Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 7, No. 2, 2023

Vibration Control of Marine Flexible Riser with Uncertain Model

Miaomiao Chen, Ruihan Zhang, Li Zhou, Shuyu Xiao, Xu Zheng, Xueyi Wu

School of Mechatronic Engineering, Southwest Petroleum University, Chengdu 610500, China

Abstract: When flexible risers in the ocean are subjected to various environmental loads in the ocean, vibration will inevitably occur. Due to the nonlinearity and uncertainty of the actual riser system, it is impossible to obtain an accurate mathematical model of the riser system. The existing control algorithms designed based on the precise model of the riser system cannot meet the actual control requirements. A flexible riser boundary control method based on fuzzy control algorithm is proposed to suppress the vibration of marine flexible riser systems with uncertain models. Firstly, the dynamic models of existing marine flexible risers were studied. In response to the uncertainty of the riser system model, the control experience was transformed into an automatic control strategy in the form of fuzzy language control rules to improve the adaptability of the controller. Then, combining boundary control technology with fuzzy control, a boundary controller is constructed to stabilize the riser in a small neighborhood of its original position and reduce fatigue damage to the riser. Finally, the effectiveness of the designed fuzzy boundary control algorithm was verified through MATLAB simulation results, and the vibration suppression effect of the algorithm on the vertical tube was better than that of traditional PD control.

Keywords: Model uncertain, Marine flexible riser, Variable universe fuzzy control, vibration Control, Boundary control.

1. Introduction

Marine flexible risers are important components that connect underwater oil wells and offshore platforms, and are also a weak link in offshore oil transportation. Due to its unique working environment, the phenomenon of riser vibration will be difficult to avoid, and vibration will cause riser fatigue, shorten its working life, increase its production costs, and may bring fatal safety production risks [1-3].

The flexible riser system is usually simplified as a typical Euler Bernoulli beam model due to its large aspect ratio, and its dynamic characteristics are represented by both infinite dimensional partial differential equations and finite dimensional ordinary differential equations[2-4]. Its flexible structure is represented by an infinite number of modes, and its structural parameters may also change with the vibration of the riser, making its control design more difficult. In order to solve the vibration suppression problem of flexible riser systems, a large number of scholars at home and abroad have designed various control schemes. When modeling the system, He et al[4]. considered the coupling between the riser and the production ship on the sea, and added the damping coefficient of the ship on the sea to obtain a more accurate riser ship model. Based on this model, a robust adaptive boundary controller was proposed to reduce its lateral vibration displacement. JIN et al[5]. designed a flexible riser dynamic actuator for boundary control based on Lyapunov's direct and inverse methods. LIU[6] studied the vibration suppression problem of nonlinear flexible riser systems under external disturbances, and proposed a new joint control method of boundary control and iterative learning control using finite dimensional backstepping control and Lyapunov's direct method. He[7] proposed a boundary robust adaptive anti saturation control to eliminate nonlinear input saturation effects, compensate for boundary disturbances, and suppress riser vibration. In recent years, significant achievements have been made in the dynamic analysis and boundary control design of flexible riser systems[8-15]. The above control methods are all based on the precise mathematical model of flexible risers. However, due to the complexity, nonlinearity, time-varying, uncertainty, etc. of the actual system, an accurate mathematical model cannot be obtained.

In comparison, the outstanding advantage of fuzzy control as an intelligent control is that it does not rely on the precise mathematical model of the controlled object and is a rule-based control method. This article proposes a fuzzy algorithm based flexible riser boundary control method for the vibration control of marine flexible riser systems with unknown mathematical models. The system is controlled by boundary actuators, which can quickly and effectively suppress riser vibration and stabilize the riser in a small neighborhood of its original position. And the effectiveness of the designed control algorithm was verified through MATLAB simulation experiments.

