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Modeling of Wave Energy Absorption Based on BP Neural Network for Underwater Vehicles

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***Abstract* - As one of the renewable energy, the absorption and utilization of wave energy is always an important research field home and abroad, and energy absorption efficiency is the key. A wave energy absorption system based on inertial pendulum is presented, and dynamics equations are established. Neural network with learning rate adaptation is adopted to model in time domain. The results obtained by simulation software and by BP neural network are compared, which validate the method used are correct and make basis on future research.**

Index Terms* - *Wave energy. Inertial pendulum. Capture width ratio. Energy absorption efficiency. BP network with learning rate adaptation.

I. INTRODUCTION

Ocean is with a vast territory, and among which there is huge sea wave energy. As a renewable energy, wave energy has a prodigious development potential, and on national security, use of the earth's resources and scientific research, environmental monitoring, research and utilization of marine resources in both the present and the future are no doubt a very important strategic position. In recent years, with the impact of ocean on human society is growing, and the role ocean play on national security and economic is more important, marine unmanned system and autonomous system has become a frontier research area with strategic significance. Thus energy supply of marine unmanned autonomous system has become a new frontier technology. Currently, the utilization and research on ocean wave energy are mainly based on the way of onshore or anchoring, and the research of utilizing wave energy on artificial underwater carrier has been applied, such as a docking system developed by the AUV Laboratory at Massachusetts Institute of Technology (MIT), which can support the Autonomous Underwater Vehicle (AUV) to exchange power and data, and to transfer energy [1]. In 1997, sea trials of this system were done, and the results demonstrated that the maximum energy transfer rate of this system was estimated to be 80% [2]. In 2001, A. Maridan et al completed sea trials of their docking system for AUV, this trial mainly aimed at the complex task of docking an AUV, and the conversion efficiency was not mentioned [3].

Currently, there are some common problems in power used in artificial marine mobile systems (such as underwater vehicle, AUV et al), such as one-time energy, complex and difficult energy supplement et al, which make severe restriction but in marine system's autonomous task and duration time, also in research progress and application of artificial marine system. Ocean energy is one of the key technologies of unmanned and autonomous system, and autonomous power supplement technologies have been paid more attention to by researchers home and abroad. And AUV droved by solar energy and temperature difference energy come out one after the other [4], which produce new technical approaches for autonomous power supplement of ocean artificial system.

Aiming at solving problem of the autonomous power absorption of artificial load underwater, a new method faced on autonomous power supplement of small artificial ocean system is presented, and the energy absorption mechanism, based on inertial pendulum, is adopted. Meanwhile, the relative kinematics and dynamics model are gained, and a method based on adaptive learning rate BP network is adopted for modeling accurate mathematical model of wave energy absorption efficiency. The numerical results of wave energy absorption efficiency about inertial pendulum system gained by dynamics software and dynamics equations are trained by BP network, and an accurate mathematical model is gained, which will produce an effective theory analysis method and mathematical basis for further structure design and realization of inertial pendulum wave energy absorption structure.

II. MODELING OF INERTIAL PENDULUM SYSTEM

The pendulum without friction, in general mean, will reciprocate under the effect of gravity. If an outside excitation acts on the pendulum and makes it move, an inertial pendulum system is formed. And if the reciprocation of wave is used as outside excitation to drive the load with inertial pendulum to move, the inertial pendulum will move too. The movement of inertial pendulum is converted into usable mechanical energy, and the wave energy can be absorbed and utilized.

Based on this idea, a mechanical design of inertial pendulum used in absorbing wave energy is proposed, the diagram of this system is shown in Fig.1.

Suppose that an inertial pendulum with a mass m and multi-DOF is installed in a load with a mass M, and the whole system is ensured to float near the water surface. Besides gravity and buoyancy, the force on the system is mainly wave force. Under the action of wave force, the load will move with wave, and the velocity and acceleration of load are produced, and then the hydrodynamic forces are produced too.

