Ocean Engineering 164 (2018) 284–297

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Health monitoring of mooring lines in floating structures using artificial neural networks

Hamed Rezaniaiee Aqdam, Mir Mohammad Ettefagh*, Reza Hassannejad

Faculty of Mechanical Engineering, University of Tabriz, Tabriz, 51666-16471, Iran

ARTICLE INFO

Keywords:
Structural health monitoring
Damage diagnosis
Mooring lines
Finite element method
Uncertainty
Radial basis neural networks

ABSTRACT

Health monitoring of mooring lines is essential to ensure the safe performance of floating structures during the service life. In the literature and offshore industries, damage diagnosis of mooring lines is based on fatigue analysis by considering rope behavior. Mostly, this type of diagnosis is accomplished by the results, obtained from the simulation model of mooring system. Further, one of the important factors in modeling is applying uncertainties in the simulation model. In this paper, due to the complex behavior of mooring lines, a new design of Radial Basis Function (RBF) neural network is proposed for damage diagnosis. Also, the modeling method is based on Rod theory and Finite Element Method (FEM). In the proposed modeling process, for improving the accuracy of the modeling, boundary conditions uncertainty are applied using Submatrix Solution Procedure (SSP). Additionally, round-off error is removed by SSP. Finally, the proposed modeling and diagnosis are investigated experimentally. The obtained results showed that proposed RBF has better performance compared with conventional one and other well-known methods in the literature.

1. Introduction

Mooring lines are one of the critical components in the offshore structures such as TLP, floating vessels and wind turbines. Therefore, many academic researchers are interested in studying the mooring static and dynamic behavior. Moreover, because of the applied strong forces in the floating structures due to initial tensions and sea waves, the early diagnosis of mooring lines plays a crucial role in safe operation of these structures. The studies of the damage process in the mooring lines are based on different parameters such as fatigue rate analysis (Ma et al., 2013), strength capacity of a mooring system (Brindley and Comley, 2014), fatigue damage (Philipp et al., 2014), tension and durability of mooring lines (Christopher et al., 2000), (Banfield et al., 2005), (Ridge, 2006) and the failure risk of the mooring lines based on extended-period environmental loads (Huang and Pan, 2010). Thus, due to possible damages of mooring system, monitoring and maintaining should be performed according to the above mentioned parameters. One of the most common diagnosis methods in this field is based on Fuzzy logic (MentesIsmail, 2011), (Jahangiri et al., 2016), (Jamalkia et al., 2016). Despite the many advantages of the Fuzzy method in identifying severe damages, this method is not very successful in identifying the small and moderate damages. Another method for diagnosis is based on Fault-tolerant control (Fang et al., 2015). In control methods, fault diagnosis is possible by using vibration signals and structural reliability index. This type of diagnosis cannot be used in the floating structures with moving parts such as wind turbines, because in these structures, identification of defects in the moving parts of the turbine and mooring lines from each other is impossible.

The most powerful methods for the diagnosis of the mooring systems are based on the computer simulation. In the field of the mooring line modeling, the FEM is suggested as more accurate method. Similarly, a significant research in the modeling with FEM is suggested by reference (Tahar and Kim, 2008). In mentioned research, by introducing shape functions and suitable numerical method for the solution, the weak formulations for applying the FEM technique are written. It should be noted that, the uncertainty should be considered for accurate modeling of the mooring lines. Therefore, one of the most important steps in damage diagnosing of the mooring lines is applying the uncertainty in modeling of the mooring system (Vazquez-Hernandez et al., 2006), (Zhang and Gilbert, 2006), (Montes-Iturrizaga et al., 2007).

In this paper, firstly, SSP is employed to apply boundary conditions uncertainty in modeling. Furthermore, SSP is used to avoid large computational costs and round-off errors. Secondly, a new design of

Abbreviations: TLP, tension leg platform; ANN, artificial neural network; RBF, Radial Basis Function; RADBAS, radial basis neuron; FEM, Finite Element Method; *dist*, Euclidean distance function; SSP, Submatrix Solution Procedure

* Corresponding author.
E-mail address: ettefagh@tabrizu.ac.ir (M.M. Ettefagh).

https://doi.org/10.1016/j.oceaneng.2018.06.056
Received 22 July 2017; Received in revised form 30 April 2018; Accepted 22 June 2018

