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Control Method of Constant Force Grinding based on Active and Passive Control *

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***Abstract* - In recent years, bone cutting tool-ultrasound osteotome has been used in the treatment of spinal stenosis. However, the contact force has a great influence on its cutting performance. The cutting speed will be reduced, if the connecting force is too small or too excessive. At present, the clamping devices at the end of the surgical auxiliary robot are mostly rigid connections, which will lead to the instability of the contact force between the surgical instruments and the vertebrae and the inability to achieve efficient and safe grinding. In this paper, a flexible force stabilizer for clamping ultrasonic bone knives is designed based on active-passive combined control mode. A flexible element is added in the ending grasp device to eliminate the sudden change of the contact force. An adaptive fuzzy controller is designed outside the loop to adjust the ideal contact force between the osteotome and the lamina according to the difference with the actual contact force for real-time adjustment. Through comparison experiments, the validity and feasibility of the active-passive combined hybrid control method for the contact force control of the end of the bone knife was verified.**

Index Terms* - *fuzzy control, active and passive control, grinding

I. INTRODUCTION

Ultrasonic osteotome is a new type of surgical instrument, which has the advantages of precise resection of specific bone tissue and good tissue selectivity [1, 2, 3]. In recent years, more and more attention has been paid to ultrasonic osteotome in the medical field, especially in spinal surgery [4, 5]. it is sensitive to the end contact force, and the contact force will directly affect the cutting quality, which will affect the surgical effect. Therefore, how to ensure that the contact force is relatively stable within a certain range is an urgent problem to be solved in the application of ultrasonic bone knives in robot-assisted surgery.

Lumbar spinal stenosis (LSS) is a common spinal disease with low back pain caused by compression of the medial spinal cord nerve in the spinal canal wall [6,7].Laminectomy, shown in Figure 1, is the primary means of relieving pain, discomfort, and disability caused by LSS [8,9].At present, the traditional bone drill is used as the main surgical instrument for grinding operation in the laminectomy [10,11]. However, the cutting process of traditional bone drill can not identify biological tissue [12]. Irreversible serious damage will be caused when it touches nerves or blood vessels, if it is not handled properly. So, most researchers focus on how to ensure accurate positional positioning in the field of robot-assisted spinal surgery research [13]. It is suitable for the traditional bone drill operation scheme to focus on accuracy location, which can ensure the patient's surgical safety and surgical effect. However, when using ultrasonic bone knife, accurate position control can not ensure a stable contact force because of the influence of respiratory movement.

Ultrasonic bone cutter is a surgical tool which converts electrical energy into mechanical means by using piezoelectric transducer to make the titanium alloy cutter head in high-frequency resonance mode, and uses the strong mechanical acceleration of the cutter head to smash and cut the target bone tissue. The different cutting rate and heat dissipation rate of the cutter head will be leaded by the unstable contact force, which will affect the cutting quality of the operation. When the existing surgical auxiliary robot operation is used during the operation, it is difficult to maintain the stable contact force between the ultrasonic osteotome and the spine, which leads to the reduction of the cutting efficiency of the ultrasonic osteotome, and the surgical effect can not be guaranteed [14].

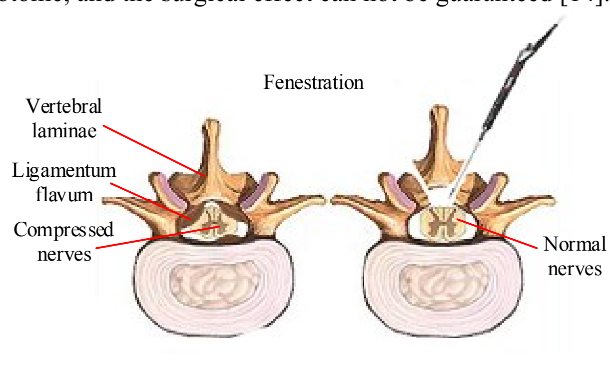

Figure 1. Laminectomy

How to ensure the stability of the cutting contact force of the ultrasonic osteotome in spinal surgery is actually a problem of following the force of a non-cooperative target. In

