

Chapter 2

Overview of Physics for Electromechanical Systems

In this chapter, an overview of physics is provided for electromechanical systems concerned with electronic components, low frequency magnetic components, higher RF components, and motors and actuators. As shown in Fig. 2.1, several relevant physical scales exist when considering electromechanical systems ranging from the material or device level to the component, subsystem, or fully assembled system level. Microelectromechanical systems (MEMS), which refer to devices of size less than 1 mm but greater than 1 μm , are multiphysics by nature and fall within the broader category of electromechanical systems. However, several authoritative texts related to the design and optimization of MEMS currently exist, and the reader is referred to the literature for a comprehensive review of the topic; see for example [8, 9, 11, 20].

The majority of the numerical examples presented in this book are focused on design optimization at the component or sub-component level. Thus, in the context of these somewhat larger scales, the coupling of several physical phenomena may be defined, as shown in Fig. 2.2, where the systems considered in this text are categorized. This flowchart provides a high-level overview of interactions that engineers must consider when designing electromechanical systems. More specifics are provided on the multiple physical interactions encountered for electronic system components in Sect. 2.1. From there, the physics involved in the simulation of low frequency magnetic components including inductors and transformers are outlined in Sect. 2.2, where operating frequencies in the kHz–MHz range are generally considered. Radio frequency (RF) components operating in the MHz–GHz frequency range are subsequently described in Sect. 2.3 followed by motors and actuators in Sect. 2.4.

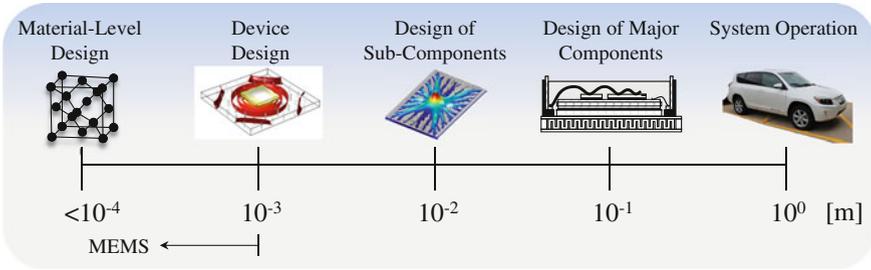


Fig. 2.1 Range of physical scales encountered in the design of electromechanical systems

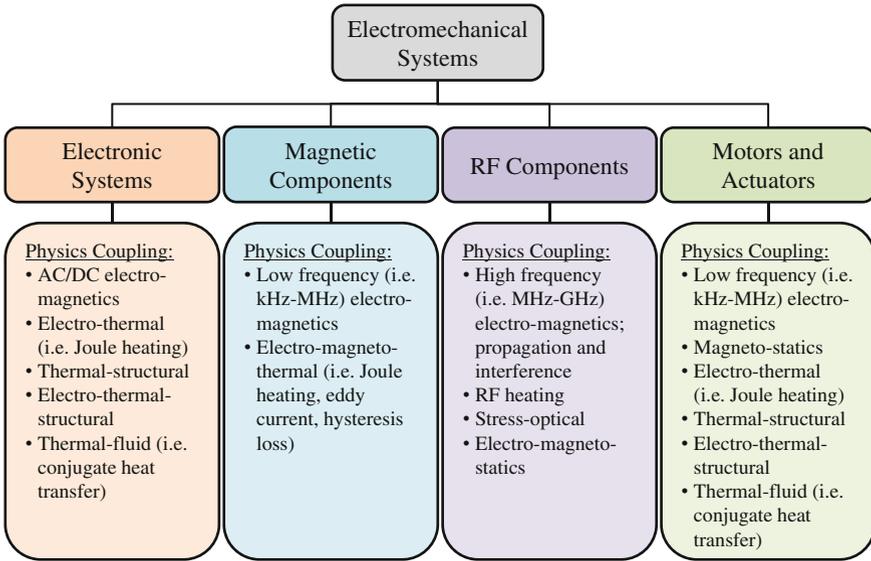


Fig. 2.2 Commonly encountered physics couplings for electromechanical system components including electronic systems, low frequency magnetics, radio frequency (RF) components, and motors and actuators

2.1 Electronic System Components

Modern electronic equipment is highly complex, and the effect of electric current flow and the resulting device power dissipation on the temperature and reliability of the package is significant. In Fig. 2.3, a representative structure is shown to illustrate the typical components found in an electronics package. While this package features a planar integrated circuit (IC) device, the main features of the structure are similar to those found in packages with discrete devices.

