

Ultrasonically-Lubricated Catheters: A Proof of Concept

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INTRODUCTION

Over the past few decades, minimally-invasive endovascular interventions have proved its benefits over conventional open heart surgeries, leading to shorter recovery times and lower infection rates. In a typical endovascular procedure, the interventionist inserts a catheter in the radial or femoral artery and navigates it through the arteries to the heart, where the intervention is performed. In order to safely reach the heart, the catheters (and guidewires) used during these procedures need to easily follow the curves in the vascular system, while creating as little friction as possible with the blood vessel wall. If these devices exhibit high friction, there is a risk of damage to the mucous membranes or the intima of the blood vessels, which may lead to infectious diseases or thrombus formation [1], [2]. While low friction is beneficial to avoid damage to the membranes and blood vessel wall, it makes holding a specific location in open spaces, such as inside the heart, difficult. This is particularly true when high forces need to be applied, such as when cutting or puncturing tissues. This suggests the need for new advanced catheters whose frictional properties are controllable and can be adjusted depending on the phase of the catheterization procedure; for instance, having low friction while navigating through the vasculature and switching to a high friction state while executing the surgical task.

In this work, we propose a novel concept of a variable friction catheter, which comprises discrete modules for friction control. We hereby present the proof-of-concept of the friction control modules, which we characterized in simulation and experimentally. Finally, we present the preliminary results of the sliding friction experiments.

MATERIALS AND METHODS

A. Ultrasonic Lubrication

When two objects slide over each other, it was found that inducing transverse ultrasonic vibration, in one of those objects, can reduce the effective friction force experienced by the sliding bodies, in what is called Ultrasonic Friction Modulation (UFM). This ultrasonic excitation creates a pressurized thin cushion of the surrounding fluid medium, which separates the two surfaces

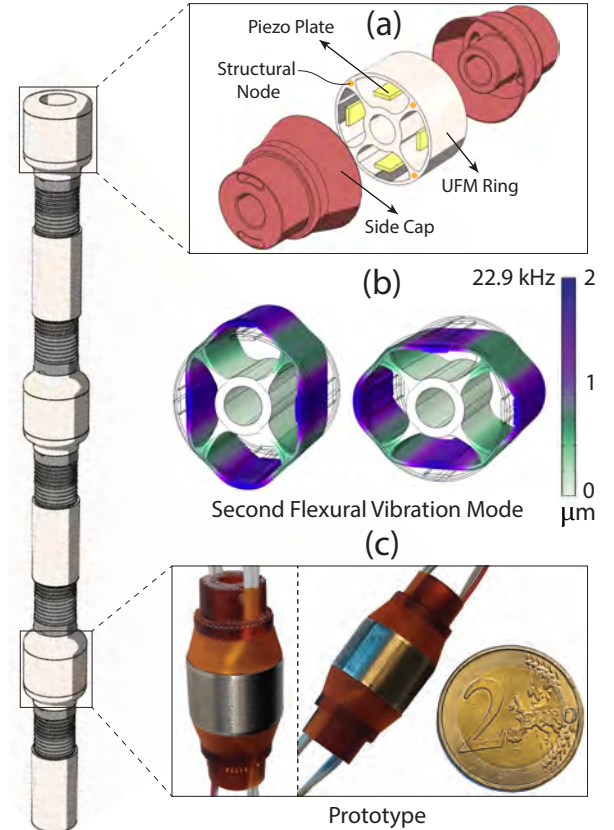


Fig. 1 Illustration of the concept of ultrasonically lubricated catheters (a) Design of the friction control module (b) Eigenfrequency simulation of the designed module (c) Module prototype.

away from each other, resulting in controllable active lubrication at the interface [3]. This technology proved its effectiveness in different applications where modulating friction is desirable, such as haptic touch displays and squeeze film air bearings. The capability of UFM to switch between high and low friction states, suggests the potential of this technology to fulfill the friction modulation requirement of future smart catheters.

