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A Novel Master Haptic Interface Based on MR-Fluids for Endovascular Catheterization

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***Abstract*- Insufficient force feedback and collision warning of teleoperation surgical tools increase the risk of endovascular catheterization. This paper proposed a novel master haptic interface that takes advantage of a surgeon's natural manipulation skills obtained through experience, as well as generates collision warning with haptic cues to ensure safe operation. Moreover, it can eliminate the influence of external friction on the haptic force. Aiming at the Bingham model of the damper with the longest research time and the most widely used, a Simulink mechanical simulation model was built. The perception power provided by the tactile feedback device at the main end of the vascular interventional surgery robot was simulated and related mechanics tests were carried out. The results show that the designed tactile feedback device can provide a tactile force for the surgeons during the operation. It verifies the mechanical properties of the MR fluid damper for vascular interventional surgery. The device can give surgeons real haptic feedback during vascular interventional surgery to distinguish whether the catheter tip collides with blood vessels or not by collision warning with haptic cues, thus achieving the goal of safe operation.**

***Index Terms* - Master haptic interface, Magnetorheological fluids, Endovascular catheterization, Safe operation, Vascular interventional surgery**

I. INTRODUCTION

According to a report by the American Heart Association (AHA), cardiovascular and cerebrovascular diseases have become one of the three major causes of human death (heart disease, stroke and vascular diseases). Even in developed countries, the number of deaths from cardiovascular disease is still as high as 34% every year [1]. The number of patients with sudden cardiac death caused by arrhythmia is increasing year by year. If they can not be treated effectively in time, it will lead to myocardial infarction and stroke, which will directly lead to death, which is a serious threat to human health.

With the rapid development of medical technology, vascular interventional surgery has become a common method to diagnose and treat a variety of cardiovascular diseases, such as arterial stenosis, thrombosis, atherosclerosis and so on. In the process of vascular interventional therapy, a flexible catheter and guidewire are usually inserted into the lesion target along the vessel wall through a small incision of the inguinal femoral artery or wrist radial artery. This process usually uses a digital subtraction angiography (DSA) system to visually assist the interventional physician in intravascular navigation and final placement of the catheter [2,3]. However, the surgeon's fatigue and physiological trembling during the operation will affect the success rate of the operation, and long-term repeated exposure to X-rays will cause occupational hazards to the surgeon, such as cancer, cataract, etc. [4]. Even if you wear protective clothing, your face and hands cannot be completely covered. In addition, wearing heavy protective clothing for a long time can cause fatigue and neck and back pain.

In recent years, robot-assisted technology has played an important role in the field of medicine. To solve the above problems, many research institutions and commercial organizations have combined robot-assisted technology with vascular interventional surgery to develop a variety of robot-assisted operating systems for intravascular surgery. They can solve the serious problem of cumulative radiation of traditional Chinese medicine students in vascular interventional surgery, improve stability and accuracy and reduce surgical risk. The system used in clinical trials shows significant advantages [5]. At present, the vascular interventional surgery robot systems certified and approved by FDA include the amigo TM remote catheter system developed by catheter robotic incorporation [6], Niobe remote magnetic navigation system developed by stereotaxis company of the United States [7], Sensei x catheter system developed by Hansen medical company of Canada [8], and corpath200 robot-assisted operating system developed by corindus company of the United States [9].

In traditional intravascular interventional surgery, experienced surgeons obtain the tactile hint of catheter tissue by sensing the small axial force and torque of the fingertip when operating surgical tools (catheter and guidewire) into different arteries of patients. With the help of real-time image data, the risk of vascular perforation at the bend can be reduced by inserting, retracting and rotating in different directions at the proximal end of the tool. However, in robot-assisted vascular interventional surgery, surgeons cannot directly operate tools and obtain tactile information. It is difficult to determine whether blood vessels collide in the area of vascular curvature only by visual assistance [10]. Therefore, some researchers embed the force measurement device into the robot catheter system to more intuitively reflect the force information of blood vessels in the process of intravascular. With the continuous development of force sensor technology towards miniaturization and high precision, the application of force/torque sensing devices is very important for the remote operation of the robot catheter system. It can remind the surgeon to adjust the direction of surgical tools in time when the catheter head collides with the blood vessel wall. To this end, fiber-optic-based sensors have been applied to the catheter tip to provide force feedback to the operator [11,12], and the potential of this technology has been confirmed by clinical studies. Payne et al. designed a novel master-slave force feedback system by using two strain gauges on both sides close to the tip of the catheter and two micro force sensors at the main operating side. In the process of simulating vascular intervention, it showed that the system could reduce the size and duration of contact force [10].

