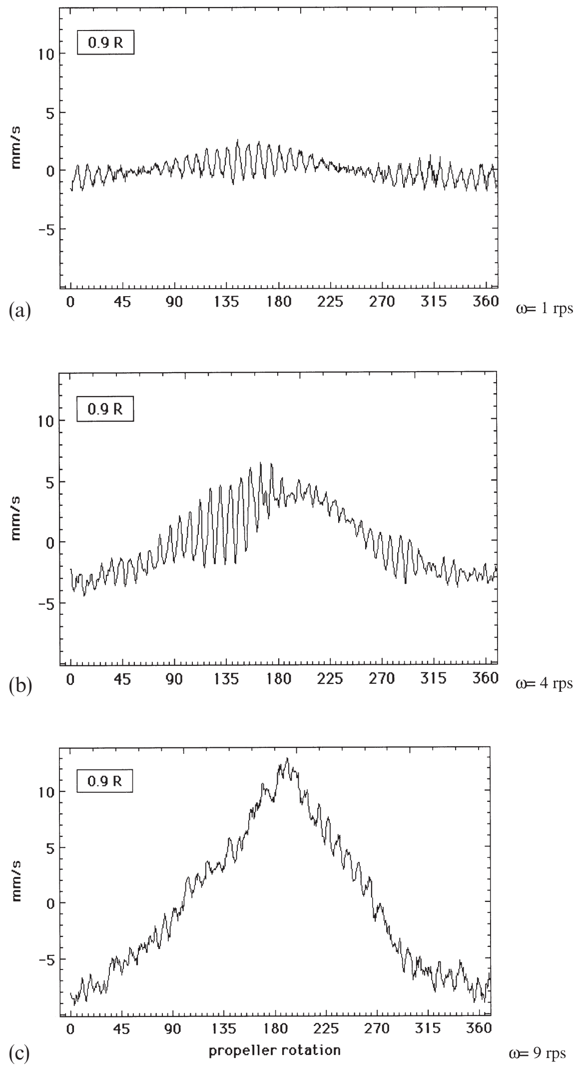
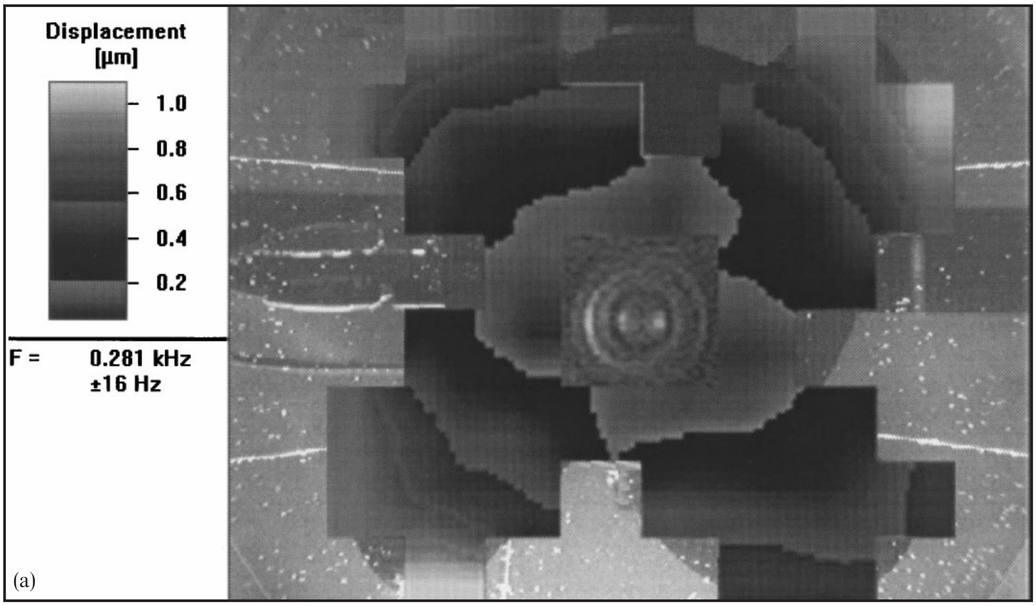


Fig. 8. Velocity vibration signal at different rotational speeds.

different speeds on the same point on a blade. The correspondence between the frequency and phase of the carrier signal and the rotation speed is respected in the whole range of velocity.