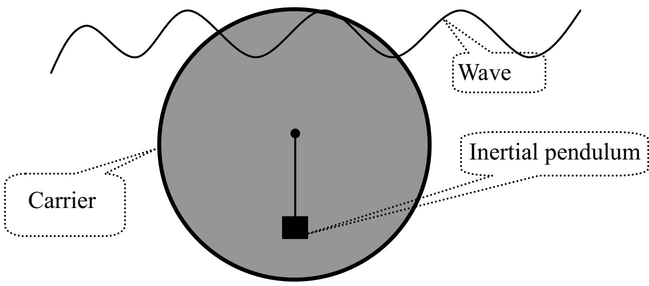

Fig.1 The diagram of inertial pendulum system

In order to gain the circumstance of inertial pendulum absorbing wave energy, dynamics equations and kinetic equations of total system under wave force should be modeled first. Then, an entity model can be established in dynamics simulation software to know circumstance of energy obtained by inertial pendulum inner.

Under the rigid body dynamics modeling method, and underwater carrier kinematics equations are set up. Assuming that carrier with inertial pendulum moves with wave and the angle of wave direction is zero, it can be known that there are three wave forces (or moment) acting on carrier, they are longitudinal force, vertical force and pitching moment respectively. That is, the equations can describe campaign state of carrier with wave force acting on [5].

$$\begin{cases} (m+\lambda_{11})\dot{u} - my_G\dot{r} - mvr - mx_G r^2 = F_{xwave} + \frac{1}{2}C_x\rho V_T^2 S \\ (m+\lambda_{22})\dot{v} + (mx_G + \lambda_{26})\dot{r} + mur - my_G r^2 = F_{ywave} \\ +\frac{1}{2}C_y\rho V_T^2 S \\ (I_z+\lambda_{66})\dot{r} - my_G\dot{u} + (mx_G+\lambda_{26})\dot{v} + mx_G ur + my_G vr = \\ G(-x_G\cos\theta + y_G\sin\theta) + M_{zwave} + \frac{1}{2}m_z\rho V_T^2 L \\ \dot{\theta} = r \\ \dot{X}_e = u\cos\theta - v\sin\theta \\ \dot{Y}_e = u\sin\theta + v\cos\theta \\ V_T = \sqrt{u^2+v^2} \\ \alpha = \arctan(-v/u) \end{cases} \tag{1}$$

where, m is mass of system, I_z is rotational inertia, u、v are system velocity in directions of horizontal force and vertical force respectively, r is rotational angular velocity of system, and (x_G, y_G, z_G) is the coordinate of mass centre of system. Because of the moving pendulum, coordinate of mass centre of system is changeable. $F_{xwave}, F_{ywave}, M_{zwave}$ are wave forces (and moment), $\lambda_{11}, \lambda_{22}, \lambda_{26}, \lambda_{66}$ are coefficients of inertial hydrodynamic forces, C_x, C_y, m_z are the coefficients of viscous hydrodynamic forces, θ is pitching angle of system, and （ X_e, Y_e, Z_e ） is the relative position of mass centre of system and ground coordinates. α is incidence angle of system, V_T is the velocity vector of system, i.e., the velocity of system coordinates origin.

III. BP Network Modeling of Wave energy Absorption Efficiency of Inertial Pendulum

A. *Several Definitions*

To analyse and study the energy absorption efficiency of inertial pendulum, the following definitions are made:

Capture width ratio (η): ratio of average energy obtained by system in one wave period to the average wave energy in the same width.

Energy absorption ratio (η_r): ratio of average energy obtained by inertial pendulum in one wave period to the average energy obtained by system.

Energy absorption efficiency (β): $\beta = \eta_r \cdot \eta$.

As all know, the average wave energy of units' horizontal area can be described by:

$$E = \frac{1}{8}\rho g H^2 \tag{2}$$

where, ρ is the consistency of liquid, is H the height of wave (wave peak to wave valley), and g is the gravity acceleration.Thus, the average wave energy in system horizontal area can be gained by (2).

