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Preliminarily Design and Evaluation of Tremor Reduction Based on Magnetorheological Damper for Catheter Minimally Invasive Surgery

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***Abstract* - To avoid the impact of radiation on surgeons during catheter minimally invasive surgery, vascular interventional surgical robots are commonly developed and used. However, when a surgeon operates with tremor, the operational accuracy will be seriously affected. In this paper, the tremor suppression is introduced into the robot-assisted invasive surgery to reduce the surgeons' tremor. A novel method using magnetorheological damper is proposed, and its performance is preliminarily evaluated by simulation. The simulation results show that it can reduce tremors effectively. This method can not only improve the accuracy of operation but also extend the professional career of surgeons.**

Index Terms* - *Catheter minimally invasive surgery, Vascular interventional surgical robot, Tremor reduction, Magnetorheological damper

I. INTRODUCTION

Nowadays, the number of people suffering from cardiovascular and cerebrovascular diseases is increasing. Vascular intervention therapy is an important method to treat these diseases. There are many advantages of vascular intervention therapy, including smaller incision, quicker recovery, and fewer complications [1]. However, surgeons need to use X-ray plate to get some monitor information during the surgery. To avoid the impact of the radiation, many researchers focus on the development of vascular interventional surgical robot and much significant progress has been achieved.

The Catheter Robotics Inc. designed Amigo robot system [2], and it can operate steerable catheter with three degrees of freedom. This Amigo robot system was tested via experiments and verified that it has good performance. The Stereotaxis Inc. developed Niobe robot system [3], which controls a catheter by magnetic fields. Moreover, a user interface was also provided. The Corindus Vascular Robotics deveolped Corpath robot system [4]. This system operates the catheter and rotate it by using friction wheels. Hansen Medical designed Magellan robot system [5], which can operate catheter and sheaths and can realize remote operation. Meanwhile, a remote-controlled vascular interventional robot developed by T. Wang *et al*. [6] can manipulate a catheter with two degrees of freedom and provide image guidance system. C. He *et al.* [7] developed a variable stiffness catheterization system that can provide stable and accurate endovascular intervention procedure with a linear stepping mechanism. K. Wang *et al*. [8] designed a novel vascular intervention robot with four manipulators. It mimics the four hands of a physician and an assistant and has three degrees of freedom. An endovascular robotic system developed by N. Sankaran *et al*. [9] can augment surgeon's actions by using conventional surgical tools, and it can also generate force feedback to ensure safety during the procedure.

Moreover, we have developed a magnetic fluid-based manipulator, which can capture the operation signals and realize force feedback [10], [11]. We have developed several types of robots for catheter minimally invasive surgery, and they can operate the catheter or guidewire with 2 degrees of freedom and generate force feedback for the operators [12]-[21]. In addition, one of these robots have evaluated by both animal and human experiments [22]. The experiment results demonstrated that the developed robot has good performance and can be used in clinal surgeries. Based on these robots, a novel suppression algorithm was proposed to reduce the tremor [23].

The operational accuracy has a great impact on the catheter minimally invasive surgery. Inaccurate operation will cause damage to the blood vessels, or even cause medical accidents. However, when a surgeon operates with tremor, the operational accuracy will be seriously affected. Hand tremor can be caused by many reasons, such as operating time, physical condition, and human nervous system. The tremor is a common movement disorder and is most common in the hands, but it also occurs in the arms, head, vocal cords, torso, and legs [24]. In order to solve the problem, several researchers dedicated to the study of tremor suppression. S. Dosen *et al.* [25] proposed a tremor suppression strategy, which detects tremor from the electromyographic signals of the muscles. This strategy originates and counteracts tremor by delivering electrical stimulation to the antagonist muscles in an out of phase manner. A robust tremor suppression algorithm was proposed by B. Taheri *et al.* [26]. This algorithm was derived for patients with pathological tremor in the upper limbs. The experimental results show it has good performance. These researches are related to the study of tremor suppression algorithm. Meanwhile, some researchers have been devoted to the tremor orthoses. M. L. Aisen *et al.* [27] developed a controlled energy dissipation orthosis. It uses magnetic particle brakes to provide resistive loads to the patient's wrist. The results show that it can reduce tremor severity. J. Kotovsky *et al.* [28] designed a "viscous beam" orthosis, which uses viscous damping along a single degree of freedom to reduce the tremor. J.-M. Belda-Lois *et al.* [29] developed a new orthosis allowing tuning of the damping properties. This orthosis has less restriction to general motion and can realize the flexion or extension of the wrist. E. Rocon *et al.* [30], [31] developed an orthosis with constant damping rate. The orthosis can effectively reduce the amplitude of patients' tremor. However, it has large size and heavy weight and results in inconvenient use for patients.