2. Dynamic Model of Riser System

Figure 1 shows a typical type of marine flexible riser system. The origin of the coordinate system is located at the bottom of the riser, and the controller is located at the boundary of the riser (introducing the acquisition ship's brake (i.e. the top boundary of the riser) as the control input to generate lateral force to suppress the vibration of the riser, and the direction is to the right. Among them, the length of the riser is L, the lateral vibration offset of the riser is $w(x,t)$, the distributed current load acting on the riser is $f(x,t)$, the boundary disturbance is $d(t)$, and the time and space variables are t and x, respectively. For simplicity, the following simplified symbols are used in the text:

$$w'(x,t)=\frac{\partial w(x,t)}{\partial x},\ w''(x,t)=\frac{\partial^2 w(x,t)}{\partial x^2},\ w'''(x,t)=\frac{\partial^3 w(x,t)}{\partial x^3},$$

$$w''''(x,t)=\frac{\partial^4 w(x,t)}{\partial x^4},\ \dot{w}(x,t)=\frac{\partial w(x,t)}{\partial t},\ \ddot{w}(x,t)=\frac{\partial^2 w(x,t)}{\partial t^2}。$$

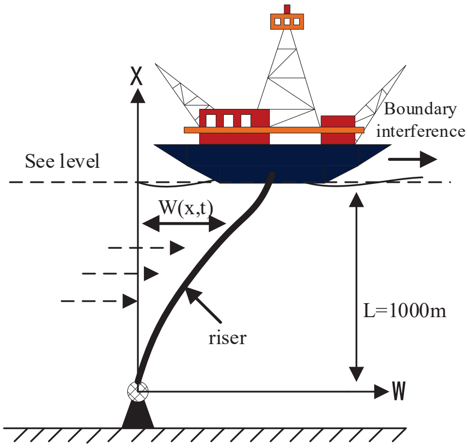

Figure 1. Typical Marine Flexible Riser System

To verify the effectiveness of the control algorithm designed in this article, a dynamic model of the flexible riser system from reference [4] was introduced for simulation analysis. According to equations (9) - (15) in reference [4], the state equation for riser control is obtained as

$$\rho\ddot{w}(x,t)+EIw''''(x,t)-Tw''(x,t)-f(x,t)+c\dot{w}(x,t)=0 \tag{1}$$

$\forall(x,t)\in(0,L)\times[0,+\infty)$, the boundary conditions are

$$w''(L,t)=w'(0,t)=w(0,t)=0 \tag{2}$$

$$-EIw'''(L,t)+Tw'(L,t)-d(t)+d_s\dot{w}(L,t)+M_s\ddot{w}(L,t)=u(t) \tag{3}$$

$\forall t\in[0,+\infty)$, the initial condition is

$$w(x,0)=\dot{w}(x,0)=0 \tag{4}$$

2.1. Time-varying ocean current load

The distributed ocean current load interference on flexible risers can be expressed as follows [4]

$$f(x,t)=\frac{1}{2}\rho_s C_D U^2(x,t)D+A_D\cos(4\pi f_v t+\theta) \tag{5}$$

Among them, ρ_s is the density of seawater, C_D is the resistance coefficient, D is the outer diameter of the pipeline, A_D is the amplitude of the oscillation part of the resistance, which is taken as 20% of the first term in $f(x,t)$, and the vortex shedding frequency f_v can be expressed as

$$f_v=\frac{S_t U(x,t)}{D} \tag{6}$$

Among them: S_t is the Strouhal number. The relationship between ocean current velocity and depth [9] can be expressed as

$$U(x,t)=\frac{x}{1000}U(t) \tag{7}$$

The velocity $U(t)$ of the ocean surface current is [4]

$$U(t)=\bar{U}+U'\sum_{i=1}^{4}\sin(w_i t)\text{，}\quad i=1,2,3,4 \tag{8}$$

Among them: $w_i=(w_1,w_2,w_3,w_4)=(0.867,1.827,2.946,4.282)$, $\bar{U}=2m/s$ is the average flow velocity of the internal flow, $U'=0.2$ is the average flow velocity of the internal flow.

