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Precise position control of a helical magnetic robot in pulsatile flow using the rotating frequency of the external magnetic field

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We propose a position control method for a helical magnetic robot (HMR) that uses the rotating frequency of the external rotating magnetic field (ERMF) to minimize the position fluctuation of the HMR caused by pulsatile flow in human blood vessels. We prototyped the HMR and conducted several experiments in pseudo blood vessel environments with a peristaltic pump. We experimentally obtained the relation between the flow rate and the rotating frequency of the ERMF required to make the HMR stationary in a given pulsatile flow. Then we approximated the pulsatile flow by Fourier series and applied the required ERMF rotating frequency to the HMR in real time. Our proposed position control method drastically reduced the position fluctuation of the HMR under pulsatile flow. [http://dx.doi.org/10.1063/1.4975127]

I. INTRODUCTION

Coronary artery disease has become a severe health problem for modern people due to meat-based eating habits, lack of exercise, and aging. Coronary artery disease is mainly caused by arteriosclerosis, angina pectoris, and vascular occlusion in coronary arteries. Catheterization is one of the most popular medical operations to treat coronary artery disease. A flexible and biocompatible tube called a catheter is inserted into a blood vessel to create a passage for other wired medical devices. However, medical doctors cannot ensure that the catheter reaches the target region in complicated and narrowed coronary arteries because they are restricted in their ability to steer the catheter. The success of this operation thus considerably depends on the experience of individual medical doctors.

To overcome the limitations of the conventional catheterization process, researchers have been investigating helical magnetic robots (HMRs) that are wirelessly manipulated using an external rotating magnetic field (ERMF) generated from a magnetic navigation system (MNS). HMRs have a simple structure and great steering and mobile ability.[1] Ishiyama *et al.* proposed an HMR with a spiral structure and investigated its navigating performance according to the frequency of the ERMF.[2] Choi *et al.* developed an HMR and manipulation method that can generate three-dimensional locomotion and a drilling motion.[3] Jeon *et al.* proposed a saddle structure for the MNS to generate navigation, mechanical drilling, and drug delivery motions in the HMR.[4,5] Lee *et al.* proposed a dual-body HMR whose navigation, mechanical drilling, and cargo delivery motions were controlled via the ERMF.[6] However, none of the prior research considered the disturbance caused by the pulsatile blood flow in real coronary arteries. The HMR should perform not only navigation but also various medical actions such as drug and stent delivery under pulsatile flow. When the HMR performs medical action, the HMR should maintain its current posture stationary at the target location to perform next medical

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action. If a stent expands in the wrong place, a major surgery may be required to remove the stent.[7] Therefore, we should minimize the position fluctuation due to the pulsatile blood flow in order to precisely perform the medical actions.

We propose a position control method for an HMR that uses the rotating frequency of the ERMF to minimize the position fluctuation of the HMR caused by the pulsatile flow in human blood vessels. First, we experimentally investigated and obtained the relation between the flow rate and the required rotating frequency of the ERMF to make the HMR stationary in a given flow rate. Then we performed several experiments in pseudo blood vessels under pulsatile flow to validate the effectiveness of our proposed position control method.

II. CONTROL METHOD FOR AN HMR FOR STABLE MOTION IN PULSATILE FLOW

An HMR is composed of a helical body and a diametrically magnetized cylindrical magnet, as shown in Fig. 1(a). The HMR generates a propulsive force when the helical body rotates along the axis of the HMR in a fluidic environment. To generate the rotating motion along the axis, we use magnetic torque generated by the magnet in the HMR under the ERMF, which can be expressed as follows:

$$\mathbf{T} = \mathbf{m} \times \mathbf{B} \tag{1}$$

where **m** and **B** are the magnetic moment of the magnet and magnetic flux density of the ERMF, respectively. The external magnetic field that interacts with the magnet to generate the magnetic torque and rotating motion along the ERMF, as shown in Fig. 1(b), can be expressed as follows:

$$\mathbf{B}_{ERMF}(t) = B_0(\cos 2\pi ft\mathbf{U} + \sin 2\pi ft\mathbf{N} \times \mathbf{U}) \tag{2}$$

