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Network dynamic stability of floating airport based on amplitude death

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ABSTRACT

A large scale floating airport, consisting of multi-modules coupled with flexible connectors, can be viewed as a dynamic network. The special dynamic behavior of amplitude death, a suppressed weak oscillatory state, is studied by using the nonlinear network theory. A generalized network model is established for the floating airport, and an analytical solution of its response is formulated. A semi-analytical method is employed to analyze the amplitude death phenomenon and then a critical condition is derived. The parameter domain for the onset of the amplitude death is obtained by numerical simulations which match well with the analytical results. The work provides a typical application of the network theory in the marina engineering and illustrates the importance of amplitude death mechanism in the stability design of very large floating structures.

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1. Introduction

With growing population and expansion of urban development, engineers have proposed the construction of very large floating structures (VLFS) for industrial space, floating airport, storage facilities and even habitation because of the distinct advantages of relatively simple construction and ease of maintenance (Watanabe et al., 2004; Cui et al., 2007). Design and construction for VLFS have been discussed and studied to some extent at least as far back as 1924 that Edward R. Armstrong patented the Sea Station to be used as airplane supply and navigating stations (Armstrong, 1924). The Sea Station was to serve as refueling airfields at sea in Armstrong Seadrome for transatlantic aircraft hauling freight and passengers between the United States and Europe (Armstrong, 1943). However, the enthusiasm for building these floating structures was dampened due to very high cost and failure to address security concerns. It was not until 1970s that the VLFS technology was revived and developed further by the Japanese to create a floating airport for the Kansai International Airport (Wang and Tay, 2011). Although the Kansai airport did not adopt the floating airport design, the research and development exercise prepared the Japanese engineers and naval architects to build the Mega-Float in Tokyo Bay in 1995 as a test floating runway. Different from the pontoon-type proposed by Japanese, the US navy also proposed mobile offshore base (MOB) which consists of several semi-submersible modules with a total length of about 5000 ft in the late1999s to support military operations where conventional land bases were not available (Bhattacharya et al., 2006). Apart from Japan and USA, other countries such as Norway (Faltinsen, 1996; Rognaas et al., 2001), the United Kingdom (Taylor and Waite, 1978), Netherlands (Pinkster and Fauzi, 1997), China (Chen et al., 2001; Fu et al., 2007), Korea (Hong et al., 1999) and Singapore (Koh and Lim, 2009) have carried out researches on VLFS. Design of large scale floating airport is difficult, because it has to satisfy stringent functional and operational requirements (Gao et al., 2011). For example, the maximum pitch angle between modules must be less than about 0.86° for the aircraft operation on Mobile Offshore Base in Sea State 6 (Rognaas et al., 2001). So the stringent tolerance on the deformation of the floating structure requires relatively precise prediction on dynamic responses in the design stage.

Due to massive size of the VLFS, methods of dynamic prediction are very much different from that of other marine structures. Based on flat structure characteristic of floating airport, some scholars adopted the beam or plane models, including the hydroelastic effect to analyze the dynamic responses (Aoki, 1997; Hamamoto, 1994; Kashiwagi, 1998; Khabakhpasheva and Korobkin, 2001; Kim and Ertekin, 1998). These simplified models are only suitable for the pontoon type VLFS. In general, since the

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VLFS has much larger horizontal dimensions than the vertical one, it is usually constructed by connecting multiple standardized modules with connectors for easy construction, transportation and deployment (Watanabe et al., 2004). For the multi-modules floating structures, the simplified beam or plate models are no longer suitable due to the effect of the stiffness of flexible connector. Considering the stiffness of the flexible connector between the adjacent modules which is much less than the stiffness of the module structure itself, some scholars proposed hinged elastic beam or plate models (Du and Ertekin, 1991; Lee and Newman, 2000; Maeda et al., 1979; Riggs and Ertekin, 1993) and dynamics predictions were carried out by using linearized modal superposition or finite element discretization methods. We stress that linearlization methodology could generally fail to analyze the true dynamics of VLFS. Due to the considerable differences in the scale sizes between the floating modules and flexible connectors, small displacements of the floating modules may cause very large displacements at joints of connectors, which gives rise to strongly geometrical nonlinearity when establishing the connector model. Xu et al. (2014a) and Zhang et al. (2015) reported that the nonlinear stiffness of connectors may significantly amplify the module responses through jumping phenomena, which the linear methods cannot reveal.

