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Robot Machining Method Bases on Dynamic System and Compliant Control

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Abstract—**This paper proposes a force control strategy based on velocity modulation and impedance control algorithm to address unstable contact problem between the tool and workpiece in machining. In many application scenarios of industrial robots, contact force is required to some extent. Therefore, a force control component guarantees that robot can maintain stable contact force with the predetermined trajectory and react in the rapidly changing environment. The position controller is used to adjust the movement of the robot. During movement, position controller combined with speed-based impedance control can compensate for the uncertainty of controller and robot. Meanwhile, the velocity of the robot is controlled in the velocity modulation subspace to reduce the vibration force in contact, thus the contact overshoot decreases and the machining accuracy of the workpiece is improved. Evaluations through non-contact to contact transition experiment indicates that low contact vibration and reliable position/force control can be achieved by this proposed controller.**

Index Terms—**compliant control, velocity modulation, force control**

I. Introduction

With the enhancement of industrial robot functions and the continuous increase of application requirements, the application of robot gradually evolves from non contact to simple contact and then to complex contact. This makes the perception and control of physical contact forces of industrial robots become one of the hottest research topic in robot technology.

In general, traditional industrial robots only have the ability to the position control, which can only perform some simple contact tasks such as welding, painting, and handling. However, there are many different tasks which need a contact with the environment and has certain requirements for contact force. Obviously, this is a big challenge for present industrial robots. It has always been a worthy research topic for robot control task to conduct energy exchange with the environment through dynamic interaction and two basic control methods. Outlining the past-present history of compliant control, two fundamental control methodologies have been proposed. The first approach, known as hybrid position and force control, have been proposed by Raibert and Craig[1]. Although this approach is interesting, it fails to achieve precise control due to the dynamic coupling between the mechanical arm and environment. In order to solve this problem, the second approach called hogan impedance[2] is proposed. This method uses as an extension of stiffness control by adjusting the mechanical impedance of the manipulator to adapt to the mechanical impedance control of the target model. The control goal of this method focuses on static behavior[3]. The dynamic relationship between end-effector position and force is established through this method, which provides a unified control framework for the manipulator to contact with the environment in free space and flexible motion. Despite that, there is still considerable ambiguity with regard to get accurate end-effector's reference trajectory and environment stiffness, position[4]. Many new methods of compliant control are proposed, such as the adaptive environmental parameters estimation[5], the estimation of the stiffness using an Extended Kalman Filter[6], using a neural network to compensate for uncertainties[7], etc.. that the accuracy of force in compliance control is still not solved.

At the same time, the contact operation requires the robot to maintain a stable contact force in a predetermined trajectory and to respond in a rapidly changing environment. In the practical robot control, when the movement transits from free space to contact space, due to the fact that the velocity cannot be zero in practice, the discontinuity of the control system will lead to excessive impact force[8]. Moreover, the impact causes multiple shocks of the contact point/surface and leading to the instability of the system. It is required to have a fast running speed and high work efficiency when the force control method is applied in industrial production, so the speed adjustment is also very important[9]. Simple impedance control obviously cannot solve these problems completely.

Therefore, a new control method is proposed in this paper. It combines the modulation strategy of the dynamic system with the impedance algorithm to control the robot. The space of the robot motion is divided into free space, transitional space and the contact space. By changing the parameters of modulation strategy to adjust the robot's speed to a very small value when enters the transition area, so as to be in contact with the target surface stably[10]. The slower speed can contribute to reduce the vibration force of the contact and decreases the damage of the robot or processing components caused by unnecessary collision damage[11]. The high speed in free space, which shortens the time to contact surface, improves the

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efficiency. When there is a sudden environmental disturbance, the system can respond quickly to strengthen the operability of the system.

Our control method has the following advantages: (a) the dynamic system modulation algorithm reduces the vibration force during contact and avoids the damage to the workpiece. (b) the desired force can be applied to the surface when the end-effector reaching the contact surface.