where B_0, f, **N**, and **U** are the magnitude and frequency of the ERMF, the unit vector of the rotating axis, and the unit vector normal to **N**, respectively. Because the HMR generates a helical motion using the rotating motion of the magnet under the ERMF, as shown in Fig. 1(c), we can manipulate the HMR by controlling the ERMF. According to previous empirical studies,[2,8] the velocity of the HMR is proportional to the frequency of the ERMF. To maintain the HMR in a stationary position under pulsatile flow, the propulsive velocity or propulsive force of the HMR should be equal to the flow velocity or resistive force of the pulsatile flow. Because the propulsive force can be controlled by the rotating frequency of the ERMF, we need to find the frequency that will compensate the resistive force for any given flow condition. The flow velocity can be obtained by dividing the measured flow rate by the cross-sectional area. Fig. 2 represents the proposed control algorithm. An HMR is in the middle of a water-filled glass tube serially connected with a peristaltic pump and a flowmeter. The peristaltic pump generates pulsatile flow in the tube, and the flowmeter measures the flow rate. Because the flowmeter measures the flow rate discretely, we interpolated the measured flow rate using the Fourier series to provide continuous information linking the flow rate to the power supply as follows:

$$Q_{flow}(t) = \sum_{m=1}^{n} a_m \cos(m\omega t + \phi_m) \tag{3}$$

where a_{m} and ϕ_m are the Fourier constant and phase of the m^{th} term, respectively. For the HMR to maintain a stationary position, the propulsive force has to be controlled according to the varying

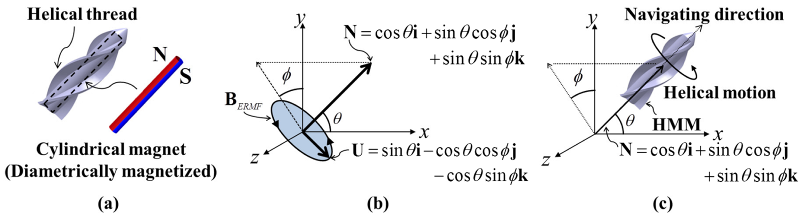

FIG. 1. (a) Structure of the HMR. (b) ERMF to generate helical motion of the HMR. (c) Helical motion of the HMR and its navigating direction.

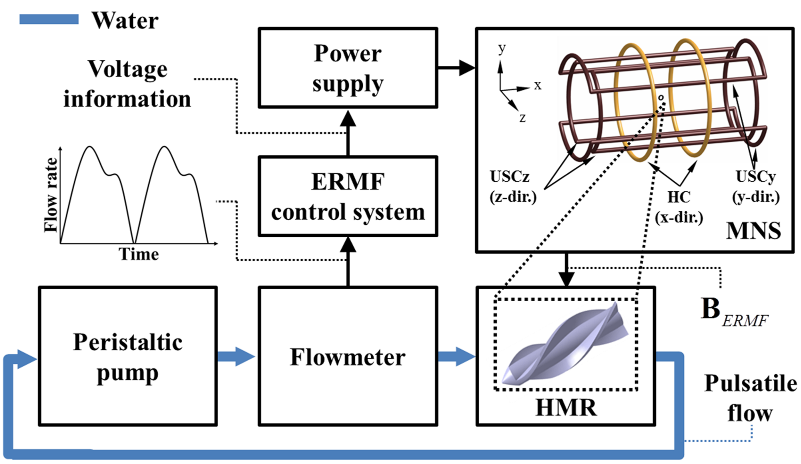

FIG. 2. Control algorithm to compensate for the disturbance of an HMR caused by pulsatile flow.

flow rate. After we define the proportional constant f_s between the flow rate Q_{flow} and the rotating frequency $f(t)$, the ERMF frequency required to maintain the HMR in a stationary position can be expressed as follows:

$$f(t) = f_s Q_{flow}(t) \tag{4}$$

Using the required frequency of the ERMF from Eq. (4), the voltage information for each coil of the MNS can be calculated and transferred to the power supply to effectively overcome the pulsating flow and precisely maintain an HMR's stationary position.

III. RESULTS AND DISCUSSION

We developed an MNS, as shown in Fig. 3(a), to generate a three-dimensional ERMF. The MNS consists of three pairs of electromagnetic coils perpendicular to one another (x-directional Helmholtz coil, y- and z-directional uniform saddle coils). The major specifications of the MNS are given in Table I. We prototyped the HMR with 3D printing technology in ultraviolet curable plastic, as shown in Fig. 3(b). A diametrically magnetized cylindrical magnet with a length of 10 mm and diameter of 1 mm was inserted in the HMR. First, we experimentally measured the rotating frequency of the HMR required to maintain a stationary position with respect to flow rate, interpolating the measured data by the least square method, as shown in Fig. 4(a). We found that the required rotating frequency is linearly proportional to the flow rate with a scale factor of 0.2042. Next, we set the peristaltic pump to generate a pulsatile flow of 99 beat/min and 100 mL/min, as shown in Fig. 4(b), which is similar to the fluidic environment of a coronary artery. The measured flow rate was interpolated by the Fourier series to determine the Fourier coefficients and the phases. By using Eq. (4) and the scale factor, we could specify the rotating frequency of the HMR required by the flow rate, as shown in Fig. 4(c). Fig. 4(d) shows the position fluctuations when we applied our proposed control method at a

