微纳技术著作丛书（影印版）

执行器技术：微机电方法

Emerging Actuator Technologies

Pons José L.

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内 容 简 介

执行器是将电能转换成机械能的装置，通常用于电气、气动、液压系统。由于执行器技术在生物医学、人工器官修复、器械矫形中应用的需要，对高效且具有微纳米尺寸级别的复杂精密机械产品的需要不断增长。

本书对执行器的新应用进行了全面的介绍，内容包括：介绍了压电执行器、形状记忆执行器、磁致伸缩执行器的机电一体化设计、控制、集成技术；检验了微纳米级别新兴执行器的特性和性能；评估了各种执行器技术的优点，勾画了今后的应用领域。

本书可供从事微纳器件设计制造领域的科研人员、工程师参考。

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序

科学出版社准备出版一套《微纳技术著作丛书》，包括原创作品和引进作品（影印或翻译）两种形式，并聘请专家组成编委会。这是一件大事，希望能坚持把它办好。

微纳米技术作为21世纪重要的一项技术，已成为国际科学界和工程技术界研究的热点。近年来，微米纳米技术进展迅速，已经发展成为一个包含机械、材料、电子、光学、化学、生物、基因工程、医学等基础学科的综合领域，而不仅仅属于任何单一的科学和技术门类。就其产品而言，也早已超越了人们广为熟悉的微型加速度传感器和纳米碳管等，呈现出向各个科学和技术领域全面渗透的趋势。

由于微纳米技术使得人们除了可以在同一基片上实现包括机械、流体、化学、生物、光学等器件外，也可以将信号处理和传输系统集成在同一基片上用以处理信息，决定计划，控制周围环境，从而大大提高最终产品的综合性能，实现高度智能化。在未来的航空航天、生物医学、环境监控、无线通信、汽车和交通、石油化工、能源、工农业、国家安全、食品和消费的各个领域都将有广泛应用，对国民经济、科学技术、社会发展与国家安全具有重要意义。今后的几十年里，随着微米纳米技术的迅速发展和向现代科学和技术的各个门类渗透，其对我们现代生活的各个方面带来的影响将是长期和深远的。从某种意义上来说，微米纳米技术的发展，可能改变人类的工作和生活方式，乃至基本概念，其潜在的影响有可能和以计算机技术为代表的微电子工业对世界的影响相提并论。

正是由于其诱人的应用前景和巨大的潜在市场，微米纳米技术目前已成为世界各国大力投资进行研究和发展的热点领域，其研究范围包括了材料、器件和系统，涉及的技术包含机理研究、设计分析、计算仿真、制造工艺、系统集成或组装、测控技术和应用研究等。随着微纳米技术的迅猛发展，近年来国外有大量这方面的专业书籍出版。

《微纳技术著作丛书》涵盖材料开发、系统设计、检测技术、集成技术、通信网络、传感系统、微加工技术等方面，它们都是本领域的研究热点。这套丛书的出版对促进我国微米纳米技术的发展将有很大的推动作用。

这套丛书中，原创作品收录的都是国内从事微纳技术的一线研究人员在本领域的研究成果与心得，具有很强的独立性、创造性和系统性。引进作品都是与国际知名的出版集团合作，经国内专家的甄别，挑选出能反映国外最新研究成果、对国内读者又有借鉴价值的作品，具有权威性、前瞻性和可读性。因为微纳米技

术是一个交叉学科领域，我们有意识的选择了一些由多人合写的专著。通常这类著作都是由相关领域的知名专家，各自在每一章节涵盖一个专题，既有进行综合性的论述，也有个人的具体独创性研究。这样的书籍，通常能帮助读者既获得某一领域的研究概况，又能从一个具体的应用专题中获得收益。

2007 年初推出的第一批影印版图书，我和王万军教授进行了评读，此套丛书很实用，不少作者在该领域有很高的声望。我们建议致力于微米纳米技术的研究人员，包括研究生、技术人员，能够花些时间阅读。

总之，我们对科学出版社组织出版这套丛书的举措很赞赏，也希望他们能将这一工作认真、长期地做下去。同时，我们也希望国内的专家能够积极、踊跃地加盟，为我国微米纳米技术的推进做出贡献。

周兆英 王万军

2006 年 12 月 7 日

Contents

1

Actuators in motion control systems: mechatronics

Actuators are irreplaceable constituents of mechatronic motion control systems. Moreover, they are true mechatronic systems: that is, concurrent engineering is required to fully exploit their potential as actuators.

This chapter analyzes the actuator as a device included in motion control systems. It introduces the intimate relationship between transducers, sensors and actuators, and discusses the implications of sharing these functions on the same component.

