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Vibration analysis of partially cracked plate submerged in fluid

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ABSTRACT

The present work proposes an analytical model for vibration analysis of partially cracked rectangular plates coupled with fluid medium. The governing equation of motion for the isotropic plate based on the classical plate theory is modified to accommodate a part through continuous line crack according to simplified line spring model. The influence of surrounding fluid medium is incorporated in the governing equation in the form of inertia effects based on velocity potential function and Bernoulli's equations. Both partially and totally submerged plate configurations are considered. The governing equation also considers the in-plane stretching due to lateral deflection in the form of in-plane forces which introduces geometric non-linearity into the system. The fundamental frequencies are evaluated by expressing the lateral deflection in terms of modal functions. The assessment of the present results is carried out for intact submerged plate as to the best of the author's knowledge the literature lacks in analytical results for submerged cracked plates. New results for fundamental frequencies are presented as affected by crack length, fluid level, fluid density and immersed depth of plate. By employing the method of multiple scales, the frequency response and peak amplitude of the cracked structure is analyzed. The non-linear frequency response curves show the phenomenon of bending hardening or softening and the effect of fluid dynamic pressure on the response of the cracked plate.

1. Introduction

The dynamic behavior of plate structures is significant to many applications ranging from automobile to engineering industries. Moreover submerged plates are integral parts of ship building, nuclear, ocean and naval engineering. The literature shows that the presence of singularities in the form of crack(s) affects the stiffness thereby changing the vibration behavior of plates in vacuum. The vibration characteristics of intact plate coupled with fluid medium is rigorously treated and well documented in relevant literature. It is thus known that the vibrations of submerged intact plate are different than those in vacuum. However cracks may appear in the submerged structures due to significant pressure fluctuations of fluid. Thus the influence of crack on the behavior of submerged plates becomes significant. This problem of vibration of fluid-structure interaction in the presence of crack needs further investigation.

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It has been established in the literature that the presence of crack affects the vibration characteristics of plate. The static solutions for cracked plate are mostly studied by numerical techniques. A few published works on analytical modeling of cracked plates are available and most of them considered the analysis in the absence of fluid medium. To investigate the vibration characteristics of plate with cracks, Stahl and Keer [1] used homogeneous Fredholm integral equations of the second kind to find the natural frequencies of plate with a side crack and centrally located internal crack. Solecki [2] constructed a solution for bending vibrations of a cracked rectangular plate by using the Navier form of solution, along with finite Fourier transformation technique. Khadem and Rezaee [3] and Hirano and Okazaki [4] utilized Levy's form of solution for vibration analysis of cracked rectangular plate with different boundary conditions. The finite element method and the Ritz method are commonly used for vibration analysis of cracked plates. Qian et al. [5] and Krawczuk [6] developed a finite element solution by deriving the stiffness matrix for cracked plate. Liew et al. [7] employed the Ritz method along with the domain decomposition technique to determine the upper-bound solutions for vibration frequencies. An approximate analytical solution has been made possible by means of the Line Spring Model (LSM) proposed by Rice and Levy [8], wherein the surface crack is represented as continuous line springs with stretching and bending compliances. Delalae and Erdogan [9] improved the line spring model by considering the transverse shear deformation of the plate. King [10] simplified the line spring model by reducing the coupled integral equations given by Rice and Levy [8] to a pair of linear algebraic equations for analyzing fracture parameters. Zheng and Dai [11] then applied this simplified line spring model to compute the stress intensity factors in their analytical modeling of a rectangular plate with angled crack subjected to biaxial stresses. The modified comparison functions for vibration analysis of cracked rectangular plate were introduced by Khadem and Rezaee [3] in which they considered the effect of compliance due to bending only. Using the LSM, Israr et al. [12] developed an approximate analytical model for thin isotropic plate with a part-through surface crack located at the centre. They employed three different boundary conditions in the formulation based on the classical plate theory. Their work gives a relationship between tensile and bending forces at far sides of the plate and at crack location. Ismail and Cartmell [13] extended the work of Israr et al. [12] and developed an analytical model for cracked plate considering various angular orientations of the crack. They validated their results by experimentation also. It is concluded from their work that the fundamental frequencies of plate decreases with increase in length and angular orientation of crack. Recently, Joshi et al. [14] extended the work of Israr et al. [12] for two perpendicular part through cracks located at the centre of plate. They also modified the previously developed model to accommodate the effect of internal cracks. The authors also extended the model to thin partially cracked orthotropic plate [15].

