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Electromagnetic Braking-based Collision Protection of a Novel Catheter Manipulator

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***Abstract*- A robotically assisted catheterization system can obviously reduce the radiation exposure to the surgeon and lesson the fatigue caused by standing for long time in protective clothing. However, few designs have taken the collision protection function of a catheter manipulator into consideration. Additionally, limited research has been conducted in the damage of the clamping mechanism to the catheter. This paper presents a novel clamping mechanism based on the electromagnetic braking for a catheter manipulator which can be used in the minimally invasive surgery training system. A significant advantage is that the proposed design has the collision protection function which can realize the relative sliding between the catheter and the clamping device so as to avoid the vessel puncture, when the measured force exceeds a certain threshold. In addition, the simulation verification of this function is carried out. The results show that the clamping force of the catheter obviously decreases when the measured force increases. This clamping mechanism provides important insights into the design of safe and reliable robotic catheter manipulators incorporating effective and lossless clamping for intraoperative navigation.**

Index Terms -Electromagnetic force, Lossless clamping mechanism, Slave manipulator, Collision protection

I. INTRODUCTION

A survey showed that: cardiovascular and cerebrovascular diseases have become one of the three major causes of death in human beings, which is a serious threat to human health. Even in the developed countries, cardiovascular disease remains the major cause of mortality, accounting for 34% of deaths each year [1].For vascular tumors, thrombosis, vascular malformations, vascular contractions, vascular sclerosis, and other vascular diseases, vascular interventional surgery (VIS) is a revolutionary surgical technique，and it is an effective treatment method for the vascular diseases [2]. A surgeon manipulates a flexible catheter (a rigid hose, with a guide wire) within human vascular vessels to access a target and carry out operations under the guidance of a digital reduction shadow angiography (DSA) system. Compared with traditional surgery, VIS has many advantages: smaller incisions, quicker recovery and fewer complications. Thus, it has been widely adopted all over the world [3].Nonetheless, the operation has obvious disadvantages: The success of the surgery will be reduced due to the surgeon's fatigue, physiological tremors and miss operation during fatigue [4]. However, there are many problems of safety in traditional VIS, and the surgeon must be highly skilled and specialized due to the high risks involved.

In recent years, the use of medical and surgical robotic systems has become a hot study topic. Most of the systems currently used in medical surgery contain master-slave manipulators. However, to solve the VIS problems mentioned above, the combination of robot technology and vascular interventional technology is very necessary [5], [6]. Moreover, an efficiency tele-operated robotic catheter system should be adopted, which can assist the surgeon to operate the catheter interventional from a safe space [7].The physiological tremors and miss operations of a surgeon can be filtered out through the system, increasing the success of surgery [8].Many research groups around the world are committed to the development of robotic catheter operating system. J.Payne et al. [9] presented a novel master-slave system with force feedback for endovascular catheterization. Compared with manual catheterization, the novel force feedback system reduced the magnitude and duration of force exerted during a simulated endovascular procedure. A novel master-slave robotic catheter operating system with force feedback and visual feedback for vascular interventional surgery was proposed by Guo et al [10]. A load cell and torque sensor was used to detect the force signals in the axial direction and the torque signals in the radial direction, respectively. It has good

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manoeuvrability and the surgeon's skill can be transmitted to the slave side to insert and rotate the catheter under the force and visual feedback. The dynamic and static performance of the system, and the synchronization between master and slave sides were evaluated [11], [12]. Also, a compact, cost-effective force-sensing device based on strain gauges was placed at the front end of the slave manipulator to detect the force signals directly without any mechanical transmission, and this can increase the measurement accuracy of force information [13]. In order to improve the skills of catheter manipulation for operators, Wang et al. developed a training system integrated cooperation of VR simulator and haptic device to train the surgeon, and the results demonstrate that the operation safety is improved 15.94% and task completion time is cut 18.80 seconds for maximum. In addition, the non-medical subjects will be more confident in the real operation according to the training of VR system [14]-[16]. Yogesh et al. [17] developed a novel remote catheter navigation system to reduce the physical stress and irradiation to the user during a fluoroscopic X-ray guided catheter intervention. The results of two experiments showed that the system had the ability to sense and replicate motion to within 1 mm and 1° in the axial and radial directions, respectively. Rafii-Tari et al. proposed a framework for automated and objective assessment of performance by measuring catheter-tissue contact forces and operator motion patterns across different skill levels, and using language modes to learn the underlying force and motion patterns that are characteristic of skill [18]. Fu et al. proposed a master-slave catheterization system, which included a steerable catheter with a positioning function and an insertion mechanism with force feedback [19]. The design concept of a human operator-centered haptic interface was firstly introduced [20]-[23]. A new compact and sterilizable tele-robotic system with three degrees of freedom was proposed, which allowed the interventionalist to use conventional steerable catheters [24]. Zhou et al. [25] described the cardiovascular interventional surgery (CIS) virtual training platform, which was composed of a mechanical manipulation unit, a simulation platform and a user interface. The tests of translation and rotation showed that the accuracies improved by 50% and 32.5%. Compared to traditional catheter interventional methods, these systems can provide some advantages such as improving stability and comfort, reducing radiation exposure to the surgeon and eliminating physiological tremors. On the downside, the collision protection and force feedback in the slave site do not combine with each other. Therefore, it is extremely urgent for tele-operated robotic catheter systems to provide the patient with collision protection during conventional catheterization procedures because excessive forces could rupture the blood vessel walls and result in bleeding.

In this paper, a novel design of the clamping structure with collision protection in the slave manipulator is proposed. The clamping structure of three jaws is designed to realize the clamping and relaxation of the catheter based on electromagnetic brake clamping mechanism. The design is a lossless clamping mechanism which uses the conical clamping principle to complete clamping. It has big clamping contact area and reliable clamping which can reduce the clamping injury of catheter. It can control the clamping force by adjusting the input current. And the clamping mechanism has the advantages of fast response and reliable performance. What's more, the designed clamping structure is a flexible clamping mechanism which will automatically release the catheter when the feedback force is greater than a critical value, so as to effectively avoid vessel puncture caused by system malfunction or human error. In addition, the relationship of cone angles of the collet and clamping force of catheter has been analyzed which is of great significance to ensure the stability of the clamping.

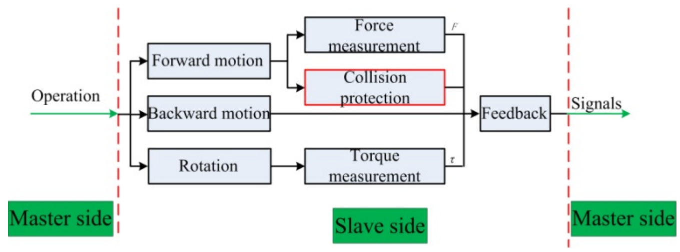
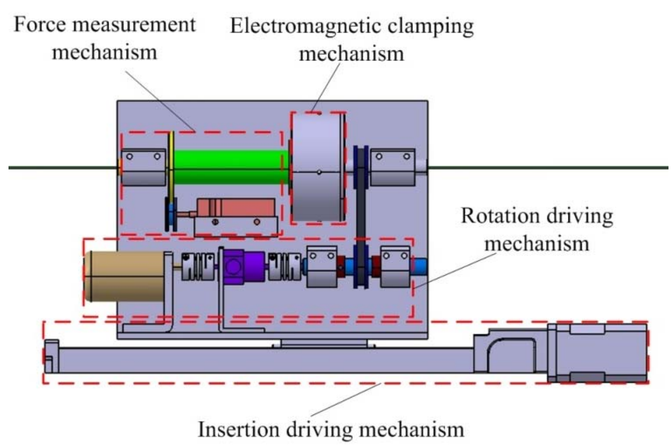
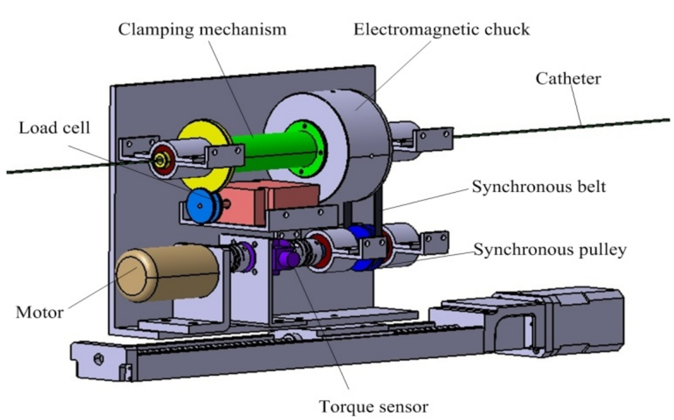


Fig.1 The overview of the master-slave robotic catheter system



(a) The front view of the catheter manipulator



(b) The isometric view of the catheter manipulator
Fig.2 Structure diagram of the slave side

II. STRUCTURE DESIGN OF A NOVEL SLAVE MANIPULATOR

The conceptual diagram of the robotic catheter system, shown in Fig.1, describes the flow chart of the operational process. The robotic catheter system consists of five subsystems: master subsystem (master manipulator), slave subsystem (slave manipulator), local control subsystem on the master side and the slave side, and communication subsystem via the internet. To protect the surgeon from the radiation of X-ray, the surgeon can tele-operate the VIS in a secure area on master side. The operating information is acquired and transmitted to the slave side. Once receiving the operating information, the slave manipulator drives the catheter or guide wire to insert into the blood vessel. In addition, it is necessary that the force signals and torque signals feedback to the master manipulator measured by the slave manipulator.

For the clamping of catheter, the clamping force of existing clamping mechanism is easy insufficient or excessive clamping, and cause the catheter cannot be fully clamped or be damaged because of excessive clamping force. Base on such defects to design a lossless clamping mechanism which uses the conical clamping principle to complete clamping [26], [27]. Also the clamping force can be controlled by electromagnetic force. In this section, the designed clamping device will be introduced in details.

A. Structure diagram of the slave side

The schematic diagram of the slave side is shown in Fig.2. Fig.2 (a) and (b) describe the front view and the isometric view of the catheter manipulator with the application of the electromagnetic break clamping mechanism, respectively. The body of the slave manipulator is composed of four parts. One part is the force measurement mechanism, which is adopted to measure the haptic force between the catheter and the blood vessel. One another part is electromagnetic clamping mechanism. It is used for clamping the catheter and then the catheter will do the movement of forward, backward and rotation with the catheter manipulator. The other part is the rotation driving mechanism, which is used to make the catheter rotate under being clamped. And the torque also will be measured by the torque sensor which is installed in the rotation driving mechanism [27]. The last part is the insertion driving mechanism, and it is used to drive the whole catheter manipulator to do the forward or backward movement when the catheter is clamped. In addition, it also can be used to compensate the catheter when the catheter is released.

The application of the electromagnetic brake clamping mechanism in the catheter manipulator can improve the response and stability of clamping. Because it adopts the cooperation of electromagnetic force and spring to control the clamping of the catheter, and the response of electromagnetic force is very fast. Also the clamping mechanism uses a collet which has big clamping contact area to clamp the catheter, and then the clamping of the catheter will be stable, so that the clamping injury of catheter can be reduced.

In order to provide a surgeon with the force and torque cues for the tele-operated robotic catheter during conventional catheterization procedures, the application of force sensing on the slave side is extremely critical. The load cell and torque sensor are applied to measure the force signals and the torque signals. When the catheter is clamped by the clamping mechanism, the whole structure can do the forward, backward motion and rotation by the motors, then the load cell and torque sensor can measure the force and torque signals. However, a slave manipulator wants to be good to measure the force and torque signals, which is necessary to base on a good design of clamping mechanism. And in the next section, the good design of clamping mechanism will be described in details.

B. Composition of Clamping Mechanism

The composition of the electromagnetic break clamping mechanism, shown in Fig.3, is composed of a sleeve, a collet, an iron corn, a compression spring and an electromagnetic chuck. The specific coordination relations are as follows: the compression spring will be fitted on the iron corn which is connected with the collet by screws. When the spring is against the electromagnetic chuck, the core will enter the hole of it, and then they will be nested inside the sleeve, so that the collet can be pressed by the compression spring to clamp catheter. The electromagnetic chuck is used to generate electromagnetic force which can be controlled by the current [26]. Furthermore, the design can reduce the clamping injury of catheter due to the large clamping contact area and reliable clamping.

C. Principle Analysis for Clamping Structure

The principle diagram of electromagnetic brake clamping mechanism is shown as Fig.4. It is a normally closed mechanism. When the coil is not energized, the compression spring will press the collet into the taper hole of the sleeve, so that the collet will be tightened up to clamp the catheter. Then the catheter can do the movement of forward, backward and rotation with the slave manipulator. However, when the coil is energized, the coil will generate the electromagnetic force, so that the collet will overcome the pressing force of the compression spring to move in the direction of iron corn, thus the collet will be relaxed to make the catheter release. After that, we can carry out the compensation of the catheter when the slave manipulator goes back at the same time [21]. In addition, a removable wedge ring is adopted, which can be controlled by two screws to adjust the range of the clamping force, and then the electromagnetic force is used to fine-tuning in the range.

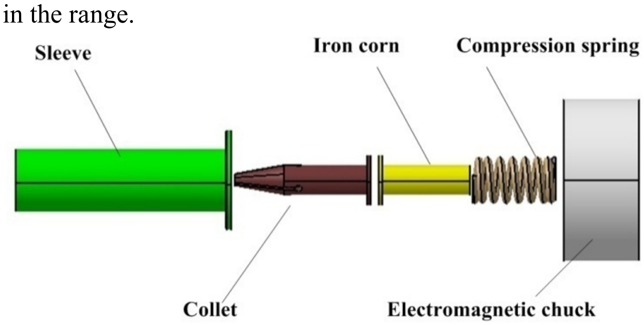


Fig.3 Structure diagram of the electromagnetic break clamping mechanism

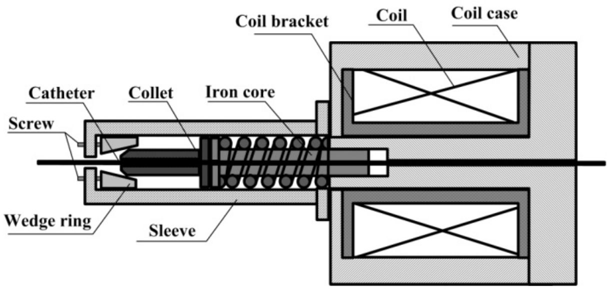


Fig.4 The schematic diagram of clamping principle

III. Collision Protection Function

During a conventional catheterization procedure, the collision protection is extremely critical for tele-operated robotic catheter systems to provide the patients with the safety guarantee because excessive forces could rupture the blood vessel walls and result in bleeding.

A. Stress analysis of the clamping structure

Fig.5 shows the clamping force analysis of the catheter. The force will be balanced when the catheter is clamped. In addition, the contact method of point-surface is adopted in order to reduce the influence of the friction force on the clamping force. According to the mechanical equilibrium (ignore friction force), we get:

$$Fc * \tan\theta = Fs \tag{1}$$

That is,

$$Fc = Fs * \cot\theta \tag{2}$$

where Fc is the clamping force of the catheter. Fs is the pressure which is generated by the compression spring. And θ is the oblique angle of the clamping ring' inside. From the equation (1) we can see that the clamping force of the catheter is inversely proportional to the oblique angle. Therefore, on the premise of meeting other requirements, the oblique angle should be as small as possible so as to increase the clamping force to ensure the stable clamping.

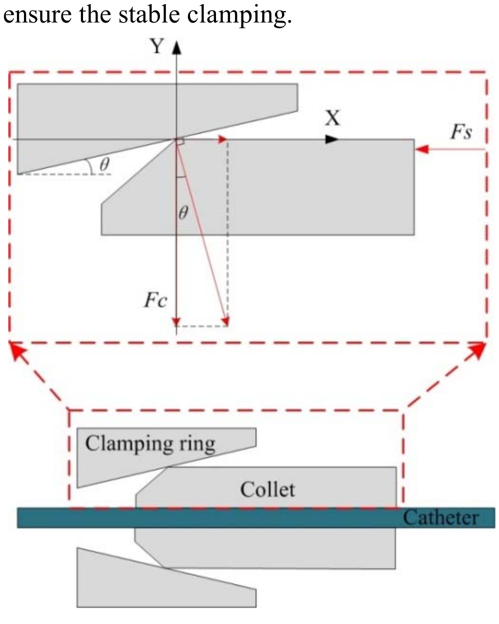
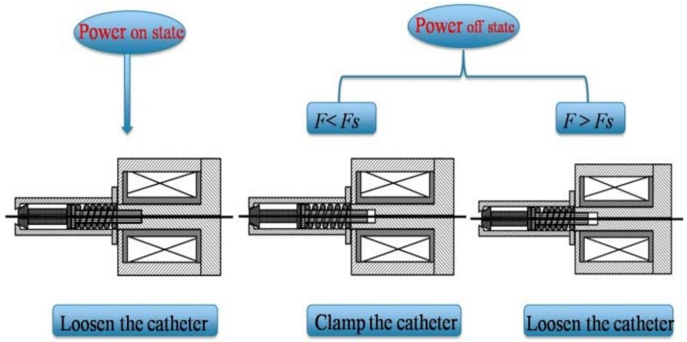


Fig.5 Schematic diagram of the stress analysis for the collet



F: The sum of the contact force and axial force
Fs: The pressure of compression spring

Fig.6 The illustration of collision protection function

B. Principle analysis of the collision protection

The structure design of the collision protection based on electromagnetic braking is proposed. As shown in Fig.6, when the power of electromagnetic chuck is on state, the catheter will be released by the collet because the collet will be pressed by the compression spring. However, there are two kinds of situations when the power is off state. One is that the catheter will be clamped when F is smaller than Fs, and this case is the same with that of power on. The other is that the catheter will be released when F is greater than Fs. In this case, the collet will compress the spring to the side of iron corn due to the electromagnetic force and the clamping force will disappear. And then the catheter will slide relative to the collet and thus play a role in collision protection. Once the measured force exceeds a certain threshold, this action is equivalent to an automatic retraction of the catheter, and will not cause damage to the blood vessels because of inertia or machine lock, increasing the safety of the interventional surgery.

IV. Verification of The Collision Protection Function

In order to verify the feasibility of the collision protection function for the proposed clamping mechanism, the simulation experiment is carried out by the ANASYS software.

A force generated by a compression spring was exerted on the surface (A) of the collet and a varying contact force from 0N to 1.4N was exerted on the surface (B) of the catheter with 0.2N increase as shown in Fig.7. From the simulation results (as shown in Fig.8) we can see that the clamping area of the catheter will decrease with the increase of the contact force which was exerted on the catheter. And the clamping force of the catheter disappeared when the contact force was up to 1.4N. Thus, the simulation results indicate that the proposed design of clamping mechanism is effective to the collision protection. In addition, the bearing capacity of the clamping mechanism for the measured force can be reduced by adjusting the oblique angle and the spring force. In this way, when the measuring force reaches a reasonable threshold, the collision protection function will play an important role, so as to effectively avoid vessel puncture caused by system malfunction or human error.

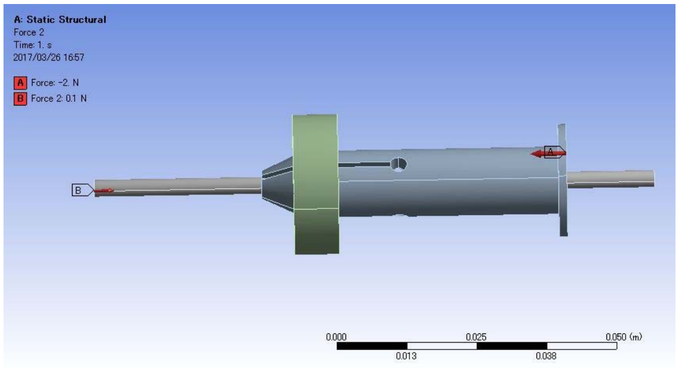
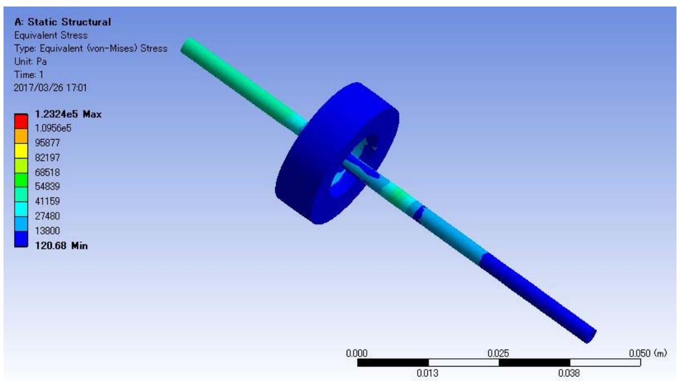
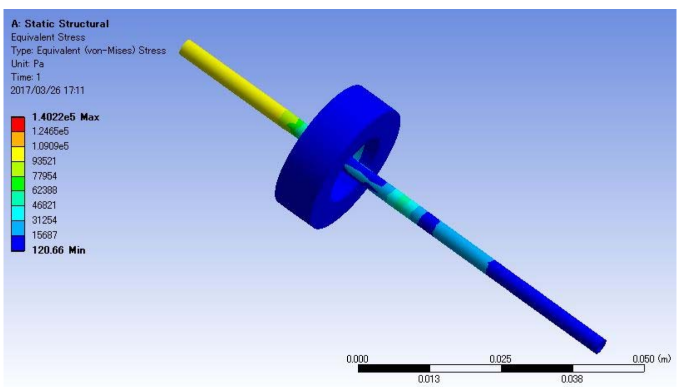


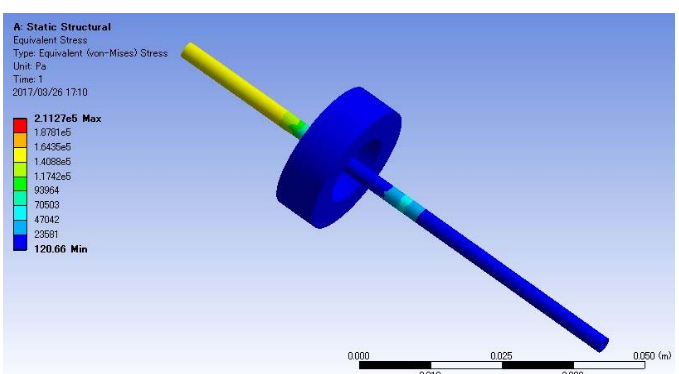
Fig.7 The illustration of force position



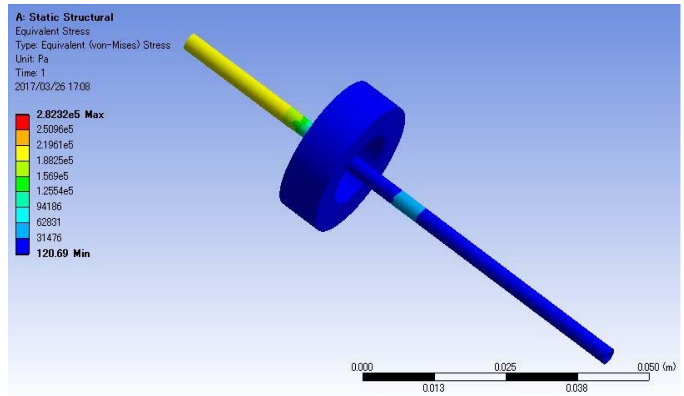
(a) The measured force is 0.2N



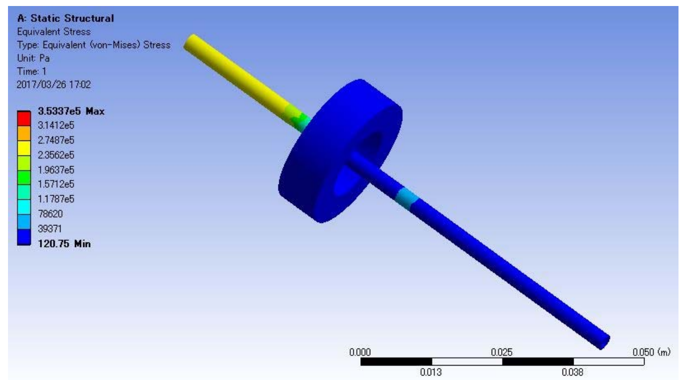
(b) The measured force is 0.4N



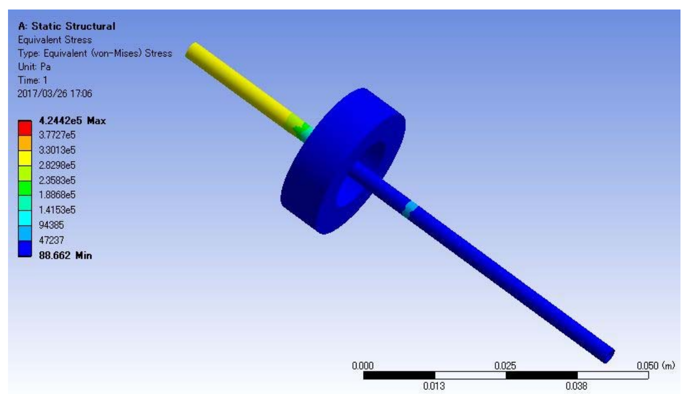
(c) The measured force is 0.6N



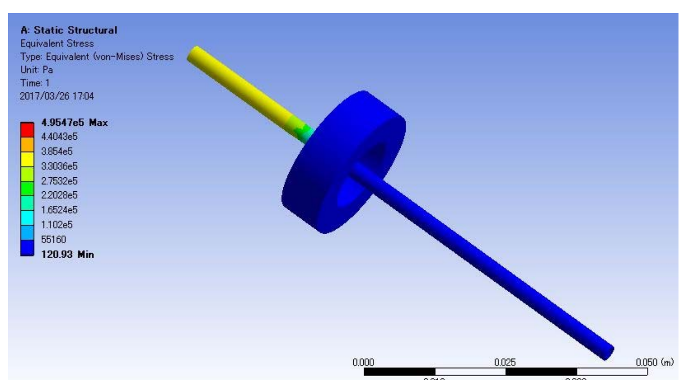
(d) The measured force is 0.8N



(e) The measured force is 1.0N



(f) The measured force is 1.2N



(g) The measured force is 1.4N

Fig.8 The simulation results for the collision protection

V. Conclusion and Future Work

In this paper, the collision protection function based on the electromagnetic brake clamping mechanism for a novel catheter manipulator of robot-assisted catheterization system is proposed. The proposed clamping mechanism can offer a fast response and lossless clamping due to the big clamping contact area. The significant advantage of the proposed design is the collision protection for the patient. When the measured force is in a reasonable rang, the proposed clamping mechanism provides a stable clamping. When the measured force exceeds a certain threshold, the collision protection function will play a role to protect the vessel of a patient. And the simulation verification of the collision protection function carried out. The experimental results show that the clamping force will decrease with the increase of the measured force, thus the collision protection function will be effective to the vessel. Therefore, the electromagnetic braking clamping mechanism presented is of great significance for improving the safety of the surgery.

In the future work, some experimental tests for the whole system will be conducted for contributing to development of high intelligence and high precision robot-assisted catheterization system.

Acknowledgment

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