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Bridge Safety Assessment Based on Complex System Theory and Nonlinear Time Series

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Abstract: This study presents a method of safety assess of existing bridges based on Complex System Theory and Nonlinear Time Series. Bridge Structure System has characteristics of complex system. Such as dissipation, fractals, chaos and so on. Chaotic nonlinear time series of monitoring information of ASCE Benchmark and Masangxi bridge. By G-P and C-C algorithms to extract the largest Lyapunov Exponent and Embedding Dimension. The results showed that: the structural system of Correlation Dimension greater than2 and not an integer, the largest Lyapunov Exponent is greater than 0, Indicating that the systems exist Chaotic Phenomena. So, Complex System Theory is using for bridge system.

Key words: Complex system, bridge safety assessment, nonlinear time series

INTRODUCTION

Large complex of bridge structure, Its security has been increasingly concerned about health monitoring and safety monitoring has made certain achievements. However, It also needs to develop a more effective method for Structural Health Monitoring (SHM). Due to material nonlinearity, geometric nonlinearity, boundary conditions of uncertainty, randomness of external loads and environmental interactions, bridge damage exists complexity. Mainly for its complexity as: (1) Bridge structure system, its overall behavior or characteristic can not be determined by its members to determine the behavior or characteristic. That bridge structure system security situation can not determined by its subsystems conditions. (2) Bridges System behavior can not advance to determine on large scale (long or large space). Such as accumulating damage of Bridge for short time can not predict overall behavior for long time. (3) Bridge System has a large number of interacting subsystems or separated from each other, There are nonlinear coupled together. For example, a bridge pier, pile, the upper structure, cable-stayed bridge with cable, beam, main tower. (4) Bridge System is an open system, with the external environment information, energy and material exchange. For example. Structural vibration, concrete carbonation, corrosion of steel components, earthquakes, external load.

In 1928, The Austrian Biologist Bertalanffy first proposed the "Complexity" concept. After centuries of Complex Systems Theory to improve gradually. In 1954, Xuesen Qian published in"Engineering Cybernetics". It is well combine the general, broad theoretical with practical engineering experience. It made a comprehensive study on each system of automatic control and automatic regulation theory. In 1969. Prigogine proposed theory of Dissipative Structure Theory, H. Haken proposed Synergy Theory. It has a fundamental breakthrough on Self-organizing Theory fo system complexity. The Santa Fe Institute (SFI), Founded in 1984. Proposed Complexity Science, the complexity of system complexity science research to a New climax. Currently, the Complex System Theory in Rock mechanics, Structural Dynamics and other aspects of the research has achieved some results. Among them, the theory of Dissipative Structures explain rock instability (Qin, 2000), Fractal Theory bridge cracks mechanism (Zhongru Wu, 1996), kinetic theory of nonlinear chaotic analysis of existing bridge state (Yang, 2011).

This study analyzes the complexity of the mechanism of the bridge structure system and then use the theory of chaotic time series analysis of bridge acceleration time series. The resulting get structural damage and decay characteristics of chaotic time series correlation index, and then proposed the bridge condition assessment method based on chaotic characteristic index.

BASED ON THE COMPLEX SYSTEM THEORY OF BRIDGE STRUCTURAL DAMAGE IDENTIFICATION OF COMPLEX MECHANISM

Bridge structure system due to material nonlinearity, geometric nonlinearity, boundary conditions uncertain and other factors, structural systems exhibit many degrees of freedom, high-dimensional nonlinear characteristics. Nonlinearity is the source of complex systems. So bridge

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system architecture decay nonlinear time series also showed large scale dissipative appears of Chaos Fractal Dimension, self-organization, mutation, bifurcation and series of characteristics of complex system (He and Yuan, 2000).

Based on Dissipative Structure Theory of Bridge Structural Damage Identification of complex mechanism: Dissipative Structure System (Shen *et al*., 1987) is an open system far from equilibrium. Continuously with the external system through the exchange of energy and information and material, changes in the environmental conditions to a certain threshold. The quantitative may cause qualitative, structural disorder possible state transition from the original into a time, space or function with order status. Bridge system is an open system, and the environment are closely linked. Due to the internal or external environment lead the structural damage to accumulate, then the system is moving away from equilibrium.

