

Research on Tower Crane Structure Damage Detection Based on ARX Model

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Abstract—In view of the health inspection of tower crane, the paper puts forward an ARX model to detect the status of the tower crane structure which uses the node displacements of tower crane below standard section as input and the up standard section of the node displacements as the output. Combining with statistical recognition technology the states detection of the structure are detected. First, the paper establishes a counterpart finite element model based on the laboratory existing mini tower cranes to obtain the displacement signals of tower crane nodes in intact and damaged states with excitation load. Then it chooses a better identified ARX model to define the damage characteristic parameter. Finally it judges the dynamic response of the good state as a reference to analyze the differences between the response signals of damage status and normal structures, so as to complete the diagnose with the method of statistical analysis. The method shows a high ability of damage identification.

Keywords—tower crane; statistical recognition technology; ARX model; the damage characteristic parameter

I. INTRODUCTION

Tower crane is mainly used in construction lifting and transport machinery. Metal structure is the main part of the work which determines the safety and reliability of tower crane. How to avoid and promptly detect and eliminate the fault risks hidden inside tower structure has become the focus issue of the industry.

Tower crane is composed of chassis, tower, turning pedestal, tower, balance arm, boom, cab, ladders and platforms, jacking frame and beams parts. The tower crane tower which is connected together by a standard section is the main component of a tower crane. The constitution of connecting part mainly includes strength bolts, shear bolts, horizontal pin and tile sets connections. The loosening of strength bolt is the main reason of tower crane accident. Thus, early detection of loose bolts and making right judgments has become an important task for researchers.

This paper presents a model based on the structure of the state ARX diagnostic methods. The system identification technology which is based on ARX model builds a dynamic mathematical model of the tower crane. The input and output data of the system uses displacement signal of the following standard points and the above standard point. Model parameters are estimated with the method of least squares estimation, the order is determined by Akaike information criterion (AIC).

It defines the damage characteristic parameters of the model, forms reference for the judgment of the intact dynamic response, analyzes the signal differences between damaged and good condition, and then verifies the validity of the model through diagnosing the structural state with statistical analysis.

II. A FINITE ELEMENT MODEL AND SIGNAL ACQUISITION

A. Finite Element Model

According to the structural characteristics of the tower crane, in the analysis in ANSYS, the paper adopts the beam element Beam188 to simulate tower crane steel structure. It remains Tower crane model and the actual geometry of the shape the same and gives appropriate treatments to the little effected local structures: the rotating components are dealt equivalently with beam units; attachments (such as motors) and other geometric smaller entity components are dealt with Mass21 quality elements. Model boundary conditions: boom, balance arm is connected to the roots through the pin can be considered fixed hinge bearings with coupled processing; the bottom of the structure which is connected to the anchor bolts of foundation is assumed to be fixed support, constraining all degrees of freedom of four nodes in the bottom [2]. The rods of each part of tower crane are made of steel. The elastic modulus is 210 GPa , poisson's ratio is 0.3, density is 1780 kg/m^3 [3]. The established finite element model of tower crane is shown in FIGURE 1:

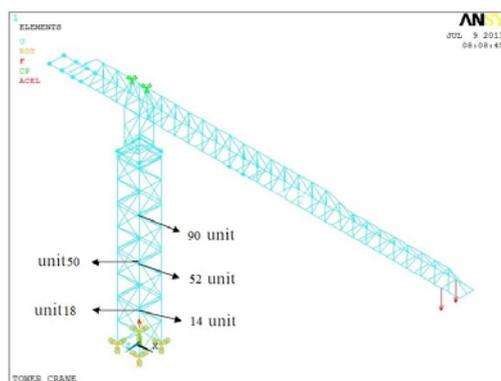


FIGURE I. FINITE ELEMENT MODEL OF TOWER CRANE.

B. Analog Value Signal

Tower crane is a multi-degree of freedom vibration system. In order to simplify the calculation, the simplified three quality two degrees of freedom model is often used nowadays [1].