In general, the research on these vascular interventional robot systems has made gratifying progress, including reducing radiation exposure, improving motion accuracy and stability, and accurate force feedback [13]. However, for most systems in this field, sensors installed on robots or surgical devices are used to capture tool tissue interaction. Surgeons must monitor the trend and value of force in real-time to determine whether a collision has occurred. Staying focused all the time will make the operator more prone to fatigue. In addition, the existing commercial force feedback equipment is fixed and driven by a motor. Such force feedback equipment has some problems, such as insufficient safety and stability, and the operator cannot interact naturally.

Therefore, this paper proposed a master haptic interface that generates haptic feedback through the magnetorheological effect to overcome the shortcomings of the existing force feedback equipment. The innovative points of this master haptic interface relative to other interfaces are as follows. First, the interface makes full use of the magnetorheological fluid. The most unique and attractive feature of MR fluid is its rheological effect, that is, its rheological characteristics can change with the change of external magnetic field strength. MR fluid actuator has the characteristics of stepless controllable output, adjustable and good stability of force feedback system. Second, compared with other masters, this master haptic interface completely simulates the real surgical operation scenario. Although the surgeon does not perform on-site surgery, the surgeon is still operating the real surgical device, which can completely simulate the movement of the guide wire during the operation, giving full play to the surgeon's natural operation skills. This method can not only make the surgeon realize the sense of on-the-spot operation, but also make it easier to distinguish whether the proximal force exceeds the safety threshold of the blood vessel, so as to enhance the safety of the operation.

II. DESIGN OF THE NOVEL MASTER HAPTIC INTERFACE

Magnetorheological fluid is a special controllable fluid, which is composed of magnetic particles with strong permeability and weak hysteresis and non-magnetic liquid. As shown in Fig.1, in the state of zero magnetic fields, the magnetic particles in the magnetorheological fluid are randomly and evenly dispersed in the mixed liquid, making the viscous flow in the form of a Newtonian fluid, and the viscosity is very low; When an external magnetic field is applied, the magnetorheological fluid will produce a special magnetorheological effect and change the magnetic chain structure. The magnetic particles in the magnetorheological fluid form a chain with a relatively stable structure along the direction of the magnetic field line, and the magnetic chain will become more and more solid and stable due to the increase of the magnetic field strength. Under the action of the magnetic field, the viscosity of the magnetorheological fluid will increase by an order of magnitude, and show solid characteristics with the increase of the magnetic field strength. This change can be carried out in both directions, that is, when the applied magnetic field disappears, the magnetorheological fluid returns to the original fluid state.

In combination with the characteristics of the MR fluids in a magnetic field and the haptic desire of the robot-assisted catheter system, it will generate a resistance torque between the MR fluids and a rigid cylinder that rotated in the MR fluids with a magnetic field (see Fig.2). Under the action of the magnetic field, MR fluid will produce a shear resistance moment for the rotating cylinder placed in it. The shear resistance moment changes with the change of magnetic induction intensity added to MR fluid. Therefore, by adjusting the magnetic induction intensity in the working gap, the resistance moment output by the actuator can be adjusted.

Based on analyzing the characteristics of the MR fluids and the haptic desire of the robotic catheter operating system, the prototype of the master haptic interface is proposed as shown in Fig.3, which is composed of two electromagnetic coils with two iron cores, an MR fluids container. The detailed design specifications for the haptic interface had been introduced in [14,15]. The advantage of this novel design is that it can avoid the influence of the friction between the operating rod and the magnetorheological fluid container on the haptic force A pinion and rack mechanism coupled to two rotary encoders. Two encoders are used for capturing and transmitting translation and rotation singles to the slave manipulator during the procedures, respectively. When the catheter collides with the vascular wall and the contact force measured at the slave platform exceeds the corresponding threshold, the master haptic interface will quickly generate resistance as the collision warning to remind the operator of the collision, thus avoiding the vessel puncture.

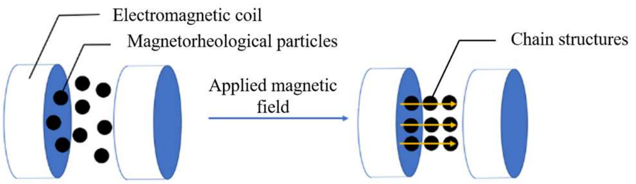

Fig.1 The magnetic field characteristic of magnetorheological particles

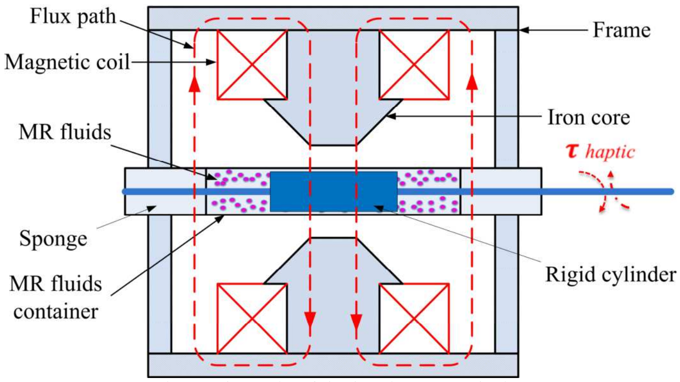

Fig.2 Schematic of the haptic master device

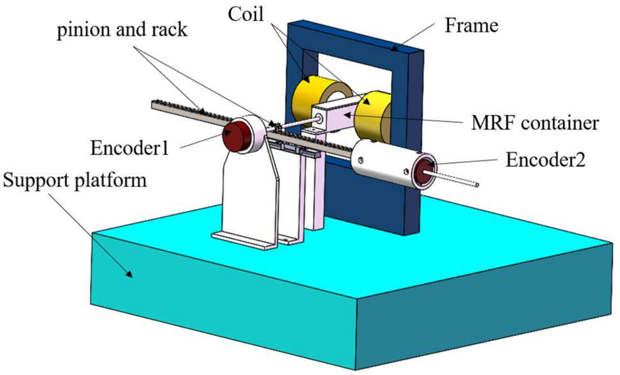

Fig. 3 A prototype of the master haptic interface

III. ESTABLISHMENT OF MECHANICAL MODEL OF MASTER HAPTIC INTERFACE

The above-mentioned mechanical structure design of the master haptic interface based on MRF determines the performance indicators of the device, such as adjustable accuracy, response speed, real-time performance, mechanical loss, etc. The reasonable structural design and modeling of the main haptic interface is an important part of analysis and parameter correction, which is of great significance to optimize the structural design and obtain better feedback effects. Throughout the domestic and foreign academic research fields, the Bingham model is one of the earliest and most widely used models.

Under the steady-state shear field, the stress-strain relationship of the magnetorheological fluid is as follows:

$$\tau = \tau_H + \eta\gamma, \tau \geq \tau_H \tag{1}$$

In the formula, τ is the shear stress of the MR fluid；τ_H is the dynamic yield stress of the MR fluid；η is the viscosity coefficient of the MR fluid；γ is the viscosity coefficient of the MR fluids. Build a model for the master haptic manipulator as shown in Fig.4.

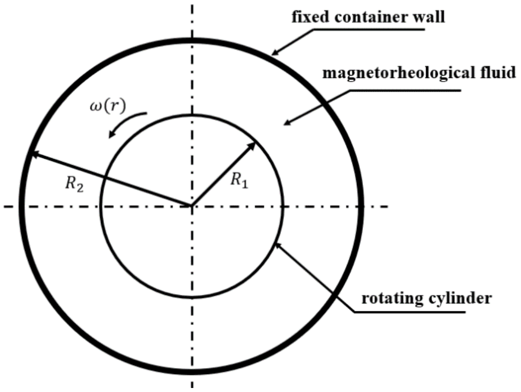

Fig.4 Master haptic operating interface model

In the figure：R1 and R2 are the radius of the rotating cylinder and the fixed container, and the magnetorheological fluid is filled between them. When the rotating cylinder rotates at an angular velocity ω, the magnetorheological fluid is rotated by shearing with an angular velocity of $\omega(r)$.

The resistance torque analysis is carried out as follows:

When an external magnetic field is applied, the fluid transfer torque at a radius r is

$$T = 2\pi r^2 L_e \tau_r \theta \tag{2}$$

In the formula, L_e is the effective length along the axial direction of the magnetorheological fluid under the action of the magnetic field that can produce the magnetorheological fluid effect.