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order to realize the position control and contact force control of the robot end of the polishing system, Huang Ting proposed a force/position hybrid control strategy of robot polishing system based on passive compliance device. A compliant device is installed at the end of the robot and nonlinear PD control is used to decouple the force control and position control at the end of the tool [15]. In [16], a method combining active compliance control with passive compliance is proposed. In this paper, a position active compliance controller based on terminal one-dimensional force feedback is designed, which equates a leg with a linear virtual leg, and combines the function of passive compliance device to realize the smooth ground contact of foot robot. In order to solve the problem of contact force instability caused by the sudden change of material stiffness during surface treatment, a solution based on adaptive sliding mode control is proposed in [17]. In order to solve the problem of contact force control in automatic polishing process, a new type of ending effector, which is also a force controller, is designed by using nonlinear controller in [18]. By adding a linear motor to the end effector structure, the author only needs to control the position of the end effector to obtain the required polishing force. In order to solve the problem of geometric error of workpiece surface and difficult to control grinding depth caused by tool deflection in robot grinding process, a synthetic grinding force control strategy is proposed in [19]. A supervised fuzzy controller is designed to optimize the grinding operation. In the above methods, accurate mathematical modeling of robot system or environment system is carried out. In some actual spinal surgery environments, it is difficult to accurately model the robot system and environmental system due to the influence of implicated motion caused by uncertain factors such as respiratory motion [20]. Therefore, the actual performance of the above methods are not very good in such a surgical environment. In addition, ultrasonic osteotome is a very advanced surgical instrument, the robot using ultrasonic osteotome for spinal surgery related facilities are not complete. The surgical instrument holding device at the end of the existing surgical robot is mostly rigidly connected, which causes the actual contact force to be transmitted as a rigid transmission, and a very small displacement will lead to a large fluctuation of the contact force. It is impossible to carry out mechanical filtering in the control process in this kind of transmission , and the noise of high frequency force signal is obvious in the grinding process, so it is difficult to use the end contact force signal for adaptive control of contact force , and it is also not conducive to the ideal cutting of ultrasonic osteotome.

In order to solve the problem of unstable contact force between surgical instruments and bone tissue, a flexible clamping device is designed to clamp surgical instruments which are sensitive to connecting force. An adaptive fuzzy controller is designed for active control, which achieves ideal stable contact force control, ensures the cutting effect during the operation, and improves the safety and quality of the operation. The first part is the background introduction, the second part introduces the structural design of the passive compliant device, the third part introduces the fuzzy control algorithm, the fourth part introduces the experimental results and analysis, and the last part is the full text summary.

II. PASSIVE COMPLIANT FIXTURE DESIGN

Elastic elements generally are added to the actuator loop in the flexible clamping device to change the stiffness of the system in contact with the acting target and ensure the stability of the contact force. The same strategy is used in this paper, a passive compliant clamping mechanism is added to the end of the auxiliary surgical robot in order to solve the stability problem in the grinding process. There are three main benefits of designing a clamping device. First, it can solve the problem of sudden change of contact force due to small displacement, and transform rigid contact into flexible contact, which is convenient for constant force control. Second, the spring in the device can be used as a stabilizer to reduce the high frequency signal in the grinding process and make the contact force more stable. Finally, the force-position relationship between the end contact force and the position is established, so that the contact force can be controlled by controlling the position.

Hollow design is adopted in the flexible clamping device as shown in figure 2. The ultrasonic osteotome is clamped inside the fixture. When the end of the osteotome is in contact with the bone tissue and fluctuates up and down with the patient's respiratory movement, it will drive the inner sleeve up and down, and then squeeze or release the elastic parts. At this time, the connection between the osteotome and the outer tube is a flexible connection, which avoids the sudden change of the contact force at the end of the osteotome, due to the existence of elastic parts. It lays a foundation for the stable control of the contact force at the end of the osteotome.