The paper organized as follows:section II describes the basic methods that use in the framework. Section III introduces the integrated control framework. And the experiment setup and results are showing in section IV. Finally, the paper is concluded and the future work is discussed in the Section V.

II. Method

A. Impedance Control

Since the impedance control method of Hogan system was proposed in 1985, it has been greatly developed. This method is mainly developed by considering the interaction between physical systems[12]. The impedance control method is to replace the actual robot dynamic model with the target impedance[13]. When there is deviation between the robot end position and the ideal position, the corresponding impedance force will be generated at the robot's end-effector.

The position error input is calculated to get the force, and the position is output through a force controller.

Let's assume that the environment is rigid. Consider a single degree of freedom system in which mass interacts with the environment[14]. m and x represent the displacement under generalized inertia and mass respectively. The equation of motion for the mass can be written as follows:

$$m\ddot{x} = F + F_{ext} \tag{1}$$

The goal of impedance control is to design a applied force F, so we can establish a second-order relationship between F_{ext} and e to achieve an appropriate F with an error by adjusting the parameter value. The second-order relationship can be expressed as follows:

$$M_d\ddot{e} + D_d\dot{e} + K_d e = F_{ext} \tag{2}$$

Where e is the error between x and the desired position x_d, M_d, D_d and K_d are positive constants that represent the desired inertia, damping and stiffness, respectively.The transfer function between e and F_{ext} is denoted by

$$G_d(s) = \frac{1}{M_d s^2 + D_d s + K_d} \tag{3}$$

Since the impedance control is the mechanical impedance, we can deduce that the impedance control law is

$$F = (\frac{m}{M_d} - 1)F_{ext} + m\ddot{x}_d - \frac{m}{M_d}(D_d\dot{e} + K_d) \tag{4}$$

B. Position Controller

In the following experiment, we will carry out velocity modulation, which adopt different modulation parameters according to different positions. So we use a position controller which the motion of mass follows a desired trajectory x_d. We combine impedance control with a position controller to generate desired force along the path and to be able to modulate velocity. The position controller can be applied by using a regular PD controller as following:

$$f(\dot{x}, x, t) = -k_v(\dot{x}) + k_p(x_d - x) \tag{5}$$

By evaluating the algorithm through the uniaxial motion experiment of the robot arm, we can achieve a simple trajectory planning through the position controller, and define the current state of the robot arm through the value of $f(\dot{x}, x, t)$, so as to carry out velocity modulation.

C. Modulation Strategy

Impedance control can make the machine arm be able to response to the external force to make certain when interacting with the outside world, but when in contact with the contact area will produce larger vibration, which makes some precision instruments suffer certain damage. Diffrent function can be achieved by adding different M matrix on the modulation, different velocity can realize the corresponding function respectively. In this work, we make it by adding a specific M matrix to change the velocity of contact with the contact surface, so that the robots can keep in contact with the contact stability, reduce the damage due to vibration.

First, defining the modulation mode of the M for the dynamic system as follows. The M matrix is added before the mapping relationship between the robot state and the expected acceleration of the robot so that it can adjust the acceleration.

$$\ddot{x} = M(\dot{x}, x) f(\dot{x}, x, t) \tag{6}$$

Where $f(\dot{x}, x, t)$ represents the behavior of the robot at a certain moment, $M(\dot{x}, x)$ is the modulation function of the system. The modulation method is mainly to divide the robot's range of activity into three different areas, free space, transition space and contact space. Then the current position of of end-effector is determined according to the state of the robot. Different state of the robot have different speeds, reach the contact surface and maintain stability finally. We define the modulation function as follows:

$$M = Q\Lambda Q^T \tag{7}$$

Where $Q = [q_1, q_2 ... q_d]$, $q_i \in R^d$ is an orthonormal basis, and q_1 points in the normal direction of the contact surface. In order to avoid excessive modulation carried out on the part of the transition zone, we adopt local modulation method put forward in literature[10],the method are defined as follows:

$$\boldsymbol{\lambda}_{ij}(x, \dot{x}) = \begin{cases} \lambda_{ij}(x, \dot{x}) & if \quad i = 1, \Gamma(x) \leq \rho \\ (\lambda_{ij}(x, \dot{x}) - 1)e^{\frac{\rho - \Gamma(x)}{\varepsilon}} + 1 & if \quad i = 1, j = 1, \rho < \Gamma(x) \\ (\lambda_{ij}(x, \dot{x}))e^{\frac{\rho - \Gamma(x)}{\varepsilon}} & if \quad i = 1, j \neq 1, \rho < \Gamma(x) \\ 1 & if \quad i \neq 1, i = j \\ 0 & if \quad i \neq 1, i \neq j \end{cases} \tag{8}$$

$\forall i, j \in \{1, 2, ...d\}$, where ρ is defined as the size of the transition region, that is, the region affected by the modulation function. $\Gamma(x)$ represents the shortest distance between the robot's current position and defined contact surface. Then $\Gamma(x) = 0$ only if the robot's current position is defined as the contact surface.

The division of three different regions can be judged by the relationship between ρ and $\Gamma(x)$.$\rho < \Gamma(x)$ means in free space, $0 < \Gamma(x) < \rho$ means in transition space, $\Gamma(x) \leq 0$ means in contact space. Through the different circumstances of λ_{ij}, so as to achieve the speed of modulation.

III. The Overall Framework

For purpose of realizing constant force control and balance the vibration force in contact, the control scheme combines impedance control and velocity modulation is presented. The impedance control method is used to realize the force tracking and then achieve the balance vibration force through the velocity modulation algorithm of the dynamic system. The principle block diagram is as follows: Different space control

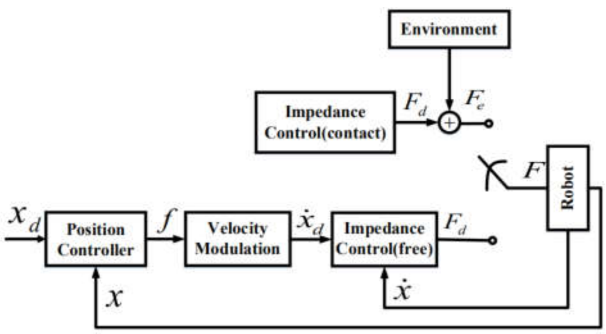

Fig. 1. The Framework Diagram.

mode changes to realize the small vibration force and certain force when end-effector contact with the contact surface. As shown in Fig.1, the contact process between robot and environment can be divided into two stages. The end-effector approaches the environment in the first stage,and contacts the environment in the second stage. Then the robot is modulated through impedance control and velocity modulation to reach a low speed in the first stage, and only a single impedance control is used to maintain a steady force in the second stage.

Considering the uncertainty of the actual situation in the environment, it is hard to specify a very accurate target location. The single velocity modulation method may not make contact between the robot arm and the contact surface. The impedance control is used to solve the problem by judging contact through force. According to the force(whether there is environmental disturbance force or not), we can divide the impedance control into two different spaces for control, so we can express the impedance control law(2) in the following form.

$$M_d\ddot{e} + D_d\dot{e} + K_d e = -F_d(free\ space) \tag{9}$$

$$M_d\ddot{e} + D_d\dot{e} = F_e - F_d(contact\ space) \tag{10}$$

Under these conditions, set the expected force F_d to 0N and the robot is completely driven by the environmental force F_e. The robot can react quickly to the environment when it's end-effector comes into contact with the surface. In the free space, we perform the impedance control in (9) and modulate the velocity in combination with velocity modulation. In the contact space, we apply a single impedance control through (10).