Generally, electric current is applied to the device, which generates an electromagnetic field and dissipates power in the form of heat. The device is attached to a

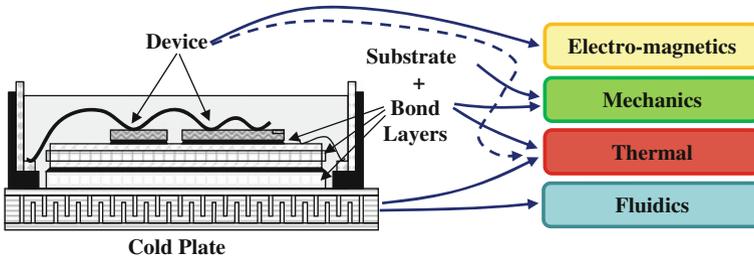


Fig. 2.3 Cross-section schematic of a representative electronics package highlighting the physics involved with various components. Although a planar type of structure is shown, the illustrated components (i.e., device, substrate, bond layer/TIM, and a cold plate/heat sink) are common to most electronics applications

substrate such as a multi-layer direct-bonded structure, or in some cases a printed circuit board (PCB), where electrical connections are made. The device is electrically and thermally coupled to the substrate via a bond layer using solder and/or some other thermal interface material (TIM). The cold plate (or heat sink) may then be attached in an electrically isolated fashion to either the bottom of the substrate or in some cases directly to the top of the device depending on the various electrical connections that are required in the final application.

Referring now to Fig. 2.2 in conjunction with Fig. 2.3, several physical interactions occur in an electronics package. These physical interactions are typically initiated by applying electrical power to a semiconductor device such as a diode or transistor. The device is usually constructed out of silicon, germanium, gallium arsenide, or an organic semiconductor, and Joule (or resistive) heating occurs due to device power dissipation. During device steady-state and transient operation, structural deformation often occurs as a result of the material coefficient of thermal expansion (CTE) mismatch between the various package layers, which may be composed of different types of metals, ceramics, plastics or other compliant TIMs. This structural deformation leads to thermally induced stress in the various package components, and while Joule heating may be examined as a standalone problem, this heating phenomenon may also be coupled into a thermal-structural multiphysics analysis.

The miniaturization of electronics enables compact form-factor designs. However, high power devices and smaller package sizes lead to higher power densities. As a result, efficient cooling of electronics is an enabling technology, and some combination of heat conduction, convection, and radiation must typically be examined in analyzing the performance of an electronics system. Conjugate (solid-fluid) heat transfer is a classic situation in which multiphysics analysis is especially important; here, heat is transported by conduction in the package plus either free or forced convection via a fluid that must efficiently interact with a heat sink. While this topic has been extensively studied, see for example [12, 14, 15, 18], the goal in addressing it here is to provide a unique set of numerical tools for the optimization of electronics cooling structures and associated fluid distribution manifolds.

The above descriptions highlight the host of multiphysics challenges that arise in the design of electronic equipment. The governing equations for electronic systems involving Joule heating, thermally induced stress, and conjugate heat transfer are provided in Chap. 3 along with several example design studies in Chap. 5. Note that other single physics phenomenon such a vibration are also important in assessing the reliability of an electronics package; however, the reader is referred to the existing literature [23, 24] since this topic has been extensively studied.

2.2 Magnetic Components

Magnetic components (e.g., inductors and transformers) are essential components in the construction of electrical circuits. Figure 2.4 shows a schematic of a representative magnetic component. Copper wires are wrapped around a core, which is generally made of an iron-related material. Magnetic components transform electric energy into magnetic energy, and vice-versa. More specifically, the electric current in the wires generates a magnetic field, which might again induce an electric current. In order to facilitate the conversion between electric and magnetic energy, the core material is inserted inside the windings of the wires because the resistance of the magnetic field (i.e., reluctance) of the core material is much lower than that of air. This electromagnetic energy conversion enables us to change the waveform of an electrical signal or the related power. During the conversion process, a portion of the total device energy is dissipated in the form of heat. Thus, a heat sink might be attached to the device to prevent overheating of the magnetic component.