Combined with the relevant structural parameters of the master haptic manipulator designed in the literature, we can get:

$$T = 2\pi L_e C_1 \tag{3}$$

C_1 can be represented as:

$$C_1 = \frac{2\eta R_1^2 R_2^2}{R_2^2 - R_1^2}\left(\frac{\tau_H}{\eta}\ln\frac{R_2}{R_1} + \omega\right) \tag{4}$$

Substituting equation (4) into equation (3), we can get:

$$T_1 = \frac{4\pi L_e R_1^2 R_2^2 \ln(R_2 / R_1)}{R_2^2 - R_1^2}\tau_H + \frac{4\pi L_e R_1^2 R_2^2}{R_2^2 - R_1^2}\eta \tag{5}$$

When there is no external magnetic field, the magnetorheological fluid exhibits the characteristics of a Newtonian fluid, L_1 is the circumferential length of the place without the action of magnetic flux, viscous flow occurs, and its viscous resistance moment is,

$$T_2 = \frac{4\pi L_1 {R_1}^2 {R_2}^2 \omega}{{R_2}^2 - {R_1}^2}\eta \tag{6}$$

In which, $L_1=2\pi R_1$, the total torque can be obtained by formula (5) and formula (6)

$$T = T_1 + T_2$$
$$= \frac{4\pi L_e {R_1}^2 {R_2}^2 \ln(R_2/R_1)}{{R_2}^2 - {R_1}^2}\tau_H + \frac{4\pi(L_1+L_2){R_1}^2 {R_2}^2 \omega}{{R_2}^2 - {R_1}^2}\eta \tag{7}$$

IV. SIMULATION ANALYSIS OF THE MASTER HAPTIC INTERFACE

The MRF-132DG magnetorheological fluid is used as the research object. This type of magnetorheological fluid is time-sensitive and reversible for magnetic field changes. It provides lower yield strength in the state of zero magnetic fields and higher yield strength in the state of the external magnetic field, and its adjustable range, controllability, high-temperature resistance and other properties meet the requirements of this device. With a wide range of controllability and high-temperature resistance to meet application requirements. Its basic parameters are shown in Table I.

According to the relationship between the yield stress τ of the magnetorheological fluid MRF-132DG and the magnetic field strength H, the fitting relationship between the yield stress τ and the magnetic field strength H is as follows,

$$\begin{cases} \tau(H) = 9913\times10^{-7}H^3 - 1.069\times10^{-3}H^2 + 0.3894H, (0 \le H \le 300) \\ \tau(H) = 47.4, (H > 300) \end{cases} \tag{8}$$

The main structural parameters of the device are shown in Table II.

The relational formula for the magnetic field generated by the energization of the copper coil is:

Table I Basic parameters of magnetorheological fluid

Model	Density(cm^2)	Quality Score (%)	Viscosity (Pa·s)	Temperature (°C)
MRF-132DG	2.98~3.18	80.98	0.092±0.015	40~130

Table II Main structural parameters of the master tactile operator

Parameter name	Parameter value
Effective magnetic path length (L/mm)	30
Operating Sense Effective Length(L$_e$/mm)	24
Rotation cylinder radius (R1/mm)	10
Fixed container radius (R2/mm)	13
Copper coil turns (n/turn)	1200

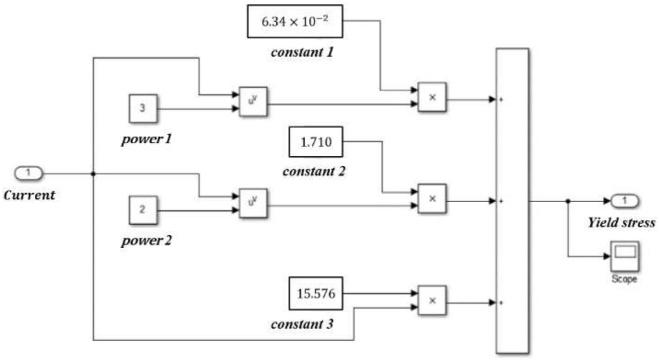

Fig. 5 Simulink block diagram for yield stress τ and current I

$$H = \frac{nI}{L} \tag{9}$$

From equations (8) and (9), the relationship between yield stress τ and current I are obtained:

$$\begin{cases} \tau(I) = 6.344\times10^{-2}I^3 - 1.71I^2 + 15.576I, (0 \le I < 7.5) \\ \tau(I) = 42.723(I \ge 7.5) \end{cases} \tag{10}$$

In Simulink, a mathematical model is established for the yield stress τ and the current I, and the block diagram shown in Fig. 5 is obtained.

Based on the performance parameters of the magnetorheological fluid and the main structural parameters of the master operation interface, the relationship between the moment T, the yield stress $\tau(I)$ and the angular velocity ω is obtained:

$$\begin{cases} T = 1.2296I^3 - 3.3148\times10I^2 + 301.87I + 24.586\omega, (0 \le I < 7.5) \\ T = 918.2, (I \ge 7.5) \end{cases} \tag{11}$$

Equation (7) shows that the resistance torque consists of two parts. Compared with T_1, the value of T_2 is very small, especially when it is used for force feedback, the speed of the operator is very slow, and the speed of the rotating cylinder is also very slow, namely ω value of is small, so the viscous drag torque is small. A comprehensive analysis of formula (11) shows that the angular velocity has little effect on the resistance torque, that is, under different angular velocities ω, the relationship between the torque and the excitation current of the rotating cylinder in the magnetorheological fluid almost coincides.