According to the different forces in these two stages, the position controller can also be expressed in two different forms. In the free space, the form of the position controller is shown in(11). In the contact space, the form of the position controller is shown in (12).

$$f(\dot{x}, x, t) = -k_v(\dot{x} - \dot{x_d}) + k_p(-x + x_d) \tag{11}$$

$$f(\dot{x}, x, t) = -k_v(\dot{x}) + k_p(-x + x_d) \tag{12}$$

After the position controller represents the state of the robot arm at this time, we can modulate the velocity through the modulation strategy. The $\lambda_{1j}(x, \dot{x})$ of (8) can be expressed as (13) when $q_1(x)^T\dot{x} < \dot{\delta}_x$, expressed as (14) when $\delta_x \leq q_1(x)^T\dot{x} \leq 0$ and expressed as (15) when $0 < q_1(x)^T\dot{x}$.

$$\lambda_{1j}(x, \dot{x}) = (-\dot{x}^T \bigtriangledown q_1(x)^T\dot{x} + \omega(-q_1(x)^T\dot{x} + (\delta_{\dot{x}} + v)))\boldsymbol{f}_j(x, \dot{x}) \tag{13}$$

$$\lambda_{1j}(x, \dot{x}) = (-\dot{x}^T \bigtriangledown q_1(x)^T\dot{x} + \omega(\tfrac{v}{\delta_x}q_1(x)^T\dot{x} - \omega(1 - \tfrac{q_1(x)^T\dot{x}}{\delta_x})\Gamma(x)))\boldsymbol{f}_j(x, \dot{x}) \tag{14}$$

$$\lambda_{1j}(x, \dot{x}) = (-\dot{x}^T \bigtriangledown q_1(x)^T\dot{x} + 2\omega q_1(x)^T\dot{x} - \omega^2\Gamma(x))\boldsymbol{f}_j(x, \dot{x}) \tag{15}$$

Where

$$\boldsymbol{f}_j(x, \dot{x}) = \frac{f(\dot{x}, x, t)^T q_j}{f(\dot{x}, x, t)^T f(\dot{x}, x, t)} \tag{16}$$

Substitute the values calculated in (11) and (12) into the above equation and carry out velocity modulation through the modulation strategy.

Position controller obtains the initial position and modulates according to the specified parameters, and then obtains a corresponding velocity which is transmitted to the impedance controller. The impedance controller calculates the corresponding force through this velocity. By means of velocity modulation in free space, the robot arm has a lower velocity when it contacts with the surface, thus generating a smaller vibration force. When in contact with the surface, constant force contact is achieved through impedance control.

IV. Experimental Evaluation

A. Experimental Setup

The performance of the proposed framework is evaluated on a robotic platform shown in Fig.2. The robot motion control based on hardware and software is realized through discretization and programming of robot controller. This paper studies and realizes the vibration balance by using real time controller. Controller is designed based on embedded controller CX5130-0125 (Beckhoff Automation Inc., GER) with an Intel dual-core 1.75GHz processor, under the TwinCAT3 software environment.

TABLE I
MEASUREMENT OF STIFFNESS

X(mm)	3.2	4	5.2	6.4	7.2	8
F(N)	8	23.5	45	68.7	84.7	100

A force/torque sensor (Delta IP60, ATI Industrial Automation Inc.) is fixed to the end-effector of manipulator to measure the contacting force. Controller integrates network force/torque sensor system via a Real-Time EtherNet/IP interface. Output rate of the force/torque sensor up to 7000 Hz over Ethernet/IP. In order to meet the high-efficiency and real-time requirements, the communication between the controller and the servo system is designed based on the EtherCAT protocol[15].

Based on the above platform conditions, we set the acquisition frequency of experimental data at 1kHz and the algorithm cycle period at 1ms, so that the system has a small delay and can effectively ensure its stability and accuracy.