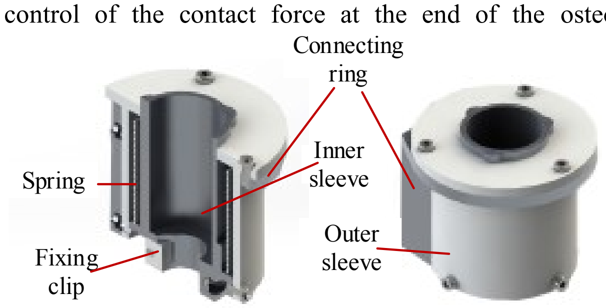

Figure 2. Structure diagram of the force stabilizer

The force sensor is connected to the back end of the structure, and the change of the contact force between the end of the osteotome and the bone tissue is obtained by the force sensor in real time. The displacement information is converted to a force signal by the spring and transmitted to the force sensor, when the end of the bone knife comes into contact with the bone tissue and fluctuates with the patient's breath. The force signal is used by the controller to control the movement of the back-end UR manipulator, and drive the whole clamping mechanism up and down to ensure the stability of the contact force between the osteotome and the bone tissue. The detailed material for the prototype of the overall structure is shown in Table I.

TABLE I. MAIN MATERIAL TABLE OF THE DEVICE

member	material
Outer sleeve	Plastic (POM)
Inner sleeve	6061 aluminum alloy
Connecting ring	6061 aluminum alloy
Fixing clip	6061 aluminum alloy
Spring	SUP6

A non-standard coil spring is used and its spring constant w needs to be recalibrated. The natural extension state of the spring is set to the zero position and the spring compression direction is positive. The positive pressure signal f of the spring under different spring compressions x are collected. The force of the spiral spring varies linearly, so curve fitting is performed. Here, the least square method is used for data fitting:

$$F(\Delta x) = \mathrm{w}\Delta x + b \tag{1}$$

Where $F(\Delta x)$ is positive spring pressure, Δx represents the amount of spring compression, w and b are regression coefficients.

Then the sum of squared residual functions is:

$$R = \sum_{i=1}^{n} (F_i(\Delta x) - F_i(\Delta x))^2 \tag{2}$$

Where n is the number of tests, and the formula (1) is brought into the formula (2). By minimizing the first-order condition and obtaining the partial derivative of the parameter, the estimator of w and b can be obtained as follows.

$$w = \frac{\sum_1^n \Delta x_i F_i - n\overline{\Delta x}\overline{F}}{\sum_1^n \Delta x_i^2 - n\overline{\Delta x}^2} \tag{3}$$

$$\mathrm{b} = \overline{F} - w\overline{\Delta x} \tag{4}$$

Where $\overline{F}$ with $\overline{\Delta x}$ represents the mean of the spring positive pressure and compression. the Matlab toolbox is used to calculate and plot the measured data, as shown in Fig.3.

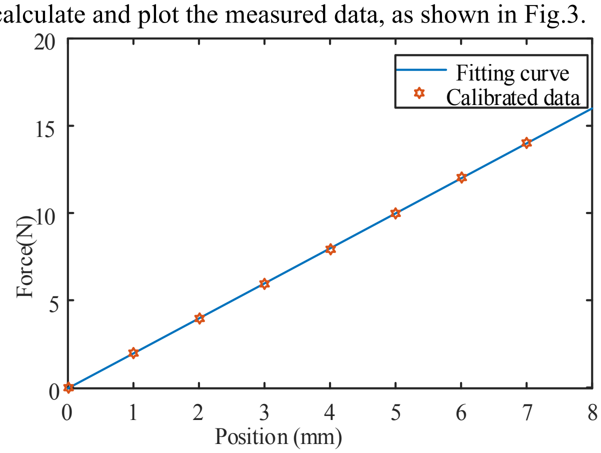

Figure 3. Fit curve

The value of w can be found to be 2.024, and the calculation result of b is -0.0017. The spring constant of the spring to be measured K_S is 2.024 N/mm.

