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A Novel Sensing System of Catheter/Guidewire Operation for Vascular Interventional Surgery

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***Abstract* - Recently, robotics and computing technology plays an increasing important role in the evolution of modern vascular interventional surgery (VIS). During operation procedure, thrust force and torque that surgeon applied to catheter is one of the most significant information for statistical analysis of surgery procedure and robotic assisting surgery system. Online precision detection of catheter thrust force and torque with minimized interference to surgeon is a critical issue. A novel sensing device is proposed to detect catheter operation force during surgery operation. Based on strain gauge principle and elegant structure design of elastic component, the proposed sensing device achieves trust force detection and torque detection simultaneously with a compact structure. The experimental equipment is developed for calibration and evaluation of the proposed sensing device. It can be seen from experimental results that the maximum torque and force detecting error of designed force/torque sensing device are 3.2 mN·m and 1.237N respectively. The maximum relative torque and force detecting error are 15.238% and 14.56%. The average error of torque and force detecting are 0.455mN·m and 0.0278N. The average relation error of torque and force detection are 2.13% and 0.327% respectively. The root-mean-square error of torque and force detection are 0.164mN.m and 0.267N. It indicates that the proposed catheter operation force detection device is rational.**

Index Terms – Vascular interventional surgery; Surgery robot navigation; Force sensing device; Operation sample acquisition

I. INTRODUCTION

VIS shows many advantages compared traditional surgery, such as less bleeding, fewer complications, small trauma, quick recovery, etc [1]. However, currently human intervention operations have its shortages. Firstly, because of long operation time, the doctor must be exposed to large dose of X-ray radiation, which will harm their health. Secondly, operation performance depends to large extent on doctor's priori knowledge of human anatomy and physiology and operating experience. Lastly, doctor's miss-operation easily leads to failure of surgery and high risk of patient life. Research on development of VIS technology is of significant importance. A lot of research work has been conducted on robotic assisted interventional surgery system to improve complex VIS by combining robot technology and the integration of vascular interventional technique [2]. In addition, application of machine learning techniques in surgery skill assessment and surgery robot fields has been arousing increasing interests in recent years. In research work of VIS combining robotic assisted technology and machine learning technology, detection of operation parameters of surgeon's hand is one of the critical issues.

Most of the current VIS robotic assisted systems are based on master-slave teleoperation principle. The master system contains an operating handle, which imitates the catheter. Surgeons manipulate the operating handle to do all kinds of operations needed to implement the surgery. Meanwhile, the master controller accurately detects the kinematic characters of the operating handle, which comprehensively represent the surgical operation characters. The slave manipulator operates the guide wire and catheter to accomplish this complicated surgery under these signals from the master controller. There are several representative VIS robotic systems such as Sensei Robotic Catheter System by Hansen Medical [3], remote catheter system called Amigo by Catheter Robotic Inc.[4], 'Catheter Guidance Control and Imaging' (CGCI) system by Magnatecs Inc. [5], magnetic navigation system called the Stereotaxis Niobe by Stereotaxis Inc. [6]. Yogesh Thakur et al. developed a kind of remote catheter navigation system [7]. This system allowed the user to operate a catheter manipulator just like operating a real catheter. Shuxiang Guo et al. [8] put forward a new kind of pipe robot control system, the system uses a master-slave control mode and it achieves the remote operation. Yu Song et al. [9] developed a haptic interface based on MR fluids for endovascular tele-surgery. Jian Guo et al. The haptic feedback in the axial direction can be generated by altered the viscosity of MR fluids. Jian Guo et al. [10] detected the operating force of the slave manipulator adopting a load cell that fixed on the slide platform. Xuanchun Yin [11] et al. firstly introduced a human operator-centered haptic interface design concept into actuator choice and design. Jin Guo [12] presented a catheter-sensing unit used to measure the motion of the catheter and a force feedback unit used to provide a sense of resistance force. Linshuai Zhang et al. [13] developed a strain-gauge force sensor for the slave side of haptic robot-assisted catheter operating system. Xuanchun Yin et al. [14] proposed a haptic catheter operation system for teleoperation through exploiting magnetorheological fluids. Yu Wang et al. [15] developed a training system integrated cooperation of VR simulator and haptic device. Jin Guo et al. [16] proposed a novel master-slave robotic catheterization system with force feedback for vascular interventional