B. Experiments and Discussion

In this section, we evaluate the algorithm through the uniaxial motion experiment of the robot arm. Before the experiment, the stiffness of the grinding head and the mechanical arm was firstly measured: $k_e = f/x$. The measurement results were shown in table 1, i.e., the fitting for mula was $f = 19163x - 53605$, so $k_e = 19163N/m$. In the process of experiment, real-time force acquisition is carried out by force sensor, and real-time motion speed, position and force of the robot arm are collected by TwinCAT ScopeView.

In the experiment, the grinding head at the end of the robot arm falls rapidly $100mm$ away from the contact surface, and $10N$ force is maintained rapidly after contact surface. This apparatus has several features, as shown in Fig.2, the contact surface is metal and rigid, and the grinding head is plastic. It is expected that the overshoot of contact force is small and can be stabilized to $10N$ rapidly when the surface is rapidly touching. We compared the experimental results through three different groups of experiments and evaluated the algorithm through the stability time of contact force and amplitude of vibration force on the contact surface.The damping parameter values used in our experiments are as follows:

$$M_d = 1, D_d = 50, K_d = 625$$

In the first set of experiments, we only use impedance control, changing stiffness before and after contact to rapidly stabilize to $10N$ force. Impedance control is implemented using (2) and (4). When the contact force is higher than a certain threshold ($3N$ in this experiment), the contact force is used to determine which space it is. In the free space, the stiffness is set to 200N/m and 500N/m respectively, and in contact space, stiffness is $3000N/m$ and $19163N/m$ respectively.

Fig.3 shows the process that the end-effector falls from $100mm$ till contacts with the surface spends approximately $2000ms$. Through the real-time force curve, we find that the highest force exceeds 60N. It can be seen that when the grinding head contacts the surface with a single impedance control method, the overshoot of force is large (more than $60N$) and the falling time to more than $2000ms$. When the stiffness is set to $500N/m$ in free space and $19163N/m$ in contact space, it can be seen from Fig.4 that the time to contact with the surface becomes longer (more than $5000ms$). Although the overshoot of force becomes smaller (about $30N$), it takes longer to balance out at $10N$. Through the above comparison experiments, it is suggested that the increase of stiffness makes the duration of the whole process longer. It

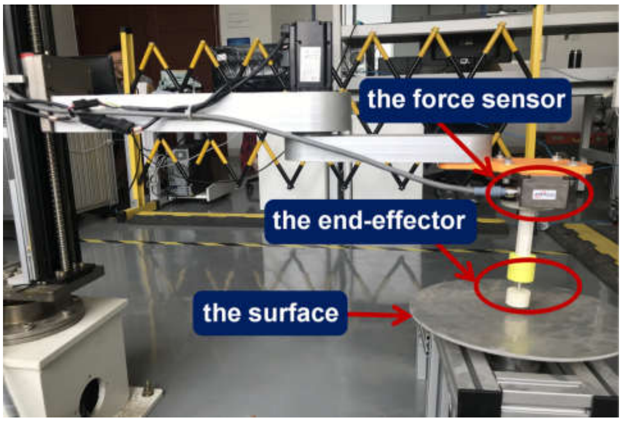

Fig. 2. The experiment platform.

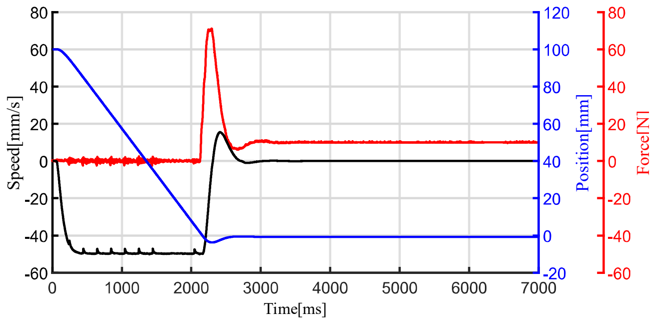

Fig. 3. Velocity, position and force curve without velocity modulation ($K_e = 200$ in free space and $K_e = 3000$ in contact space).

