Damage Targeting Method to the Ship Pipe Network Based on Monte Carlo and Fuzzy Clustering Co-simulation

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Abstract: Pipe network safety and damage locate is essential to the ship safety. This article established the static model of ship pipe network, it make used of Monte Carlo simulate to run the ship pipe network and acquiring corresponding node data. Take use of fuzzy method apply to this data, the fuzzy clustering to the membership as a parameter to characterize the amount of the ship pipe network damage. The test shows that: This method can be quickly and easily locate the damage to the ship pipe network.

1. Introduction
Pipe network system is an important part of modern ship. The ship pipe network contains numerous nodes and piping arrangement according to certain composition, which bears the ship fluid medium transportation, and has an important impact to the ship vitality [1]. With the development of marine equipment large-scale, system complexity, integration and high speed, intelligent pipe network management applications is an inevitable trend of the next generation ship [2, 3]. In this article, Monte Carlo simulation analysis implicate to the static ship pipe network, using the fuzzy theory by membership function to locate the damage position of pipe network.

2. Establish of ship network system model
The static analysis and calculation method was used to solve complex model. Hence, the simple model, fast speed analysis, rapid capture outliner features method for the ship pipe network damage location would be a great success [4]. Establish of the ship network system model, and then simplify the network model from certain dimensions. The simplified network model can enhance the speed of analysis effectiveness. Pipe network model form a cyclic structure, as can be seen in Fig. 1, which shows the pipe network contains numerous nodes. Each node has different attributes, depending on the node attribute setting to simulate the network operation.
For the pipe network, set Junction(t), Pipe(t), Pump(t) as the research target, from the view of time-series analysis the relationship among them. Thence, considering a circular pipe network under the usual assumption, the pipe network operating status can be written in the following form.

\[ H(t) = F(\text{Junction}(t), \text{Pipe}(t), \text{Pump}(t)) \]

Usually the steady composition (E.g.: key node arrangement; piping layout; pump Selection; etc.) are used for the pipe network analysis. Take used of the key variable of the pipe network; establish the structural model for network analysis. Of course, there are still difficult to analyze the operating state based on the structural model using mathematical methods for each node and pipeline. Therefore, based on the static structure of the ship pipe network system using the Monte Carlo simulation method, analysis from the data layer, the co-simulation method obtain the appropriate variables and moderate parameters to measure the damaged state of the system.

3. Ship pipe network operating based on Monte Carlo simulation method

Operation of ship pipe network system is a discrete event system, which related to the state of the mission profile of the ship. Discrete event system depends on the state related to the discrete time changes. The changes which focus on the behavior of the system state called “events”, such systems are event-driven. Meantime, events tend to occur at a random time, so it is called random events [5].

To solute the discrete random events, three model suit for the Monte Carlo simulation: For the event model that does not consider the system run time and using a non-sequential order mode— so called non-sequential mode — form a large number of randomly drawn sample, then to simulate the system operation; for the event model that events according to the distribution model using sequential mode, that is according to the migration time series sequentially generates a corresponding random samples, then to simulate the system operation; for the event model that analyze the state transition model that acquire the sample during the state transition process, both to put forward a time-dependent and related to the status sample, then to simulate the system operation [6].

Ship pipe network system is a relatively complex system, and each node’s operation state affected by the ship’s tasks and the pipe network’s health status. For independent mission profile, the operating state of the pipe network relatively independent and randomness, and independent to the timing. Take the pipe network state into considerate, the non-sequential (non-sequential) mode Monte Carlo simulation method is suitable for the analysis.

Ignore all the key nodes anisotropy, assuming that the pipe network consist of N key nodes, i represents the i-node of the pipe network system, P represents the distribution system operating state, U(i) represents the pipe network system operating state of the i-node, Q(i) represents the state of design parameters of the normal operating range of the i-node network system. To the ship pipe network system, each node’s operational status is relatively independent, which can be expressed as:

\[
s_i = \begin{cases} 
0 , u_i \in q_i \text{(Node operating normally)} \\
1 , u_i \notin q_i \text{(Node operating abnormally)} 
\end{cases}
\]

Extracting any node operating state, q(i) combined with the state of the ship pipe network analysis, operational status of each node assessment, then acquire an operating state array:
Comparing with the parameters under normal operating conditions, acquire the k th sampling operating state array of the ship pipe network system:

\[ P(k) = (u_{1s1}, u_{2s2}, \ldots, u_{NsN}) \]

By K times sampling, the ship pipe network system operating state can be represented by a K × N matrix, which contains all key nodes. During the calculation process of operating state matrix, judging the normal operating key nodes, exclude the abnormal operating key nodes (the operating state \( s_i = 0 \)), and save the normal operate state permanents of each key nodes.

