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Parameters influence on maneuvered towed cable system dynamics

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ABSTRACT

The dynamic response of a towed cable system to ship maneuver is parametrically simulated. Three dimensionless parameters influence on towed cable system maneuverability is investigated. They are ratio of total length to turning radius R/L, ratio of cable mass to vehicle mass σ, and ratio of mass unit length to hydrodynamic force w/r. An oscillatory motion of towed vehicle is found in simulation of spiral towed courses. Features of this oscillation in different spiral courses are compared. The sharp turns, gradual turns and their transient states of towed cable dynamics for different course directions are discussed extensively. According to the characters of transient states and horizontal trajectories evolution of maneuvered cable system, the dynamic behaviors can be divided into three situations in Fig. 8 turning maneuvers. The behavior of towed cable system during a zigzag turning course is simulated in the end. Two ingredients of heave motion are found during small ratio of turning radii to length in this course. The primary damp to initial turning becomes weak and the response to alternative turns plays a more and more important role. The damping properties of the transient behavior in different maneuvers show a periodical invariance to σ during some turning maneuvers.

1. Introduction

This paper concerns to describe a maneuvered towed cable system dynamics which have potential applications in towed system collision avoidance and planning tow strategies of exploring complex seafloor terrain. A systematic discussion of surface maneuver gives a strong guidance to the towing maneuverability.

An algorithm based on the characteristic of the classical finite difference schemes proposed by Ablow [1], Howell [6], and Wu [9] is used to decide ocean towing dynamics. With an application to the towed cable system during ship turning maneuvers, a description of the cable system transient behavior that occurs during changed towed direction is given in detail. The dynamics of maneuvered towed cable system can be described by several dimensionless parameters such as the ratio of the weight per cable length in water w to flow drag per cable length r i.e. w/r, and the ratio of the immersed weight of whole cable $w{\cdot}L$ to the immersed weight of towed vehicle W i.e. $\sigma = wL/W$. A reasonable selected range of w/r and σ can reveal various phenomena of towed system dynamic response. The reciprocal transitions between sharp turns and gradual turns should give us a clear comprehension of towed cable system dynamics during turning.

Ablow [1], Milinazzo [8], Gobat [4] and many others used a full turning maneuver case as an illustration and a confirmation of the feasibility of their nonlinear dynamic modals. Little research has been conducted in applying dynamic model to enforce a very deep understanding of the scope of maneuvered towed cable system dynamics. Chapman [3] characterized the dynamic behavior of cable as three following situations, a gradual turn with a low towed speed and a large turning radius to cable length ratio, a sharp turn with a high towed speed and a small turning radius R to the cable length L ratio i.e. R/L, the transient state between two turns. Kishore [7] improved Ablow's [1] model and simulated the behavior of towed array during a full circle turning course. Grosenbaugh [5] recalculated the dynamic response of towed cable system during ship full turns and U shape turns. The dynamic behavior of a towed cable in a turn can be regarded as a trade-off between the period of the turn and the decay time of the transient. In a large radius turn, a long time period decides a stable profile of cable system. Instead, a long decay time causes a sudden drop down depth. However, there is not enough comprehensive knowledge about the cable transient behavior which can be obtained from previous studies. We still know quantitatively little about the transient behavior of towed cable system during a variety of ship maneuver.

Chapman [3] roughly indicated possible dynamic response of towed cable system to a spiral course with reduced radius. In this situation of a slow declined ratio of a large radius R to the cable length L i.e. R/L, the cable profile can be characterized as a perturbation of the profile in a straight tow course at a low towed speed. The depth of the vehicle increases slowly and the horizontal trajectory shows a slight inward displacement inside the turning circle. The cable behavior can be considered as a gradual turn with a

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nonsignificant drop down depth when R/L is a large value. When R/L decreases to 1.0, the effect of a drop down depth becomes appreciable. When R/L approaches 0.7, a transient phenomenon appears. When R/L approaches 0.4, the cable is in a state of a sharp turn with the drop depth nearly equal to the cable length. A clear difference between a gradual turn and a sharp turn is observed during the decrease of R/L, but with the difficulty of a quantitative judgment.

Chapman [3] and Grosenbaugh [5] both applied two dimensionless parameters w/r and σ to describe the dynamic behavior of towed cable system during maneuvers besides R/L. Ramani [10] used the perturbation method to solve the quadratically damped Mathieu equation which has application to the dynamics of towed arrays system. A secondary bifurcation is fully discussed by perturbation solutions using Mathieu functions and combining with Padé approximate. Also the transient behavior of cable system during turns may be a bifurcated area of dynamic response to turning maneuver.

Nonlinear dynamic behavior of a maneuvered towed cable system are fully simulated and analyzed in this paper. Detailed numerical explorations are carried out to introduce more dynamic behavior like bifurcation and resonance as Ramani [10] indicates. However, in practice, maneuver parameters of sea surface mother ship in given towing strategies can be summarized as curvature change rate of ship courses.

