A magnetorheological fluid-based tremor reduction method for robot-assisted catheter operating system

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Abstract: Robot-assisted catheter operating systems are commonly developed since they can improve the operation accuracy and avoid the impact of radiation on surgeons. However, when surgeons perform operations with tremors, the operating efficiency and accuracy will be seriously affected. In this paper, a novel method was proposed to reduce tremor during interventional vascular therapy (IVT). Magnetorheological (MR) fluids are used not only to generate force feedback for surgeons but also to produce resistance to the operations with tremors. Simulations and experiments were carried out to verify the performance of the proposed method. Experiments and simulations results indicated that tremors can be reduced effectively with the proposed method. A robot-assisted catheter operating system with the proposed tremor reduction method, can not only improve the safety and efficiency of operations but also extend the professional career of surgeons.

Keywords: tremor reduction; interventional vascular therapy (IVT); robot-assisted catheter operating system; magnetorheological (MR) fluids.

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1 Introduction

People suffering from cardiovascular diseases and cerebrovascular diseases is increasing in recent decades, and these diseases have become the main reason of global deaths. Since the high risk and the serious sequelae of conventional surgery, surgeons and researchers focus on developing and improving safer and more effective treatment approaches. At present, interventional vascular therapy (IVT) within many superiorities is the most promising method to treat cardiovascular and cerebrovascular diseases. IVT is a minimally invasive surgery which uses a small, flexible catheter to repair hurt and weakened vessels, clogged arteries, and other affected parts of abnormal hearts or brain. The essential advantages and benefits of IVT include less pain, quicker recovery time, and fewer complications (Rafii-Tari et al., 2014). During the surgical procedure, the surgeon makes the medical diagnosis and manipulate the surgical tools according to the image information by X-rays plate. Since surgeons are exposed to X-rays radiation for a long time, it can present a risk of illness and curtail their professional career. To reduce the adverse impacts of the X-rays radiation on surgeons, many research groups have been developing a robot-assisted catheter operating system, and this system can remotely manipulate the movement of the catheter (Da et al., 2008).

Several medical companies have developed robot-assisted catheter operating systems, and some of these systems have been successfully implemented into clinical use. The CorPath Vascular Robotic System developed by Corindus Vascular Robotics, Inc., translates the surgeon's movement by using joysticks and a touchscreen (Britz et al., 2019). The R-One™ robotic assistance platform from Robocath, Inc., comprises two core elements of a radio-protected control unit and robotic unit and can be used for the remote delivery and adjustment of guidewires and stents during the percutaneous coronary intervention (Robocath Inc., 2019). The Stereotaxis Niobe® Robotic Magnetic Navigation System developed by Stereotaxis, Inc., utilized the magnetic navigation technology to precisely direct and steer catheters (Hwang et al., 2020). Meanwhile, some laboratories have made great progress in the research of the robot-assisted catheter operating system. Omisore et al. (2018) designed a novel robotic catheter system for accessing the human cardiac area through radial vasculature. Sankaran et al. (2018) developed an endovascular robotic system, and the system can augment the operator's actions and generate force feedback. Molinero et al. (2019) proposed a robot-assisted endovascular system with 3D haptic guidance, and this system can further improve surgical performance and safety. In our previous research, we have developed a haptic robot-assisted catheter operating system and presented a manipulator based on the magnetorheological (MR) fluids. It can provide a haptic sensation to surgeons (Yin et al., 2016, Song et al, 2018). We also developed several types of clamping structures to realize the replicated motions: pull, push and twist of the catheter (Guo et al, 2019, Zhang et al, 2018, Bao et al., 2018 a, Yang et al., 2019). In addition, we have tested the robot-assisted catheter operating system by the animal and human experiments (Bao et al., 2018 b, Zeng et al., 2019).

Catheters need to be inserted into the vascular system to treat the related diseases, and the minor misoperation will cause serious problems during the insertion. Tremor is an involuntary oscillation or twitching movements of the body. With the increase of the operating time or the surgeons' age, the physiological hand tremor of surgeons will increase inevitably. This physiological hand tremor reduces the operational accuracy and may cause damage to blood vessels or result in the rupture of blood vessels. To minimise the impact of physiological hand tremors on operations, many researchers focus on methods of tremor suppression.

Pledgie et al. (2000) proposed a tremor suppression system, which controls the impedance of the human-machine interface to achieve a specified reduction in pathological tremor power. Kelley et al. (2020) developed a control method leveraging the low mechanical impedance of dielectric elastomers to suppress tremor. Zhou et al. (2020) developed an available tremor suppression device to reduce tremor on the elbow and wrist. The experimental results show good performance of the proposed device. Dosen et al. (2015) proposed a tremor suppression strategy that can originate and counteract tremor from the electromyographic signals of the muscles. Wang et al. (2016) proposed an algorithm using a fast sliding Fourier to transform an interpolation procedure and a limitation module of the frequency range to estimate tremor frequency and separate the tremor components from raw data. In our previous studies, we proposed a method based on a recognition algorithm and adaptive filter method to rectify the wrong operations caused by physiological tremor (Guo et al., 2018 a and b). Moreover, we proposed a novel method using MR fluids to reduce tremor in catheter minimally invasive surgeries. We preliminarily evaluated its performance by mathematical calculation and simulations (Zheng et al., 2019).

Based on the literature analysis, the researchers achieve tremor reduction by using active strategies or passive strategies. In the active strategies, the damper is generally used. However, the MR fluid is mainly used in the commercial vehicle shock absorbers. Case et al. (2013) developed a small-scale MR damper to reduce tremor and demonstrated the feasibility of application in the rehabilitation field. 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. Nevertheless, to our knowledge no effective method has been proposed and applied to the robot-assisted catheter operating systems in IVT.

A novel method based on MR fluids was proposed to reduce tremor during catheter minimally invasive surgeries in this paper. Section 2 describes the overview of our robot-assisted catheter operating system. The details of the proposed method are described in Section 3. Section 4 presents the simulations, experiments and discussions for the results. Finally, a conclusion is given in Section 5.

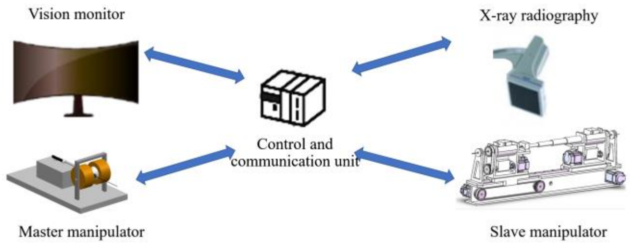


Fig. 1. Conceptual diagram of the robot-assisted catheter system

2 Robot-assisted catheter operating system

The conceptual diagram of the robot-assisted catheter system is shown in Fig. 1 and the system can be divided as three major parts: master manipulator, slave manipulator, and control and communication unit. The master manipulator controlled by surgeons is located in a procedure room or control room which is separated from the operating room. Since operations are implemented in the operating room, it can effectively reduce the radiation exposure to surgeons. The slave manipulator provides flexible operation and inserts catheters and guidewires into the blood vessels of the patient. The control and communication unit is devoted to signal processing and transmission. The system is a closed-loop control system that improves the safety of the operation.

2.1 Master manipulator

To make full use of the existing experience of surgeons, the master manipulator is designed to retain surgeons' original operating experience in catheter minimally invasive surgeries. Catheters and guidewires are used as the operating handle in the master manipulator. Surgeons directly manipulate the catheters and guidewires by their hands, which enable them to adapt the robot-assisted catheter operating system quickly almost wittout training time. The movement information of the catheter is collected by using the sensing unit in the master manipulator. The catheter can be operated with 2 degrees of freedom: axial motion and radial motion. Then the information of the catheter is passed to the control and communication unit. In addition, the master manipulator is also a force feedback device that can feedback the force of the catheter in the blood vessels. This force was caused by the friction or collision between the vessel wall and catheter. In this research, the master manipulator is also a tremor elimination device that can directly process the operating signal from the surgeon's pathological tremor.

2.2 Slave manipulator

The slave manipulator installed beside the patient is used to operate catheters and guidewires to move along blood vessels. The slave manipulator replicates the movement of surgeons measured by the master manipulator and delivers catheters and guidewires. The slave manipulator driven by motors, controls catheters and guidewire for insertion, retraction, and rotation. Moreover, the slave manipulator collects the force signal of the catheter interaction with the blood vessel wall. Then the force single in the slave manipulator is sent to the control and communication unit in the real-time. When the value of the detected force is out of the normal range, the slave manipulator works as a protection mechanism and stops to operate the catheter. This device offers a protection function to decrease the collision trauma between the catheter tip with the vessel wall effectively.