Wherein, during the K times sampling, \( \eta_i \) represents a random number on \([0,1]\) uniformly distributed, the parameter value of each node was produced by the linear congruently generator[7]. The recurrence formula can be show as:

\[
\begin{align*}
\eta_i &= \frac{x_i}{m} \\
x_i &= (ax_{i-1} + c) \mod m
\end{align*}
\]

In which, \( x_i \) means pseudo-random number, \( x_0 \) means initial value, \( m \) means modulus, \( a \) means multiplier, \( c \) means increments, and \( x_0, m, a, c \) are non-negative integers.

Via above method, each node’s operating status and key parameters can be obtain by sampling during the pipe network system operating under diversity conditions. Then a large number of random sampling network operations to obtain the state matrix, which can be used to assess the network or the nodes’ situation.

### 4. Ship pipe network damage targeting method based on fuzzy theory

After K times sampling based on Monte Carlo simulation method, we can acquire a set of operating state matrix \((K \times N)\) about the pipe network system. The sample collection can be show as \( Y = (y_1, y_2, \ldots, y_M) \subset \mathbb{R}^m \) (m means the dimension of the sample space, K means the number of samples). Divide the samples into c \((c > 1)\) subset based on the fuzzy clustering method [8]. This division method makes the objective function \( J(U, V) \) smallest under certain constraints, the function can be expressed as

\[
J(U, V) = \sum_{i=1}^{c} \sum_{j=1}^{n} u_{ij}^m d_{ij}^2
\]

s.t.

\[
\sum_{i=1}^{c} u_{ij} = 1, \quad 0 < \sum_{j=1}^{n} u_{ij} < n,
\]

\[
0 \leq u_{ij} \leq 1, \quad 1 \leq i \leq c, \quad 1 \leq j \leq n
\]

By iterative calculation function can be updated to acquire c clustering centers, the clustering center iterative calculation function can be expressed as

\[
v_i = \frac{\sum_{j=1}^{n} u_{ij}^m y_j}{\sum_{j=1}^{n} u_{ij}^m}
\]

By calculating the membership degree of sample points \( y_j \) departing from the cluster center \( u_{ij} \)

\[
u_{ij} = \left\{ \begin{array}{ll}
\left[ \sum_{r=1}^{c} \left( \frac{d_{ij}}{d_{rj}} \right)^{\frac{2}{m-2}} \right]^{-1}, & l_j = \emptyset \\
1, & l_j \neq \emptyset
\end{array} \right.
\]

\[
l_j = \{ (i, j) | y_j = v_i, \quad 1 \leq i \leq c \}\]

The fuzzy clustering algorithm classification of sample data to obtain the corresponding cluster center, through membership situation test sample to calculate the corresponding cluster center, and judging the classify of the sample point. Make use of Monte Carlo simulation method described above, a lot of random sampling pipe network operation parameters obtained by sampling the state matrix. The pipe network status matrix can be used as sample data to fuzzy clustering algorithm, the state
value of the pipe network at any time as the test sample, via the fuzzy clustering membership calculation result, to assess the ship pipe network system operational status and targeting the damage position. Specific steps are as follows:

Step 1: Build up the physical model of ship pipe network system, using the Monte Carlo method to set different operating states parameters and obtain the operating states matrix that is the sample data set.

Step 2: Standardized sample data sets. After the sample data generation, in order to eliminate the influence caused by differences during the nodes, linear function conversion method have been choose to normalize the characteristic parameters.

\[ x_j = \frac{y_j - \min\{Y\}}{\max\{Y\} - \min\{Y\}} \]

Step 3: Via the normalized sample data sets using fuzzy theory obtained by the method of fuzzy clustering model, access to the center of each cluster node during the normal operating state.

Step 4: Using the normalized fuzzy clustering sample data set established model test data spreadsheet and calculate the membership situation cluster centers test data.

Step 5: According to the analysis of membership degree, evaluate the state of the pipe network and acquire the operate assessment result of the network.

| Start |
|-------|
| Establish Ship Pipe Network System Model |
| Monte Carlo Simulation Calculation |
| Sample Data Set |
| Data Standardization |

Figure 2 Ship Network Operating State Evaluation Based on Monte Carlo Simulation

5. Case Analysis

During this paper, fire water pipe network of ship is selected as the research object to verify the applicability of the proposed method. The ship fire water pipe network is a complex dissipation pipe network, the relevant parameters can reflect the state of the pipe network system, such as the water consumption, the head pressure and the friction coefficient [9].

The case analysis model choose the fire water distribution system of a ship. The model is established and calculated by Epanet which was developed by Environmental Protection Agency of the USA.
Figure 3  Fire Water Pipe Network of Ship

Setting the sea surface as the ship fire water source, setting two main pump and one spare pump, and set the user node attributes, which to simulate the cabin or the location of the use of fire water. Each user node according to the design of water demand, under normal circumstances, according to different hydrant opening, the actual water demand in the 0 to design water requirements between the changes.