Figure 2.2 together with Fig. 2.4 illustrates the various physical interactions that occur in magnetic components. Accurately modeling the coupling of electric and magnetic fields is key to the performance analysis of magnetic components. The relevant frequency range of the electromagnetic fields for the magnetic components considered herein generally spans kHz–MHz frequencies, and this frequency range is treated as a low frequency regime. The associated electromagnetic energy is dissipated as heat both in the component wires and core material. In the wires, power is dissipated due to Joule heating, which is a result of the current flow in the electrically conducting wires. In the core material, power dissipation in the form of heat occurs due to two phenomena: (1) Joule heating due to eddy currents (i.e., time variation of the magnetic field which induces current within electric conductors and associated resistive heating) and (2) hysteresis heating (i.e., energy loss dissipated in the form of heat that occurs during the repeated process of magnetization and demagnetization). The temperature rise due to heat affects the electric and magnetic material properties (e.g., electric conductivity and magnetic permeability). Thus, the coupled electro-magneto-thermal problem must be addressed in the analysis of magnetic components.

The research trend in magnetic component design is to miniaturize the component size. Particularly, magnetic components are known to be the bulkiest components in power applications. A fundamental way to reduce the size of magnetic components

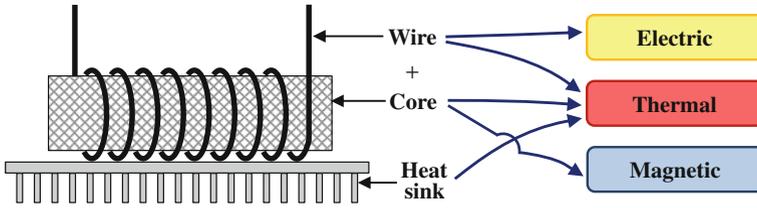


Fig. 2.4 Side view schematic of a representative low-frequency magnetic device with defined physics couplings. Although an I-shaped type of inductor structure is shown, the illustrated components (i.e., wire, core, and heat sink) are common to most magnetic components

is to increase the operating frequency. This frequency increase enables us to raise the reactive impedance without an increase in component size. However, a higher operating frequency means greater energy loss since core losses due to eddy current and hysteresis loss are proportional to the time variation of the magnetic field. The high losses of magnetic components cause not only an efficiency problem, but a thermal management problem, both of which deteriorate overall performance. To deal with these issues, multiphysics simulations considering coupled effects may be a fundamental and effective approach. The governing equations for multiphysics analysis involving low-frequency electric/magnetic fields, and Joule/hysteresis heating are provided in Chap. 3 along with several design example studies in Chap. 5. Note that basic analysis principles and design rules based on fundamental physical interpretations have been extensively investigated; for this, refer to the literature [3, 5, 7].

2.3 RF Components

Modern technologies make machines, such as computer controlled machines or unmanned vehicles, intelligent. In the commercial market, these technologies improve efficiency and safety, which are two major responsibilities of both manned and unmanned vehicle industries. Such intelligent technologies are built upon sensing and wireless communication devices, which in turn are based on electromagnetic wave devices.

Radio frequency (RF) systems represent a class of electromagnetic systems that have a high operational frequency range, and related numerical analysis schemes must be able to handle electromagnetic wave propagation at frequencies ranging from 3 kHz to 300 GHz. However, sometimes, the same numerical analysis scheme is applicable for frequencies beyond the optical range, such as infrared, visible, and ultraviolet frequency bands. Thanks to recent progress in micro or nano machining technology, controlling light waves in the RF regime via electronics has become feasible, and electromagnetic simulations at related scales have become more meaningful [13, 22].

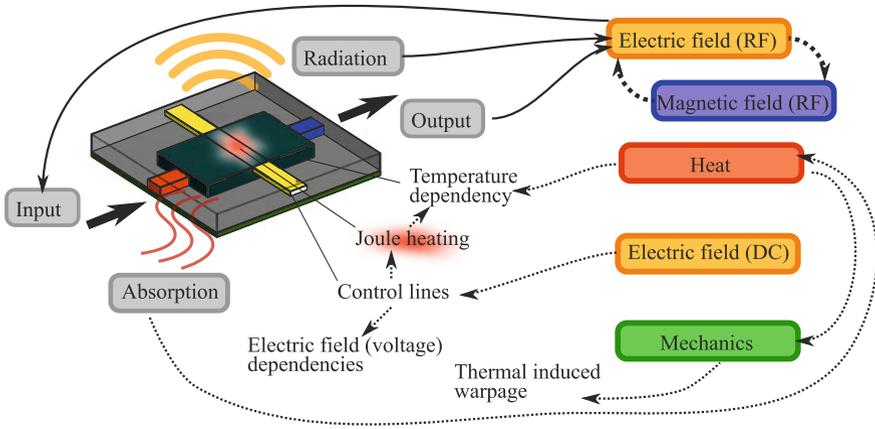


Fig. 2.5 Schematic of a representative RF device with typical multiphysics interactions