2.3 Control and communication unit

The control and communication unit is designed for remote or local control, protection and fault indication, condition monitoring in the surgical procedure. The unit collects and processes the operating information captured by the master manipulator and then controls catheters and guidewires by the slave manipulator. By using the wide-area network (WAN), telemedicine can be realized that patients and surgeons are not present with each other. The telemedicine not only can reduce health-care costs, but also can improve the medical effectiveness and quality (Pattichis et al., 2002). As for the indication function, the force information of catheters and guidewires in the blood vessel feedbacks to the master manipulator to prompt the surgeon, and if the catheter collision with the vessel wall the unit will remind the surgeon to avoid the vessel puncture. Angiography is one of the X-ray radiography technique that can produce detailed, clear and accurate images of the blood vessels. The angiography imaging can be showed in the vision monitor in the control room avoid the radiation suffered to surgeons.

3 Tremor reduction method

3. 1 Tremor analysis

When the robot system is used to perform surgeries, the surgeon operates the master manipulator and the operation information will be captured by the sensing unit in the master manipulator. In Fig. 2, the captured operation information is used as the input of the slave manipulator and then the slave manipulator will replicate the surgeon's operation. However, some surgeons operate with tremor inevitably and thus the operation with tremor will be performed on the salve side. Operating handles are often used and the operating handles have the same movement as the surgeon' hand. When the surgeon operates the operating handle without tremors, the captured displacement is equal to the surgeons' operation and it can be written as

$$s_{\mathrm{M}} = s_{\mathrm{H}} \tag{1}$$

where s_{M} is the displacement of the master manipulator sent to the control unit, and s_{H} is the displacement of the surgeon's hand.

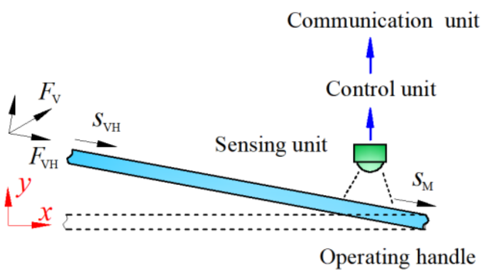


Fig. 2 Schematic diagram of operations affected by tremors.

As shown in Fig. 2, the operating handle has a certain inclination angle relative to the horizontal direction due to tremors, and the captured displacement can be written as

$$s_M = s_H + s_{VH} \tag{2}$$

$$s_{VH} = s_V \cos\theta \tag{3}$$

where s_{VH} is the horizontal displacement caused by the vibration on surgeons' hand, s_V is the displacement of the vibration on surgeons' hand, and θ is the angle of the operating handle relative to the horizontal direction. Substituting equation (3) into equation (2) results in

$$s_M = s_H + s_V \cos\theta \,. \tag{4}$$

When the horizontal displacement caused by tremors is added to the surgeons' operation, catheters and guidewires have different movement with the expected process of surgeons and thus it would cause damage to bleed vessels or result in unsuccessful surgeries.

3. 2 Magnetorheological-fluid-based solution

Given previous research related to the magnetorheological damper, the tremor can be reduced to a certain extent, especially in rehabilitation robotics (Belda-Lois et al., 2007). In this study, a magnetorheological-fluid-based solution is introduced into robot-assisted catheter minimally invasive surgeries. A master manipulator was fabricated by using a MR damper. It can improve the operational performance for surgeons with force feedback generated by the damper, and increase the operation accuracy by reducing tremors in surgeons' arms or hands.