The floating airport under consideration in this paper consists of multiple modules that are coupled with flexible connectors in a chain topological form. Each floating module can be viewed as an oscillator in waves and the connector between adjacent modules can be viewed as a coupling. Thus the integrated platform becomes a typical dynamic network system in which the nonlinearity may be derived from fluid–structure interaction, elastic material properties or geometric nonlinearity of the flexible connectors. The dynamic characteristics may involve complex network dynamic phenomena such as synchronization, hysteresis, phase lock and shift (Kaneko, 1993; Ott, 2002; Pecora and Carroll, 1990). Among the remarkable phenomena, amplitude death refers to the dynamic stability for the network structure system (Bar-Eli, 1984). Different from the traditional concept of stability, amplitude death means that the oscillation of all oscillators in the network system collectively tends to zero motion in autonomous networks (Saxena et al., 2012) or a suppressed weak oscillatory state in non-autonomous networks (Resmi et al., 2011) due to the interaction among coupled oscillators. Amplitude death is a typical stationary state for nonlinear network systems.

In this paper, we investigate a special dynamic behavior of the suppressed weak oscillatory state of a floating airport based on the mechanism of amplitude death because it is important for the stability design of the floating airport and load reduction in flexible connectors. Our recent works (Xu et al., 2014a; Zhang et al., 2015) pioneered the application of network theory to the nonlinear dynamics prediction of the floating airport, and preliminarily investigate the complex nonlinear dynamic phenomena of the floating airport in two degrees of freedom of the surge and heave motions. The results indicated that the traditional methods may greatly underestimate the actual responses and loads on the structure of the floating airport (Xu et al., 2014c). The previous works (Xu et al., 2014a; Zhang et al., 2015) mainly explored the feasibility of the new methodology and did not cover a complete and strict mathematic explanation for the important phenomenon of amplitude death. This paper gives a full explanation of amplitude death and further extends the floating airport model to the three degrees of freedom including surge, heave and pitch motions. A new model of rubber-cable connector is adopted. A chain-type nonlinear network dynamic model of floating airport is formulated based on the linear wave theory, a dynamic model of single floating module, a coupling model of the new connector and a constraint model of a mooring system. A semi-analytical critical condition of amplitude death is derived by using an averaging method. Based on the mechanism of amplitude death, we investigate the parametric domain for the suppressed weak oscillatory state of the floating airport and the results can be used as a theoretical guideline for the stability design of the floating airport. It is worthy to notice that the methodology of network dynamic theory applied in this paper can be extensible to many engineering problems with similar network structures.

2. Network model of floating airport

The sketch of the chain-type floating airport is shown in Fig. 1 in which the original point of global coordinates is set in free surface, the x-axis is on the undisturbed free-surface and the z-axis is upwards. The network model of the multi-module floating airport is to be integrated by using the dynamic model of a single floating body and coupling model of connector and the constraint model of the mooring system.

2.1. Model of a single floating body

In this paper, the floating modules are considered as rigid bodies and the surge, heave and pitch motions are considered. The mathematic model of the i-th module can be formulated by *Cummins Equation* (Taghipour et al., 2008) using a linear wave theory (Stoker, 2011),

$$(\mathbf{M}_i+\boldsymbol{\mu}_i)\ddot{\mathbf{X}}_i+\boldsymbol{\lambda}_i\dot{\mathbf{X}}_i+\mathbf{S}_i\mathbf{X}_i=\mathbf{F}_{iW}+\mathbf{F}_{iC}+\mathbf{F}_{iM} \tag{1}$$

where $\mathbf{X}_i=[x_i,z_i,\beta_i]^T$ denotes the generalized displacement for surge, heave and pitch motions of i-th module. $\mathbf{M}_i$, $\mathbf{S}_i$ indicate the mass and hydroelastic restoring matrix, written as

$$\mathbf{M}_i=\begin{bmatrix} m & 0 & m(z_c-z_g) \\ 0 & m & -m(x_c-x_g) \\ m(z_c-z_g) & -m(x_c-x_g) & I_{xx}^V+I_{zz}^V \end{bmatrix} \tag{2}$$

$$\mathbf{S}_i=\begin{bmatrix} 0 & 0 & 0 \\ 0 & \rho g A_W & -\rho g I_x^W \\ 0 & -\rho g I_x^W & \rho g(I_{xx}^W+I_{zz}^W)-mg(z_c-z_g) \end{bmatrix} \tag{3}$$

where m is the mass of the single module, A_W denotes the area of

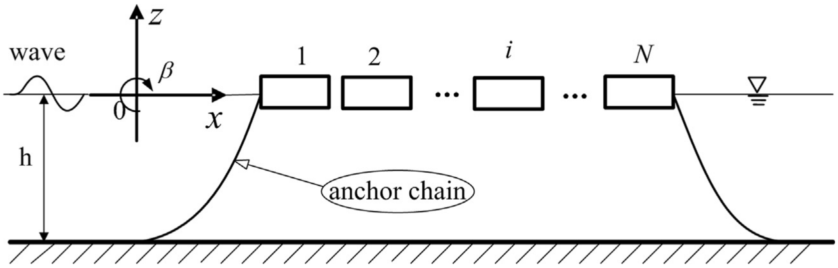

Fig. 1. Sketch for the multi-module floating airport.

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