Based on the literature analysis, the researchers achieve the tremor reduction by using active strategies or passive strategies. In the active strategies, the damper is generally used. However, the magnetic fluid is mainly used commercially in vehicle shock absorbers. D. Case *et al.* [32] developed a small-scale magnetorheological damper to reduce tremor and demonstrated the feasibility of application in rehabilitation field. Nevertheless, in the catheter minimally invasive surgeries, the tremor existing on surgeons' hands not only affect the accuracy of operation, but also reduce the professional career of surgeons as tremors will occur in some elderly surgeons.

To reduce the surgeons' tremor during the catheter minimally invasive surgery, we introduced the tremor suppression into the robot-assisted invasive surgery. Combining with our previous research, we proposed a novel method to address this challenge. The rest of this paper is organized as follows. A novel method was proposed and described in Section II. Section III describes the performance evaluation, including the simulation set-up, results, and discussion. Finally, the conclusion of this paper is given in Section IV.

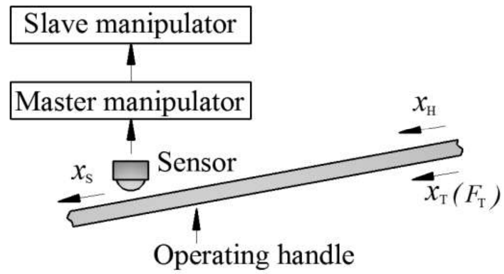

Fig. 1. Schematic diagram of operation information collection and exchange.

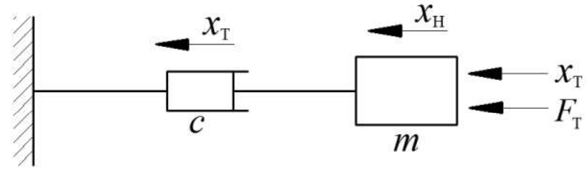

Fig. 2. Mass-damper model for the tremor suppression.

II. Method

When surgeons perform surgeries by using surgical robot, he/she will operate master manipulator on the master side. During the process of human-robot interaction, the master manipulator collects or provides operation information through an operating handle. The operating handle is similar to catheter or guidewire. To make full use of existing surgical experience, some researcher used real catheters as the operating handles [11]. As shown in Fig.1, the surgeon operates the operating handle and thus the operating has the same movement as surgeon. The sensor captures the movement information of the operating handle and send it to the master manipulator. The slave manipulator then starts to deliver the catheter after information exchange with master manipulator.

However, when the surgeon operates the operating handle with tremors, the operating handle will capture some additional movement information (x_T). This additional movement is generated by tremors. Owing to vibration force of tremors (F_T), this movement exists inevitably and has an adverse effect on the real operation information collection. The relationship between these movement is as follow:

$$x_S = x_H + x_T \tag{1}$$

where x_S denotes the linear movement captured by the sensor (i.e. linear movement of the operating handle), x_H denotes the linear movement of surgeon's hand, and x_T denotes the linear movement generated by tremors.

In view of previous research related to magnetorheological damper, the tremor can be reduced to a certain extent, especially in rehabilitation robotics. In this study, we introduce the magnetorheological damper into robot-assisted catheter minimally invasive surgery. The magnetorheological damper can not only generate force feedback for the operators, but also reduce the tremor existing in the surgeon's hands or arms. Kinematic analysis model is shown in Fig. 2. It is a mass-damper system, and the mass and damper are in series. The operating handle is equivalent to the mass and its movement (x_S) can be calculated by using equation (1). Meanwhile, the linear movement generated by tremors (x_H) is affected by the mass, damper, vibration force of tremors and time, and the relations could be written as follow:

$$x_T = \Gamma(m, c, F_T, t) \tag{2}$$

where x_T the additional linear movement of operating handle generated by tremors, Γ is an uncertain function for x_T, m is the equivalent mass of the operating handle, c is the apparent viscosity of magnetic fluid, F_T is the vibration force of tremors, t is the time.