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surgery. Also, a multidimensional monitoring interface is developed to realize the visualization of force feedback. Xu Ma et al. [17] proposed a novel robotic catheter manipulating system to reduce the performance error and irradiation to surgeons. Yu Wang et al. [18] introduces standard linear solid model to formulate the vascular physical model and determine this model's parameters based on vascular wall elasticity analysis in the virtual-reality simulator. Yuan Wang et al. [19] introduces a haptic feedback function in the developed interventional surgical robot system.

In recent years, machine learning technology such as Logistic regression [20], Support Vector Machine [20], hierarchical Hidden Markov Model [21], GMM based learning approach [22] [23] are adopted to study of surgery skill assessment. In these research works, a device is developed to detect catheter motion and using encoders and roller set to detect catheter motion (by encoders and roller set) and force (by force/torque sensor installed under vascular model). The roller set and encoder would introduce friction and inertia force influence. The method detect catheter operation force is also affected by inertia force of the vascular model and platform. Carlos et al. [24] proposed a catheter motion detect method based on optical encoder in their research on endovascular surgery technical skills measurement. However, the detecting average errors achieves 0.39mm in liner displacement and 10.78 ºin roll angle. Also, the catheter operation force does not be measured in this research work. Catheter operation parameters acquisition plays a critical role in research of surgery skill assessment. It needs more research.

In this paper, a novel sensing device is proposed for catheter/guidewire operation force and torque information acquisition. In section II, design of the proposed force/torque sensing device is elaborated. In section III, the designed force/torque sensing device is calibrated. In section IV, the performance evaluation experiments are conducted and the result is discussed. In section V, the research work is concluded and the future work is pointed out.

II. Design of the Force sensing system

A. Over view of catheter/guide-wire operation force information on line acquisition system

Catheter/guide-wire operation force information acquisition is a critical issue in research of surgery skill assessment and automation of surgical robotic system. In terms of this issue, two design tenets have always been pursed. On the one hand, detection accuracy should be sufficient with the demand of delicate surgery operation. On the other hand, interference to surgeons caused by the detection device should be minimized, like friction and inertia force influence of motor and transmission mechanism.

In this work, an catheter/guide-wire operation force information on line acquisition method is proposed with a special designed force/torque sensing device, as shown in Fig.1. In traditional VIS, surgeons always hold a commercial medical catheter gripper to manipulate the guidewire. The gripper is always used to clamp the guidewire during VIS operation procedure. In this catheter/guide-wire operation force information on line acquisition system, the miniaturization designed sensing device is fixed with the gripper, which is improved to be capable of clamping catheter and guidewire in this work. Manipulator operates catheter/guidewire with certain trust force and torque through the sensing device with minimum interference. The sensing device based on strain gage detects force and torque and output small voltage change signal. Then, the small voltage signal is amplified and translated from analog voltage signal into digital voltage signal via an A/D converter. The digital voltage signal is collected to a computer by a signal acquisition card afterwards. Then, the designed force/torque sensing system is calibrated to provide accuracy force/torque signal. In this way, operating force and torque information of catheter/guidewire could be acquired online.

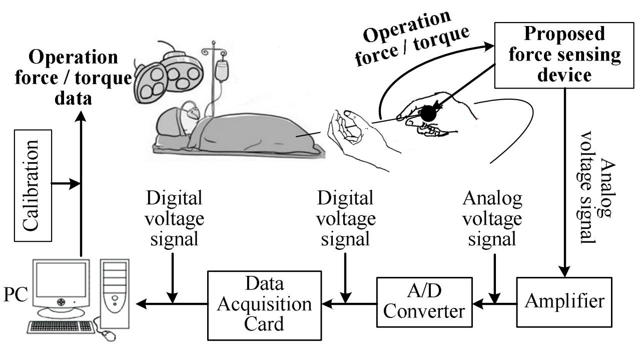


Fig. 1 Schematic of catheter/guide-wire operation force information on line acquisition system

B. Design of force/torque sensing device

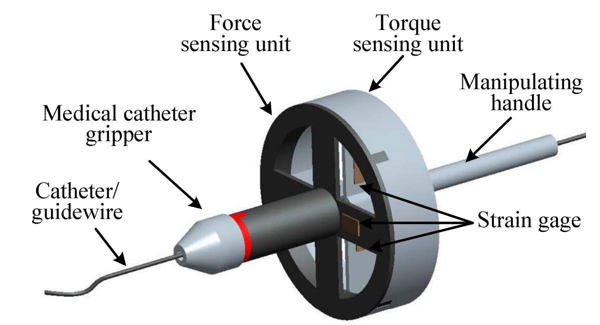


Fig.2 Mechanical structure of catheter/guide-wire operation force detection device

According to the two critical design tenets elaborated above, the force/torque sensing device should be designed follow miniaturization principle. So, resistance strain gage is adopted to detect catheter/guidewire operation trust force and rotating torque. Resistance strain gage consists mainly the sensitive grid. Resistance strain gage is firmly pasted onto the measuring point of the elastic component. External force will bring strain to the elastic component, which will transmitted to the resistance strain gage. Then, sensitive grid inside the strain gage undergo extension or contraction, which gives rise to increase or reduce of resistance of sensitive grid. So, structure of the elastic component and paste position of resistance strain gage are important factors affecting the detection accuracy.

As shown in Fig.2, the sensing device mainly contains two parts, the force sensing unit and torque sensing unit, which are fixed with each other. Cross beam structure is adopted to design the elastic components of both force sensing unit and torque sensing unit. Cross beam direction of force sensing unit is perpendicular to axis of catheter gripper. Cross beam of force sensing unit is susceptible to push and pull action of catheter/ guidewire. On the contrary, cross beam direction of torque sensing unit is parallel to axis of catheter gripper. So, it is susceptible to rotation operation of catheter/ guidewire. During operation process, surgeon holding the manipulating handle to push and rotate the guidewire via the common medical catheter gripper. In this way, catheter operation trust force and rotating torque can be detected in the manner of axial and rotational strain of cross beams.

C. Optimal analysis

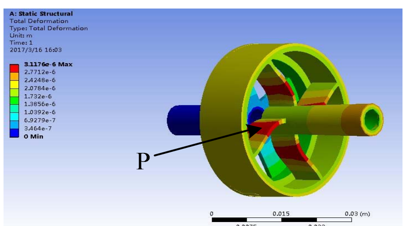


Fig.3 Total deformation of elastic component under torque load

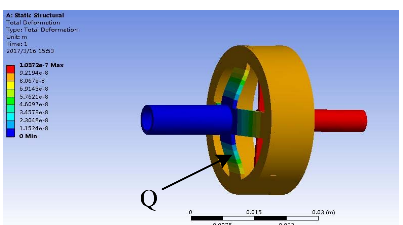


Fig.4 Total deformation of elastic component under axial force load

To optimal the paste position of resistance strain gage on the elastic component, simulation analysis is conducted based on ANSYS. Considering that the trust force and rotation torque is always in a small order, acrylonitrile butadiene styrene (ABS) plastic material is used to analysis deformation distribution of elastic component. The elasticity modulus of selected ABS plastic is 2.2 Gpa and the Poisson ratio is 0.394. Simulation results are shown in Fig.3 and Fig.4. Under torque load, the maximum strain generates at point P of elastic component. under axial force load, the maximum strain generates at point Q of elastic component. It is beneficial for improving the resolution ratio of the sensing device to paste the strain gage near the maximum strain generating point. So, strain gages are pasted near point P and point Q, as shown in Fig.5.