Nomenclature

$\boldsymbol{p}_1^i$	First input vector that is closest to weight vector
A_l	Cubic shape function
$\boldsymbol{p}_2^i$	Second input vector that is closest to weight vector
$\mathbf{a}^1$	First layer output
Q	Input vector/target pairs
$\mathbf{a}^2$	Second layer output
R	Number of elements in input vector
$\overrightarrow{B}$	Buoyancy force on the rod per unit length
r	Position vector
B	Bias
s	Arc length of the rod
$\mathbf{b}^1$	First layer bias
S^1	Number of neurons in first layer
$\mathbf{b}^2$	Second layer bias
S^2	Number of neurons in second layer
EI	Bending stiffness
$\tilde{T}$	Effective tension in the rod
$\overrightarrow{F^s}$	Hydrostatic force on the rod
t	Time
$F(x)$	Sum square error
t_Q	Q^{th} target vector
f_{net}	Extracted features of model
$\overrightarrow{w}$	Weight of the rod per unit length
IW	First layer weight
$\overrightarrow{\tilde{w}}$	Effective weight of the rod
K	Number of classes
$\mathbf{w}$	Weight vector
LW	Second layer weight
α	Noise level parameter
m	Midpoint of each class
μ	Probability distribution
n_c	Number of input vectors are located from the training set
ρ	Mass per unit length of the rod
P	Hydrostatic pressure
λ	Lagrangian multiplier
P_m	Quadratic shape functions
σ	Standard deviation
$\mathbf{p}$	Input vector
δ_{ij}	Kronecker Delta

artificial neural networks (ANNs) is proposed for health monitoring of the mooring lines. Selection of the proper ANN for specific case study is based on the input data of the ANN. In RBF networks, a vector distance is calculated directly (Euclidean distance), so RBF has more accurate results than the vector inner product which is used in other ANNs. The main disadvantage of conventional RBF is the limitation of the number of input data for training the ANN. Subsequently, the proposed new architecture of RBF is designed for solving the problems of conventional one.

The remainder of the paper is organized as follows. In Section 2, we start with modeling of the mooring systems by using the Rod theory, FEM and SSP, and then the proposed modeling is validated experimentally; Section 3 describes the uncertainties and damage classification of the considered case study; Section 4 presents the new architecture of RBF; The achievable performance of proposed method and other methods are investigated in Section 5; The conclusion of this paper is presented in Section 6.

2. Modeling of mooring lines

To mitigate the motion of the floating structures, mooring lines with different materials have been used in offshore industry. A steel wire rope with chains at both ends has been installed for Spar platform in deep water. Also, taut vertical mooring lines and tethers, composed of several vertical steel pipes, are intended to be installed in the TLP. Nowadays, synthetic mooring lines, made of polyester are considered as a more efficient solution. These types of mooring lines are applied in the floating structures in very deep water (over 6000 ft) (Young-Bok, 2003).

In this section, the static deflection of the polyester rope and the line tension are obtained by using the catenary equations. In the catenary equations, hydrodynamic forces on the line are not considered. However, for consideration of hydrodynamic effects on the line, the boundary and measurement uncertainties are used. Further, the strain and stress of the rope with geometric nonlinearity are solved with the beam theory using the updated Lagrangian approach. For this purpose, the Tensioned string theory is applied. In this theory, the string is modeled by using beam elements, where it is called the elastic Rod theory (Tahar and Kim, 2008) which is based on the formula, derived by Nordgren and Garret (Nordgren, 1974), (Garrett, 1982).

2.1. Rod theory

The behavior of a slender rod can be expressed in terms of the variation of the rod position. A position vector $r(s, t)$ is the function of the rod arc length " s " and time " t ". The Equations (1) and (2) are the fundamental equations of motion for the elastic rod, applied to the FEM formulation (Young-Bok, 2003).

$$\frac{1}{2}\left(\overrightarrow{r'}\cdot\overrightarrow{r'}-1\right)=\frac{T}{AE}\approx\frac{\lambda}{AE}-\left(EI\,\overrightarrow{r''}\right)''+\left(\lambda\,\overrightarrow{r'}\right)'+\overrightarrow{w}+\overrightarrow{F^s}=\rho\ddot{\overrightarrow{r}} \tag{1}$$

$$\rho\ddot{\overrightarrow{r}}+\left(EI\,\overrightarrow{r''}\right)''-\left(\tilde{\lambda}\,\overrightarrow{r'}\right)'=\overrightarrow{\tilde{w}} \tag{2}$$

$$\overrightarrow{\tilde{w}}=\overrightarrow{w}+\overrightarrow{B} \tag{3}$$

Where EI is the bending stiffness, ρ mass per unit length of the rod, scalar function $\lambda(s, t)$ is called Lagrangian multiplier, $\overrightarrow{w}$ is the weight of the rod per unit length, $\tilde{T}$ is the effective tension in the rod, and $\overrightarrow{\tilde{w}}$ is the effective weight or the wet weight of the rod. Prime denotes the derivative with respect to arc length s and the dot denotes the time derivative. Also, $\overrightarrow{F^s}$ is the hydrostatic force on the rod which is defined as follows:

$$\overrightarrow{F^s}=\overrightarrow{B}\left(P\overrightarrow{r'}\right)' \tag{4}$$

Where $\overrightarrow{B}$ is the buoyancy force on the rod per unit length, and P is the hydrostatic pressure at the point $\overrightarrow{r}$ on the rod.

2.2. Finite element method

As described in previous part of this section, the application of the FEM is started on the Equation (2) and following equation: