Energy based modeling and control of a dielectric elastomer cardiac assit device

Supervision

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Doctoral School

University of Bourgogne Franche-Comté, SPIM (Engineering Sciences and Microtechnologies), speciality Automatic control

Keywords

Soft smart actuators, Dielectric elastomer actuators, Nonlinear system modeling and control, Port-Hamiltonian systems, Partial differential equations, Medical robots

Context

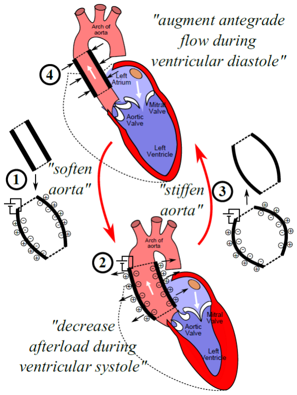
The thesis will be a joint work between the Automatique et Systèmes Micro-Mécatroniques (AS2M) department of FEMTO-ST Institute in France and the Integrated Actuators laboratory (LAI) of EPFL in Switzerland.

FEMTO-ST Institute (Franche-Comté Electronics, Thermal Mechanics and Optics - Sciences and Technologies, UMR 6174) is a mixed French research unit, placed under the main supervision of the National Center for Scientific Research (CNRS) and the University of Bourgogne Franche-Comté (UBFC). The institute is organised in 7 departments, among which the AS2M department counts a total staff of more than 80. The research activities of AS2M department cover automatic control, nano- and micro-robotics, mechatronics, and artificial intelligence. The research group PHS (port-Hamiltonian systems) has a strong knowledge on energy-based modeling and control of multiphysics systems, with an application on soft actuators, biomedical robots, and fluid-solid interactions, etc.

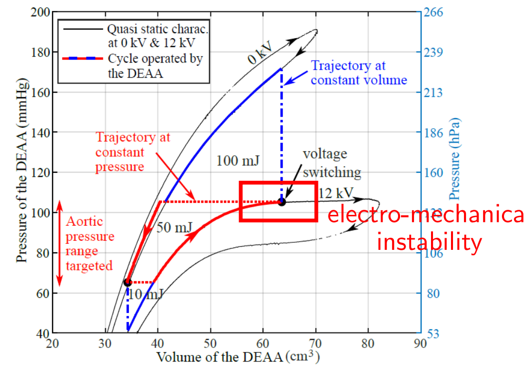
The LAI (Integrated Actuators Laboratory) of EPFL (Ecole Polytechniques Fédérale de Lausanne) is specialized in modeling and design optimization of piezoelectric motors and actuators. Since 2018, with the establishment of the CAM (Center for Artificial Muscles), the LAI has a particular research activity focusing on the design, fabrication and modeling of artificial muscles with the use of electroactive polymer actuators. Last April, the CAM team has successfully implemented a tubular dielectric elastomer actuator on the descending aorta in order to assist the cardiac function in a porcine model.

Scientific context of the thesis

During the last two decades, soft smart actuators based on electroactive polymers, and more specifically based on dielectric elastomer actuators (DEAs), have known a huge growth of interest in the field of biomedical robotics [1] because of their large deformation, fast response time, high compliance, low power consumption, and good bio-compatibility. In order to treat heart failure, researchers at LAI have proposed to replace a part of the aorta with tubular DEAs (see Fig.1a for a schematic representation). The tubular DEA is firstly pre-stretched because of the blood pressure. With a high voltage (kV) applied on the compliant electrodes of the DEA at the end of diastole, the generated Maxwell stress will compress the elastomer along the thickness direction. Following the volume conservation law, the DEA will also expand radially, which decreases the inside blood pressure. After that, the DEA is deactived at the end of systole and contracts, which augments the recoil force of the aorta. A measured pressure-volume diagram under three different scenarios (constant voltage in bold line, pressure balance in red line and pressure unbalance in blue line) is illustrated in Fig.1b. One can obviously notice that with the activation and deactivation of the DEA cyclically, the pressure inside the tube decreases and augments accordingly, which can better assist the systole and diastole of the heart.
However, the DEAs have also certain limits, especially regarding the electro-mechanical instability (also known as snap-through instability). This instability comes from the relation between the electric field and the deformation of the DEA.



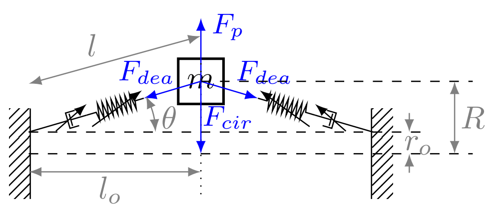
(a)



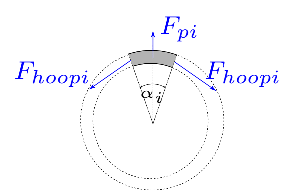
(b)

Figure 1: (a) Schematic representation of tubular DEA in augmented aorta [2]. (b) Measured pressure-volume relation without and with DEAA [2], where 'DEAA' represents the tubular DEA.