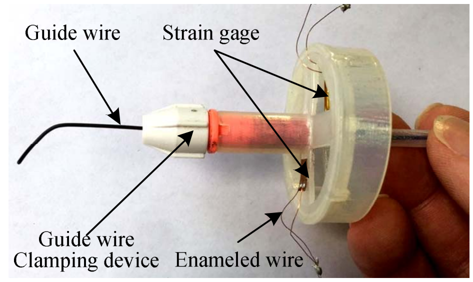


Fig. 5 Prototype of the designed force/torque sensing device

III. Sensing System Calibration

As the sensing device transform the strain of cross beams to force and torque signal, it is important to identify the relationship between the force/torque value and digital voltage signal value. Due to the complexity of material properties, structure of elastic compliment and uncertainty of strain gage attachment condition, relationship between force/torque value and digital voltage signal value is complex and flexible. Therefore, this important relationship is identified via experiment methods.

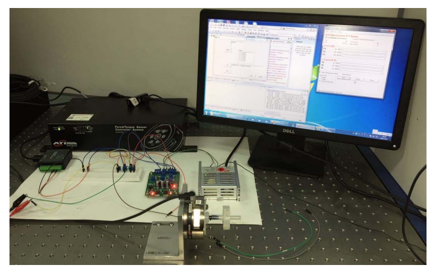


Fig. 6 Calibration experimental setup of the designed force/torque sensing device

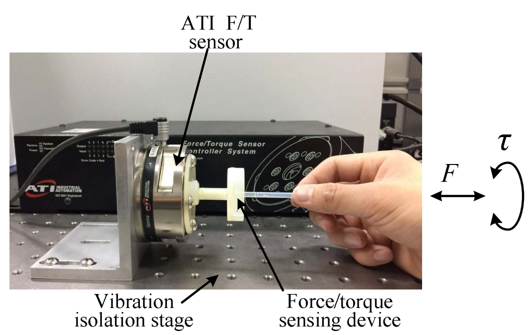
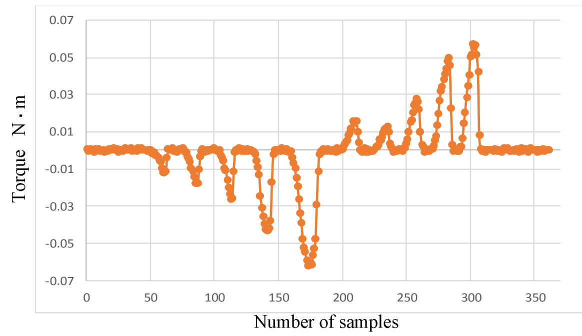
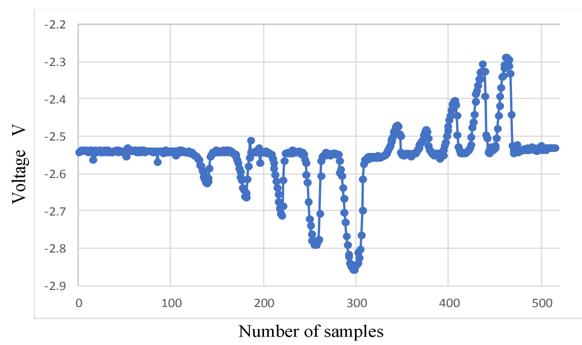


Fig. 7 Calibration experiments

The calibration experimental setup is shown in Fig.6. The whole setup is fixed upon an optical vibration isolation stage to eliminate environmental vibration noise. An Six-Axis Force/Torque sensor system produced by ATI industrial automation, Inc. is adopted to help to given certain trust force and rotation torque. The 9105-T-Gamma transducer is fixed with the vibration isolation stage. The designed force/torque sensing device is fixed with the ATI force/torque sensor coaxially by a special designed fixture. During the trust force calibration experiments, push and pull the handle of sensing device with forces uniformly reciprocating changing with gradually increasing peak value. During the rotating torque calibration experiments, rotate the handle of sensing device in both clockwise and anticlockwise with forces uniformly reciprocating changing with gradually increasing peak value. Each test is repeated by 20 times. Meanwhile, record the force/torque value of ATI force/torque sensor and digital voltage signal value of designed. The detected results of torque signal curve and voltage signal value in one experiment is shown in Fig.8.



(a) Torque signal collected by ATI Force/Torque sensing system



(b) Voltage signal detected by designed sensing system

Fig.8 Detected results of rotation sensing calibration experiments

The peak values of detected data afterwards is used to regression analysis with the least squares fitting method. Finally, the relationship between force/torque value and digital voltage signal value are been identified. The fitted equation is shown in Fig.9. Linear dependence of these fixed point is 0.9954.

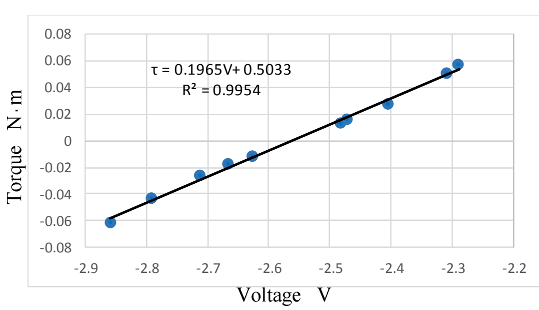
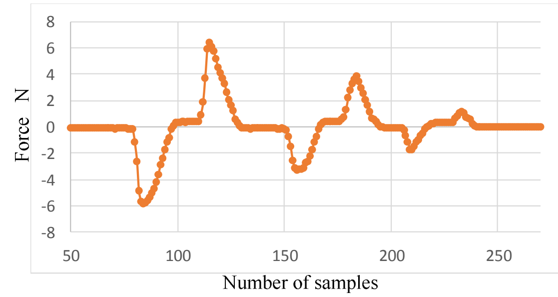
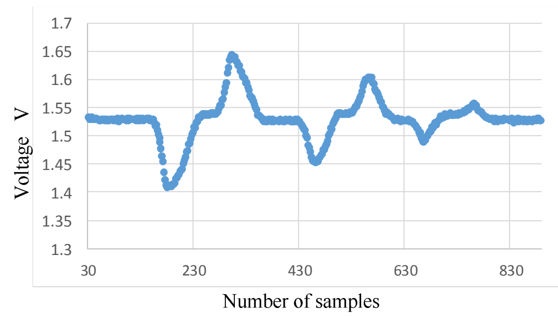


Fig.9 Liner fitting chart with peak value of torque and voltage

The detected results of force signal curve and voltage signal value in one experiment is shown in Fig.10.



(a) Force signal collected by ATI Force/Torque sensing system



(b) Voltage signal detected by designed sensing system

Fig.10 Detected results of rotation sensing calibration experiments

The peak values of detected data afterwards is used to regression analysis with the least squares fitting method. Finally, the relationship between force value and digital voltage signal value are been identified. The fitted equation is shown in Fig.11. Linear dependence of these fixed point is 0.9944.

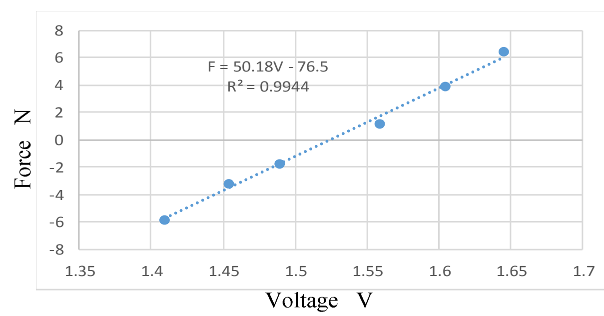
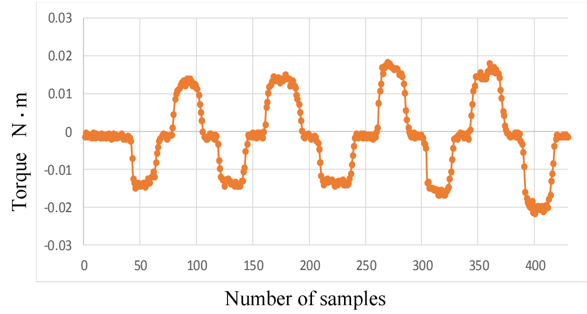


Fig.11 Liner fitting chart with peak value of force and voltage

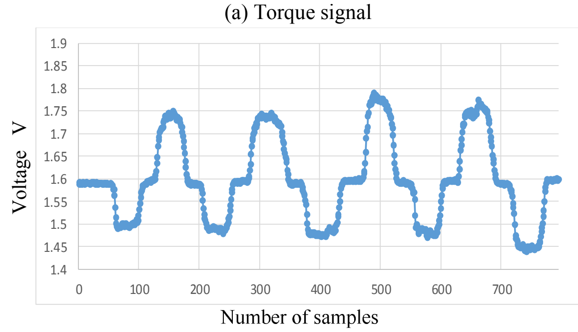
Ⅳ. Experimental Details and Results

A. Detection error tests and results

To assess the performance of proposed catheter operation force/torque sensing system, evaluation experiments imitating vascular interventional surgery operation of surgeon's hand are conducted using the experimental setup shown in Fig.6. A sets of value of forces from about -5 N to 9 N and rotation torques from about -22 mN·m to 20 mN·m are applied to the handle of sensing device respectively. Difference between the force/torque values detected by respectively ATI force/torque sensor and proposed force/torque sensing system is analyzed.



(a) Torque signal



(b) Voltage signal

Fig.12 Detected results of rotation sensing evaluation experiments

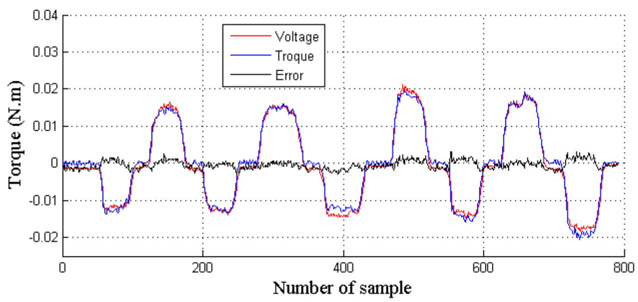
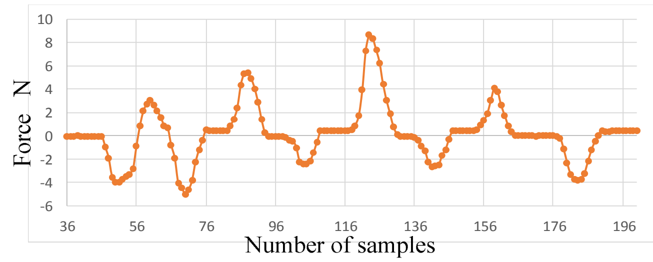