III. CONSTANT FORCE CONTROL ALGORITHM

The anatomy of the lamina consists of two bones with completely different mechanical properties, cortical bone and cancellous bone. The surface of the lamina is often uneven, which would cause many unstable factors such as collision and vibration during the robot-assisted laminar grinding process, resulting in the contact force not being obtained by accurate mathematical derivation. It is difficult to predict the whole process system model, because of the irregularity of lamina bone and the difference of mechanical properties of bone. For nonlinear time-varying systems, fuzzy controllers have the advantage of not requiring accurate mathematical models of the system, good robustness, high fault tolerance, high computational efficiency, easy integration of existing control experience, and simple and intuitive design. Figure 4 shows the structure of a classic fuzzy logic controller (FLC). In the process of robot-assisted lamina grinding with ultrasonic bone knife, the adaptive control strategy of grinding contact force at the end of surgical robot based on fuzzy controller is adopted in this paper. On the one hand, the dynamic stability of the system can be improved. On the other hand, the grinding efficiency of the ultrasonic bone cutter can also be improved too.

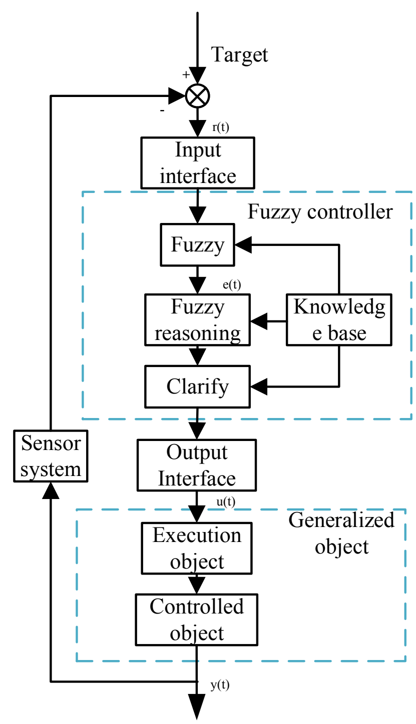

Figure 4. fuzzy control schematic

A standard two-dimensional control structure is selected, and the fuzzy controller has dual input and single output. The expected value F_{tar} of the axial contact force between the osteotome with the lamina and the difference $F_z(k)$ of the actual value $e(k)$ collected in real time by the force sensor of the kth sampling time and the variation value $de(k)$ of the difference between the two adjacent sampling intervals are taken as the input variables of the two-dimensional fuzzy controller. the correction amount u of the contact force between the ultrasonic osteotome and the lamina is output.

$$e(k) = [F_{tar} - F_z(k)] \cdot K_{\mathrm{e}} \tag{5}$$

$$de(k) = [e(k) - e(k-1)] \cdot K_{de} \tag{6}$$

Where K_{e}, K_{de} are the standard quantization factor used to normalize two input parameters into a set domain. They can be obtained by the following formula:

$$\begin{cases} K_e = \dfrac{N}{e_H} \\ K_{de} = \dfrac{N}{de_H} \end{cases} \tag{7}$$

Where N is the maximum value of the set domain e_H, de_H, $e(k)$ with $de(k)$ are the maximum value within the actual range.

The corresponding output $u(k)$ is the adjustment of the contact force between the osteotome and the lamina. The actual position adjustment of the robot $p(k)$ can be obtained according to the following formula:

$$p(k) = u(k) / K_S \tag{8}$$

Where K_S is the spring constant of the spring.