Based on Fractal Theory of Bridge Structural Damage Identification of complex mechanism: In1977, Mandelbrot proposed "fractal theory"?Fractals is its some way similar to the whole, Fractal refers to a class without rules, confusing and complicated but there are similarities between the part and the whole system. Fractal Dimension is to describe the fractal characteristics of quantitative parameters, Fractal Dimension calculation includes similar dimension, capacity dimension, information dimension and correlation dimension, group dimension and quality dimension and so on. By analyzing the system exists "Scale-free Zone"to determine the fractal characteristics of the system.

Research shows that the degree of cracking girder can be expression by Fractal Dimension (Wu, 1996), Fractal theory also used in slope stability analysis, Dynamic response of bridge structures exhibit similar multifractal (Symonds and Lee, 1995). However, In the process of bridge damage, injury, damage before and after the structural dynamic response, damage caused by changes in the surrounding environment has self-similarity, structural damage dynamic response of Nonlinear Time Series within certain parameters, there are Scale-free Zone; locally damage and partial damage, partial damage and overall injury also has a Self-similarity; bridge system damage in the structure, morphology, information, functionality or time self-similarity.

Based on Chaos Theory of Bridge Structural Damage Identification of complex mechanism:Chaos is a seemingly random movement that appears in the decisive dynamical system. Chaos describes a complex, unpredictable and disordered state. Chaotic motion restricted to limited areas and tracks never repeat, sensitive dependence on initial conditions, with rich gradation and self-similarity structure, with strange attractor.

Through the preliminary exploration of chaos theory, bridge structure damage during certain parameters, status, function, response to experience that Period-doubling bifurcation route. Paroxysmal way and Quasi-periodic motion bifurcation approach. These pathways are making the structure into a chaotic state.

Based on Soliton Wave Theory of Bridge Structural Damage Identification of complex mechanism: J. Scott. Russel found solitary wave phenomena. A large number of nonlinear evolution equations (Lin, 2011) has soliton solutions. Solitary Wave has a very peculiar nature. They interact to maintain a stable waveform. This is quite similar to the nature of particle collisions. Thus, It was to become"Soliton".

Bridge structure as the nonlinear dynamic system, Its evolution must exist solitary wave phenomenon. Through structural damage accumulation finite dimensional and infinite dimensional nonlinear evolution equations, respectively, analyze the dispersion, nonlinearity, volatility; solutions decay, smoothness and chaos, singularity set, global attractor, the existence of inertial manifolds. Thus, You can build a structure based on the theory of solitary wave nonlinear evolution patterns of behavior.

ANALYSIS OF BRIDGE STRUCTURES CHAOTIC CHARACTERISTICS AND NONLINEAR TIME SERIES

Based on Melnikov method analysis of bridge structures critical condition of chaos: Any structure can be abstracted into the mass, damping and stiffness matrices of the mechanical system of mathematical model. When the structure for vibration damping of persecution. The vibration equation can be written as equation:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F(t)\} \tag{1}$$

where, [M], [C], [K], are the mass matrix, damping matrix, stiffness matrix; $\{\ddot{x}\}$, $\{\dot{x}\}$, $\{x\}$, namely the acceleration vector, velocity vector, displacement vector; $\{F(t)\}$ yes load vector (stimulus array).

Melnikov method is used to determine when a particular kind of nonlinear systems in the sense of chaos appear Smale analytical methods. Currently, Research in this area has some of the results (Liu *et al*., 2001). Finally the system of high-dimensional of Smale transform got the chaotic parameter condition (Wang, 2001):

$$\frac{\beta^2}{\delta\omega^2} > \left|\frac{B_\pm(\alpha,r,\Omega,v_0)}{A_\pm(\alpha,r,\Omega,v_0)}\right| = R_\pm(\alpha,r,\Omega,v_0) \qquad (2)$$

So, In theory, Can prove the chaotic existence of the bridge structure critical condition.

ASCE benchmark chaotic analysis: Through the American Society of Civil Engineers builded Structural Health Monitoring (SHM) Benchmark Structural Model (Johnson *et al*., 2000; Johnson *et al*., 2004) (Fig. 1). Use of G-p, C-C methods to extract the maximum Lyapunov index and embedding dimension from monitoring information (Yang and Zhou, 2010). Using Wolf method to extraction and analysis of the largest Lyapunov exponent through ASCE Benchmark random excitation oscillation experiment data In 2002. The specific experiment is as follows:

- Structural integrity of the case, Analysis of sample data, The electric oscillation excitation monitoring information, about maximum Lyapunov exponent's sensitivity
- 9 kinds of state structures and the same number of parameters in this. Use of maximum Lyapunov exponent to analysis of Electric oscillation excitation monitoring information, The experimental results shown in Fig. 2

The results showed that: under the random electric excitation of ASCE Benchmark Structure. Its response message both in the structural integrity or damage in a variety of circumstances have appeared maximum Lyapunov exponent greater than 0. That the system appears chaotic.