Load lifting process can be divided into two stages: the first stage is the weight staying still on the ground, rope tensions gradually from relaxed state, then exerting external excitation to the tower structure until it begins to vibrate. When the wire rope lifting force is equal to gravity load, the load is lifted off the ground, the first phase ends. The second stage starts when load is lifted off the ground, the entire system vibrates freely. When lifting speed reaches the rated lifting speed, the structure still on the equilibrium position, the second phase is completed.

Before heavy object is lifted off the ground, the rope force is time variable. In order to simplify the calculation process, the formula can be calculated as following according to the linear load:

$$F(t) = At + B \quad (1)$$

When the weight off the ground, according to the mechanical models, the motion differential equations of each weight are obtained, the simplifications of which obtain hoisting loads. The calculation formula is [4]:

$$F(t) = KV \sqrt{\frac{m_1 m_2}{m_1 + m_2} \cdot \frac{K_0}{(K_0 + K)} \cdot K} \sin \omega t - \frac{m_2}{m_1 + m_2} (P - Q) \cos \omega t + \frac{m_2}{m_1 + m_2} \cdot (P - Q) + Q \quad (2)$$

The tower machine technical parameters: boom maximum working range: 3.5m; boom at maximum working range of nominal weight: 15Kg; maximum lifting: 100Kg; Lifting height: 2m; Lifting speed: 0.33m/s. The system is lifting; one second at the end lifting off the ground, five seconds at the end hoisting speed reaches the rated speed.

It exerts the obtained excitation loads to the lifting finite element model range at the maximum working range, sets load step and adopts the full method for transient dynamic analysis of lifting process. Through the ANSYS post-processing module, it extracts the displacement information of important body node.

III. DAMAGE FEATURE EXTRACTION

A. The Proposed Method ARX Model

For a single-input, single-output process, the simplest description of the relationship between input and output is a linear equation:

$$A(q^{-1})y(k) = B(q^{-1})u(k) + e(k) \quad (3)$$

$u(k)$ and $y(k)$ are the amount of system input and output ($u(k) \in R^n, y(k) \in R^n$), $e(k)$ indicates the model error ($e(k) \in R^n$). q^{-1} refers to the post-shift operator.

$$A(q^{-1}) = I + \sum_{i=1}^n A_i z^{-i}, B(q^{-1}) = \sum_{i=1}^n B_i z^{-i} \quad (4)$$

Here I represent a unit matrix $n_y * n_y$, A_i is $n_y * n_y$ the matrix dimensions, B_i is $n_y * n_u$ dimensional matrix, n_u, n_y the dimension of the system input and output, n_a, n_b the order of the model. And n_a the input order of the system n_b the order determined by the system identification [5].

Based on the vibration feature, the paper selects the first section of standard node information at the bottom of tower crane as input, the corresponding node information of the second criterion as the output to establish a single-input and single-output ARX model.

B. Model Identification

Identification is a process which is based on the observation of input and output data in the system to ensure an equivalent model of the measurement system from a given model class. Model identification, includes identification of the model structure and estimation of model parameters. ARX model identification method commonly uses methods of least squares and instrumental variable. According to AIC criterion, it determines the model order by finding an estimating model with a smaller AIC value. AIC value is defined by the following formula:

$$AIC = \log(V) + 2d / N \quad (5)$$

Here, V is the loss function, d is the number of estimated parameters, and N is the number of estimates.

Based on the theory of digital signal processing, the data are standardized. It extracts the first half of intact state data to establish the reference model, another half for model identification. Based on physical properties of the system and a priori knowledge of the model, the paper gives an upper limit model order of n_a and n_b , then it uses the method of least squares parameter estimation to calculate the values of AIC from low to high individually, finally it ensures the model order combining the order selection criteria.

C. Damage Feature Extraction

Firstly, the paper establish ARX model with intact data of the input $u_u(k)$ and output $y_u(k)$:

$$y_u(k) = \sum_{i=1}^n A(i)y_u(k-i) + \sum_{j=1}^n B(j)u_u(k-j) + e_u(k) \quad (6)$$

At this point, the residuals should be white noise sequence [6].