The MR damper is filled with MR fluid and the MR fluid consists of nonmagnetic carrier medium and microscopic magnetizable particles. When a magnetic field is applied to the MR fluid, the MR fluid appears two totally different fluid states: Newtonian manner and Bingham manner. The MR fluid behaves in a Newtonian manner in the absence of a magnetic field, while it behaves in a Bingham manner in the presence of the magnetic field. Particles of the MR fluid are arranged in disorder with the absence of a magnetic field (Fig. 3 (a)). When the magnetic field was applied, the particles become oriented. As shown in Fig. 3(b)-(d), with the increment of magnetic field intensity, the particles suspended

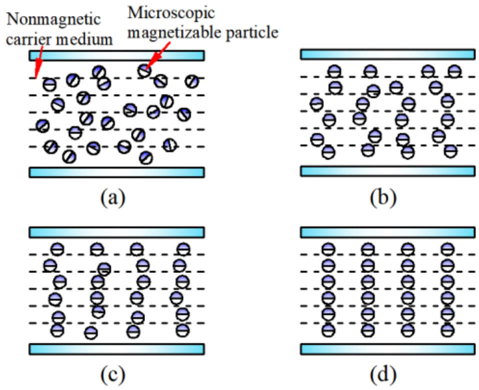


Fig. 3 Particle configuration in the magnetic field with different intensities: (a) no magnetic flux; (b)-(d) different configurations with the gradually increasing intensity (Zheng et al., 2019).

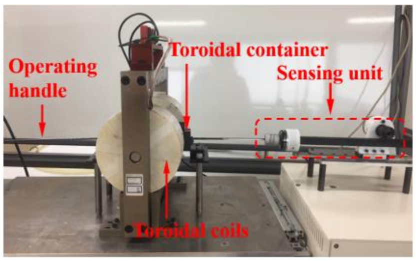


Fig. 4 Master manipulator based on MR fluid

in the fluid starts to form chains along the magnetic flux lines. The apparent viscosity of the MR fluid can be changed by adjusting the magnetic field intensity. Therefore, we take full advantages of this principle to reduce the tremor, as well as generate force feedback.

Based on this solution, a master manipulator was fabricated and shown in Fig. 4. It is composed of a sensing unit, MR fluids, toroidal container, toroidal coils, support, and operating handle. To make full use of existing experience of surgeons, we use catheter/guidewire as the operating handle and surgeons can perform operations by pushing, pulling and rotating this catheter/guidewire. The catheter/guidewire is located in the MR fluids and it can obtain the resistance generated by the MR fluids. The toroidal container is used to hold the MR fluids. The toroidal coils generate magnetic fields and change the resistance of MR fluids when it is provided with different voltages. The sensing unit is used to measure the linear and rotational displacement of catheter/guidewire. It obtains the operation signals and sends them to control system as the operator push or pull the catheter/guidewire during surgeries.

When surgeons perform surgeries with tremors, due to the regular vibration of the tremors, we suppose the vibration force of tremors as simple harmonic motion. Therefore, the vibration force of tremors can be defined as

$$F_V = F_A \cos\omega t \tag{5}$$

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. Since the operating handle has a certain inclination angle relative to the horizontal direction due to tremors, the component vibration force of tremors in the horizontal direction is

$$F_{VH} = F_A \cos\omega t \cos\theta \tag{6}$$

where θ is the angle of the operating handle relative to the horizontal direction.

This master manipulator is a mass-damper system, and the mass and damper are in series. The kinematic analysis model is shown in Fig. 5. The operating handle is equivalent to the mass and MR fluids are regarded as the damper. The linear movement generated by tremors is affected by the mass, damper, vibration force of tremors and time, and the relations could be written as follow:

$$s_{VH} = \mathrm{H}(m, c, F_{VH}, t) \tag{7}$$

where s_{VH} the additional linear movement of operating handle generated by tremors in the horizontal direction, H is an uncertain function for s_{VH}, m is the equivalent mass of the operating handle, c is the apparent viscosity of the MR fluids, F_{VH} is the vibration force of tremors in the horizontal direction, t is the time.

To determine the uncertain function H, a dynamic differential equation for the mass-damper system is established. The dynamic differential equation is as follow:

$$m\ddot{s}_{VH} + c\dot{s}_{VH} = F_{VH} \tag{8}$$

Substituting equation (6) into equation (8) results in

$$m\ddot{s}_{VH} + c\dot{s}_{VH} = F_A \cos\omega t \cos\theta \tag{9}$$

The result for equation (9) is

$$s_{VH}(t) = \frac{F_A \cos\theta}{\omega\sqrt{m^2\omega^2 + c^2}} \cos(\omega t - \varphi) \tag{10}$$

$$\varphi = \arctan\frac{-c}{m\omega} \tag{11}$$

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

On the other hand, if the operation signals are captured without tremor reduction, the dynamic differential equation is

$$m\ddot{s}_{VH} = F_A \cos\omega t \cos\theta \tag{12}$$

The result for equation (12) is

$$s_{VH}(t) = \frac{F_A \cos\theta}{m\omega^2} \cos\omega t \tag{13}$$

According to equation (10) and (13), the influence of tremors on linear movement can be altered by changing the amplitude F_A, phase angle ω, and equivalent mass m. However, the amplitude F_A and phase angle ω are the intrinsic characteristics of tremors, and the equivalent mass m is the intrinsic characteristics of the operating handle. They all cannot be altered easily. However, in equation (10)

