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Mastering the complexity of an Ultrasonic Sealing System: The port-Hamiltonian approach ☆

Luca Gentili [a,b], Alessandro Macchelli [a,*], Claudio Melchiorri [a], Alberto Mameli [b]

[a] University of Bologna, Dept. of Electronics, Computer Science and Systems (DEIS), viale del Risorgimento 2, 40136 Bologna, Italy
[b] Tetra Pak Packaging Solutions S.p.A., viale Delfini 1, 41100 Modena, Italy

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ABSTRACT

This paper deals with the problem of simulating an Ultrasonic Sealing System (USS). The USS is a complex electromechanical system used to seal aseptic packages for liquid foods that is the core of the most advanced filling machines. Since the overall device is the result of the interconnection of several sub-systems that belong to different physical domains, the problem is tackled within the port-Hamiltonian framework, which is naturally multi-domain and multi-scale. On the other hand, the simulation of the whole sealing process is not a trivial task due to the presence of a Compact Transducer (CT) that can be modeled only by means of commercial finite-element software. Then, only extremely high-order models are available, which makes the simulation of the complete system impractical. Consequently, a novel model reduction procedure for port-Hamiltonian systems has been developed. The method is able to preserve the frequency behavior of the original system in a neighborhood of a predefined set of frequencies of interest. In this way, simulation times have been drastically shortened without loosing the essential dynamical information. The reduced order model can be adopted to test the validity of the controller, and to simulate and perform the diagnosis of the entire sealing process. The results of the model reduction algorithm have been experimentally validated. Moreover, also the complete USS model has been derived.

1. Introduction

The research activity presented in this paper deals with the problem of modeling and simulating the Ultrasonic Sealing System (USS), one of the key technologies used in the sealing process of multi-layered packaging materials, which is based on ultrasounds. The complete system consists of several interconnected sub-systems belonging to different physical domains and described by lumped or distributed parameter models. The overall complexity poses formidable challenges to its designers, and the port-Hamiltonian framework has shown its potentialities for investigating the physical phenomena that occur throughout the system in detail, and for providing a general model development methodology for each sub-system and for the entire system as a whole.

In recent years, in fact, port-Hamiltonian systems [1–3] have proved their capabilities in modeling, simulation and control of *complex* dynamical systems. Here, the word "complex" refers to the presence of several sub-systems belonging to different energetic domains (e.g. mechanical, electrical, thermal), that can exchange power among them and are mathematically described by finite and infinite dimensional models (i.e. by ODEs and PDEs). This is exactly what happens in the USS. The basic idea is to describe a dynamical system as the power-conserving interconnection of simpler sub-systems in an *object-oriented* or *multi-scale* fashion. In some sense, the port-Hamiltonian framework can be considered as the mathematical formalization of the bond-graphs [4] modelling language, with strong connections, also, with the Modelica [5] language. It is worth mentioning that several simulation packages practically implement both the approaches, e.g. [6,7].

On the other hand, the most complicated part of the USS is the Compact Transducer (CT), shown in Fig. 1, which is responsible of the sealing process. Physically, the CT is excited by applying an high-frequency sinusoidal voltage to a piezo-electric actuator (more details in Section 5.2). The CT has been designed by using the finite-element software ABAQUS [8], and the resulting model is proved to be accurate but not suitable for simulating the sealing process. Indeed, the finite element model is characterized by a large number of degrees of freedom (dof), about 300,000, and the implicit dynamic procedure needed to simulate the sealing process requires direct integration of each dof, leading to a very large simulation time, of the order of several months on a common workstation. This is clearly unacceptable for control development purposes. As a consequence, it is also necessary to deal with the "numerical

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* Corresponding author. Tel.: +39 051 20 93031; fax: +39 051 20 93073.
E-mail addresses: luca.gentili@tetrapak.com (L. Gentili), alessandro.macchelli@unibo.it (A. Macchelli), claudio.melchiorri@unibo.it (C. Melchiorri), alberto.mameli@tetrapak.com (A. Mameli).

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