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Predicting catastrophes of non-autonomous networks with visibility graphs and horizontal visibility

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ABSTRACT

Prediction of potential catastrophes in engineering systems is a challenging problem. We first attempt to construct a complex network to predict catastrophes of a multi-modular floating system in advance of their occurrences. Response time series of the system can be mapped into an virtual network by using visibility graph or horizontal visibility algorithm. The topology characteristics of the networks can be used to forecast catastrophes of the system. Numerical results show that there is an obvious corresponding relationship between the variation of topology characteristics and the onset of catastrophes. A Catastrophe Index (CI) is proposed as a numerical indicator to measure a qualitative change from a stable state to a catastrophic state. The two approaches, the visibility graph and horizontal visibility algorithms, are compared by using the index in the reliability analysis with different data lengths and sampling frequencies. The technique of virtual network method is potentially extendable to catastrophe predictions of other engineering systems.

1. Introduction

Catastrophic events happen occasionally in various fields such as economic system, ecology system, biology system and engineering system [1–4]. Especially, modern systems rarely isolated and inextricably interlinked in complex manners [5,6], and mutual interaction among sub-systems will increased systemic risks [7,8] and lead to cascading catastrophes [9]. A question of paramount importance is how to predict catastrophes in advance of their possible occurrences to avoid heavy casualties and serious economic losses [10].

Catastrophic events can occur in different forms among which bifurcation cascades, sudden change, crisis, etc., caused by nonlinear properties are universal in engineering system [11]. There are abundant research works about predicting the onset of catastrophes using bifurcation or catastrophic theory [12] based on the established complete mathematical model. The above method relies on prerequisites that the underlying system is completely known. However, there is no exaggeration to say that most systems are unavailable for precise mathematical models due to the complexity in the real world. Prediction of potential catastrophes without models of underlying dynamical system becomes especially challenging. There are various efforts to predict dynamical systems via reconstructing systems based on time series using nonlinear dynamic theory [13]. The scope of these methods ranges from phase space methods [14,15] to time delay embedding methods [16]. However,

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quickly and reliably predicting is still an issue due to the local reconstruction and the difficulty with the required computations [10].

Complex network theory has undergone a remarkable development in the last decades [17–19], which provide us a new insight to deal with complex systems from different disciplines [20–24]. Very recently, a pioneer work [25] has greatly promoted the work in time series analysis, where Zhang and Small first proposed a mapping method to convert time series to complex networks to analyze pseudo-periodic time series. Different from the above method in which the virtual networks were mapped from the reconstructed phase space or the linear correlation coefficient, Lacasa et al. proposed a quite simple mapping method, named visibility graph (VG) [26] and subsequent horizontal visibility graph (HVG) [27], which can inherit the time series properties in the structure of the associated graphs. Owing to the advantages, such as low computational cost, straightforward implementation and easy way to find connections, the method becomes popular and applicable in various fields [28]. Flanagan and Lacasa made use of visibility algorithms to quantify the irreversibility of the financial time series [29]. Liu et al. studied the statistical properties of complex networks constructed from time series of energy dissipation rates in three-dimensional fully developed turbulence using the visibility algorithm [30]. Elsner et al. demonstrated how to construct a network from a time series of U.S. hurricane counts and showed how it can be used to identify unusual years in the record [31]. Luque et al. provided a complete graph theoretical characterization of iterated maps undergoing period doubling route to chaos based on HVG algorithm [32]. Li and Dong constructed networks of human ventricular time series with the visibility graph approach to detect and predict the onset of human ventricular fibrillation [33]. Apart from applications listed above, there are abundant related research works documented in the review literature [28]. However, both the mathematical grounding of this promising theory and its applications are in its infancy [34].