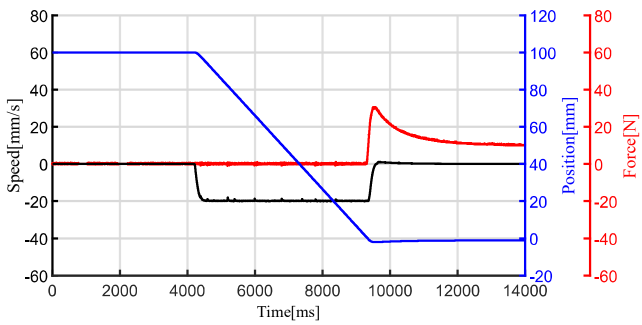

Fig. 4. Velocity, position and force curve without velocity modulation ($K_e = 500$ in free space and $K_e = 19163$ in contact space).

also can't be ignored that the overshoot of force decreases to some extent with the increase of stiffness, but the convergence time to 10N is sacrificed.

In the second set of experiments, velocity modulation is added before contacted with the surface. When $\Gamma(x) \leq 0$ means that the grinding head contacts the surface, we switched to impedance control to achieve the desired force. In this experiment, The parameters of the position controller are set as follows:

$$k_v = 50, k_p = 625$$

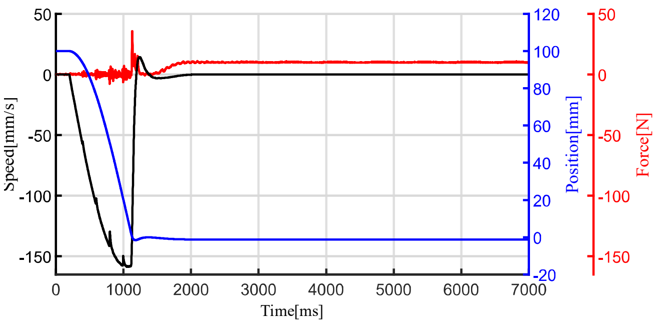

Fig. 5. Velocity, position and force curve when velocity modulation is received only in free space($K_e = 3000$).

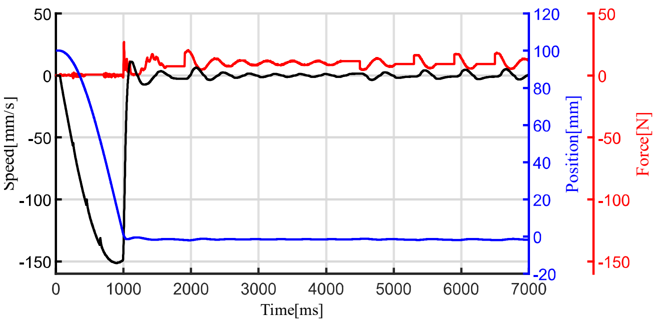

Fig. 6. Velocity, position and force curve when velocity modulation is received only in free space($K_e = 1000$).

Fig.5 shows the real-time position, velocity and force of the manipulator under the combination of velocity modulation and impedance control(when K_e is set to $3000N/m$). It can be seen that, before contact with the surface, there is a certain deceleration fluctuation due to velocity modulation and a certain fluctuation of real-time force curve. Then when the end-effector starts to get stressed, the peak of the curve is less than $40N$, indicating a small overshoot of force (less than $40N$). After contact, the force quickly reaches 10N and remains stable by adjust the impedance control. The position curve reveals the short time required to fall from $100mm$ to $0mm$ (approximately $1000ms$). When the environment stiffness K_e is reduced to $1000N/m$ (shows in Fig.6), it is surprising to find that both the force curve and the velocity curve have certain amplitude of oscillation. This oscillation always continues, making it difficult for the end-effector to maintain a steady contact of $10N$ with the contact surface. In response to this condition, we have done a number of experiments with different stiffness. Through the test, it is found that when the environmental stiffness is set to $3000N/m$, the control system is stable and can quickly reach the expected force. When the environmental stiffness is less than $3000N/m$, the system will oscillate.

