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Experimental study on the added mass and damping of a disk submerged in a partially fluid-filled tank with small radial confinement

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The dynamic response of submerged and confined disk-like structures is of interest in engineering applications, such as in hydraulic turbine runners. This response is difficult to be estimated with accuracy due to the strong influence of the boundary conditions. Small radial gaps as well as short axial distances to rigid surfaces greatly modify the dynamic response because of the added mass and damping effects.

In this paper, the influence of the axial nearby rigid distance on the dynamic response of a submerged disk is evaluated when the radial gap is very small. Moreover, the effects of the fluid depth and fluid viscosity on the natural frequencies and damping ratio of the submerged disk are studied. The study has been performed experimentally and numerically using structural–acoustic simulations.

For the experimental investigation a test rig has been developed. It consists of a disk attached to a shaft and confined with a small radial gap inside a cylindrical container full of water. The disk can be moved up and down along the shaft to vary the axial distance to the nearby rigid surface. Piezoelectric patches are used to excite the disk and the response is measured with submersible accelerometers. Several excitation patterns can be used due to the disposition of these piezoelectric patches. For each configuration tested, the dynamic response of the structure is studied analyzing the natural frequencies and damping ratio of the disk attached to the shaft. The numerical results have been compared with the experimental results.

1. Introduction

Cantilever plates or disks have been used since the middle of last century in order to easily study and interpret the dynamic behavior of submerged structures. When a structure is submerged in a dense fluid its dynamic behavior drastically change in comparison with that in vacuum. The dynamic behavior of a structure is commonly studied by analyzing the natural frequencies and the damping ratio of each associated mode of vibration or mode-shape. Current analytical studies of natural frequencies for submerged structures are based on the added mass effect. The effect on natural frequencies of a submerged structure is the same as considering an additional mass. Therefore, according to the added mass theory,

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Nomenclature

A	amplitude (units depend on the magnitude)
C	structural damping (N s m^{-1})
f	natural frequency (Hz)
F	structural force (N)
G	radial gap between the disk and the tank (mm)
g	normalized radial gap [$G r_D^{-1}$]
h_D	thickness of the disk (mm)
H_1	fluid depth (mm)
H_2	nearby rigid surface distance (mm)
h_1	normalized fluid depth [$H_1\, h_D^{-1}$]
h_2	normalized nearby rigid surface distance [$H_2\, h_D^{-1}$]
k	structural stiffness (N m^{-1})
M	structural mass (kg)
n	number of nodal diameters
r_0	averaged radius (mm)
r_D	disk radius (mm)
p	fluid pressure (Pa)
X	structural displacement (m)
y	signal sent to the piezoelectric patch (V)

Percentage calculations

E%	numerical error [100 · (Exp. − Sim.)/Exp.]
Diff%	difference between two configurations [100 · ($Conf_1 - Conf_2$)/$Conf_1$]

Greek letters

α	sweep rate (Hz s^{-1})
β	time offset to configure the frequency sweep (s)
ε	added damping factor (dimensionless)
λ	added mass factor (dimensionless)
μ	fluid dynamic viscosity (kg m^{-1} s^{-1})
ξ	damping ratio (%)
ρ	density (m^3 kg^{-1})

Acronyms

DOF	Degree Of Freedom
EMA	Experimental Modal Analysis
FEM	Finite Element Method
FRF	Frequency Response Function
FSI	Fluid–Structure Interaction
NC	Nodal circle
ND	Nodal diameter

Subscript

v	vacuum
f	fluid
a	air
w	water
A	added (mass or damping)
D	disk
T	tank

a structure submerged in water has lower natural frequencies than in vacuum or in the air. The added mass effect also explains that the closer to a rigid surface is the full-submerged structure, the lower natural frequency values it has. Moreover, it is demonstrated that an added damping appears when the structure is submerged in water. This fact implies that the vibration energy tends to be dissipated faster in water than in the air. However, there is a lack of information about the behavior of the damping with the boundary conditions, such as with nearby rigid surfaces.

The effect of the added mass in an infinite medium of water has been investigated for many years. Lindholm et al. (1965) were some of the pioneers to investigate the vibration of cantilever plates in air and water and their results unveiled the first knowledge of the dynamic behavior of submerged structures. They did theoretical predictions by modifying the simple beam theory and thin plate theory to include an empirical correction factor to take into account the added mass for variety of mode-shapes. Few years later, the added mass effect was introduced by Meyerhoff (1970) using the potential theory to study thin rectangular plates inside a fluid. Chang and Liu (2000) realized in its investigation in rectangular plates that each mode of vibration has its particular added mass. Similar investigations were carried out for submerged disks. Kwak (1991) considered an analytical method based on the integral transformation technique to study the vibrations of a submerged circular disk with different types of disk fixation. Results showed that the effect of the fluid on the natural frequencies decreased with the mode-shape order. Another analytical method, based on variational principles, was developed by Ginsberg and Chu (1992) to derive the mode-shapes of a circular plate in contact with fluid. However, the most important and current method to analytically study the added mass effect of submerged plates is the Rayleigh–Ritz method. This method was used by Amabili et al. (1996) in annular plates and by Amabili and Kwak (1996) in circular plates for different types of disk fixation. Results obtained with this method accurately agree with the experimentation as Kwak and Amabili (1999) showed in their work. Other energy-based methods, such as the Laplace method, were presented by Gorman and Horacek (2007) showing similar results than Rayleigh–Ritz method. Nevertheless, these investigations only considered submerged structures in an infinite medium of water, neither nearby rigid surfaces nor damping ratio were studied.

Other authors studied the effect of the fluid depth on the added mass of submerged structures, some of them considering the free surface of the fluid. In cantilever plates, Ergin and Ugurlu (2003) and Fu and Price (2008) experimentally estimated the influence of the submergence height on natural frequencies. A similar study was performed by studying the influence of the liquid level on the natural frequencies of a disk by Amabili (1996) and Jeong et al. (2009). For the free surface