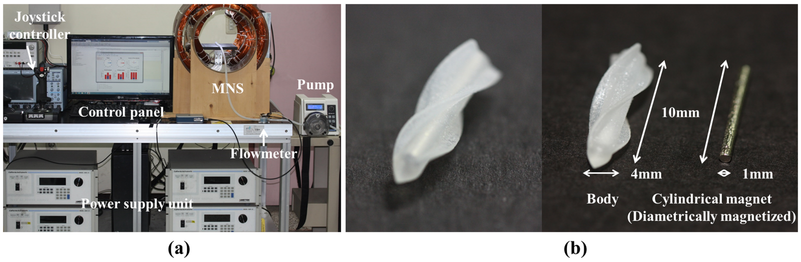

FIG. 3. (a) Experimental setup with an MNS and a peristaltic pump. (b) Prototyped HMR.

TABLE I. Major specifications of the proposed MNS.

Coil type	Radius (mm)	Wire diameter (mm)	Width (mm)	Height (mm)	Coil turns
HC	195	1.5	35	40	556
USCy	140	1.0	24	24	419
USCz	140	1.0	24	24	419

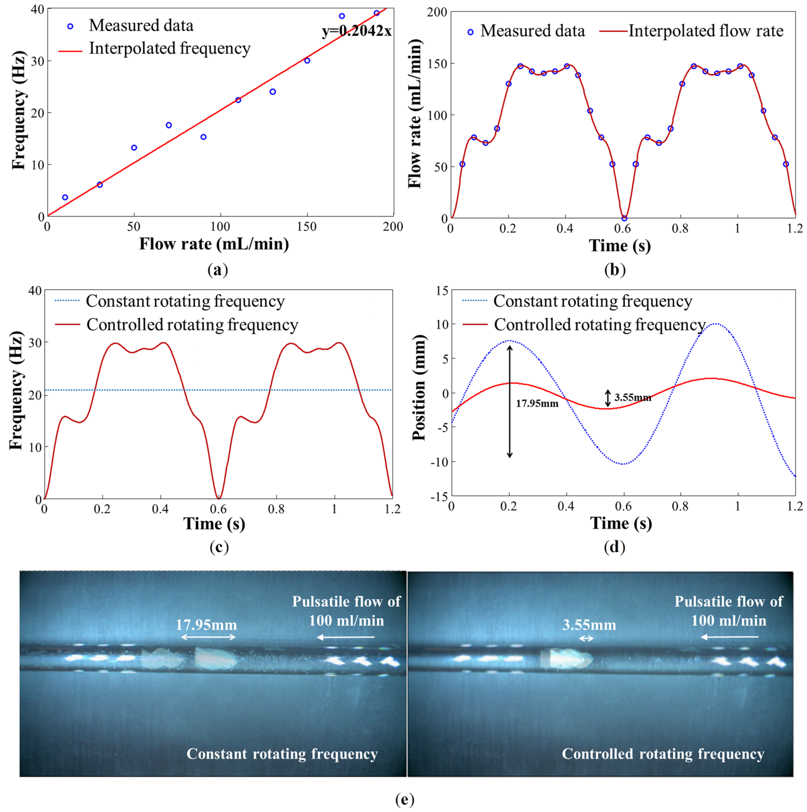

FIG. 4. (a) Rotating frequency of the HMR needed to maintain a position according to the flow rate. (b) Measured flow rate. (c) Constant and controlled frequencies. (d) Measured position fluctuations with the application of constant and controlled frequencies. (e) Photograph of measured position fluctuations with the application of constant and controlled frequencies.

constant 20.42 Hz. Fig. 4(e) represents the position fluctuation of the HMR in a transparent glass tube under the pulsatile water flow of 99 beat/min and 100 mL/min. The position fluctuation was reduced from 17.95 mm to 3.55 mm (80.2% reduction) with the application of our proposed position control method, which verifies the effectiveness of the method for controlling an HMR under pulsatile flow.

IV. CONCLUSIONS

We proposed a position control method for an HMR that uses the rotating frequency of the ERMF to minimize HMR position fluctuations caused by the pulsatile flow in human blood vessels. We experimentally obtained the relation between the flow rate and the rotating frequency of the ERMF to keep the HMR stationary in a given pulsatile flow. Then we approximated the pulsatile flow by Fourier series and applied the required ERMF rotating frequency to the HMR in real time. With the application of the proposed control method, the position fluctuation of the HMR was drastically reduced, by 80.2%. This research could be extended to the precise and effective navigation of an HMR for various mechanical and medical operations.

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