To determine the uncertain function Γ, we establish the dynamic differential equation for the mass-damper system. The dynamic differential equation is as follow:

$$m\ddot{x}_T + c\dot{x}_T = F_T \tag{3}$$

In addition, due to the regular vibration of the tremor, we suppose the vibration force of tremors as simple harmonic motion. Therefore, the vibration force of tremors can be defined as

$$F_T = F_A \cos \omega t \tag{4}$$

where F_A is the amplitude of the simple harmonic motion, ω is the angular frequency of the simple harmonic motion, and t is the time.

Substituting equation (4) into equation (3) results in

$$m\ddot{x}_T + c\dot{x}_T = F_A \cos \omega t \tag{5}$$

The result for equation (5) is

$$x_T(t) = \frac{F_A}{\omega\sqrt{m^2\omega^2 + c^2}} \cos(\omega t - \varphi) \tag{6}$$

$$\varphi = \arctan \frac{-c}{m\omega} \tag{7}$$

where φ is the phase angle of the tremor reduction motion.

According the equation (6), the influence of tremors on linear movement can be altered by changing the amplitude F_A, phase angle ω, equivalent mass m, and apparent viscosity of magnetic fluid c. However, the amplitude F_A and phase angle ω are the intrinsic characteristics of tremors, and thus they cannot be altered easily. Instead, we can reduce the tremor by changing the equivalent mass m and apparent viscosity of magnetic fluid c. In this study, we focus on reducing tremor by using the change of apparent viscosity of magnetic fluid.

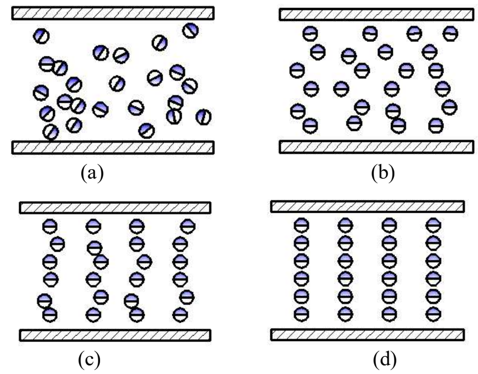

Fig. 3. Particle configuration in magnetic field with different intensities: (a) without magnetic flux; (b)-(d) the intensity gradually increasing [10].

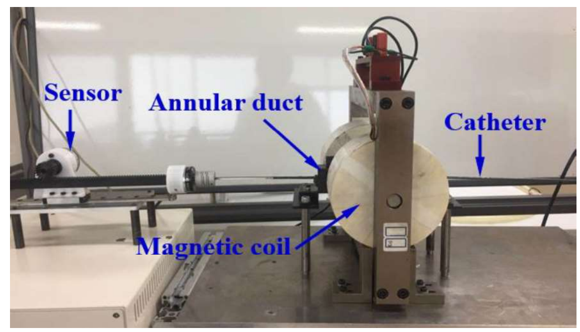

Fig. 4. Master manipulator.

In our previous research [10], [11], magnetic fluid was proposed to generate force feedback. The magnetic fluid is composed of microscopic magnetizable particles and nonmagnetic carrier medium.

The magnetic fluid has two totally different fluid states when it is in the presence and absence of a magnetic field. In the absence of a magnetic field, the magnetic fluid behaves in a Newtonian manner, while it behaves in a Bingham manner in the presence of the magnetic field. As shown in Fig. 3(a), the arrangement of particles is disorderly when the magnetic fluid is in the absence of a magnetic field. The particles become oriented when the magnetic field is present. The particles suspended in the fluid starts to form chains along the magnetic flux lines with the increasement of magnetic field intensity (Fig. 3(b)-(d)). In addition, the apparent viscosity of magnetic fluid can be altered by adjusting the magnetic field intensity. Therefore, we take full advantages of this principle to reduce the tremor, as well as generate force feedback.