It also discusses the role of the actuator as a device establishing an energy flow between the electrical and the mechanical domain, and it introduces a set of relevant performance criteria as a means for analyzing the performance of actuators. These criteria include both static and dynamic considerations, and also the performance of the actuator technology upon scaling.

Actuators are classified into active and semiactive actuators according to the direction in which energy flows through the actuator. Active technologies (Piezoelectric, SMA, EAP and magnetostrictive actuators) are then discussed in Chapters 2 through 5, and semiactive technologies (ER and MR actuators) in Chapter 6.

Finally, after explaining the distinction between emerging and traditional actuators, this chapter concludes with an analysis of other actuator technologies (electrostatic, thermal and magnetic shape memory actuators) not specifically dealt with in separate chapters.

Emerging Actuator Technologies: A Micromechatronic Approach J. L. Pons

1.1 What is an actuator?

The mechanical state of a system can be defined in terms of the energy level it has at a given moment. One possible way of altering the mechanical state of a system is through an effective exchange of energy with its surroundings. This exchange of energy can be accomplished either by passive mechanisms, for example, the typical decaying energy mechanism through friction, or by active interaction with other systems. An actuator is a device that modifies the mechanical state of a system to which it is coupled.

Actuators convert some form of input energy (typically electrical energy) into mechanical energy. The final goal of this exchange of energy may be either to effectively dissipate the net mechanical energy of the system, for example, like a decaying passive frictional mechanism, or to increase the energy level of the system.

An actuator can be seen as a system that establishes a flow of energy between an input (electrical) port and an output (mechanical) port. The actuator is transducing some sort of input power into mechanical power. The power exchange both at the input and output ports will be completely defined by two conjugate variables, namely, an effort (force, torque, voltage etc.) and a flow (velocity, angular rate, current, etc.). Eventually, some input power will be dissipated into heat. See Figure 1.1 for a schematic representation of the actuator.

The ratio of the flow to the effort (conjugate variables) is referred to as *impedance*. If an electrical input port is considered, the voltage and the current drawn will completely define the power flowing in the actuator, and the ratio is the familiar electrical impedance. By analogy to the electrical case, at the mechanical port, the ratio of flow (velocity or angular rate) to effort (force or torque) is referred to as *mechanical impedance*, and both variables will define the power coming out of the actuator.

The concept of power exchange at the input and output ports of an actuator gives rise to a wider definition of actuators as devices whose input and output ports exhibit different impedances. In general, neither the input electrical impedance of an actuator will match that of the controller nor the output mechanical impedance will match that of the driven plant. This lack of match between input and output

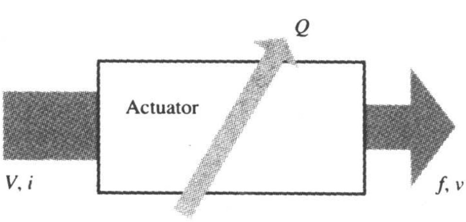

Figure 1.1 Actuator concept: energy flows from the input to the output port. Eventually, some energy is dissipated (undesired losses).

impedances means that impedance adaptation is required both at the input and output ports. The issue of impedance matching will be dealt with in more detail in Section 1.3.

Actuators are most often found in *motion control systems, (MCS)*. In these systems, the ultimate objective is to drive the plant along some reference trajectory. The role of the actuator in such a system is to establish the flow of power by means of some control actions (inputs) in response to process models or sensory data so that the desired trajectory is effectively accomplished.

The dynamic interaction between the actuators and the controlled system can be defined according to the magnitude of the energy being exchanged, $\mathrm{d}W = F \cdot \mathrm{d}X$, Hogan (1985a). In some particular situations, the instantaneous energy exchange can be ignored. This is the case where the force or the displacement is negligible. On the one hand, if the force is zero ($F = 0$), the system can be considered position controlled. On the other hand, wherever the displacement is zero ($\mathrm{d}X = 0$), the system is force controlled.

In general, the interaction will take place with a finite, nonzero instantaneous energy exchange ($\mathrm{d}W \neq 0$). In such a case, the motion control system will be able to impose the effort (force, torque), the flow (velocity, angular rate), or the ratio between them (the impedance), but not both simultaneously.

Depending on the sign of the admissible instantaneous work exchange, $\mathrm{d}W$, actuators can be classified as:

1. *Semiactive actuators*: the work exchange can only be negative, $\mathrm{d}W \leq 0$. In practice, this means that semiactive actuators can only dissipate energy as a consequence of mechanical interaction with the controlled system. These actuators are dealt with in Chapter 6.