In order to investigate the relation between the dynamic response of towed cable system and the curvature of ship course, three kinds of change rates of spiral towing trajectories curvature are designed in this paper. First, the dynamic response of a towed system to a smoothly increasing rate of trajectory curvature is investigated. We carry out detailed simulations of towed cable system dynamics during spiral towed course with increasing radius. A new phenomenon of low frequency damped oscillation response is found in the simulation of the towed vehicle depth time histories. Two definitions of heave ratio are given to describe stability of this kind of towed vehicle motion histories. Second, we carry out detailed dynamic simulations of towed system at a given circular turn with different arc angles. Third, the abruptly changed curvature of Fig. 8 turning maneuvers with different radii ratios is designed to investigate the transient behavior of towed cable system. Further simulations of towed cable system with a zigzag half circle course are introduced in the end. The heave motion and the horizontal trajectory of towed cable system are also discussed. Towed cable system passive response to these schematized maneuvers shows particular nonlinear dynamic behavior including resonances and bifurcations from a viewpoint of nonlinear system.

This paper is totally different from most of research work in which the cable dynamics model and numerical algorithm are overemphasized. A validated dynamic model similar to Ablow's [1] classical model is introduced with some numerical improvements in this paper.

2. Dynamic model

The cable is considered as a homogeneous, slender, flexible circular cylinder without considering bending or torsional stiffness. It is assumed that the dynamics of a cable are determined by buoyancy, gravity, hydrodynamic loading and inertial forces.

The orthogonal coordinates (i, j, k) represent the fixed inertial frame at the ship, i, j being in the horizontal plane and k pointing downward. The governing equations are written in local orthogonal coordinates (t, n, b) at each point of the cable. The orientation of the local frame is so chosen that t is tangent to the cable in the direction of increasing unstretched cable length from the surface end to the bottom, n is the normal vector of the cable curvature, and b the binormal vector as shown in Fig. 1. The surface maneuver course is defined in the plane (i, j). The motion of bottom vehicle is always transformed into the inertial frame for convenience. Surface excitation is transmitted to the vehicle via cable which is expected to response with different damping levels in the tangential and vertical directions. The dynamic behavior of maneuvered cable system is also extensively discussed in the fixed inertial frame.

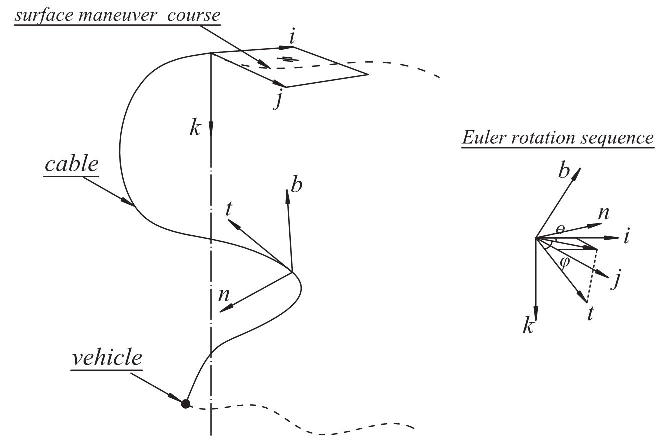

Fig. 1. Definition of global and local coordinates.

At any point of a cable the two frames (i, j, k) and (t, n, b) are related by

$$(t, n, b) = (i, j, k)[R] \tag{1}$$

where R is the Euler rotation matrix with φ and θ defined in Fig. 1.

$$R = \begin{bmatrix} \cos\theta\cos\varphi & -\cos\theta\sin\varphi & \sin\theta \\ \sin\theta\cos\varphi & -\sin\theta\sin\varphi & -\cos\theta \\ \sin\varphi & \cos\varphi & 0 \end{bmatrix} \tag{2}$$

Similar to Ablow [1], Howell [6], Wu [9], Gobat [4], Park [12] and many other authors, in local coordinates, the governing equation can be written

$$M_{6\times6}\frac{\partial Y_{6\times1}}{\partial s} = N_{6\times6}\frac{\partial Y_{6\times1}}{\partial t} + Q_{6\times1} \tag{3}$$

The non-zero components of the upper triangular matrix M are as follows

$$\begin{aligned} &M(1,1) = M(2,2) = M(3,3) = M(4,4) = 1, \;\; M(5,5) = -T\cos\varphi, \\ &M(6,6) = T, \;\; M(2,5) = v_b\cos\varphi, \;\; M(2,6) = -v_n, \\ &M(3,5) = -v_b\sin\varphi, \;\; M(3,6) = v_t, \;\; M(4,5) = -v_t\cos\varphi + v_n\sin\varphi \end{aligned} \tag{4}$$

The non-zero components of N are as follows

$$\begin{aligned} &N(1,1) = -kv_t, \;\; N(1,2) = m, \;\; N(1,5) = -N(6,5) = m_a v_b\cos\varphi, \\ &N(1,6) = -m_a v_n, \;\; N(2,1) = e, \;\; N(3,6) = e/k, \\ &N(4,5) = -e\cos\varphi/k, \;\; N(5,1) = -m_a k v_b, \;\; N(5,4) = N(6,3) = m_a, \\ &N(5,5) = m_a v_n\sin\varphi - m_a v_t\cos\varphi, \;\; N(6,1) = -k m_a v_n, \\ &N(6,6) = m v_t \end{aligned} \tag{5}$$