The master manipulator is shown in Fig. 4. It consists of catheter, magnetic fluids, annular duct, magnetic coil and sensor. The catheter is located in the magnetic fluids and it can obtain the resistance generated by the magnetic fluids. The annular duct is used to hold the magnetic fluids. The magnetic coil can generate magnetic field and change the resistance of magnetic fluids when it is provided with different voltages. The sensor captures the linear movement of the catheter. It obtains the operation signals and send them to control system as the operator push or pull the catheter during surgeries.

III. Performance Evaluation

In order to verify the feasibility of the proposed method, extensive tests have been carried out both theoretically and practically. The results of both simulation studies and real experiments are given and discussed in this section.

A. Simulation set-up

When different surgeons perform surgeries, the specific operating parameters varies because the medical equipment is diversified based on the diseases. In addition, different surgeons have different operation skills and habits, as well as the types of tremors. To verify our model, some conventional parameters were selected and inputted to our model in Matlab. This simulation experiment consists of two types of simulations. In Simulation I, we evaluated the influence on linear operation with and without tremors. In Simulation II, the influence on linear operation was evaluated by using the damper with different apparent viscosity.

In Simulation I, the operating handle was operated with uniform linear motion. It was pushed forward and then was pulled backward at the same speed. The moving speed is 0.01 m/s. To simulate the effort of tremor, a vibration was added to the uniform linear motion. The amplitude and frequency of this vibration are 0.5 N and 8 Hz, respectively. The equivalent mass of the operating handle is 0.05 kg.

In Simulation II, the moving speed of the uniform linear motion is 0.01m/s. The operating handle was pushed forward and then was pulled backward at the same speed. Similarly, a vibration was added to the uniform linear motion, and the amplitude and frequency of this vibration are 0.5 N and 8 Hz, respectively. The equivalent mass of the operating handle is 0.05kg. Three simulations were conducted by changing the apparent viscosity of magnetic fluid. The apparent viscosity is defined as 10 Pa•s, 30 Pa•s and 50 Pa•s, respectively.

B. Results

The simulation results are shown in Fig.5. The comparison of linear operation with and without tremors is shown in Fig.5(a). The blue line represents the “real” operation performed by surgeon (i.e. x_H, without tremors), and the red line represents the captured operation (i.e. x_S, with tremors).

In Fig.5 (b)-(d), the blue line represents the real operation performed by surgeon (i.e. x_H, without tremors), the red line represents the captured operation (i.e. x_S, with tremors), and the black line represents the linear operation with tremor reduction. The apparent viscosity for Fig. 5(b), Fig. 5(b) and Fig. 5(c) are 10 Pa•s, 30 Pa•s and 50 Pa•s, respectively.

