Journal of Sound and Vibration 333 (2014) 5004–5017

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Added mass matrix estimation of beams partially immersed in water using measured dynamic responses

Fushun Liu [a,*], Huajun Li [a], Hongde Qin [b], Bingchen Liang [a]

[a] Shandong Provincial Key Lab of Ocean Engineering, Ocean University of China, Qingdao 266100, China
[b] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Article history:
Received 4 March 2014
Received in revised form
29 April 2014
Accepted 17 May 2014
Handling Editor: L.G. Tham
Available online 13 June 2014

ABSTRACT

An added mass matrix estimation method for beams partially immersed in water is proposed that employs dynamic responses, which are measured when the structure is in water and in air. Discrepancies such as mass and stiffness matrices between the finite element model (FEM) and real structure could be separated from the added mass of water by a series of correction factors, which means that the mass and stiffness of the FEM and the added mass of water could be estimated simultaneously. Compared with traditional methods, the estimated added mass correction factors of our approach will not be limited to be constant when FEM or the environment of the structure changed, meaning that the proposed method could reflect the influence of changes such as water depth, current, and so on. The greatest improvement is that the proposed method could estimate added mass of water without involving any water-related assumptions because all water influences are reflected in measured dynamic responses of the structure in water. A five degrees-of-freedom (dofs) mass-spring system is used to study the performance of the proposed scheme. The numerical results indicate that mass, stiffness, and added mass correction factors could be estimated accurately when noise-free measurements are used. Even when the first two modes are measured under the 5 percent corruption level, the added mass could be estimated properly. A steel cantilever beam with a rectangular section in a water tank at Ocean University of China was also employed to study the added mass influence on modal parameter identification and to investigate the performance of the proposed method. The experimental results demonstrated that the first two modal frequencies and mode shapes of the updated model match well with the measured values by combining the estimated added mass in the initial FEM.

1. Introduction

A slender beam is considered to be a simple yet very frequently used engineering structure. The frequency of using the beam "in air" is usually higher than "in water", mainly due to the influence of added mass and the "contact with water". One can also conclude that the added mass will influence many other factors, such as area coefficients, beam/draft ratio, boundary conditions of a water tank (or sea), slenderness ratio, environmental conditions, etc. For offshore structures, environmental conditions such as waves and currents change all the time, which implies that the added mass will not be constant throughout a structure's service life.

* Corresponding author.

http://dx.doi.org/10.1016/j.jsv.2014.05.036

When submerged in a fluid, the dynamic response of a solid body is altered by the effect of the added mass of the fluid ($\mathbf{M}_a$). Consequently, the ratio between the natural frequency of a given mode of vibration in water (f_w) and in air (f_v) can be approximated as follows:

$$\frac{f_{w,i}}{f_{v,i}} \approx \sqrt{\frac{1}{(1+(\mathbf{M}_a/m_i))}} \tag{1}$$

where i denotes each particular mode shape and m is the corresponding modal mass.

From Eq. (1), an added mass coefficient, C_m, can be defined with:

$$C_m = \left(\frac{f_{v,i}}{f_{w,i}}\right)^2 - 1 \tag{2}$$

One problem in Eq. (2) is that all parts of the structure in fluid will be assumed to have the same value C_m once Eq. (2) is solved, which opposes practical situations. Most of the existing relevant works have been obtained from experiments in which the most popular technique is evaluation of the added mass at the resonant frequency corresponding to the peak of a frequency response curve obtained from the 'forced' vibration analysis. The semi-circular cylinder is often adopted to simplify an object's cross-section in the analysis of added mass. The added masses of circular cylinders and cylinders with other cross-sectional shapes in deep water are available (Newman [1]). De Tarso et al. [2] investigated the added mass and damping of rectangular cylinders mounted at the seabed and presented the shallow water effect on added mass and damping. Clarke [3] used conformal mapping and calculated the added mass of a circular cylinder in shallow water. He demonstrated the effect of water depth through a comparison of results from different methods based on conformal mapping techniques and concluded that the approach of using a row of distributed dipoles gave the best accuracy. Clarke [4] also provided the added mass for the complex case of an elliptical cylinder in shallow water using a general mapping technique based on the Schwartz–Christoffel method. Clarke [5] used a similar method to calculate the added mass of an elliptical cylinder with a vertical fin stabilizer in shallow water. Lin and Liao [6] applied the fast multiple boundary element method (FMBEM) to calculate the added mass coefficients of complicated three-dimensional (3D) underwater bodies calculated by the FMBEM. The FMBEM is much more computationally efficient than the traditional boundary element method. Therefore, the FMBEM provides an effective numerical method to predict added mass coefficients of complicated underwater bodies.

Recently, Benaouicha et al. [7] addressed a theoretical study of the added mass effect in cavitating flow. The cavitation is considered to induce a strong time–space variation of the fluid density at the interface between an inviscid fluid and a three degrees-of-freedom rigid section. The added mass coefficients decrease as the cavitation increases, which should induce an increase of the natural structural frequencies. Torre et al. [8] used a non-intrusive excitation and measurement system based on piezoelectric patches mounted on the hydrofoil surface to determine the natural frequencies of the fluid–structure system. Kramer et al. [9] investigated the effects of material anisotropy and added mass on the free vibration response of rectangular, cantilevered composite plates/beams via combined analytical and numerical modeling. The results show that the natural frequencies of the composite plates are 50–70 percent lower in water than in air due to large added mass effects. Torre et al. [10] studied the influence of the boundary conditions on the added mass of a NACA0009 cantilever hydrofoil, including experiments. A detailed fluid–structure model has been built for both cases, and a modal analysis has been carried out. The obtained results are in reasonably good agreement with experimental data.

In practice, most added mass determination techniques involve solving Laplace's equation, which governs the induced water field; in other words, water-related assumptions are involved. In this paper, we try to estimate the added mass of beam structures from the view of structure (i.e., using only dynamic responses of the structure in water and in air). A five degrees-of-freedom (dofs) mass-spring system will be used to identify the performance of the proposed scheme, and a steel cantilever beam with a rectangular section in a water tank will be employed to demonstrate the approach.

2. Transverse vibration of a cantilever beam

Overlooking shear, damping, and axial-force effects, the solution for free bending transverse vibration of a beam is obtained by solving the differential equation of motion of a Bernoulli–Euler beam, which can be written as follows [11]:

$$m\frac{\partial^2 v}{\partial t^2} + \frac{\partial^2}{\partial x^2}\left(\mathrm{EI}\left(\frac{\partial^2 v}{\partial x^2}\right)\right) = 0 \tag{3}$$

where m is the mass distribution of the unit of length, EI is the flexural rigidity, and v is the transverse displacement, which is a function of the spatial coordinate (x) and time (t).

The solution of Eq. (3) is assumed in the form of a product of two functions:

$$v(x,t) = w(x)Y(t) \tag{4}$$

Substituting Eq. (4) into Eq. (3) results in

$$w(x)m\frac{\partial^2 Y(t)}{\partial t^2} + \frac{\partial^2}{\partial t^2}\left(\mathrm{EI}\frac{\partial^2 w(x)}{\partial x^2}\right)Y(t) = 0 \tag{5}$$