2.2.1.2 Boundary environmental interference

The environmental interference $d(t)$ [4] at the boundary is

$$d(t)=[3+0.8\sin(0.7t)+0.2\sin(0.5t)+0.2\sin(0.9t)]\times10^5 \tag{9}$$

3. Controller Design

The control objective is to suppress the vibration of the riser under the action of time-varying distributed ocean current load $f(x,t)$ and boundary environment interference $d(t)$, so as to stabilize the riser in a small neighborhood of its original position. In this section, a variable universe fuzzy algorithm will be used to construct a fuzzy boundary controller on the upper boundary of the riser, which will control the vibration of the riser.

3.1. Fuzzy Control

Fuzzy control is a type of computer mathematical control method based on fuzzy set theory, fuzzy language variables, and fuzzy reasoning. It does not rely on the mathematical model of the controlled object and has strong robustness and anti-interference ability. The system adopts a two-dimensional fuzzy controller, which is a dual input single output fuzzy controller. The input signal e is the error signal ec and its rate of change, and the control output of the controller is u . Firstly, based on the database, determine the membership degree of fuzzy language variables corresponding to the precise values of input elements in the basic domain, and complete fuzzification. Then, based on the membership degree of the input element and the rule base inference, the membership degree of the output element is obtained, and fuzzy inference is completed. Finally, based on the membership degree of the output elements and the deblurring method, accurate values of the output elements are obtained to complete deblurring.

3.1.1. Determining the Basic Domain and Fuzzy Domain

The basic domain is described as a set of precise input and output values of a fuzzy control fuzzy controller. The input value is the deviation error e of the vertical pipe vibration and the change rate ec of the deviation error of the vertical pipe vibration, and the output u is the controller output control force. The fuzzy domain is described as a set of language values for the input and output of a fuzzy controller. Three language variables are divided into 7 language value levels, with the language level of input e being { ZO 、 BS 、 MS 、 M 、 SB 、 MB 、 B }, and the corresponding language numerical values being {0, 1, 2, 3, 4, 6, 8}. The language value level of input quantity ec is { MB 、 NM 、 NS 、 ZO 、 PS 、 PM 、 PB }, and the corresponding language numerical values are {-3.5, -2, -1, 0, 1, 2, 3.5}. The language value level of the output is { NB 、 NM 、 NMS 、 NS 、 ZO 、 PS 、 PM }, and the corresponding language numerical values are {-5, -4, -3, -1, 0, 1, 2}.

3.1.2. Creating a Database and Rule Base

The purpose of establishing a database is to determine the membership functions of input and output fuzzy language variables. The database includes three membership functions for input and output, which can be set to be consistent during preliminary design based on experience. Considering the accuracy and simplicity of fuzzification, fuzzy reasoning, and the process of solving fuzziness, Z-shaped membership functions are used at both ends, and triangular membership functions are used in the middle region. The two input quantities of the two-dimensional fuzzy controller are set to 7 language value levels, so 49 control rules can be obtained, forming a control rule table. The fuzzy response table is shown in **Table 1**.

Table 1. Fuzzy Response Table

ec \ e	0	1	2	3	4	6	8
-3.5	2	2	1	1	0	-1	-1
-2	2	1	0	-1	-1	-3	-3
-1	1	0	-1	-1	-3	-3	-4
0	0	-1	-1	-3	-3	-4	-4
1	-1	-1	-3	-3	-3	-4	-4
2	-1	-3	-3	-4	-4	-5	-5
3.5	-3	-3	-4	-5	-5	-5	-5

3.1.3. Fuzzy Control Operation

The fuzzification process directly determines the membership function values of elements based on the database. The Mamdani method is used for fuzzy reasoning, and the area center of gravity method is used for solving ambiguity.

4. Simulation Analysis

To verify the effectiveness of the flexible riser boundary control method based on variable universe fuzzy algorithm proposed in this article, this control method was applied to the vibration control of the neutral pipe system (see equations (1) - (4)) in reference [4]. The system parameters are shown in Table 1 of reference [4]. This section uses the finite difference (FD) method to simulate and analyze the vibration of a 1000m long marine flexible riser system 400 under the combined action of distributed ocean current loads and boundary disturbances.