$e(k)$, $de(k)$ are vaguely transformed into 7 values by the triangle membership function: {PB(positive big), PM(positive middle), PS(positive small), ZE(zero), NS(negative small), NM(negative middle), NB (negative big)}. The u with the same output value of 7 values also uses the same triangular membership function as the input. as shown in Figure 5.

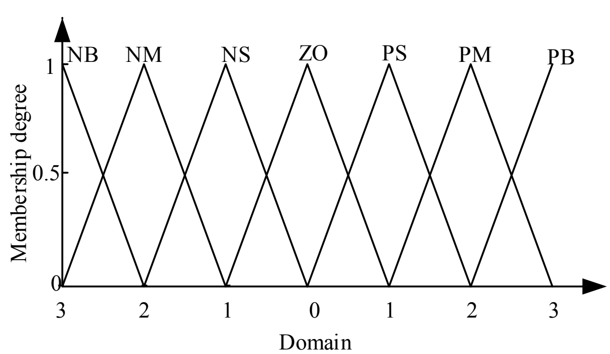

Figure 5. Membership function of input and output variables

The input and output have 7 values, so the controller has 49 fuzzy logic rules. Based on the expert experience, by referring to the fuzzy control related literature, the fuzzy control rule table can be summarized as shown in Table II.

TABLE II. CONTROL RULE BASE OF FUZZY CONTROLLER FLC

u		***de***						
		NB	***NM***	***NS***	***ZO***	***PS***	***PM***	***PB***
e	***NB***	NB	NB	NB	NM	NB	NB	NB
	NM	NB	NM	NM	NM	NM	NM	NB
	NS	NM	NS	NS	NS	NS	NS	NS
	ZO	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PS	PS	PS	PS	PS	PS	PS	PM
	PM	PB	PM	PM	PM	PM	PM	PB
	PB	PB	PB	PB	PM	PB	PB	PB

Fuzzy control is developed by using MATLAB's fuzzy logic toolbox and Simulink. Each control rule can be represented by the following way:

R:if ***e*** is E_i and ***de*** is E_j; then ***u*** is $U_{n(i,j)}$

Where ***e, de*** is the linguistic variable of the error and its rate of change, and u is the linguistic variable of the output control signal. E_i, E_j and $U_{n(i,j)}$ are their corresponding language values. The output u can be obtained using the Mamdani fuzzy inference method and the centroid method. So, the adjustment amount of the robot end position can be obtained:

$$u = \frac{\sum_{i,j} [\mu_{E_i}(e) \wedge \mu_{E_i}(de) U_{\mathrm{n}(i,j)}]}{\sum_{i,j} [\mu_{E_i}(e) \wedge \mu_{E_j}(de)]} \cdot K_u \tag{9}$$

Where K_u is the mapping coefficient that transforms the output u from the universe to its actual interval, which can be obtained by equation (7). $\mu_{E_i}(e)$ and $\mu_{E_i}(de)$ are the membership functions of ***e*** and ***de***.

$$K_u = \frac{u_H}{N} \tag{10}$$

Where N is the maximum value of the domain, u_H is the maximum value of $u(k)$'s actual range.

IV. EXPERIMENTAL VERIFICATION

A. Platform Construction

The system platform construction is an important part of the experiment, and the platform software used in the experiment is the QT framework. The physical composition of the experimental platform is shown in Figure 6. It is mainly composed of a breathing simulation platform, a feeding device, a flexible clamping device, a control system and a bone drill.