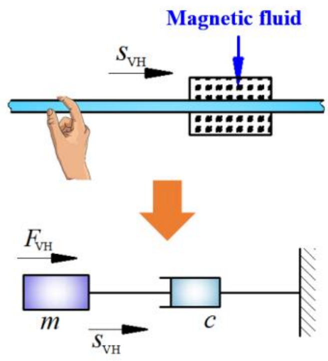


Fig. 5 Mass-damper model for the tremor suppression.

the horizontal displacement caused by tremors can be adjusted by the apparent viscosity of the MR fluid c. The apparent viscosity of the MR fluid c changes with the current variation of the magnetic field. Therefore, in this research, we focus on reducing tremor by using the change of apparent viscosity of the MR fluid.

Moreover, to evaluate the effect on tremor reduction with MR fluid and calculate the relationship between different parameters conveniently, we define a tremor elimination rate (TRE) and it is as follows:

$$TRE = 1 - \frac{A_E}{A_O} \tag{14}$$

where A_E is the amplitude of tremors with elimination by MR fluids, and A_O is the amplitude of tremors without elimination by MR fluids. Substituting equation (10) and (13) into equation (14), the tremor elimination rate for the MR fluids can be written as:

$$TRE = 1 - \frac{1}{\sqrt{1 + (\frac{c}{m\omega})^2}}. \tag{15}$$

In the light of equation (15), we find that bigger apparent viscosity of the MR fluid results in more effective tremor elimination. However, if the apparent viscosity of the MR fluid is set to a large value, it may cause a negative effect on the force feedback since the generated force feedback should be the same as the measured force as far as possible. Therefore, the apparent viscosity of the MR fluid needs to be chosen based on a good balance between the force feedback and tremor reduction.

4 Simulations and experiments

To evaluate the performance of the proposed method, simulations and experiments were both carried out. We first implement simulations using MATLAB and then conduct experiments to verify the feasibility. The results of both simulation studies and real experiments are given and discussed.

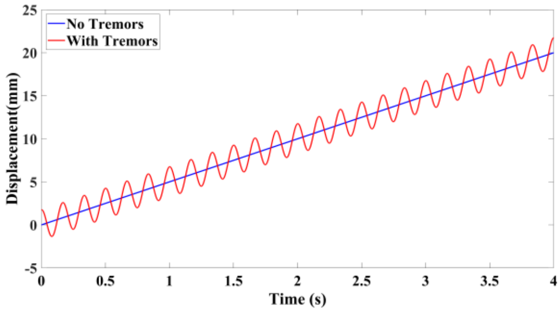


Fig. 6 Results of Simulation I.

Table I Tremor elimination rate for each simulation.

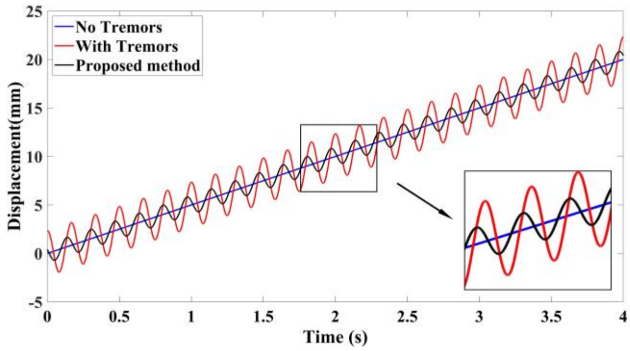
	c/ (Pa•s)			
	5	25	45	65
TRE	92.82%	98.56%	99.20%	99.45%