Energy absorption efficiency β is a very important parameter, which decides the performance of system. Even wave frequency and wave height are in the same condition, with the different radius of external carrier and mass of pendulum, capture width ratio and energy absorption ratio may be different, and the energy absorption efficiency will also major changes. From equation (1), can be known that the dynamics equations are strong nonlinear and coupling. So, it will be difficult to gain capture width ratio and energy absorption ratio of system through dynamics equations at time domain. Besides, it will also be more difficult to gain the movement circumstance of inner inertial pendulum by dynamics equations modelled, so the energy absorption circumstance is. Thus, based on dynamics equation established as (1), the dynamics simulation software is introduced to obtain movement and energy absorption circumstance of internal inertial pendulum. Through modelling in software many times, capture width ratio and energy absorption ratio of system with different radius and different mass ratio of external carrier and inner inertial pendulum can be gained, and energy absorption efficiency can be calculated. But it is so difficult and a thing wasting time to describe the relations of (1) and to model one by one. Therefore, a mathematical model of energy absorption efficiency β should be established.

B. Model System with Inertial Pendulum in Dynamics Simulation Software

An entity model can be established in dynamics simulation software based on fig. 2. And in order to be advantageous for the research, makes the following supposition: first, the fluid is the ideal and incompressible, and the campaign is irrotational; second, wave depth is infinite and belongs to the micro wave; third, the effect produced by object' exist can not be considered; forth, the inner air resistance and fiction force of object underwater can be neglected; finally, the system moves with wave, and there are only three forces and moment to be considered, longitudinal force, vertical force and pitching moment.

Besides, to study conveniently, the randomicity of wave dose not be considered for a while, and only the model of energy absorption efficiency of inertial pendulum under monochromatic wave is considered. Suppose the period of wave is 5s, the height of wave is 4m, and the density of water is $1000kg/m^3$.

In order to analyze and simulate the movement of system, the shape of load is designed as a spheroid，and the model is established in simulation software. For example, suppose that the radius of load is 0.22m, the total mass of system is 44kg, and the mass of pendulum is 20kg, and the model established as fig. 2, in which the model consists of shell, pendulum and link three part, and parameters of every part are showed in table 1.

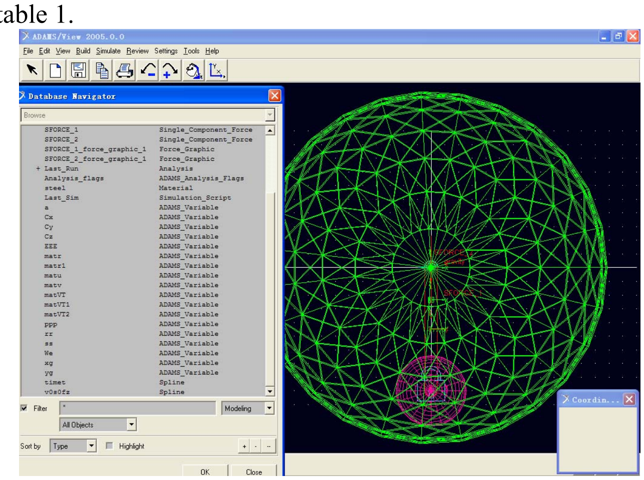

Fig. 2 Model in simulation software

TABLE I

Parameters of Every Part of Simulation Model

Part	Size(m)	Mass (kg)	Moment of inertia relative to mass centre (kg·m²)		
			Ixx	Iyy	Izz
Carrier	φ0.22（min） φ0.215（max）	22.48	1.347	1.347	1.347
Link	φ0.004×0.0298	0.002	7.85×10^{-7}	7.85×10^{-7}	7.85×10^{-7}
Pendulum	φ0.0078	22	5.36×10^{-2}	5.36×10^{-2}	5.36×10^{-2}

To describe (1) in simulation software accurately, not only the relative force, velocity and mass centre et al variables should be added to, but also many other variables should be established as shown in fig. 2. From fig. 2 can be seen that it has been very complex to model under one of system conditions, and to model under many system conditions will be more difficult.

C. BP Network Model

a. The network Structure

Researches has indicated that a network with deviation , at least one hidden layer of S-type and a linear output layer can approximate to any rational function [6]. Based on this, a BP neural network with three layers (as shown in fig. 3) is selected, which includes one input layer, one hidden layer and one output layer. When wave is in certain conditions, the factors impacting energy absorption of pendulum are major radius of external carrier and mass ratio of pendulum to external carrier. Then, there are two nodes in input layer of BP network.