To research the feedback obtained by the operator, the feedback resistance of the transmission is analyzed below. The power at the yield stress of the rotating cylinder is,

$$P_1 = \tau \cdot \omega R_1 \tag{12}$$

The main structural parameters of the transmission part of the device are shown in Table III.

Table III Main structural parameters of the transmission part

Parameter	Value
Transmission efficiency(ξ/%)	90
Gear radius(R/mm)	25
Rotation cylinder radius (R_1/mm)	10

It is known that when the cylinder rotates at an angular velocity ω, the γ shear strain rate of the magnetorheological fluid is as follows,

$$\gamma = \frac{\omega R}{L_e} \tag{13}$$

From equations (1), (10), (12), and (13), the relationship between the power P_1 of the yield stress on the rotating cylinder, the current I, and the angular velocity ω can be obtained:

$$P_1 = 6.344\times10^{-2} I^3 - 1.71 I^2 + 15.576 I + 0.3067\omega \tag{14}$$

The power from the yield stress of the rotating cylinder transmitted to the gear is P_2,

$$P_2 = P_1 \cdot \xi \tag{15}$$

$$P_2 = F\omega R \tag{16}$$

The relationship between the force F at the gear and the moving speed v of the rack can be obtained from equations (12) and (13),

$$F = 2.284\times10^{-2} I^3 - 0.6156 I^2 + 5.607 I + 4.416 v \tag{17}$$

Based on the above model, the simulation was performed to simulate the resistance of the operator under different excitation currents when the speed was 1mm/s, 5mm/s, and 10mm/s, that is, the tactile feedback effect during surgery was simulated. The simulation results are shown in Fig. 6.

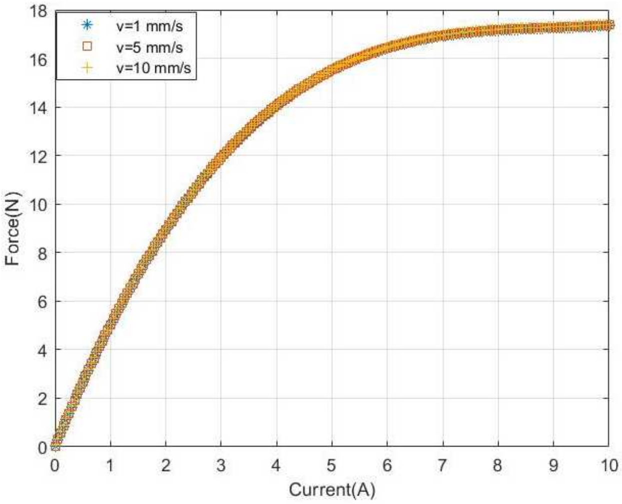

Fig.6. The relationship between the feedback resistance and current of the MRF-based haptic operating terminal when the speed changes

From the simulation results, we can get that the limited movement speed v value of the master operation rod has little effect on the resistance F. As the current increases, the magnetorheological fluid gradually exhibits the characteristics of Bingham fluid with high viscosity and low fluidity. When the current exceeds a certain value, the resistance force generated by the magnetorheological fluid will tend to be stable. When the excitation current reaches 7.5A, the device will feedback a resistance of about 17.08N, which can provide haptic force feedback that can be perceived by the operator, realize remote collision perception, and improve the precision and safety of surgery.

V. CONCLUSIONS

In this chapter, a novel master haptic interface is proposed to transmit the conventional actions of a surgeon while operating a catheter/guidewire. The application of the master haptic interface based on magnetorheological (MR) fluids and a high-precision force sensor makes the obvious collision warning in haptic cues possible. The most attractive advantage is that it can eliminate the influence of external friction on the haptic force. To verify the validity of collision warning in haptic cues, the magnitude of the haptic force is evaluated by the simulation experiment. The results show that the change of haptic force is much greater than the human's finger detection resolution(the amount of force that the finger can perceive and distinguish) and the propulsion speed does not affect the haptic force. Therefore, it can remind the operator of a collision, even for novices. The design of the proposed master haptic interface provides significant insights for the future development of ergonomically optimized endovascular robotic systems incorporating force feedback, haptic feedback and collision warning, whilst taking full advantage of the natural manipulation skills of the operators for endovascular procedures.

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