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Dynamic modelling and active vibration control of a submerged rectangular plate equipped with piezoelectric sensors and actuators

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The active vibration control of a rectangular plate either partially or fully submerged in a fluid was investigated. Piezoelectric sensors and actuators were bonded to the plate, and the assumed mode method was used to derive a dynamic model for the submerged plate. The properties of the piezoelectric actuators and sensors, as well as their coupling to the structure, were used to derive the corresponding equations of their behaviour. The fluid effect was modelled according to the added virtual mass obtained by solving the Laplace equation. The natural vibration characteristics of the plate both in air and in water were obtained theoretically and were found to be consistent with the experimental results, and the changes in the natural frequencies resulting from submersion in fluid can be accurately predicted. A multi-input, multi-output positive position feedback controller was designed by taking the natural vibration characteristics into account and was then implemented by using a digital controller. The experimental results show that piezoelectric sensors and actuators along with the control algorithm can effectively suppress the vibration of a rectangular plate both in air and submerged in a fluid.

1. Introduction

Passive methods are often inadequate to control the vibrations of structures, and as a result, we seek active methods to suppress vibrations to improve the performance of the systems of interest. To date, a tremendous amount of research has focused on using sensors and actuators to achieve active control, and smart structures have recently surfaced as systems that are equipped with sensors, actuators, and a microprocessor, that operate according to a control algorithm. Smart structure technology utilizes active controls to respond to external disturbances and can offer improvements in system performance without necessarily increasing the weight. One benefit of using a smart structure is that it can cope with changes in the environment by sensing external disturbances.

The initial studies on modelling and control for smart structures were confined to a simple beam with piezoelectric sensors and actuators. Subsequent studies have broadened their scope to include a variety of structures, such as plates and shells. Vibrations in smart structures have been successfully controlled by using piezoelectric materials with the positive

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position feedback (PPF) controller proposed by Fanson and Caughy (1990), the multi-input multi-output (MIMO) PPF controller proposed by Kwak and Heo (2007), and the modified Linear Quadratic Regulator (LQG) controller proposed by Kwak (1995, 1998). To model the behaviour of plate-like structures, Crawley and Lazarus (1991) developed an equation for the actuation strain by using the Rayleigh–Ritz method for isotropy and anisotropy plates. They proved that their theoretical model was accurate through an experiment with a beam-liked plate. Lazarus et al. (1996) carried out theoretical modelling and MIMO LQG control for a rectangular plate by using an assumed mode method. Kwak et al. (2003) proposed a modelling technique based on the Rayleigh–Ritz method to provide a dynamic model of a plate with arbitrarily oriented piezoceramic sensors and actuators. Many studies have been carried out concerning active vibration control of a plate. However, active vibration control of plates in contact with a fluid has not been investigated.

A fluid–structure interaction occurs when a structure vibrates in a fluid. The increase in the inertia resulting from the fluid motion affects structural vibrations, so that the natural frequencies of a structure in a fluid are significantly lower than those in air. This phenomenon has been described by introducing the concept of an added virtual mass. Hence, fluid–structure interaction problems often require calculating fluid-added mass. Lamb (1920) investigated the effect of a fluid on the natural vibration characteristics of a structure by determining the changes in the natural frequency of a baffled circular plate in contact with a fluid. Kwak (1991) and Amabili and Kwak (1996, 1999) extended this study by considering more general cases. Kwak et al. (2011) investigated a hanged clamped–free cylindrical shell partially submerged in fluid, where the fluid-added mass effect was represented in an analytical form. The analytical expression for the virtual mass for rectangular plates cannot be as easily obtained as it is for circular and annular plates or for a cylindrical shell, even though rectangular plates have a simple geometry. Lindholm et al. (1965) applied a strip method to calculate the natural frequencies of a cantilever plate that was fully submerged in water and also theoretically and experimentally investigated the reduction in the natural frequencies of cantilever plates due to the presence of water. For the strip method, the rectangular plate is divided into thin strips and each strip is regarded as a rigid body. Kim (1977) proposed the use of elliptical coordinates to calculate the fluid velocity potential that is induced by the vibration of a rectangular plate, so a Mathieu function (McLachlan, 1947) was introduced to the fluid-added mass matrix. Kim obtained the virtual mass matrices for all simply-supported and all clamped rectangular plates in an analytical form.

However, the use of the Mathieu equations to calculate the fluid-added mass of a rectangular plate has not received much attention due to the complexity of the Mathieu functions. Instead, the finite element method and the boundary integral-equation method have been generally used to deal with fluid–structure interaction problems. Kwak (1996) proposed a detailed numerical computational scheme for the boundary integral equation and also calculated a non-dimensionalized added virtual mass incremental (NAVMI) factor for all simply-supported and all clamped rectangular plates. Recently, Kwak and Yang (2013) obtained a fluid-added mass matrix in an analytical form for a partially submerged cantilever plate. The elliptical coordinates proposed by Kim (1977) were used to solve the boundary value problem, and the added virtual mass matrix that was expressed in terms of the Mathieu functions was combined with equations of motion for a cantilever plate in vacuo (in air if we neglect the mass density of air) obtained through the Rayleigh–Ritz method.

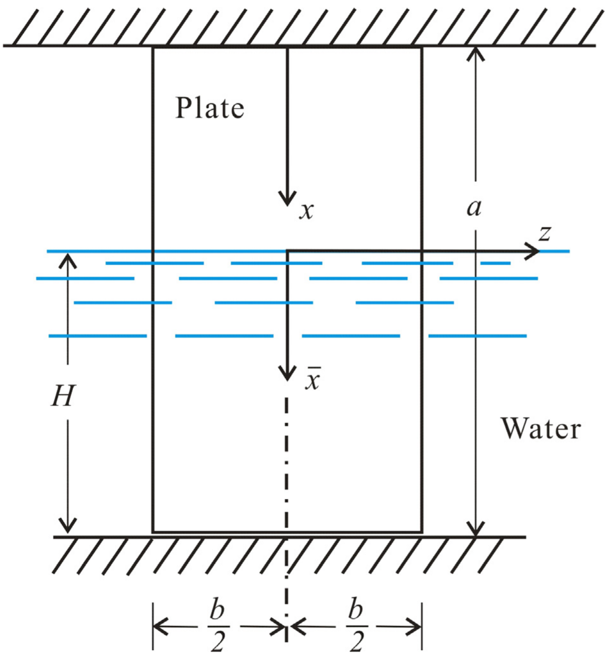

Fig. 1. Partially submerged cantilever plate.