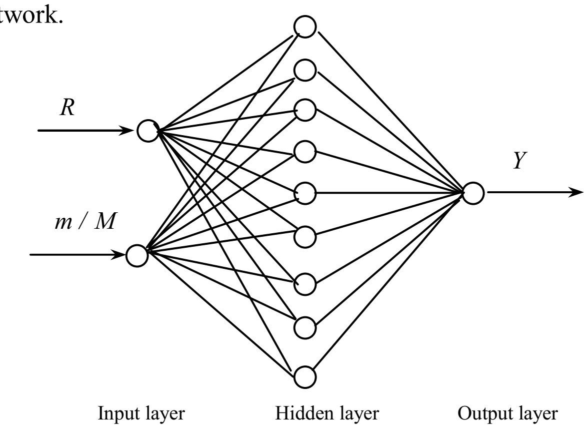

Fig. 3 Structure of BP network

Input layer includes a two-dimensional vector, namely $X^n = [R^n, (m/M)^n]$; where, R is radius of the external carrier, m/M is mass ratio of pendulum to external carrier. The output layer Y contains an element, which is the energy absorption efficiency of pendulum, namely $Y = \beta^n$,（$n = 1,2,\cdots,N$）. Besides, hyperbolic function S is adopted as input layer function and linear function is adopted as the output layer function. Therefore, the final output function should be as follow:

$$\beta = w_1 \frac{e^x - e^{-x}}{e^x + e^{-x}} + b_2 \qquad (3)$$

where, $x = w_1 p + b_1$, p is input vector combined by radius of external carrier and mass ratio of pendulum to external carrier，and others such as w_1, w_2, b_1, b_2 are gained by neural network.

b. Method of Network Learning

Gradient descent algorithm is usually adopted in conventional BP network, which only search along the negative gradient direction and can be led into local minimum value of network easier. At the same time, because of the fixed rate being adopted, the entire network convergence speed is very slow. Learning rate decides the weight variation produced in every training cycle, and bigger learning rate may result in an unstable system, on the other hand, smaller learning rate will lead longer training time and lower convergence speed. Thus, BP network with learning rate adaptation method is presented to adjust the study rate automatically during train. The concrete idea is: an initial step is set first, then to check whether the error function is lowered by modified weight. If answer is affirmative, the learning rate is low, and should be increased .If it is negative, it has been stressed and should be reduced. The adjustment equation of adaptive learning rate is as follow [7]:

$$\eta(k+1)=\begin{cases}1.05\eta(k) & E(k+1)<E(k),\\ 0.7\eta(k) & E(k+1)>1.04E(k),\\ \eta(k) & else\end{cases} \quad (4)$$

where, η is learning rate, k is training times, and $E(k)$ is the accumulated sum-square error.

IV. Simulation Results

Suppose that the radius of external carrier are 0.1m, 0.22m, 0.45m, 0.55m respectively, and models with different mass ratio of pendulum to external carrier are established in simulation software. Data gained is indicated in table2.

TABLE II
Data for BP Network Training

a (m)	0.1	0.1	0.22	0.22	0.45	0.45	0.55	0.55
m/M	0.0508	0.1070	1.0000	0.2900	0.0269	0.0553	0.0220	0.0450
$\overline{E}$ (Nm)	616.17	616.17	2982.3	2982.3	12477	12477	1863.9	1863.9
β (%)	0.17	0.29	8.15	3.36	1.14	2.32	1.15	2.30

Where, a denotes the radius of external carrier, $\overline{E}$ is average wave energy in horizontal carrier area.