As mentioned previously, with the electric field applied, the thickness of the DEA decreases due to the Maxwell stress. The reduced thickness will therefore increase the electric field and hence again thin down the actuator until the breakdown of the DEA [3, 4]. This well-known phenomenon has been observed in the literature [5, 6]. To avoid this instability, [7] put a rigid tube outside of the DEA in order to limit the radial displacement without triggering the snap-through effect. But this rigid protection limits the maximum displacement, reduces attainable energy and the compliance, and leads to a non-soft system. In order to remove the rigid protection and to use the actuator in an optimal way without deterioration, we would like to stabilize the tubular DEA with a dynamic controller. From a control point of view, this instability can be solved by implementing a controller to modify the stability of unstable equilibrium and to shape the close loop performance. First of all, a dynamic model of this tubular DEA is required. Recently, a dynamic finite dimensional model of this tubular DEA has been proposed which focuses only on the deformation of the center point of the tube [8] (cf. Fig. 2).



(a)



(b)

Figure 2: Simplified 1D model of the deformed DEA: (a) front view; (b) side view. [8]

From the fact that the DEAs do not deform homogeneously, a more precise distributed parameter model is needed. Moreover, the model of the DEA is nonlinear and multiphysical which contains both the electrical part and the mechanical one, together with their coupling. The energy-based port-Hamiltonian framework will be investigated to model and control the tubular DEAs. This framework, firstly proposed in 1992 [9], is based on the principle of conservation of energy and provides a clear physical interpretation of control design strategies. Initially proposed in the context of finite dimensional systems, the port Hamiltonian approach has been generalized to distributed parameter systems described by partial differential equations (PDEs) in [10]. It has been applied to model the electro-active polymer actuators for piezoelectric actuators in [11] , and for ionic polymer metal composite actuators in [12]. On the geometric aspect, the port-Hamiltonian systems have a Dirac structure, which implies the energy conservation through the coupling of subsystems and the interaction with the environment [13]. Furthermore, control design techniques developed for nonlinear and/or distributed parameter systems mainly use the Lyapunov theory. The Hamiltonian (*i.e.* total stored energy) can be considered as a good Lyapunov function because it is always semi-positive definite and its time derivative is semi-negative definite. With the Hamiltonian bounded from below, the system is intrinsically passive. Therefore, the port-Hamiltonian approach is naturally well adapted for nonlinear and/or distributed parameter systems controller design, especially the passivity-based control (PBC) design [14, 15]. Two approaches exist in designing controllers using passivity and port Hamiltonian formulations: the Control by Interconnection (CBI) and the Interconnection and Damping Assignment–Passivity Based Control (IDA-PBC). The former consists in shaping the energy in closed loop through an energy preserving interaction between the controller and the open loop system [15]. The latter modifies the closed loop interconnection structure and the dissipation function in order to obtain a dynamical system with desired behavior [16]. This PBC control methodology has been developed for finite dimensional systems and generalized to the boundary control of 1D distributed parameter systems in [17].

Ph.D. thesis activities and time planing

This thesis has three main activities:

- Modeling: develop a reliable model of the tubular DEAs considering the multi-physical, nonlinear and distributed parameters properties. The distributed parameter model will be discretized with a structure-preserving way and simulated hereafter.
- Control: design passivity-based control laws using the proposed distributed parameter model with the aim to solve the electro-mechanical instability of the actuators. Both the modeling and controller design work will be carried out in AS2M, FEMTO-ST.
- Experiment: an experimental set-up will be built in order to validate the proposed model and to test the proposed control design methods in LAI, EPFL.

Administrative information

3 years full-time duration doctoral contract. The Ph.D. thesis will start in September or October 2022.

Application

The candidate will have to demonstrate a strong motivation for scientific research and very good level of English language skills. He or she will have to demonstrate a great rigor in work, method, autonomy, and ease in modeling, analyzing, and experimenting. He or she will have to hold a Master/ Engineering degree in Automatic control, Mechanical engineering, Microengineering, Mechatronics or Robotics. The candidate must be proficient in Matlab & Simulink simulation and have excellent programming skills. A knowledge of dynamic mathematical models and model analysis under the port-Hamiltonian framework and/or a first experience in using Labviex would be a plus.
List of documents to be provided:

- A CV.
- A motivation letter.
- An academic transcript and ranking of Master 1 and 2.
- Recommendation letters.

For more information and application, please contact: Dr. Ning Liu.
Deadline : 15th of June.

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