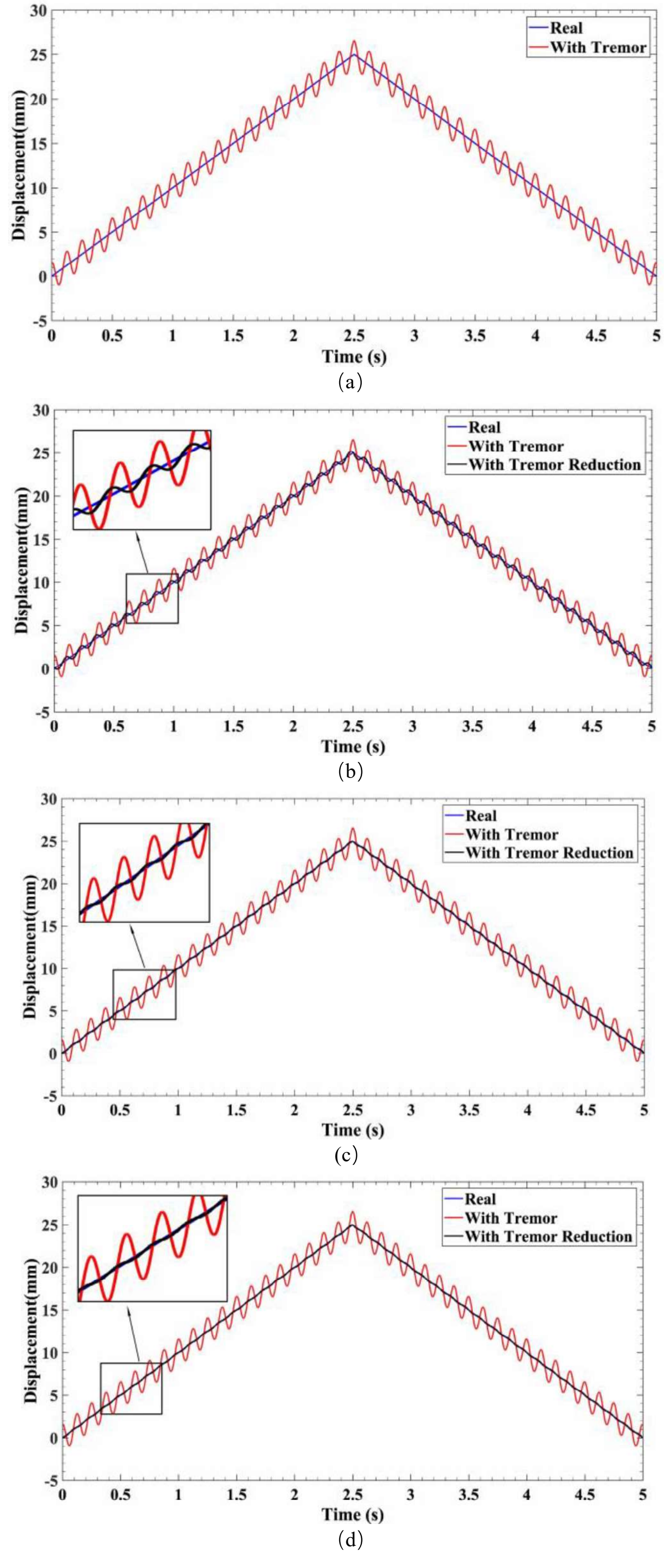

Fig. 5. Simulation results under different conditions: (a) the comparison of linear operation with and without tremors; (b)-(d) the apparent viscosity is defined as 10 Pa•s, 30 Pa•s and 50 Pa•s, respectively.

C. Discussion

When a surgeon performs surgeries with tremor, the captured operation (i.e. x_S) is different with the surgeon's "real" operation (i.e. x_H). As shown in Fig.5(a), the captured operation is severely affected by the tremors. It is the composite motion of surgeon's operation and tremor vibration. When this "wrong" operation is transmitted to the slave manipulator and then the slave manipulator will duplicate this operation. As a result, it will result in damage for blood vessels or even medical accidents.

In Fig. 5(b), the vibration amplitude of the captured operation becomes smaller when the damper was used to reduce the tremor. Meanwhile, when we used a damper with higher value of the apparent viscosity, the vibration amplitude was reduced more obviously (Fig. 5(b)-(d)). The higher value of the apparent viscosity results in better tremor reduction. Therefore, we argue that the tremor can be reduced effectively by using the magnetic fluids damper.

In the clinical surgery, when a surgeon performs surgeries with tremors, the tremors can be reduced by using the proposed method, and thus it can improve the accuracy of operation. In addition, with the increasement of ages, the tremors will occur in some elderly surgeons. They cannot perform interventional surgeries even though they have abundant clinical experience. This proposed method can extend the professional career of surgeons.

IV. Conclusion

In this paper, a novel method using magnetic fluids is proposed to reduce tremor in catheter minimally invasive surgery. The principle of this method is introduced and then the mathematical model is established. We preliminarily evaluated its performance by mathematical calculation and simulation. The simulation results show that the tremor can be reduced effectively by using the magnetic fluids damper. Moreover, the magnetic fluids-based master manipulator can not only improve the accuracy of operation but also extend the professional career of surgeons.

However, some limitations still exist in this research. First, we only preliminarily evaluated the performance of our proposed method. The feasibility of a new method should be evaluated by both mathematical calculation/simulations and real experiments. The real experiments can verify the feasibility more effectively and persuasively. Second, the adjustment of the apparent viscosity for the magnetic fluids will have an impact on the accuracy of force feedback. The master manipulator generates force feedback by altering the apparent viscosity of the magnetic fluids. In addition, the master manipulator reduces the tremor also by altering the apparent viscosity. The optimization value between the force feedback and tremor reduction needs to be obtained by theoretical calculations and experiments. In the future, we will overcome these two limitations and evaluate its performance by experiments.

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