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Investigation of structural stability characteristics of high speed underwater vehicles according to mass change

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ABSTRACT

In this study, the investigation of structural unstable characteristics of high speed underwater vehicles is performed. For simplicity, a real vehicle was modeled as a follower force subjected beam that was resting on an elastic foundation, and the lumped mass effect was simplified as an elastic intermediate support. The stability of the simplified model was numerically analyzed based on the Finite Element Method (FEM). This numerical simulation revealed that flutter type instability or divergence type instability occurs, depending on the position and stiffness of the elastic intermediate support, which implies that the instability of the real model is affected by the position and size of the lumped mass.

1. Introduction

The maximum speed of underwater vehicles with a large slenderness ratio such as submarines or torpedoes is restricted due to considerable friction drag affecting the hull surface. The maximum speed of underwater vehicles does not exceed 40 m/s, and the actual operating systems do not use even more than half of the speed. Even though the characteristic of slow-moving underwater vehicles has an advantage of underwater acoustics and fluid dynamics, modern torpedoes or submarines' underwater weapons require high-speed propulsion. In 1997, the former Soviet Union had developed a torpedo called Shkval by this demand, and its maximum underwater speed came to 100 m/s. This underwater vehicle generated supercavitation caused by its high speed. The supercavitation is a phenomenon when fluid pressure air bubbles are formed on the vehicle surface by water vapor pressure when moving under water faster than a particular speed. These air bubbles could induce noises and speed reduction to cause structural instability by changing the cavitation area due to the vehicle's speed [1].

Studies have been still continued on the underwater vehicle surface flow, and in 1997, the U.S. Navy's NUWC (Naval Undersea Warfare Center) had succeeded in obtaining an underwater vehicle's speed of 1549 m/s. This velocity exceeded the underwater sound velocity [14]. However, the thrust increase for speedup basically induces tangential follower force caused by the thrust. Structures could become unstable statically or dynamically due to this loading characteristic [9]. In other words, the structural stability analysis, which should consider dynamic stability as well as static one, becomes more important for elastic bodies receiving force with magnitude which is varied with time.

Fig. 1 shows the process of simplifying a high-speed underwater vehicle into a cantilever form which end is under load. The high-speed vehicle has a correlation between the drag, which is increased by speedup, and the thrust based on the drag point. Therefore, it could be simplified as a form of cantilever the end of which is fixed [8]. In addition, a device for preventing cavitation could be attached to the front of the high-speed underwater vehicle to induce fluid flow and to apply elasticity parameters that result from the flow characteristic of the structure [1].

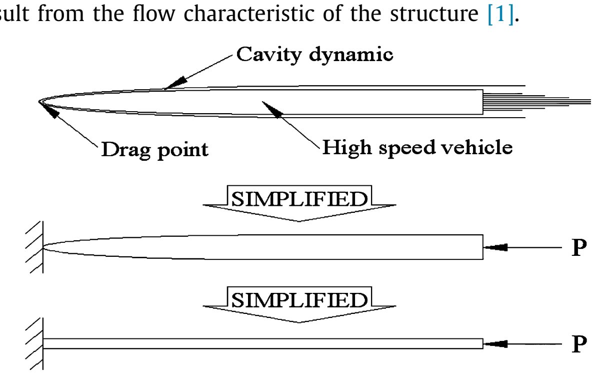

Fig. 1. Simplified vehicle model in cavitation condition.

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Simplifying a model considering inertia loads, it is simulated as a cantilever. In 1952, Beck, for the first time, had applied it to study the stability of a cantilever when the concentrated follower force is at work along its tangential direction from the beam's end [5]. Since then, it was extended into studies on the lumped mass and distributed follower force. One of the studies on the follower force is the stability problem of a beam rested on an elastic foundation receiving the follower force, which was studied by Smith and Herrmann in 1972. They found that the size of elastic foundation parameters has no effect on the threshold values generating flutter [15], and thanks to this study, lots of studies have continued to carry out for the beam on an elastic foundation. This model could be divided into studies to extend elastic foundation parameters and ones to analyze structural stability by lumped mass. Anderson studied the effect of rotational inertia and internal damping on the system's stability for the beam on an elastic foundation having concentrated mass and receiving follower force [4]. In 1992, Lee et al. studied the stability of the elastic supported Timoshenko's beam [10]. Recently, Maurizi and Bambill also reviewed the stability problem of beams rested on an elastic foundation [11]. H. Ait Atmane et al. performed study on free vibration analysis of functionally graded plates resting on Winkler–Pasternak elastic foundations using a new shear deformation theory [2]. S. Benyoucef et al. studied investigation of bending of thick functionally graded plates resting on Winkler–Pasternak elastic foundations [6]. In 2010, S. Benyoucef et al. studied bending of thick functionally graded plates resting on Winkler–Pasternak elastic foundations [7]. In 2014, M. Ait Amar Meziane et al. performed study on efficient and simple refined theory for buckling and free vibration of exponentially graded sandwich plates under various boundary conditions [3]. And also, K. Nedri et al. studied free vibration analysis of laminated composite plates resting on elastic foundations by using a refined hyperbolic shear deformation theory [12]. However, these studies used the beam rested on an elastic foundation as the model, so their parameters (external and internal damping, and concentrated tip mass, etc.) were limited to the effects on the beam's stability.