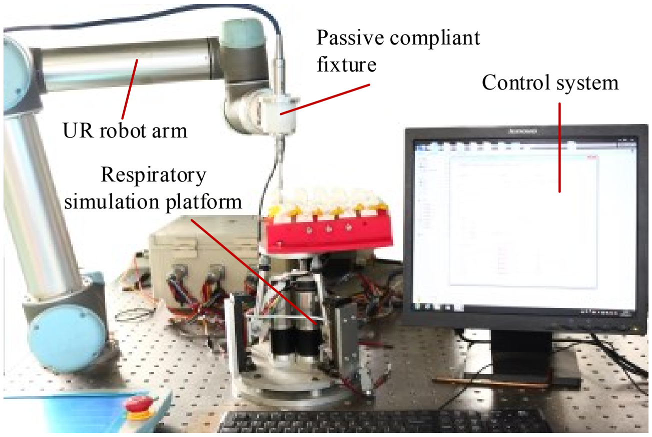

Figure 6. experimental hardware platform

UR5 robotic arm (Universal Robots, Denmark) is used as the feed device. It has six rotating joints, all wrist joints can be rotated 360 degrees, and the end joints can be rotated indefinitely. UR5 can handle up to 5kg payload, repeatable accuracy of 0.1mm, working radius of 85cm, low noise. It can be applied in a variety of industrial and medical fields. In the experiment. Its state is adjusted in real time according to the correction value u of the end position calculated by the fuzzy control system to keep the contact force constant.

A parallel platform is used as the respiratory motion platform for simulating breathing motion, which simulates breathing motion by introducing breathing data into a control program. In this experiment, the breathing parameters are simplified, and the point control mode is adopted. The breathing motion mode is set to the sawtooth shape, and the breathing platform's move range is [-2mm ~ 2mm] in the Z-axis direction.

The force sensor is a mini40 (ATI, USA), a multi-axis force/torque sensor system from ATI which measures six forces and moments. The system includes a sensor, a highly flexible shielded cable, an intelligent data acquisition system, an Ethernet/Device et connection and an F/T controller. The X-axis and Y-axis can withstand a maximum force of 80N, the Z-axis has a maximum endurance of 240N, and the measurement uncertainty is 1.25%.

According to the clinical experience, the domain of *e*, *de* and *u* is set to [-3, -2, -1, 0, 1, 2, 3]. The actual error *e*, error rate of change *de*, and control quantity *u* range is as follows:

$$\begin{cases} e=[e_L,e_H]=[-40,40] \\ de=[de_L,de_H]=[-100,100] \\ u=[u_L,u_H]=[-30,30] \end{cases}$$

Therefore, according to formula (4) and formula (7), the quantization factor can be calculated. K_e, K_{de}, K_u are 0.075, 0.03, and 10 respectively.

B. Dynamic Experiment

In order to verify the control performance of the fuzzy control algorithm and the stability of the flexible clamping device in a dynamic environment, a comparative test with the conventional rigid clamping method was set.

The experimental conditions are shown in Table III.

TABLE III. COMPARISON TEST CONFIGURATION TABLE

No.	Without Passive compliant fixture	With Passive compliant fixture
Without Fuzzy Control	A	B
With Fuzzy Control	C	D

The optimal cutting contact force of different ultrasonic bone cutters is different, so this paper only carries out the test to ensure that the contact force is 10N. In order to ensure the consistency of the signal, all the contact force signals are calibrated to zero when the contact force signal is 10N. The key parameters of each experimental equipment are set as shown in Table IV.

TABLE IV. HARDWARE PARAMETER SETTINGS

Experimental parameters	Value
Mini40 sampling frequency	200Hz
respiratory motion speed	0.5mm/s
respiratory motion amplitude	± 2 mm
UR speed	15mm
UR acceleration	$10\ mm^2/s$

The collected contact force signal is shown in Fig.7. Since the obtained force signal is mixed with many high-frequency signals, the original signal is filtered, and then the filtered signal is used for controller control. Here, we use adaptive Kalman filter for processing.

$$X(k|\ k-1)=A\cdot X(k-1|\ k-1)+B\cdot U(k) \tag{11}$$

where $X(k|\ k-1)$ is the results predicted from the previous state， $U(k)$ is the current control amount. A is the state transition matrix and B is the input control matrix.