Parameters of BP network are set that display frequency is 10, max training number is 35000, max sum-square error is 0.001, and initial learning rate is0.01. When training time reach 2452 and sum-square error is 0.000995103, training stops, and the variety of sum-square error and learning rate are shown as fig. 4. Finally, the weight and threshold of input and output network are gained, respectively, as follow:

$$w_1=\begin{bmatrix}9.1045 & 0.2864\\ -2.5151 & 5.3265\\ 5.4115 & -3.6646\\ 7.6160 & 3.7129\\ -8.6221 & -0.6258\\ 8.7719 & 1.4148\\ 3.9399 & 5.4104\\ 6.4573 & -4.1519\\ -8.7059 & 0.7142\end{bmatrix}, b_1=\begin{bmatrix}-3.2605\\ 1.0923\\ -0.2037\\ -4.2849\\ 4.6139\\ -3.6728\\ -2.4025\\ -3.2520\\ 5.0923\end{bmatrix},$$

$$w2=[0.5211 \quad 2.8832 \quad 1.3898 \quad 1.7571 \quad -0.2491 \quad 0.3381 \quad 2.8145 \quad -2.7868 \quad -0.0437],$$

$$b_2=0.4194$$

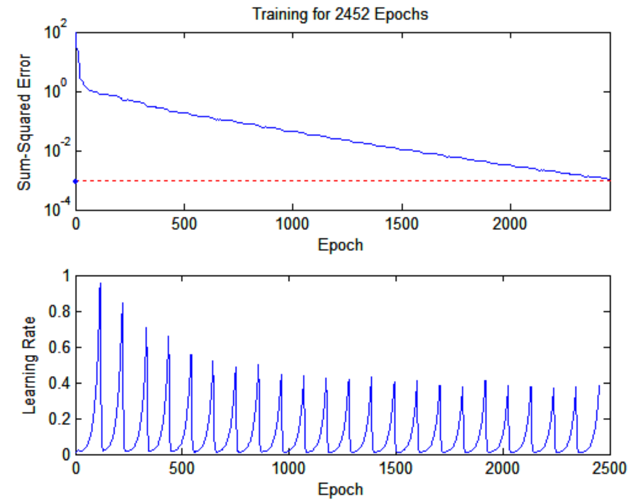

Fig. 4 Sum-square error and learning rate of neural network during training

After training is finished, accuracy of network should be validated. Therefore, network used is tested based on table 3. In the same condition, results from network trained as shown in the third row in table 3 and results from simulation in the forth row in table 3 are compared.

TABLE III
Results of BP Network Test

a (m)	0.22	0.22	0.3	0.55	0.45
m/M	0.5088	0.1267	0.0561	0.0658	0.1171
Results from network trained β (%)	5.41	1.55	1.27	3.30	4.70
Results from simulation β (%)	5.42	1.52	1.14	3.34	4.70
Error rate	-0.0018	0.0197	0.1140	-0.0120	0

From table 3, what can be known is the average error rate of trained neural network reach to 0.0295, which indicates the neural network method and trained network can describe the circumstance of energy obtained of inertial pendulum very well, and researches of system with inertial pendulum can be done based on the network trained. Based on the network trained, a relation surface of radius of external carrier, mass ratio of pendulum to external carrier and energy absorption efficiency of pendulum is formed (as shown in fig. 5), from which the best proportion of carrier radius and mass ratio of pendulum to carrier can be known when the max energy absorption efficiency is wanted.

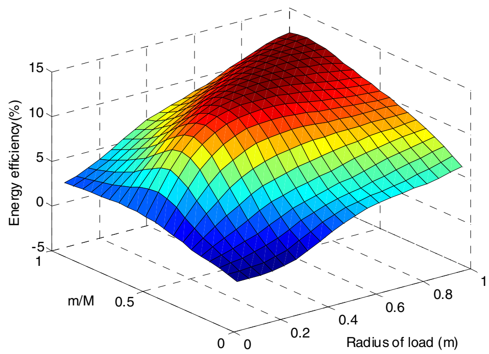

Fig. 5 Relation surface of energy absorption efficiency

V. CONCLUSIONS

Through establishing the dynamics equations of inertial pendulum system and modeling entity model in simulation software, circumstances of energy obtained of pendulum and carrier in different conditions are studied and then the energy absorption efficiency can be calculated. Then, based on data gained in different conditions, BP network is trained to gain the mathematical model of energy absorption efficiency. Finally, results gained by network trained are compared with test data obtained by simulation software, and the results proved the model is reliable, and which will provide a new validate modeling channel for future research of wave energy obtained automatically. Meanwhile, it will also lay foundations for future research energy obtained under different wave conditions. And it is needed to study energy absorption efficiency under different wave conditions further.

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