Then it uses the model to show the relationship between the input and output under the testing state, there are:

$$e_d(k) = y_d(k) - \sum_{i=1}^n A(i)y_d(k-i) - \sum_{j=1}^n B(j)u_d(k-j) \quad (7)$$

As residuals represents sections which ARX model part cannot construct in the system output, it can be considered that if the input and output of the test condition and good condition come from the same input-output system, a good condition established ARX model indicates the input and output of test state should produce less residuals; on the contrary, if they are from different systems, it will generate a large residuals. The standard deviation of the residuals $e_u(k)$ and $e_d(k)$ can be expressed by $\sigma(e_u)$ and $\sigma(e_d)$ so that it defines damage characteristic parameters as following:

$$D_F = \frac{\sigma(e_d) - \sigma(e_u)}{\sigma(e_u)} \quad (8)$$

Generally, $D_F \geq 0$. Under ideal conditions, if $u_u(k)$ — $y_u(k)$ and $u_d(k)$ — $y_d(k)$ are from the same structural state, then $D_F \approx 0$; otherwise, D_F is considerably larger than 0. Therefore, by calculating damage characteristic parameter values of each sample that corresponding to the input - output signal under structural testing state; the paper gets an injury characteristic parameter sequence of sequences $\{D_F\}$ for statistical analysis to diagnose the structure of the state.

D. Statistical Pattern Recognition

In practical engineering applications, the structures are often nonlinear and time-varying. Besides, the measurement noise, and dynamic parameters modeling process also introduces some error, so even if the structure is unchanged, damage characteristic parameters D_F may also be greater than 0. Therefore, the structural damage diagnosis must be builds on statistical analysis of large amounts of data. This paper presents a probability metric based on statistical analysis for structural damage detection.

The paper divides the obtained structural response signals into a number of samples. It establishes the ARX model with data of good condition, and extracts ARX damage feature from each sample to form injury feature parameter sequence. Through the following statistical analysis to the sequence, it can be determined that whether the injury occurred and what the extent of damage is.

1) Damage characteristic parameters to strike a confidence interval of the mean

It supposes that the given confidence level is $1 - \alpha$, and x_1, x_2, \dots, x_n are set to be normal population samples, \bar{x} and S^2 respectively sample mean and sample variance. By the knowledge of probability and statistics, it is known that $\frac{\bar{x} - \mu}{S / \sqrt{n}} \sim t(n-1)$ submits to the t-distribution,

$$P \left\{ -t_{\alpha/2}(n-1) < \frac{\bar{x} - \mu}{S / \sqrt{n}} < t_{\alpha/2}(n-1) \right\} = 1 - \alpha \quad (9)$$

$$P \left\{ \bar{x} - \frac{S}{\sqrt{n}} t_{\alpha/2}(n-1) < \mu < \bar{x} + \frac{S}{\sqrt{n}} t_{\alpha/2}(n-1) \right\} = 1 - \alpha \quad (10)$$

Then the confidence level of the confidence interval is: $(\bar{x} \pm \frac{S}{\sqrt{n}} t_{\alpha/2}(n-1))$

2) The probability of structural damage

The probability of structural damage can be expressed as: $P_A = P\{D_{F,d} > D_{F,u}\}$. The paper assumes that, $D_{F,u}$ and $D_{F,d}$ are subject to normal, their means, variances are μ_u, σ_u^2 and μ_d, σ_d^2 respectively. Then:

$$P_A = \Phi \left(\frac{\mu_d - \mu_u}{\sqrt{\sigma_d^2 + \sigma_u^2}} \right) \quad (11)$$

Where $\Phi(\bullet)$ is the standard normal distribution function, it is known that the greater P_A is, the greater the probability of structural damage occurs. Under normal circumstances, when local minor damage in the structure occurs, it can be considered that the sensor signal which is closer to the damage location has a larger value, and the farther one has a smaller value. Therefore, we can determine the location of damage occurrences according to the relative size of sensor signal values from various parts of the structure.

IV. SIMULATION RESULTS ANALYSIS

To simulate structural damage of Tower crane, the paper studies five kinds of tower crane structural state: 1) the intact structure; 2) the 14th section of the top of the tower's first standard unit (location see Figure 1) injuries in 25% (fault 1); 3) the 14th cell damages 50% (fault 2); 4) the 14th unit injury 75% (fault 3); 5) the 14th units at the top of the first standard section, the 52nd unit at the top of the second standard section and the 90th unit at the top of the third section are damaged 50% (fault 4).

In analysis of the model, the paper replaces the looseness of bolt with unit damages, structural damage can be considered to causing a loss of stiffness. E is elastic modulus whose decline is used to simulate cell damage. I.e. damage element modulus is decreased by 25%, 50% and 75%.

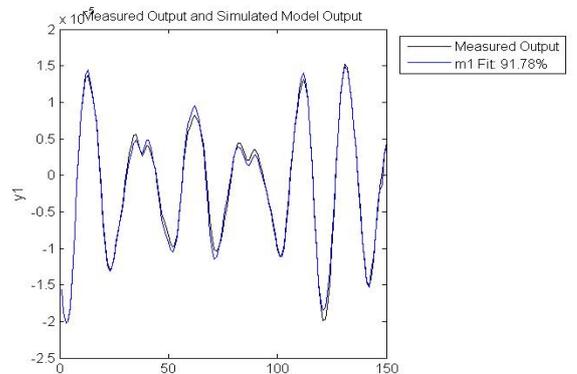


FIGURE II. ARX MODEL IDENTIFICATION.

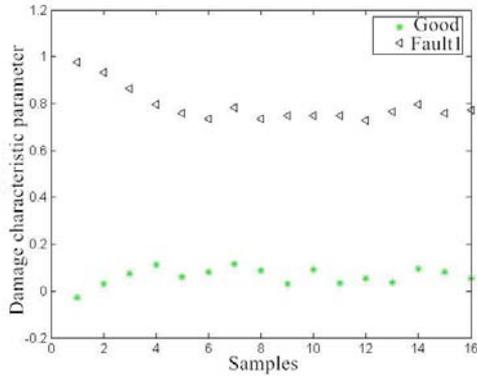


FIGURE III. THE CHARACTERISTIC PARAMETERS IN GOOD CONDITION AND FAULT CONDITION 1.

Extracting intact state data to establish reference model, this paper takes four kinds of fault status as a test state. The established ARX model takes the displacement data of node 18 at the top of the first standard tower section as input, and the displacement data of node 50 at the top of the second standard section as output, divides the good condition of the data into two parts. The first half is used to create the reference model and the second half is for model identification, FIGURE II shows the results of model identification. It can be seen that the proposed ARX model identification results are sufficiently close to the real system.

The response of the fault condition also takes the second half of the data as a status signal under test to establish 16 samples. Each sample is calculated for its corresponding damage characteristic parameters of various structural conditions. FIGURE III shows the normal state of the structure from displacement response of the node 18 and the characteristic parameters of fault 1. From the figure it can be seen that the value of D_f fluctuates near zero, and the distribution of the fault 1 is around 0.8, so it is clear feature parameters of fault 1 is greater than that of intact condition.

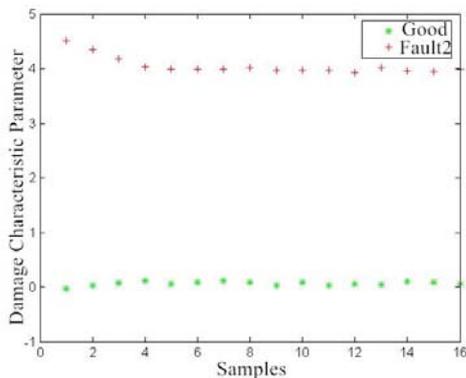


FIGURE IV. THE CHARACTERISTIC PARAMETERS IN GOOD CONDITION AND FAULT CONDITION 2.

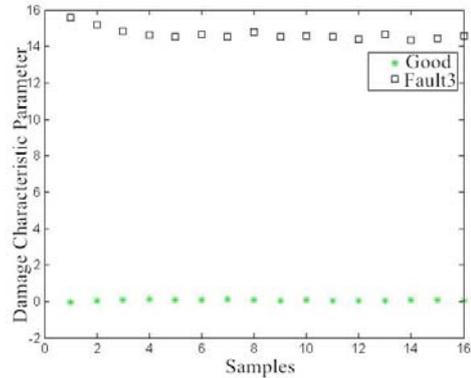


FIGURE V. THE CHARACTERISTIC PARAMETERS IN GOOD CONDITION AND FAULT CONDITION 3.