The Monte Carlo method is used to simulate the fire water distribution network of the ship. The actual water consumption is set by random sampling method, and the pressure value of each node is simulated under various working conditions. The pressure value of each node in the ship fire water pipe network system is taken as the sample data set. The Monte Carlo method is used to simulate N=2000 times, and the number of cluster center c=2, and calculate the pressure fuzzy clustering center of each node.

| ID | Design Water Consumption (Unit: L/S) | Actual Water Consumption (Unit: L/S) | Deck Height (Unit: m) | Attributes |
|----|---------------------------------|---------------------------------|-----------------|------------|
| 1  | 120                             | 0-120                           | 3               | Random Water Demand |
| 2  | 300                             | 0-300                           | 3               | Random Water Demand |
| 3  | 150                             | 0-150                           | 3               | Random Water Demand |
| 4  | 450                             | 0-450                           | 3               | Random Water Demand |
| 5  | 100                             | 0-100                           | 3               | Random Water Demand |
| 6  | 300                             | 0-300                           | 3               | Random Water Demand |
| 7  | 100                             | 0-100                           | 3               | Random Water Demand |
| 8  | 450                             | 0-450                           | 3               | Random Water Demand |
| 9  | 150                             | 0-150                           | 3               | Random Water Demand |
| 10 | 300                             | 0-300                           | 3               | Random Water Demand |
| 11 | 0                               | 0                               | 0               | Main Fire Pump |
| 12 | 0                               | 0                               | 0               | Main Fire Pump |
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![Figure 4 Fuzzy Clustering Center of Ship Fire Pipe Network System Node Pressure](image)

According to the model calculate the fuzzy clustering center of pressure detection value of each node under the normal operation state of the ship fire water pipe network system. Calculate the membership degree of each node compare with the fuzzy cluster center under normal operating condition, and evaluate the operating state of the fire water pipe network system.

Setting the No.7 as the abnormal node, the abnormal situation for the actual water consumption is greater than 20% of the maximum design water used to simulate the burst. The Epanet toolkit calling MATLAB to calculate the pressure value of each node, and the membership value of node pressure compare with the fuzzy clustering center under the normal operating state, and the result as it show in table2. The risk of damage assessment of the network is set according to the percentage of the membership, the membership degree is considered to be low-risk of damage in the range of 80%-100%; the membership degree is considered to be middle-risk of damage in the range of 50%-80%; the membership degree is considered to be high-risk of damage in the range below 50%.

| ID | Fuzzy Clustering Membership | Risk Assessment |
|----|-----------------------------|----------------|
| 1  | 90.7261%                    | Low            |
| 2  | 88.7130%                    | Low            |
| 3  | 90.8628%                    | Low            |
| 4  | 99.9997%                    | Low            |
| 5  | 99.7592%                    | Low            |
| 6  | 92.4875%                    | Low            |
| 7  | 46.0670%                    | High           |
| 8  | 81.5940%                    | Low            |
| 9  | 74.0480%                    | Middle         |
According to the results of the case analysis, when the actual water consumption fluctuates due to the occurrence of burst, the method can be used to characterize the node pressure relative to the membership degree of the node pressure fuzzy clustering center under the normal operating state. The No.7 node’s parameters deviates too much from node under normal operating state, which considered to be the high-risk of damage. The No.9 node and No.10 node considered to be the middle-risk of damage.

References

[1] Liu T. Dynamic Characteristics Analysis of the Ship Cooling Water Piping System [Dissertation]. Wuhan: China Ship Research Institute, 2014 5-9

[2] Cao H, Ma J, Jia B Z, et al. Research on Simulation and Control of Complex Turbine Network System Based on Distributed // Proceedings of 2010 The 3rd International Conference on Power Electronics and Intelligent Transportation System. Shenzhen, 2010: 468-469

[3] Moon, K. Self-reconfigurable ship fluid-network modeling for simulation-based design [Dissertation]. Georgia: Georgia Institute of Technology, 2010 20-35

[4] Liu T, Zhang J W. Static and Dynamic Characteristic Analysis of Ship Network System Based on AutoPIPE. China Water Transport, 2013, 13(11): 107-109

[5] Pan F M, Jiang M, Zhou J W. Design of Preferential Queuing Management Algorithm Based on NS2. J Chongqing Technol Business Univ., 2014, 31(11): 45-49

[6] Zeng C, Wu J, Zhu Y M, et al. Research on Monte Carlo Method in Reliability Simulation of Complex Systems. Journal of Sichuan Military Science and Technology, 2015. 13-17

[7] Zeng C, Wu J, Zhu Y M, et al. Research on Monte Carlo Method in Reliability Simulation of Complex Systems. Journal of Sichuan Military Science and Technology, 2015, 36(9):65-68

[8] Wu J, Hao G, Deng C, et al. Novel bearing performance degradation evaluation method based on fuzzy C-means clustering algorithm. Computer Integrated Manufacturing Systems, 2015, 21(4): 1047-1048

[9] Zhou Z Y, Huang G, Jin T. Research on leakage detection and location of the ship piping network. SHIP SCIENCE AND TECHNOLOGY, 36(10): 124-128