2. *Active actuators*: the work exchange can take any positive or negative value, $\mathrm{d}W \lesseqgtr 0$. For practical purposes, this means that active actuators can either increase or decrease the energy level of the controlled system.

The ultimate constituent of an actuator is the transducer. A transducer has been defined (Middlehoek and Hoogerwerf (1985)) as *a device, which transforms nonelectrical energy into electrical energy and vice versa*. This definition of a transducer emphasizes the fact that most actuators (transducers) are driven by logic elements in which the information flow is electronically established. As such, transducers ultimately transform to and from electrical energy.

Transducers have also been defined (Rosenberg and Karnopp (1983)) as *devices, which transform energy from one domain into another*. Rosenberg's definition of a transducer is broader than the previous one since it does not restrict transduction to or from the electrical domain. Finally, the broadest definition of a transducer makes a distinction between different types of energy within a single domain (differentiating between rotational and translational mechanical energy). It states (Busch-Vishniac (1998)) that a transducer is *a device, which transforms energy from one type to another, even if both energy types are in the same domain*.

A transducer can be used to monitor the status of a parameter in a system, or it can be used to define the status of such a parameter. It is the former use of transducers that produces the *concept of sensors*. A sensor is thus a transducer, which is able to monitor the status of a system (ideally) without influencing it.

On the other hand, an actuator can be defined as a transducing device, which is able to impose a system status (ideally) without being influenced by the load imposed on it.

The transduction process can be established between any two energy domains (see second definition of transducers) or even between different energy types within the same domain (see third definition). Whenever a transducer is used to impose a status on a system (actuator concept), such wide definitions of transducers would include actuators capable of establishing energy flow between any two energy domains. Throughout this book, the first definition of transducers is used and is restricted to output mechanical energy.

A transducer might establish energy flow between nonelectrical input energy domains and output mechanical energy – see the case of a thermally actuated shape memory alloy (SMA) transducer. For practical purposes, it is always possible to include any subsystem in charge of electrically driving the transducer in the actuator system. This applies, for instance, to electrically heating the SMA transducer by means of a Joule effect (delivering heat through resistance heating). The actuator system as a whole establishes a flow of energy between the electrical domain and the mechanical domain (see Figure 1.2).

The use of electrical energy at the input port of actuators has clear advantages:

1. *Compatible energy domains.* Most motion control systems (in which actuators are usually included) are controlled electronically; thus, the output energy domain of the control part is already in the same energy domain as the input actuator port.

2. *Fast operation of electric devices.* Electronic and electric devices are characterized by fast operation, in most cases much faster than the intrinsic time constants of the actuator. This improves the controllability of actuators.

3. *Availability of components.* The electronic components used in the control and conditioning system are well-known and readily available.

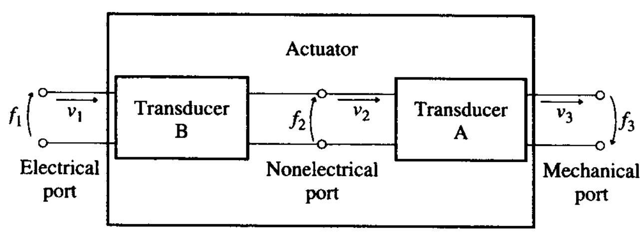

Figure 1.2 Actuator concept as a two-port transducer: input electrical port and output mechanical port.

In view of the above considerations, the actuator concept that we will use throughout this book comprises both the transducer itself (possibly between non-electrical domains and the mechanical domain) and the subsystems responsible for electrically driving the transducer. Note that the subsystems used for electrically driving the transducer could, in turn, be considered an additional transducer, according to the broad definitions noted earlier (see transducer B in Figure 1.2).

1.2 Transducing materials as a basis for actuator design

Transduction is the process of energy conversion between either different energy domains (for instance, from thermal to mechanical energy) or different energy types within the same domain (for instance, between rotational and translational energy). A more restrictive definition of transduction defines the input domain as electrical energy and the output domain as mechanical energy.

The transducer is the device in which transduction is accomplished. In general, two types of transducers can be considered (Busch-Vishniac (1998)):

1. *Geometrical transducers*. In geometrical transducers, the coupling between input electrical energy and output mechanical energy is based on the exploitation of some geometrical characteristics. Actuators resulting from geometrical transducers are called by extension *geometrical actuators*. This applies to all rotational actuators.

   In particular, if a rotational permanent magnet electromagnetic DC motor is considered, the geometry of the magnetic flux with regard to the configuration of the current flowing in the coils leads to a Lorentz interaction, which, in turn, results in a rotational motion of the coil (see Figure 1.3).

2. *Transducing materials*. A transducing phenomenon between any of the different energy domains is directly exploited to develop actuators. Examples include stack piezoelectric actuators or shape memory alloy actuators directly pulling a load.