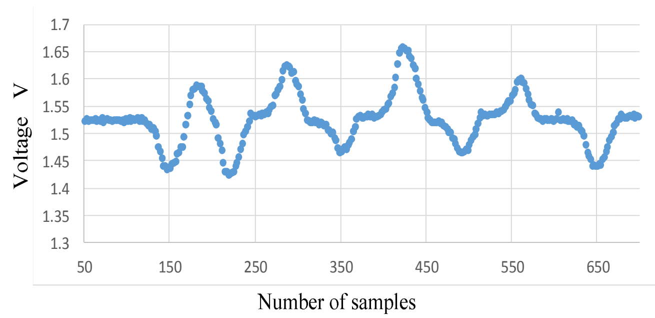
Fig. 13 Results of detected torque

Fig.12 shows the detected torque signal by ATI sensor and voltage signal detected by the designed force/torque sensor. The voltage data is smoothing processed using average filter. It can be seen that torque curve and voltage curve variation tendencies are approximate and unanimous. Then, the voltage data is translated into torque data by the calibration results. Fig.13 shows the error analysis of the torque signal detected by the designed force/torque sensor between the torque signal detected by ATI F/T sensor. The maximum torque detecting error of designed force/torque value is 3.2 mN·m. The maximum relative torque detecting error is 15.238%. The average torque detecting error is 0.455 mN·m . The average relation error is 2.13%. The root-mean-square error is 0.164 mN·m.

Fig.14 shows the detected force signal by ATI sensor and voltage signal detected by the designed force/torque sensor. The voltage data is also smoothing processed using average filter. It can be seen that torque curve and voltage curve variation tendencies are approximate and unanimous. Then, the voltage data is translated into torque data by the calibration results. Fig.15 shows the error analysis of the torque signal detected by the designed force/torque sensor between the torque signal detected by ATI F/T sensor. The maximum force detecting error of designed force/torque sensing device is 1.237 N. The maximum relative force detecting error is 14.56%. The average force detecting error is 0.0278 N. The average relation error is 0.327%. The root-mean-square error is 0.267 N.



(a) Torque signal



(b) Voltage signal

Fig.14 Detected results of push/pull evaluation experiments

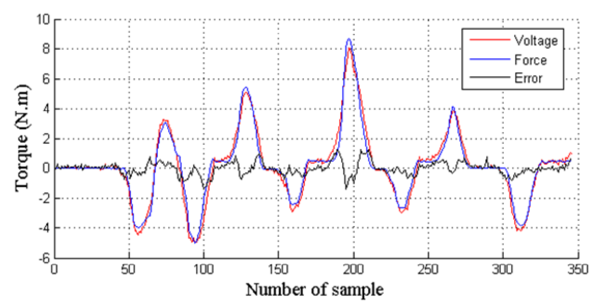


Fig. 15 Error analysis results of detected force

It can be seen from Fig.13 and Fig.15 that the force and torque detection error achieves large value at peak, valley and steep points of the curves. This phenomenon is due to the large hysteresis effects of the elastic element of ABS material with low elasticity modulus. At steep points, the force or torque loaded to the manipulator handle by operator's hands changes rapidly. Change of force and torque leads to corresponding deformation of elastic element pasted strain gage. This firstly causes deformation of strain gage and change of force/torque. Then the deformation transmit to the ATI for/torque sensor and give rise to corresponding change of force/torque value of ATI sensor. The time difference between paste point of strain gage and ATI sensor causes large force and torque detection error at steep points of the curves. At peak and valley points, tremble of human hands causes violent fluctuation of force/torque loaded to manipulator handle. It leads to large force/torque detection error in the same way.

V. CONCLUSIONS

In this paper, a novel sensing device is proposed to detect catheter operation force and torque during VIS surgery operation. Based on strain gage principle and elegant structure design of elastic component, the proposed sensing device achieves trust force detection and torque detection simultaneously with a compact structure. The experimental setup is developed for calibration and evaluation of proposed sensing device. The experimental results show that the maximum torque and force detecting error of designed force/torque sensing device are 3.2 mN·m and 1.237N respectively. The maximum relative torque and force detecting error are 15.238% and 14.56%. The average error of torque and force detecting are 0.455 mN·m and 0.0278N. The average relation error of torque and force detection are 2.13% and 0.327% respectively. The root-mean-square error of torque and force detection are 0.164mN.m and 0.267N. According to the analysis above, the force and torque detection error is caused by large hysteresis effects of the elastic element of ABS material with low elasticity modulus. So, in the future work, structure of the proposed sending device should be improved and material with large elastic modulus like spring steels should be chosen as the material of elastic element.

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