In the last set of experiments, impedance control and velocity modulation are performed throughout the motion (both approach and contact). The relevant parameter Settings were consistent with the above two groups of experiments.

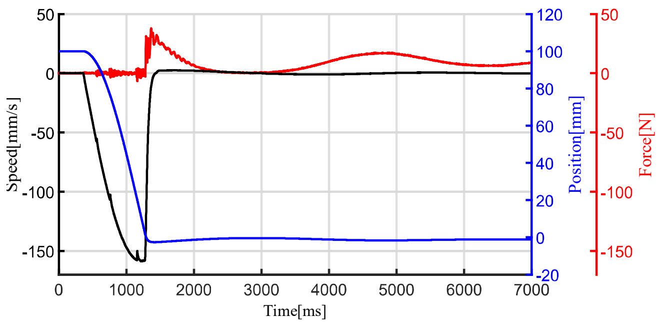

Fig. 7. Velocity, position and force curve when velocity modulation is received in both free space and contact space($K_e = 3000$).

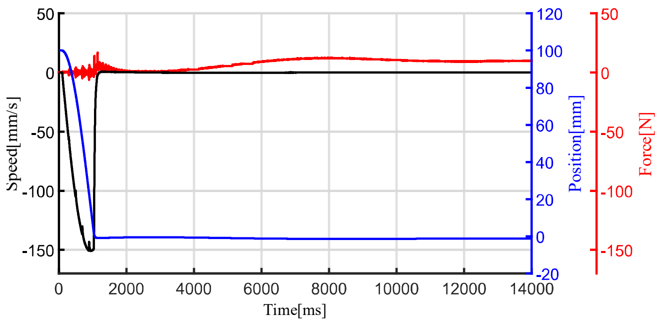

Fig. 8. Velocity, position and force curve when velocity modulation is received in both free space and contact space($K_e = 19163$).

The position curve in Fig.7 shows that it takes a short time to fall from $100mm$ to $0mm$ (about $1000ms$). In the free space, we can find that all curves are similar with the result shows in Fig.5 due to the same control mode. However, in the contact space, the force curve presents a fluctuating state and is difficult to stabilize at a constant value. This suggests that the normal velocity of the contact surface is subject to velocity modulation due to the combination of post-contact impedance control and velocity modulation, which reduces the velocity and increases the stability time. When the stiffness increases, it can be seen from Fig.8 that although the fluctuation range decreases, the stability time is longer. These tests also highlighted that although increasing environmental stiffness can give a hand to reduce the fluctuations, it makes the end-effector takes longer to stabilize to the surface.

Through the comparison of the above three groups of different experiments, the second set of experiment worked best. High speed in free space make it possible to reach the surface in short time and low speed in contact space helps it to have an acceptable value of overshoot. Single impedance control in contact space reduce the time to stabilize to expected force. From the above, the control scheme that velocity modulation only used before contact with the surface was chosen.

V. Conclusions

A compliant control scheme of a robot manipulator is proposed in this paper. Velocity modulation algorithm is used to offer a high speed in free space for improving efficiency and offer a low speed in contact space for reducing the overshoot of force. Impedance control bring the possibility of stabilizing to desired force. Although the proposed control function is not difficult, the combination of the two control algorithms is very important. When the stiffness of environment is not known exactly, the estimation of stiffness parameter is also very crucial. Experiment results proved that the proposed controller is excellent to obtain good performances in force/positiont racking. Stable force contacting were experimentally achieved based on the adjustment of appropriate parameter. The proposed controller also plays a role to reduce the vibration of the force and action time that would provide certain guiding significance to the practical production. Future work will concentrate on robustness test.

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