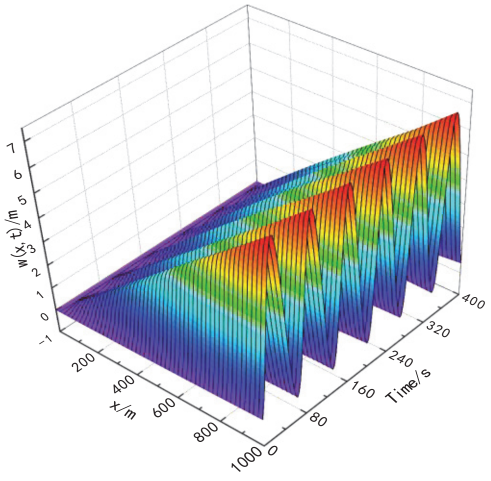

Figure 2. Vertical pipe vibration three-dimensional diagram (without control)

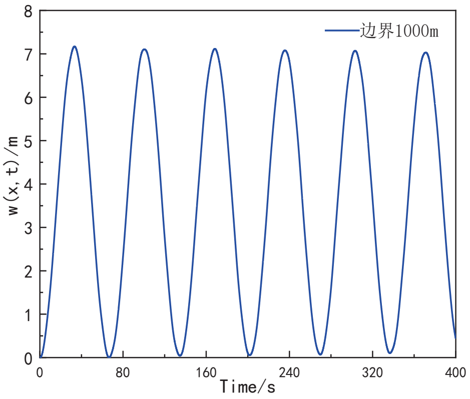

Figure 3. Offset of flexible riser boundary (without control)

From Figure 2 and Figure 3, it can be seen that under the combined action of distributed ocean current loads and boundary disturbances, without active control being applied, the riser oscillates periodically, with a large vibration offset range of 0.72m, which will seriously affect the performance of the riser.

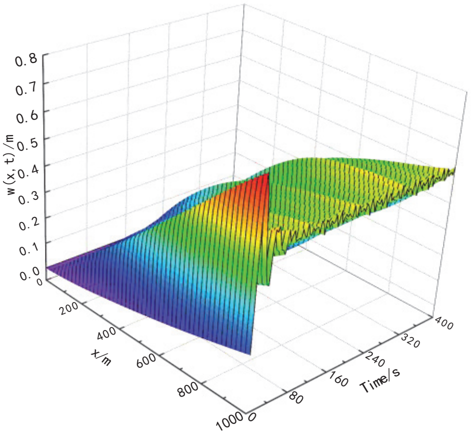

Figure 4. 3D Diagram of Riser Vibration under PD Control

Figure 4 shows a three-dimensional diagram of the vertical pipe vibration under PD control. Under PD control, the vertical pipe vibration is effectively suppressed, and the deviation of the vertical pipe boundary vibration will be stabilized at 0.4 0.5. Compared with Figure 4, the vibration of the riser is effectively suppressed.

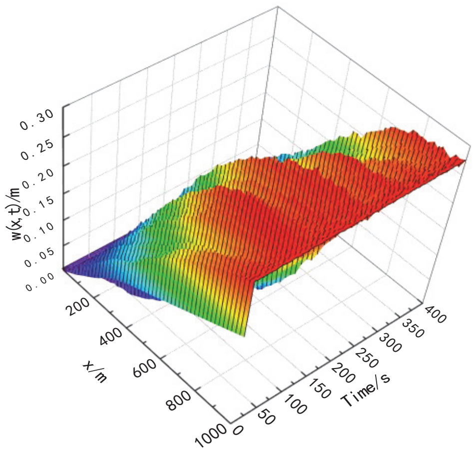

Figure 5. 3D Diagram of Riser Vibration under Fuzzy

Control (49 Control Rules)

The three-dimensional vibration state of the riser under the action of a fuzzy controller (49 fuzzy control rules) is shown in **Figure 5**. The three-dimensional vibration state of the riser under the action of a fuzzy controller (25 fuzzy control rules) is shown in **Figure 5**. From **Figure 4** and **Figure 5**, it can be seen that the more fuzzy control rules there are, the more effective the fuzzy controller is in suppressing the vibration of the opposite tube, and the better the control effect. However, the intricate and complex control rules increase the difficulty of controller calculation, leading to a decrease in control rate and affecting the real-time performance of the system.