$$P(k|\ k-1)=A\cdot P(k-1|\ k-1)\cdot A'+Q \tag{12}$$

Where $P(k|\ k-1)$ is covariance of $X(k|\ k-1)$ ，Q is the system process covariance.

$$Kg(k)=\frac{P(k|\ k-1)\cdot H'}{H\cdot P(k|\ k-1)\cdot H'+R} \tag{13}$$

Where $Kg(k)$ is the Kalman gain, H is the measurement matrix, and R is the noise。

$$X(k|\ k)=X(k|\ k-1)+Kg(k)(Z(k)-H\cdot X(k|\ k-1)) \tag{14}$$

Where $X(k|\ k)$ is the current optimal estimate， $Z(k)$ is the measured value.

$$P(k|\ k)=(I-Kg(k)\cdot H)\cdot P(k|\ k-1) \tag{15}$$

Where I is the identity matrix.

The force signal after Kalman filtering is used for constant force control, which can increase controller stability.

The standard deviation and amplitude of the four tests data were obtained from the statistical data, and the results are shown in Table 8.

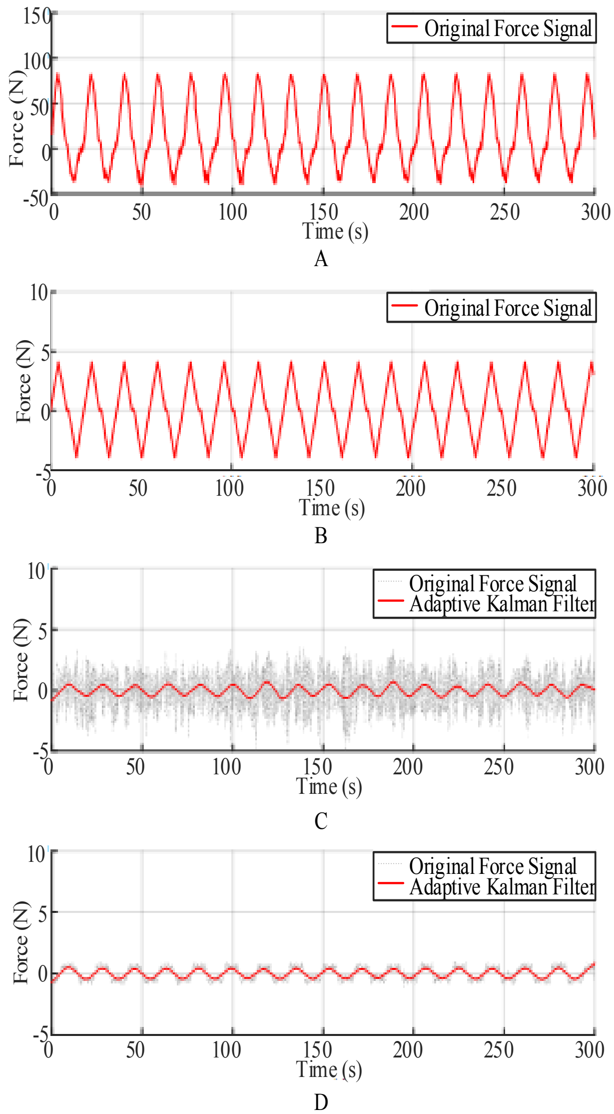

Figure 7. Dynamic test results Figure A represents uncontrolled contact force signals without constant force structure, Figure B represents uncontrolled contact force signals with constant force structure, Figure C represents controlled contact force signals without constant force structure, and Figure D represents constant Force structure with controlled contact force signal