It is well known that the presence of fluid medium decreases the frequencies of plate in comparison with those calculated in vacuum. This decrease in natural frequency is due to the existence of the fluid around the plate which causes increase in the kinetic energy of whole system without a corresponding increase in strain energy. A lot of work has been carried out by many researchers on free and forced vibration of intact plates coupled with fluid. Lamb [16] calculated the natural frequencies of a thin clamped circular plate in contact with water based on Rayleigh's method. McLachlan [17] extended Lamb's work for circular plate with free-edge. The developed method was theoretical and based on calculation of increase in kinetic energy of fluid. Powell and Roberts [18] verified the theoretical results of Lamb [16] by performing the same work using an experimental setup. Lindholm et al. [19] and Muthuveerappan et al. [20] investigated the natural frequencies of free vibrating cantilever plate in air and water using experimental study and the results were compared with theoretical predictions. The vibration analysis of vertical and horizontal cantilever plate partially and fully submerged in water has been studied by Fu and Price [21]. They employed finite element method and singularity distribution function approach to analyze the vibration response of cantilever plate in air and water. Kwak and Kim [22] studied the effects of fluid on axis symmetric vibration of floating circular plate in liquid. The added virtual mass incremental (AVMI) factor is calculated for different boundary condition which shows increase in inertia due to presence of fluid. Soedel and Soedel [23] presented an analytical solution for simply supported rectangular plate coupled with liquid in which the liquid is assumed to be incompressible with free surface oscillations. Kwak [24] shows the effect of virtual added mass on natural frequencies of rectangular plate coupled with water on one side of the plate. The Rayleigh-Ritz method combined with the Green function method is employed to calculate added virtual mass incremental (AVMI) factor for the rectangular plate. Amabali [25] used the same added mass approach for annular plates coupled with fluid on one side and determined the natural frequencies of the plate. The dynamic response of flat rectangular plates submerged in water has been investigated by Haddara and Cao [26]. They studied the effect of boundary conditions and the depth of submergence of plate on natural frequencies using both experimental and analytical study. Meylan [27] presented solution for harmonically forced vibration of thin plate floating on the surface of fluid. The author derived the governing equation of plate-fluid system and used the Rayleigh Ritz method for the solution of the governing equation. Ergin and Ugurlu [28] investigated the dynamic characteristics, such as natural frequencies and mode shapes of a vertical cantilever plate partially submerged in fluid. In their investigation they used finite element method and boundary integral equation method for finding the dynamic properties in vacuum and fluid medium respectively. Cheung and Zhou [29] studied the natural frequencies of horizontal rectangular plate connected to rigid bottom base of rectangular container filled with fluid having a free surface. The method of separation of variables and the method of Fourier series expansion has been applied for exact expression of motion of fluid. Zhou and Cheung [30] used the velocity potential to describe the fluid motion and investigated the dynamic characteristics of a rectangular thin baffled plate in contact with water from one side for different boundary conditions. Kerboua et al. [31] studied the vibration analysis of rectangular plate coupled with fluid. The velocity potential and Bernoulli's equation are used to express the fluid pressure acting on the plate. They developed a mathematical model for the structure using a combination of the finite element method and Sander's shell theory. Recently, Hosseini Hashemi et al. [32] worked on free vibration analysis of horizontal rectangular Mindlin plates