4. 1 Simulations

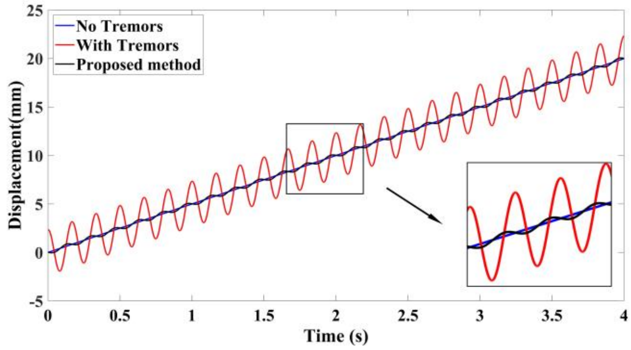
Since various surgeries require different medical apparatus, the specific operating parameters for the robot system will vary. Moreover, surgeons have different operation habits and experience, and tremors for every surgeon would also differ from each other. Therefore, two types of simulations were conducted with various parameters. In Simulation I, we evaluated the influence on linear operation with and without tremors. In Simulation II, the impact on the linear operation was evaluated by using the damper with different apparent viscosity.

In Simulation I, the operating handle was pushed with uniform linear motion at the speed of 5 mm/s. In order to simulate the operation with tremor, a vibration with an amplitude of 0.2 N and a frequency of 6 Hz was added to the uniform linear motion. The equivalent mass of the operating handle is 0.06kg. In Simulation II, the operating handle was also pushed with uniform linear motion at the speed of 5 mm/s. Similarly, a vibration with an amplitude of 0.2 N and a frequency of 6 Hz was added to the uniform linear motion. The equivalent mass of the operating handle is set as 0.06kg. Three simulations were conducted with different apparent viscosities of MR fluid. The apparent viscosities for each simulation are 5 Pa•s, 25 Pa•s, 45 Pa•s, and 65 Pa•s, respectively. Also, we calculated the tremor elimination rate for each simulation based on equation (15).

Fig. 6 shows the results of Simulation I. This figure includes the comparison of linear operation with and without tremors. The blue line indicates the displacement of the procedure performed without tremors, i.e. s_{H} , and the red line indicates the displacement of the procedure performed with tremors, i.e. s_{VH} . The results of Simulation II are shown in Fig. 7. The red line indicates the displacement of the procedure performed with tremors, i.e. s_{VH} , and bule line indicates the displacement of the procedure performed with



(a)



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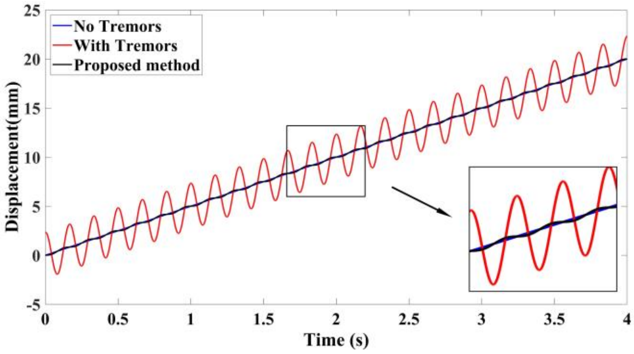
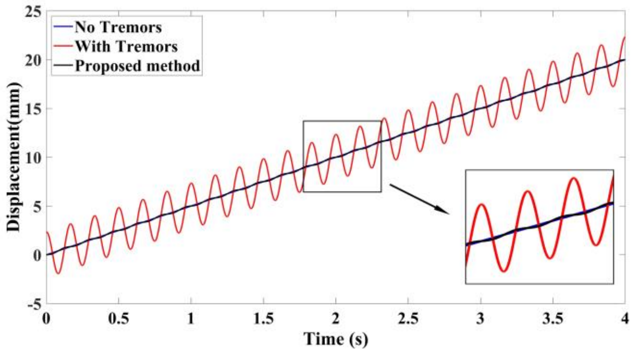


(c)



(d)

Fig. 7 Results of Simulation II: (a) c = 5Pa•s; (b) c = 25Pa•s; (c) c = 45Pa•s; (d) c = 65Pa•s.

tremor reduction by the MR-fluid-based master manipulator. The apparent viscosity for Fig. 7 (a)-(d) are 5 Pa•s, 25 Pa•s, 45 Pa•s, and 65 Pa•s, respectively. Table I shows the tremor elimination rate for each simulation with different apparent viscosities.