In the process of increasing the number of samples. The largest Lyapunov exponent value in the forward growth. After some time the trend is solid. It can be found that use of the system response signal to calculate Maximum Lyapunov index should select the appropriate number of samples. Conducive to extract precise largest Lyapunov exponent.

Largest Lyapunov exponent of structural damage cases have a certain sensitivity. It showed the largest Lyapunov exponent better identification of structural damage occurs (change).

Analysis of masangxi bridge health monitoring information of largest lyapunov exponent: Chongqing Masangxi Yangtze River Bridge is the National Trunk Yuzhan Highway from Shangqiao to Jieshi segment maximum control project. From the Yangtze River to Chongqing main city's first landmarks. Also it is the widest highway bridge across the river in Chongqing.

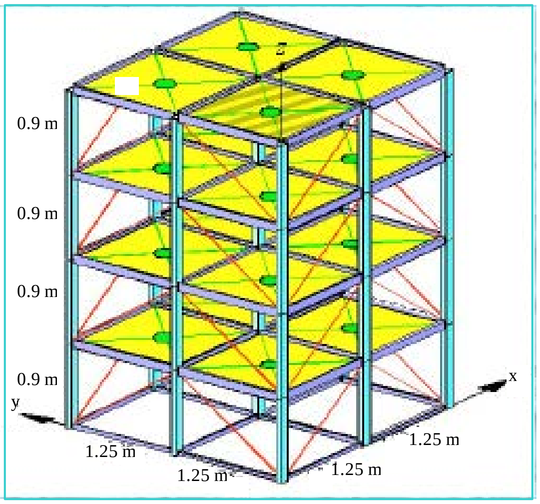

Fig. 1: ASCE Benchmark model dimensions and coordinates

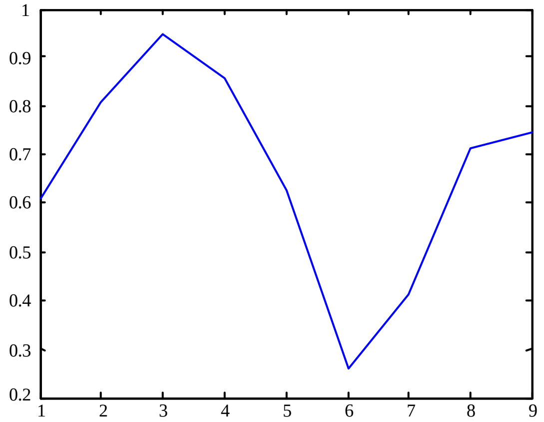

Fig. 2: Shm01s-shm09s largest Lyapunov exponent of regularity

Completed the bridge structural health monitoring system In 2005, The system sensor arrangement shown in Fig. 3. Main monitoring parameters for structural strain, the main beam deflection, deformation of the main tower, cable force and the main beam temperature, humidity and so on.. The data acquisition frequency of 10 minutes to obtain a large number of monitoring data Since July 2005. Masangxi bridge deflection, some strain measuring point time curve shown in Fig. 4, 5.

That identification of maximum Lyapunov index is made from the monitored data of dynamic deflection of Masangxi bridge started from 10:00 on date on January 14, 2006. By use of the monitored data of same time length calculation of maximum Lyapunov index is