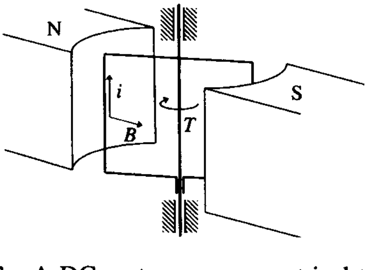

Figure 1.3 A DC motor as a geometrical transducer.

In most cases, the time lapse between the discovery of a new transducing material and its eventual application in the development of actuators might be decades or even centuries. This is the case, for instance, of ER and MR fluid actuators (see Chapter 6). The modification of the rheological behavior of both types of fluid in response to electric or magnetic fields, respectively, has been known since the late 1940s. Only recently have they been applied industrially in the context of vibration isolation (see Case Study 6.3, page 240).

1.2.1 Energy domains and transduction phenomena

Most often when dealing with transducers, seven main energy domains are considered, namely, chemical, electrical, magnetic, mechanical, optical, fluid and thermal. Transduction can be found between any two of these energy domains. In addition, different transduction phenomena are possible for a given pair of energy domains. Some of the transduction processes of interest when developing actuators are briefly analyzed in the following paragraphs.

1. *Thermomechanical transduction.* In this energy conversion process, the input energy is in the thermal domain and the output energy in the mechanical domain. Several actuators can be developed by following this conversion scheme:

   (a) *Shape memory alloy (SMA) actuators.* In this type of actuators, the input thermal energy triggers a phase transition in the alloy, which results in the shape recovery of a previously deformed state. These actuators are discussed in detail in Chapter 3.

   (b) *Thermal actuators.* In this type of actuators, the different thermal expansion coefficients of two thin metallic laminas cause a bending of the composite structure upon heating and cooling. These actuators are described in more detail in Section 1.10.2.

   (c) *Thermally active polymer gels.* Some polymer gel actuators respond to thermal stimuli. These are reviewed in more detail in Chapter 4.

   (d) *Thermal expansion actuators.* It is well-known that temperature changes cause expansion–contraction of all materials. Thermal expansion can be considered a direct thermomechanical transduction process.

2. *Magnetomechanical transduction.* These actuators establish an energy flow from the magnetic domain to the mechanical domain and vice versa. Again, several actuators can be developed, depending on various different transduction phenomena:

   (a) *Magnetostrictive actuators.* Magnetostrictive actuators exhibit a reorientation of magnetic dipoles in the presence of an externally imposed magnetic field. Magnetic domain reorientation results in extension-contraction in the dominant direction. These actuators are analyzed in Chapter 5.

(b) *Magnetorheological fluid (MRF) actuators.* MRFs exhibit changes in their rheological properties when subjected to external magnetic fields. The apparent viscosity of these materials is thus modified according to the magnetic field. They are semiactive actuators: that is, they can only dissipate energy. MRF actuators are discussed in Chapter 6.

(c) *Magnetic shape memory alloy (MSMA) actuators.* In most instances, MSMAs are considered a subclass of magnetostrictive actuators. However, they exhibit very different actuator characteristics and are evolving into an independent new class of actuators. They are addressed in Chapter 1.

3. *Electromechanical transduction.* The energy in the input electrical domain is transformed into mechanical energy. In most of the following actuator technologies, the transduction process is reversible. Some of the technologies listed below are used concomitantly with the converse transduction process in what are known as smart actuators (see Section 1.3).

   (a) *Electromagnetic actuators.* The Lorentz interaction between a flowing electrical charge and a magnetic field is exploited to supply either translational or rotational mechanical energy to the coil. The magnetic field can be established either by means of permanent magnets or by a second coil. This is a well-known, traditional actuator technology, and in this book, it is only mentioned as a reference for comparison with emerging technologies.

   (b) *Piezoelectric actuators.* The converse piezoelectric effect resulting from the interaction of an imposed electric field and electrical dipoles in a material results in a deformation. This deformation is used to drive the plant. The converse piezoelectric effect can be used directly or through geometrical transducer concepts. This is analyzed in detail in Chapter 2.

   (c) *Shape memory alloy (SMA) actuators.* These actuators have already been mentioned in connection with thermomechanical transduction. Thermal energy is usually supplied through resistive heating (Joule effect), and, hence, these can also be considered electromechanical transducers.

   In the context of smart actuators, a linear relationship between the electrical resistance and the displacement is used to establish a sensor model.

   (d) *Electroactive polymer (EAP) actuators.* Within the broad family of EAP actuators, dry type polymers directly exploit Maxwell forces or the