From the experimental results of the experiment A and B, it was found that the standard deviation of experiment B equipped with a flexible holding device was reduced by 64.0462 compared with experiment A under the experimental conditions without contact force control. The maximum contact force deviation is reduced by 100.0736N. Moreover, the relationship between the change of the contact force signal and the law of the change of the respiratory motion is close to a linear relationship. It can be explained that the flexible clamping device reduces the rigidity of the system, so that the variation range of the contact force is greatly reduced. From the experimental results of experiments A and C, it is known that under the experimental conditions without the flexible clamping device, the standard deviation of the experiment C after the addition of the fuzzy control is reduced by 35.1031, and the maximum contact force deviation is reduced by 64.5645N.This shows that the constant force control can compensate for a large degree of contact force caused by the breathing movement to a certain extent. From the results of experiment A and D, the standard deviation of the system was reduced from 36.509 to 0.5491 under the dual action of the flexible clamping device and the fuzzy control, and the maximum contact force of the experimental D was 1.3695N. It can be seen from the above results that the flexible device for holding the ultrasonic bone cutter designed this week can ideally solve the problem of sudden contact force during the operation, and can achieve stable contact force with the action of the fuzzy controller.

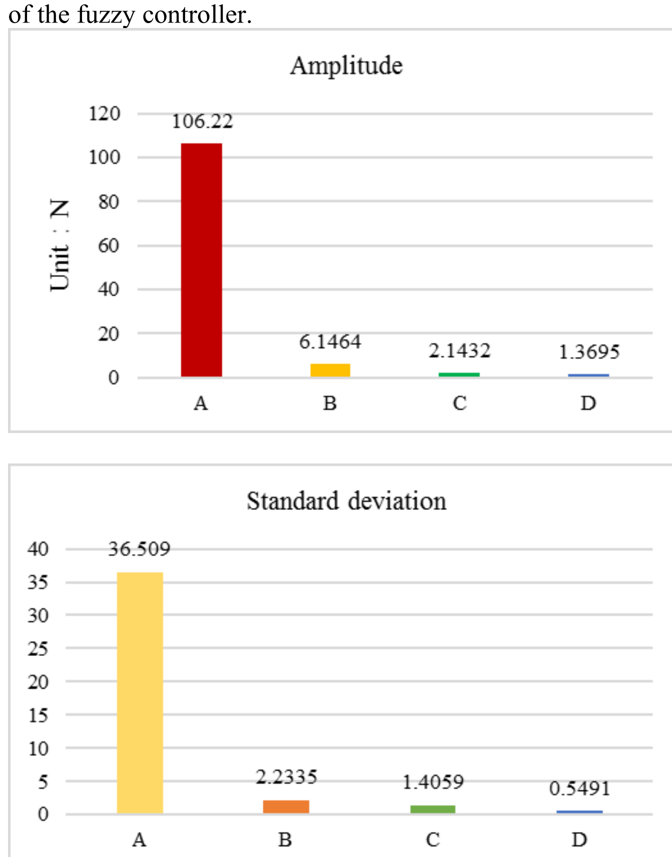

Figure 8. Amplitude and Standard deviation

V. CONCLUSION

This paper presents a control method for maintaining stable cutting forces in ultrasonic orthopedic surgery. A flexible clamping device is designed for holding a new type of surgical instrument ultrasonic osteotome which is sensitive to contact force. Through the installation of a compliant device at the end of the surgical auxiliary robot and the use of adaptive fuzzy control, the problem of unstable contact force between ultrasonic osteotome and bone tissue during operation is solved. A comparison test was set up, and the two parts of the method were compared with the whole system. Experiments have shown that this hybrid control method is very effective for controlling the contact force of the end of the ultrasonic osteotome. Since the spring is added to the force transmission loop, the high frequency vibration during the grinding process is reduced, and the contact force signal is more stable. Through the design of fuzzy controller for fuzzy control, the modeling of the whole robot system is simplified, and the ideal contact force control effect can be obtained by paying attention to the controller itself. The method is simple in structure, easy to implement and adjust. It also can be applied to different constant force control scenarios. However, there are still some problems in this experiment. For example, the contact force signal still has small fluctuations, and the clamping device is complicated to load and unload. In the following work, the structure of the clamping device will be optimized, and new control algorithms will be tried to improve the followability and stability of the contact force.

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