5. Conclusion

This article focuses on the vibration control problem of marine flexible risers under time-varying ocean current loads and boundary disturbances with uncertain mathematical models. A flexible riser boundary control method based on variable universe fuzzy algorithm is proposed to suppress riser vibration. Apply the designed control algorithm to the existing riser system model for simulation analysis, and compare the control effect with traditional PD control and fuzzy control. The simulation results show that the boundary control algorithm designed in this paper can quickly stabilize the riser in the small neighborhood of its original position, greatly reducing the vibration offset of the riser, and has good robustness and adaptability, thus effectively compensating for the uncertainty of the riser system and external load. Its control effect is better than PD control, single fuzzy control, and can use less control rules to achieve ideal control effect.

Acknowledgment

The study is support by 2022 Innovation and Entrepreneurship Training for College Students in Sichuan Province (S202210615168)

References

[1] Peng J H, Zhu B S, Zong Z. A numerical simulation model for the vortex induced vibration of flexible risers using dynamic stifness matrices [J]. Ocean Engineering, 2019, 178:306-320.

[2] Liu J, Guo X Q, Wang G R, et al. Bi-nonlinear vibration model of tubing string in oil & gas well and its experimental verifification [J]. Applied Mathematical Modelling, 2020, 81:50-69.

[3] MA B, SRINIL N. Planar dynamics of inclined curved flexible riser carrying slug liquid–gas flows [J]. Journal of Fluids and Structures, 2020, 94:102911-.

[4] HE W, GE S S, HOW B, et al. Robust adaptive boundary control of a flexible marine riser with vessel dynamics [J]. Automatica, 2011, 47(4):722-732.

[5] JIN F F, GUO B Z. Lyapunov approach to output feedback stabilization for the Euler–Bernoulli beam equation with boundary input disturbance [J]. AutomaticaM 2015, 52:95-102.

[6] LIU Y , Zhang Q Y , FU Y . Vibration suppression of a flexible riser by boundary iterative learning control [J]. IEEE Access, 2019, 7:130262-130269.

[7] ZHAO Z J, HE X Y, WEN G L. Boundary robust adaptive anti-saturation control of vibrating flexible riser systems [J]. Ocean Engineering, 2019, 179:298-306.

[8] HE W, CHEN Sun, SHUZHI Sam. Top Tension Control of a Flexible Marine Riser by Using Integral-Barrier Lyapunov Function [J]. IEEE/ASME transactions on mechatronics, 2015, 20(2):497-505.

[9] Guo F, Liu Y, Luo F. Adaptive stabilisation of a flexible riser by using the Lyapunov-based barrier backstepping technique [J]. Control Theory & Applications, 2017, 11(14):2252-2260.

[10] Guo F, Liu Y, Luo F, et al. Observer-based backstepping boundary control for a flexible riser system [J]. Mechanical Systems & Signal Processing, 2018, 111: 314-330.

[11] Zhao Z, He X, Wen G. Boundary robust adaptive anti-saturation control of vibrating flexible riser systems [J]. Ocean Engineering, 2019, 179:298-306.

[12] Liu Y, Zhang Q Y, Fu Y. Vibration Suppression of a Flexible Riser by Boundary Iterative Learning Control [J]. IEEE Access, 2019, 7: 130262-130269.

[13] Yang C, Du J B, Cheng Z B, et al. Flexibility investigation of a marine riser system based on an accurate and efficient modelling and flexible multibody dynamics [J]. Ocean Engineering, 2020, 207:107407

[14] Zhao Z J, Ahn C K, Wen G L. Cooperative disturbance rejection control of vibrating flexible riser systems [J]. Nonlinear Dynamics, 2020, 99:1779.