Design Rules for Actuators in Active Mechanical Systems

Oriol Gomis-Bellmunt • Lucio Flavio Campanile

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Unseren kleinen Clara und Giulia
A les nostres petites Clara i Giulia
To our little Clara and Giulia

Preface

The seed of this book was set in 2003, at the Institute of Structural Mechanics of the German Aerospace Center (DLR) in Braunschweig. Oriol joined the Institute as a Marie Curie Fellow and Flavio, as a member of the Center of Excellence "Adaptronics" at DLR, was in charge of coordinating the Marie Curie Training Site "Smart lightweight structures and transportation application". The "daily bread" of the Center of Excellence and, as a consequence, the focus of the Marie Curie Training Site, was solid-state actuation, in particular piezoceramic actuation.

While working with solid-state actuation, scientists always encounter (sooner or later) fancy histograms or tables showing the comparison between different actuator principles on a quantitative and seemingly objective basis. After having seen such comparisons a couple of times, (and at latest after a couple of lectures or conference talks in which he shows such a histograms or table himself) the scientist begins to wonder what is behind those numbers, which claim, for instance, that the performance of Shape-Memory-Alloy actuators is, say, twice as large as the one of hydraulic cylinders.

And since we could not find an exhaustive answer in published literature, we tried to compute performance quantities for conventional actuators on a model basis, in the way we knew from solid-state actuators. We realized soon that the designer of solid-state actuators lives in a quite ideal and comfortable universe, in which powerful design rules and meaningful performance quantities can be obtained, on the basis of simple assumptions, in a straightforward way. For conventional actuation things revealed definitely more complicated, and intriguing enough to be worth starting a research project. This project eventually became part of Oriol's doctoral thesis, and we kept working on this topic after he went back to Catalonia to get involved in CITCEA-UPC and Flavio took a new professional challenge at Empa in Dübendorf, Switzerland.

The model-based definition of performance quantities implies dealing with the whole design and optimization process of actuators in a systematic way, which gave added value to this work and taught us a lot of new things on solid-state actuation as well. Last year, we finally decided that the topic of model-based design rules for

actuators (conventional as well as solid-state ones) could be an interesting topic for a book.

Besides the original issue, i.e. on which objective and quantitative basis different actuator principles can be compared to each other, the contents of this book tries to give an answer to the following questions, which are strongly related to the above mentioned one:

- which is the dependance of the actuator's primary output quantities force and stroke from the mechanical load applied to the actuator?
- for a given actuator kind (i.e. actuators based on the same principle), which is the relationship between actuator geometry and primary output quantities?
- how scalable are actuators of a given kind?
- how are energetic output quantities (work and power) related to mechanical load and geometry?
- how should actuators be designed and sized to obtain the best performance for the chosen actuator kind and for a given application?

Of course it was not possible to answer the above mentioned questions in an exhaustive way and for all existing actuator classes in the time and space framework which was available for this book. So we had to limit the range of our treatment in a twofold sense:

- we reduced the number of dimensions of the design space by successive optimization: after having identified proper specific quantities, we look for the best combination between actuator and load, then we analyze the optimal value of the specific quantities with respect to the actuator design variables;
- we restricted our focus to four actuator principles: solenoid actuators, voice-coil actuators, hydraulic actuators and solid-state, strain-induction based actuators.

The reader who will make it to the end of this book will discover three distinct parts:

In the first one, the most common actuator principles are introduced, and the philosophy behind the above sketched actuator analysis is described in detail. The second one is dedicated to the application of the described analysis procedure to three classes of conventional actuators: solenoid, voice-coil and hydraulic actuators. The third part, dedicated to solid state actuation, is – paradoxically – of more conventional nature in the context of this book. As mentioned above, model-based analysis of solid-state actuator is a common tool and several papers or book chapters can be found in literature which deal with the basic concept treated in part three, like blocking force, free stroke, energy density or design of a pre-stressed solid-state actuator. Additionally, due to the exact mechanical scalability of solid-state actuators (under the assumptions of the prescribed-strain theory) the design analysis introduced in Chapter 2 and applied to conventional actuators in Chapters 3 to 5 reduces to a few quite simple concepts when applied to solid-state actuators. In order to make things more interesting, we put this material in an unusual form by introducing a new kind of graphic representation and by complementing the classic issues with

some remarks on hybrid actuators relying on a compliant passive element as well as on design analysis for solid-state actuators for dynamic applications.

We believe that this book can be of interest for anyone dealing with actuator design, and in particular:

- as a textbook for undergraduate and graduate students of mechanical engineering, aerospace engineering, mechatronics control and virtually all other specializations dealing with actuators and active materials; in particular, the graphic representation introduced in Chapter 6 can be an useful didactic tool to learn – by solving exercises – how to analyze solid-state actuators coupled with passive structural elements;
- as a reference for engineers dealing with the design of conventional as well as solid-state actuators;
- as a basis for researchers operating in the fascinating areas of smart mechanical systems as well as coupled mechanical design and optimization, who can profit from some criteria and general concepts exposed in this book, in particular while approaching – in a simultaneous way – the design of passive and active components of mechatronic and adaptive structural systems.

We are aware of the fact that if no book at all is perfect, a book which was compiled in one – even if intensive – year is quite far from being perfect. We are therefore thankful for any suggestion and comment which can help us to improve and enrich possible new editions of this work.

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