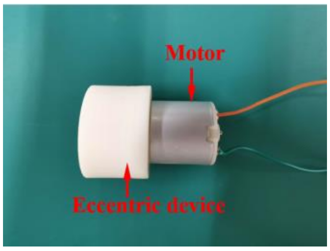


Fig. 8 Vibration generator.

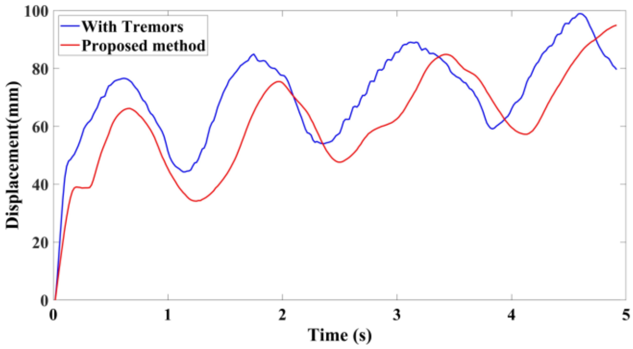


Fig. 9 Results of the tremor reduction with and without the proposed method.

4. 2 Experiments

To test the performance of the proposed method in reducing tremors, an operator manipulates the operating handle with and without the proposed method by turn. To simulate the effect of tremors on operations, we developed a vibration generator (shown in Fig. 8). It consists of a motor and an eccentric device. The eccentric device has a weight off the axis of the device, and this weight can rotate around the axis. When the motor rotates with various speeds, vibrations with different frequencies are generated. We first turned off the toroidal coils in the master manipulator and the MR fluids in the toroidal container are in Newtonian manner. The vibration generator was mounted on the operator's hand and it rotated with random frequency. The operator pushed and pulled the operating handle and the operating information was measured by the sensing unit of the master manipulator. Then we turned on the toroidal coils and then the MR fluids in the toroidal container are in Bingham manner. The operator performed a similar operation with the vibration generator mounted on his/her hand.

The experimental results are shown in Fig. 9. The blue line represents the displacement of the operating handle without using the proposed method; the red line represents the displacement of the operating handle by using the proposed method.

4. 3 Discussion

The captured operation differs with the surgeons' "real" operation when surgeons perform surgeries with tremors. As shown in Fig. 6, the captured operation is severely affected by the tremors. It is the composite motion of surgeons' operation and tremor vibration. When this "wrong" operation is transmitted to the slave manipulator and then the slave manipulator will duplicate this operation. This additional vibration is not the operation of surgeons' intention, and it may cause damage to blood vessels or result in the rupture of blood vessels.

In Fig. 7 (a), 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 a higher value of the apparent viscosity, the vibration amplitude was reduced more obviously (Fig. 7(b)-(d)). The higher value of the apparent viscosity results in better tremor reduction. When the apparent viscosities of MR fluid increase from 45 Pa•s to 65 Pa•s, the effect of vibration reduction is not obvious (Table I, and Fig. 7(c)-(d)). Moreover, MR fluids with a large value of apparent viscosity will cause a negative effect on the force feedback. So the apparent viscosity needs to be controlled in a proper range.

Blue line is zigzag since additional vibration is added to the operation, in Fig. 9. The red line with the proposed method is much smoother due to the proposed tremor reduction method. Without additional vibration, it is easier for surgeons to deliver catheters/guidewires to target positions. The safety and efficiency of operation will be improved since the additional vibration to the operation is reduced or eliminated.

5 Conclusion

In this paper, a novel method based on MR fluids was proposed to reduce tremor in catheter minimally invasive surgeries. The principle of this method was introduced and a dynamic model was established. The performance was evaluated through simulations and experiments. Simulations and experiments results show that the proposed method can reduce tremors effectively. A robot-assisted catheter operating system with the proposed tremor reduction method, can not only improve the safety and efficiency of operations but also extend the professional career of surgeons.

The master manipulator generates force feedback by altering the apparent viscosity of the MR fluids; the master manipulator reduces the tremor also by changing the apparent viscosity. The adjustment of the apparent viscosity for the MR fluids will have an impact on the accuracy of force feedback. Therefore, the apparent viscosity of the MR fluid needs to be chosen based on an excellent balance between the force feedback and tremor reduction. In the future, we will overcome this limitation and evaluate its performance by experiments.

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