B. Design of Friction Control Module

To enable friction control in catheters, we propose a discrete module design concept in which UFM modules

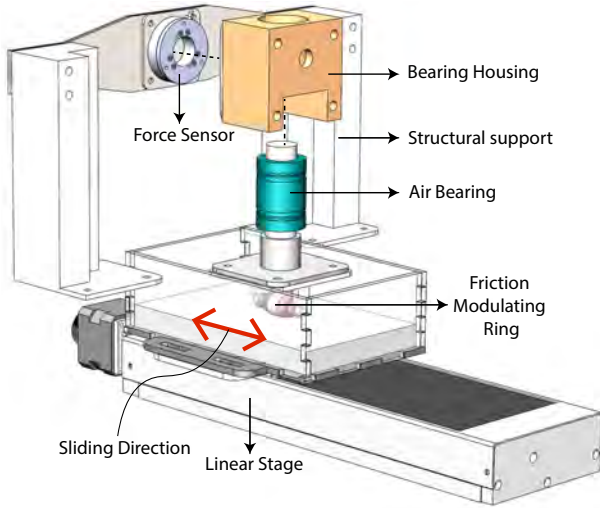


Fig. 2 Experimental setup for testing the friction modulation capabilities of the proposed system.

are integrated along the catheter's shaft as shown in Fig. 1. The design requirements for the UFM modules, to ensure proper functionality, includes technology and application requirements. The technology requires the modules to achieve around ($2\ \mu\text{m}$) transverse vibration amplitude at ultrasonic frequency ($> 20\ \text{kHz}$), while the application requires the design to be tubular, to have a lumen and to have the potential to be downsized. To tackle these requirements, we designed a resonating ring which comprises four piezoelectric plates, as shown in Fig. 1(a), such that when the piezo plates are activated, a standing flexural wave is induced in the ring as shown in Fig. 1(b). The frequency of this wave coincides with the second flexural resonance mode (second harmonic) of the ring structure, which is governed by diameter and wall thickness of the ring. To properly support the ring, the inner structure is connected to the ring at the nodes of the standing wave as shown in Fig. 1(a) to ensure minimal interference with the generated wave.

C. Experiment

To validate the concept, we fabricated a scaled-up titanium ring prototype of diameter ($15\ \text{mm}$), wall thickness ($0.5\ \text{mm}$) and length ($10\ \text{mm}$). We carried out a computational FEM simulation estimating the resonance frequency of this prototype to be ($22.9\ \text{kHz}$) and the amplitude potentially reaching ($1.8\ \mu\text{m}$) as shown in Fig. 1(b). To characterize the performance of the prototype, we conducted a frequency-sweep experiment using a laser Doppler vibrometer to reveal the actual resonance frequency and maximum achievable amplitude of the ring. Furthermore, we designed a feasibility experiment, shown in Fig. 2, in which we measured the sliding friction force experienced by the ring in both on and off cases, over a PMMA surface in a container partially filled with water, at a sliding speed of ($0.1\ \text{mm/s}$), for a stroke of ($2\ \text{mm}$) forward and backward and under a ($1.1\ \text{N}$) load which lies in the range of critical contact forces for catheters [4].

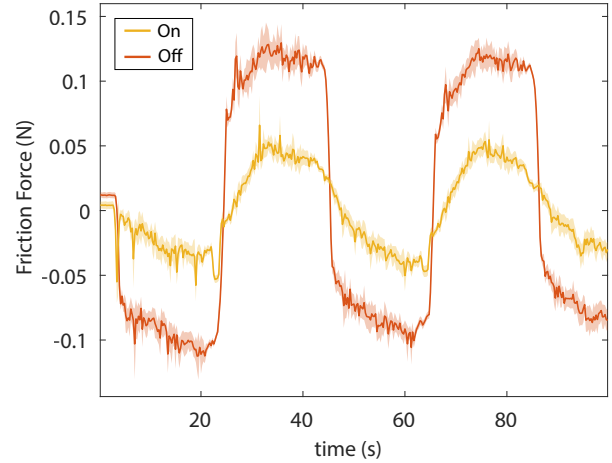


Fig. 3 Experimental measurements showing a comparison between the friction force when the UFM module is on (yellow) versus when it is off (red) under loading of ($1.1\ \text{N}$). Solid lines represent the mean of five trials while the shades represent their standard deviation.

RESULTS

The vibration characterization experiments showed that the actual frequency of the desired mode is ($19.7\ \text{kHz}$) and the maximum vibration amplitude is ($0.9\ \mu\text{m}$). The preliminary friction experiments, repeated five times, showed that the UFM ring prototype achieved up to 50% friction reduction, when activated, while sliding over solid PMMA surface, as shown in Fig. 3.

DISCUSSION

The preliminary experimental results showed that the prototype successfully achieved a significant friction reduction in the designed feasibility experiment, validating the design concept and further demonstrating its potential for medical applications. In the future, we plan to further develop the system to achieve higher vibration amplitudes, which could potentially lead to increased friction reduction. In addition, we plan to test the system in a clinically-relevant environment in tissue phantoms and ex-vivo animal tissues.

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