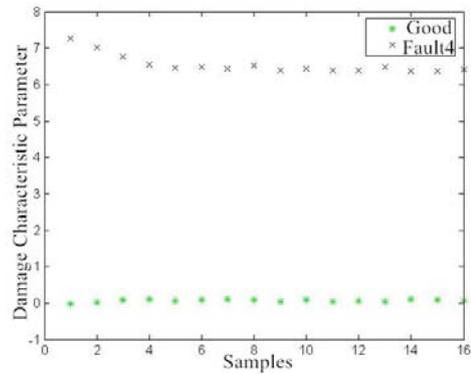


FIGURE VI. THE CHARACTERISTIC PARAMETERS IN GOOD CONDITION AND FAULT CONDITION 4.

The distributions of D_f under fault 2 and fault 3 states are shown in FIGURE IV and FIGURE V, we can see that the damage parameters distributes near 4 under the condition of fault 2 and it distributes near 16 under the condition of fault 3. Compared with the intact, the difference between characteristic parameters has been very obvious. After a comparative analysis for FIGURE III, FIGURE IV and FIGURE V, it is not difficult to find the characteristic parameter increases while the severity of injury adds, and each fault state is easily distinguished. After a further analysis for FIGURE III, FIGURE IV, FIGURE V and FIGURE VI, we can see greater degree of cell damages have more serious effects on the health of structure.

For the distribution of damage parameters, statistical hypothesis testing shows that each measuring point data which corresponds to various structural conditions of the damage characteristic parameters is basically normal distribution. FIGURE VII shows the normal structure of the normal distribution node 18 graphics test.

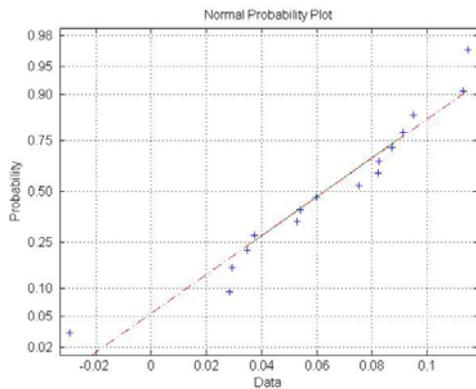


FIGURE VII. THE NORMAL STRUCTURE OF NORMAL DISTRIBUTION GRAPHICS TEST.

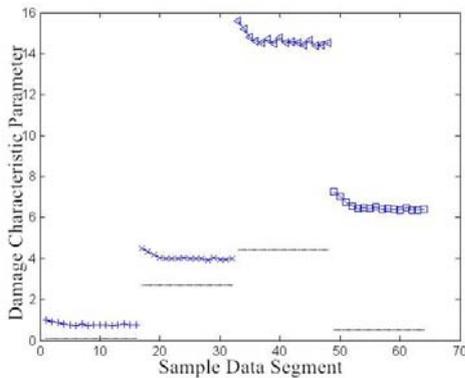


FIGURE VIII. THE DAMAGE CHARACTERISTIC PARAMETER SEQUENCE DIAGRAM

Figure VIII shows details of damage degrees corresponding to four kinds of damage characteristic parameter sequence, from left to right are fault 1, fault 2, fault 3 and fault 4. Among these a fault line beneath the sequence of the characteristic parameters indicates confidence interval upper limit of the mean characteristic parameter (confidence level 0.95) under good conditions, while the fault lines beneath characteristic parameters of fault 2,3,4 indicates confidence interval upper limit of the mean characteristic parameter (0.95 confidence level) under conditions of fault 1, fault 2, fault 3. It can be seen that four kinds of damage degrees and their corresponding 4 damage characteristic sequences could be clearly distinguished.

V. CONCLUSIONS

Through the establishment of the finite element model of tower crane, this paper have solved the transient dynamics, obtaining displacement data under impact loading tower crane in good condition and damage state. It uses processed displacement data for input and output signals to establish ARX model, defining injury characteristic parameters, analyzing parameters with knowledge of probability and statistics to determine the structure of the tower crane system status. The results show that this method can effectively

determine the structural integrity and the damage state of the tower, provides real-time online damage early warning for some value.

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