When the speed is increasing the available level of vibration signal decreases. This can be explained by the high dynamic range of acquisition for the variation of the amplitude due to misalignment and vibration signals, and for the effects due to the presence of gas bubbles around the propeller. The quality of rotating point tracking seems to be good; indeed there are no visible effects of speckle noise on the recovered signal.

The variation of rotational speed can naturally cause a change of amplitude and of spatial and frequency distribution of excitation forces. In fact, the excitation forces due to turbulence and thrust have a random distribution, independent of the rotational speed. Other forces, like unbalancements and mechanical misalignment, are narrow band excitations, but lower in amplitude.



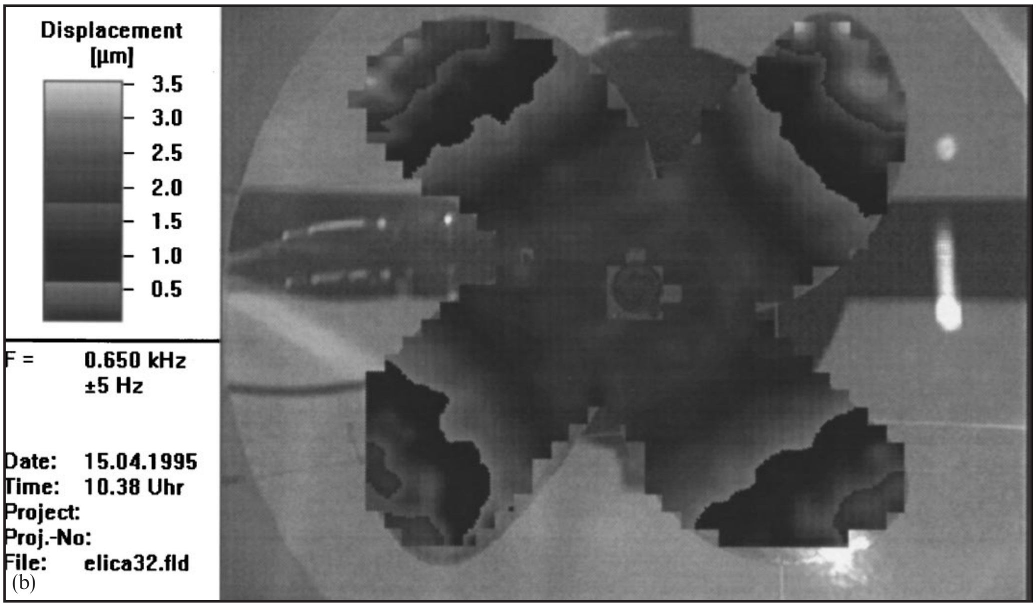


Fig. 9. Modal analysis of propeller steady in water.

The hydrodynamic phenomena such as vortex shedding or cavitation have periodic-random characteristics. The study of this kind of signal needs the acquisition of very long time histories and the development of specific analysis tools.

In Fig. 9 some of the results of vibration analysis in water of a steady propeller on a grid of 32×32 points are shown.

Fig. 10 shows vibration maps obtained with a propeller rotating at 9 rps. In this case, the grid of acquisition points is only 8×8 points to reduce the acquisition time needed, which is higher in