In this paper, we first attempt to introduce the complex network method to predict potential catastrophes of non-autonomous network systems. The model of the multi-modular floating structure is selected from [35] for the case studies because this system is typical and complicated enough in the representation of a wide range of non-autonomous multi-body systems in engineering field. The pre-warning of catastrophes from transient dynamics of such dynamic systems is important for the concerns of engineering safety. However this important topic still remains untouched especially for multi-modular floating systems in the field of offshore engineering. The non-autonomous system can exhibit the interesting phenomenon of amplitude death (AD), a state that all oscillators in the network are mutually confined in a very weak oscillatory state [36]. The system may also undergo a sudden change from amplitude death state to a large oscillation state at certain critical parameters which can threaten or even destroy the system. The sudden change in dynamics is here regarded as a catastrophe that one strives to avoid at all cost. We translate dynamical properties of time series into structural features of graphs via mapping response time series to graphic network based on VG and HVG algorithms. By studying the average degree of the VG graph and the maximum degree of the HVG graph, the onset of catastrophes can be predicted in advance of their occurrences. We further propose a numerical indicator, named as Catastrophe Index (CI), to measure a qualitative change from a stable state to a catastrophic state. The performance of the two approaches, visibility graph and horizontal visibility, is compared by using the index in terms of the reliability with different data lengths and sampling frequencies. Numerical experiment is carried out for catastrophe identifications and verifies the feasibility and efficiency of this proposed method. The technique of using graphic networks to predict potential catastrophes is new and is not restricted to the case study of the floating system, but also in principle applicable to fault detection and diagnosis of mechanical systems.

2. Graphic networks for catastrophe prediction

Based on the modeling method [35], the model of a chained multi-module floating airport can be formed by integrating the dynamic model of a single floating module and coupling model of connector and the constraint model of the mooring system. The governing equation for an N-module floating structure can be generally written as

$$(\mathbf{M}_i + \boldsymbol{\mu}_i)\ddot{\mathbf{X}}_i + \boldsymbol{\lambda}_i\dot{\mathbf{X}}_i + (\mathbf{S}_i + \delta(i, i_0)\mathbf{K}_i)\mathbf{X}_i = \mathbf{F}^w e^{i(\omega t + \varphi_i)} + \varepsilon\sum_{j=1}^{N}\Phi_{ij}G(\mathbf{X}_i, \mathbf{X}_j), \quad i = 1, \cdots, N \tag{1}$$

where the symbol $\mathbf{X}_i = [x_i, z_i, \beta_i]^T$ denotes the displacement vector of the i-th module where the state variables x_i, z_i, β_i denote surge, heave and pitch motions respectively. $\mathbf{M}_i, \mathbf{S}_i$ indicate the mass matrix and the hydrostatic restoring coefficient matrix, respectively. The matrix $\mathbf{K}_i$ denotes the environmental constraint on the floating system that is moored by the catenaries in order to restrict the drifting, and $\delta(i, i_0)$ is the Delta function which determinates the position where the catenaries are installed. $\boldsymbol{\mu}_i, \boldsymbol{\lambda}_i$ and $\mathbf{F}^w$ represent the added mass, damping matrixes and exciting force vector respectively as a result of water waves. $\omega = 2\pi/T$ denotes the circular frequency of linear wave and T is wave period. φ_i denotes the initial phase angle of the i-th module due to a head wave propagating along the huge size of the floating airport and the phase delay is defined as $\Delta\varphi_{i(i+1)} = \varphi_{i+1} - \varphi_{i+1} = k(L_i + L_{i+1})/2$ of which k indicates wave number. The second term $\varepsilon\sum_{j=1}^{N}\Phi_{ij}G(\mathbf{X}_i, \mathbf{X}_j)$ on the right hand side of Eq. (1) denotes the coupling term which represents the mechanical features of the connection between the modules. The parameter ε indicates the coupling strength (stiffness of the connector). Φ is the coupling topology matrix, of which the element Φ_{ij} is set to 1 when the i-th module connects with j-th module otherwise Φ_{ij} is set to zero. $G(\mathbf{X}_i, \mathbf{X}_j)$ denotes the coupling function which describes the geometric relationship of the connection.