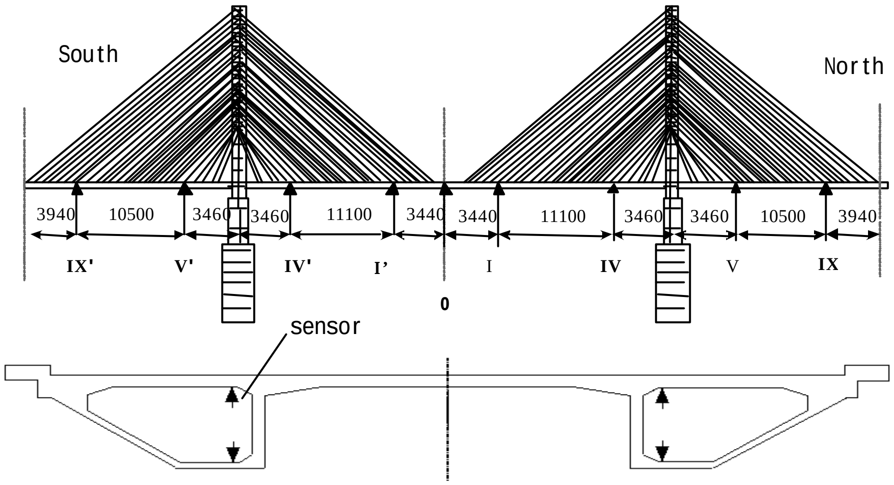

Fig. 3: Masangxi bridge health monitoring system measuring point distribution

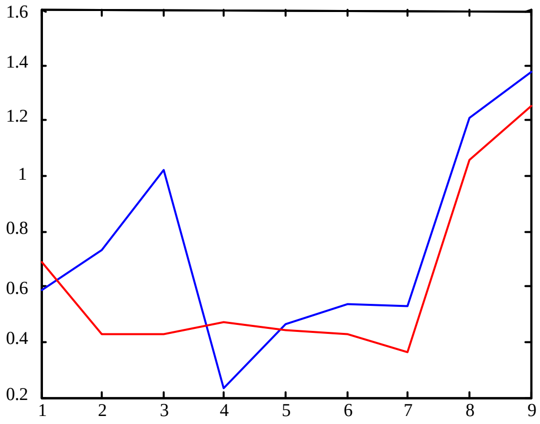

Fig. 4: Maximum lyapunov index of deflection monitored points of whole bridge of masangxi bridge

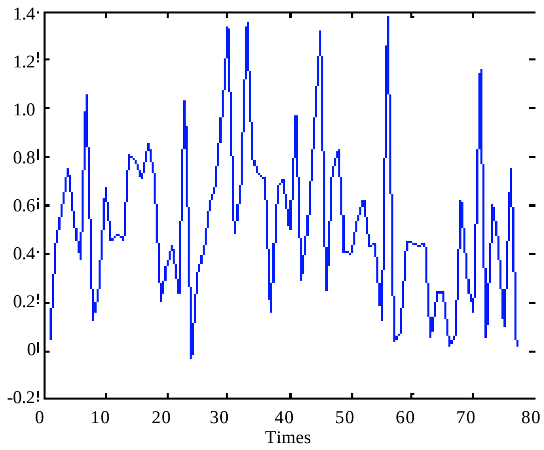

Fig. 5: Lyapunov exponent evolvement of samples collected of mid-span of masangxi bridge

made from the monitored information of deflection at 18 monitored points. The calculation results are shown in Fig. 4. in which blue and red color lines indicate respectively the calculation results of 9 monitored points at upper and lower streams. From mid-span to both ends the maximum Lyapunov exponent show rising tendency. And the Lyapunov exponent are all greater than 0.

In addition, The following shows the calculation results of Lyapunov exponent for various sample sections by use of monitored data starting at 13:00 on date of December 3rd. 2005 by Wolf method from monitored information of mid-span deflection of Masangxi bridge. In the above 36 monitoring periods are selected as time duration and the specific calculation results are shown in Fig. 5. It can be found that under condition of same parameters the value of Lyapunov based on real time monitored information varies along with variation of time of samples. The sample size for each case of the Lyapunov exponent is greater than 0.

Thus, According to the theory of chaos determination can explain the existing bridge vibration have Chaotic characteristics.

CONCLUSION

Due to Bridge structure system's material nonlinearity, geometric nonlinearity, boundary conditions and the environmental effects of uncertainty, So the system has a complex nonlinear time series. Use of

Complex Systems Theory and Nonlinear Time Series can better reveal the mechanism of the bridge structure system damage.

Bridge System is an Open System, Exchanging with the surrounding environment by material, energy and information. Due to cumulative damage, the system far from equilibrium gradually into dissipative structure;bridge system damage in the structure, morphology, information, functionality and time with self-similarity. Structural damage dynamic response of nonlinear time series exist scale-free zone within certain parameters;Structural Damage accumulation is a nonlinear time series, It can be constructed the accumulation of bridge structural damage related to infinite dimensional and finite-dimensional nonlinear evolution equations. Description of complex systems and nonlinear time series analysis in bridge structural system is feasible.

In this study, Use of complex system chaos theory. Proved that there is a critical condition for occurrence of chaos in the bridge structural system. Analysis of Benchmark Structural System under the random electric excitation by Nonlinear Time Series and system appears Chaotic; Analysis of the Masangxi bridge health monitoring information largest Lyapunov Exponent, Indicating that bridge vibration exist Chaos.

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