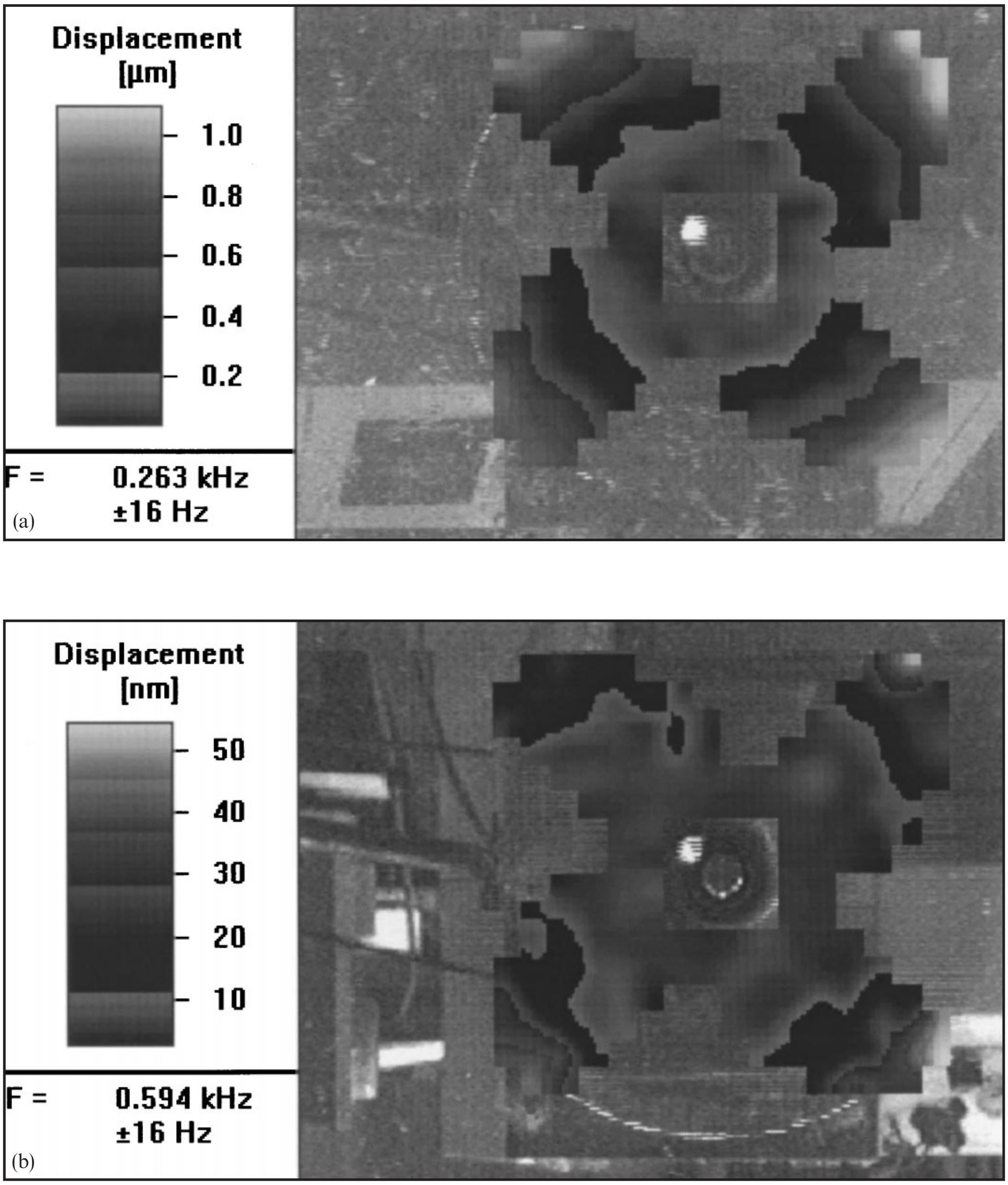


Fig. 10. Vibration map of propeller rotating in water at $\omega = 9$ rps.

rotating conditions where 40 synchronous averages are performed to highlight the contribution of natural modes.

The comparison shows a good correspondence between the deformation shapes, in particular at lower frequencies, where the coarse grid used in rotating tests can represent the smoothed modes present. In any case, the different acquisition parameters induce a different representation of the vibration field and some differences can be due not only to the reduced spatial resolution, but also to the acquisition parameter. In fact, the presence of the misalignment and, overall, of noise due to gas bubbles, affects the choice of acquisition parameters. The quality of signal can be improved with the use of a number of averages, but the acquisition time can become unacceptable. It is necessary to choose a compromise between the quality of measurement in operative conditions and time consumption (spatial resolution of the grid, frequency resolution and number of averages) to obtain good results.