In this study, actual high-speed underwater vehicles are modeled as a cantilever structure rested on an elastic foundation receiving concentrated follower force to analyze dynamic instability characteristics of the high-speed underwater vehicles. In this case, the shear transverse effect is neglected. In addition, the structure's lumped mass change at a particular position is considered as the intermediate support effect. The structure's stability is evaluated by using this model to analyze structural vibration and stability depending on the lumped mass position. For that purpose, the finite element method is used to numerically analyze natural frequencies and modes of the structure. However, the fluid characteristic is considered simply as elastic support to understand only the tendency of effects on the structure.

2. Theoretical analysis

2.1. Mathematical model

In the mathematical model of Fig. 2, the cantilever (Beck's beam), which overall length is L and has a constant cross section receiving follower force, is rested on an elastic foundation, and has a supporting point at an arbitrary position from the fixed end. Where, the beam's flexural strength, mass per unit length and the elastic foundation spring constant are EI, m and k, respectively; and, E^* is the inner material's damping coefficient.

2.2. The equation of motion

Using the extended Hamilton principle to obtain the equation of motion for the model in Fig. 2, it is as follows:

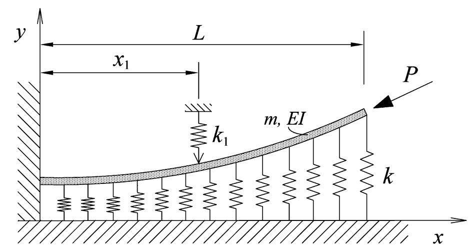

Fig. 2. Beck's beam on the elastic foundation with an intermediate support.

$$\delta\int_{t_1}^{t_2}(T+W_{\rm c}-U)dt+\int_{t_1}^{t_2}(\delta W_{\rm id}+\delta W_{\rm nc})dt=0 \tag{1}$$

where T is kinetic energy, $W_{\rm c}$ is work by force conservation, U is elastic potential energy, $\delta W_{\rm id}$ is virtual work by internal decrease and $\delta W_{\rm nc}$ is virtual work by non-conservation:

$$T=\int_0^L\frac{m}{2}\left(\frac{\partial y}{\partial t}\right)^2dx \tag{2}$$

$$W_{\rm c}=\int_0^L\frac{p}{2}\left(\frac{\partial y}{\partial x}\right)^2dx \tag{3}$$

$$U=\int_0^L\frac{EI}{2}\left(\frac{\partial^2 y}{\partial x^2}\right)^2dx+\int_0^L\frac{k}{2}y^2dx \tag{4}$$

$$\delta W_{\rm id}=-\int_0^L E^*I\left(\frac{\partial^3 y}{\partial x^2\partial t}\right)\delta\left(\frac{\partial^2 y}{\partial x^2}\right)dx \tag{5}$$

$$\delta W_{\rm nc}=-p\left(\frac{\partial y}{\partial x}\right)_{x=L}dy \tag{6}$$

For computational convenience, the following dimensionless coordinates and parameters are introduced:

$$\begin{aligned}&\xi=\frac{x}{L},\qquad \eta=\frac{y}{L},\qquad \tau=\frac{t}{L^2}\sqrt{\frac{EI}{m}},\qquad \xi_1=\frac{x_1}{L},\\&p=\frac{PL^2}{EI},\qquad \kappa=\frac{kL^4}{EI},\qquad \gamma=\frac{E^*}{EL^2}\sqrt{\frac{EI}{m_f+m_p}}\end{aligned} \tag{7}$$

where, ξ and η are coordinates of x and y, and τ, p, γ and κ are dimensionless parameters representing the time, follower force, internal damping and beam's whole elastic support spring, respectively. m_f is lumped mass change at a particular position. m_p is mass by follower force, and ξ_1 is the dimensionless parameter indicating the position of intermediate supporting point, which is not expressed in the equation, but in the calculation program, it is calculated by considering that the deflection at the supporting point's position is 0. Substituting Eqs. (2)–(6), and dimensionless parameters and coordinates in Eq. (7) into Eq. (1), it is as follows:

$$\begin{aligned}&\int_{\tau_1}^{\tau_2}\int_0^1[\eta_\tau\delta\eta_\tau+p\eta_\xi\delta\eta_\xi-\kappa\eta\delta\eta-\eta_{\xi\xi}\delta\eta_{\xi\xi}-\gamma\eta_{\xi\xi\tau}\delta\eta_{\xi\xi}]d\xi d\tau\\&\quad-\int_{\tau_1}^{\tau_2}[p\eta_\xi\delta\eta]_{\xi=1}d\tau=0\end{aligned} \tag{8}$$

The finite element method is applied to find a numerical solution to Eq. (8). Fig. 3 shows that the beam is divided into N