Some differences are also observed in the frequency of power spectrum peaks. In particular, when the propeller is rotating the natural frequencies are lower than the same ones measured in steady conditions. The variation of vibration frequencies when a structure is working in water is known as the virtual mass effect: in fact, the fluid around the object is induced by the structure to vibrate and it is necessary to calculate also its mass to understand the modal behaviour [9].

The tests performed with the propeller rotating put in evidence an effect which is larger than the effect obtained in the steady case, with an additional reduction of vibration frequencies, as is shown in Fig. 11. The variation of virtual mass is probably due to the hydrodynamic action of the working propeller. The thrust transmits the vibration of the blades through the water flow and therefore increases the mass of water interested by the blade dynamic behaviour. The mass of water "around" the blades increases, and the resonance frequencies of the system probably decrease.

On the contrary, the effects of frequency increment due to different conditions of constraint and to centrifugal force present in rotating systems are not important in this case. In fact, the boss is a rigid body with high mass, with respect to the blades, and has a very low displacement in free–free conditions, with no differences in constraint conditions. Moreover, the rotational speed is very low (about 0.6 m/s of peripheral speed) and the mass of the very thin blades is low, too. Therefore the centrifugal forces on the blades and the increase of stiffness are negligible.

Finally, in rotating conditions the bending is observed as the most important vibration mode.

In fact, the low frequency of excitation and the high torsional stiffness of blades determine the high amplitude of this kind of deformation, with low excitation energy on high frequency modes. On the other hand, Wu and Moslehy [8] demonstrate that with multiple-point distributed excitation, antisymmetric modes, e.g. torsional ones, of geometrically symmetric structures cannot be

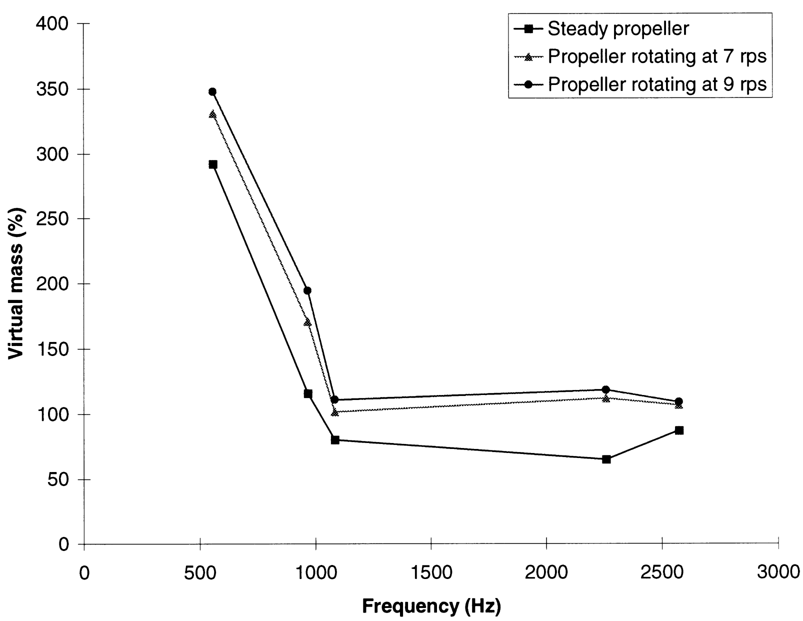


Fig. 11. Added virtual mass incremental (AVMI) factor with propeller steady and rotating at 7 and 9 rps.

determined. Therefore the excitation due to hydrodynamic effects, gas bubbles or cavitation hardly induces torsion on the blade structure.

Acknowledgements

The authors thank Ing. G. Zepponi, Professor G. Messina and INSEAN for their support of this research.

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