Similar to other electronic devices, one of the major multiphysics phenomenon present in RF devices is electromagnetic-thermal coupling (i.e., RF heating), as described in Fig. 2.2 and illustrated in the overview image in Fig. 2.5. Any medium, with the exception of vacuum, may contain a loss component in its material property such as the ohmic loss of a conductor and the imaginary part of the complex permittivity in dielectrics. Electromagnetic fields are absorbed by these loss components, and the related energy is dissipated in the form of heat. A typical application that exploits this phenomenon is microwave heating, and the absorption of electromagnetic waves by the human body (e.g., via cell phones) is a very important research topic with ramifications that are not yet fully understood. Here, electromagnetic analysis is heavily utilized to predict a specific absorption rate (SAR) to satisfy guideline criteria.

Additionally, most materials have temperature-dependent physical properties that form bidirectional coupling between high frequency systems and thermal transport. This coupling is very crucial in small-scale photonics systems and is often exploited for active modulation combined with Joule heating; this is often referred to as thermo-optical control. Furthermore, the thermal expansion of a material may cause structural changes of the RF device, which in terms of geometry, may give rise to changes in the electromagnetic field.

Another aspect of thermal coupling is heat radiation via infrared light. Technically, thermal radiation is an electromagnetic wave propagation effect, which peaks in the infrared range of the electromagnetic spectrum. Therefore, it is possible to control the heat radiated by a device by designing the electromagnetic behavior of the device surface structure. A typical application of this idea is the surface structural design of a thermo-photo-voltaic system [16, 26].

Beyond heat transfer, the coupling of electromagnetic fields at different frequencies with static fields is also important. It is very common to control RF or optical devices using a DC bias voltage or different operational frequencies. From a macroscopic point of view, such effects (e.g., Pockel's effect [4], Kerr effect [10]) can be

described in terms of material non-linearity. Or, as previously mentioned, the use of thermo-optical coupling is a common approach to optical modulation by DC bias. Similar free carrier plasma effects [17] control the amount of free carriers on the optical path to change the permittivity by an external field. Another common coupling between electromagnetic waves and static magnetic fields is Faraday's effect. Here, the polarization direction of an electromagnetic wave rotates when the wave is exposed to a magnetic field. By combining this effect with a polarization-dependent structure, it is possible to control an electromagnetic wave via a static magnetic field, and one important related application is a ferrite circulator [6].

On the other hand, unlike other electronic systems, magnetic forces are reduced as frequency increases due to difficulties in confining the magnetic field. As scale decreases, other forces become important including Coulomb forces and optical gradient forces [25]. Coulomb forces are the forces between electric charges, and these forces are commonly exploited in MEMS devices. An optically graded force is a force generated in relation to the gradient of the electric field energy (e.g., in optical tweezers).

As electromagnetic frequency increases, the associated wave length decreases. This inverse relationship results in a reduction of physical size. Hence, small geometrical changes have a large effect on electromagnetic behavior. Accordingly, by using piezoelectric materials it is possible to create a strong coupling between strain and electromagnetic fields. One application is a surface acoustic wave (SAW) filter. Finally, in optics, there is also a coupling between refractive index, or electric permittivity, and stress, that is, photoelasticity. This effect is also utilized in acousto-optics and photoelastic modulators.

Thus, many RF device applications exist, and the reader is referred to the literature for numerous examples. In this text, governing equations for high frequency electromagnetic systems are covered in Chap. 3. Then, a RF microstrip device design example is presented in Chap. 5 followed by the multiphysics design of a dielectric resonator antenna, where the focus of the study is to optimize both electromagnetic and structural response.

2.4 Motors and Actuators

Recently, electric motors and actuators have been extensively used as fundamental components of future vehicle drive-trains and robotic systems. A possible scenario is that electric motors will eventually replace traditional internal combustion engines for future eco-friendly vehicles. Actuators are essential in the development of drive-by-wire technologies, which aim to replace traditional mechanical control systems with electronic systems. Figure 2.6 illustrates a schematic of a linear actuator structure that is presented in a simplified form for ease of understanding. The permanent magnet (PM) and electro-magnet (composed of yoke and wires) generate a magnetic field loop that passes within the plunger and through the yoke (or rotor and stator, respectively, for a motor). The generated magnetic field causes a magnetic force

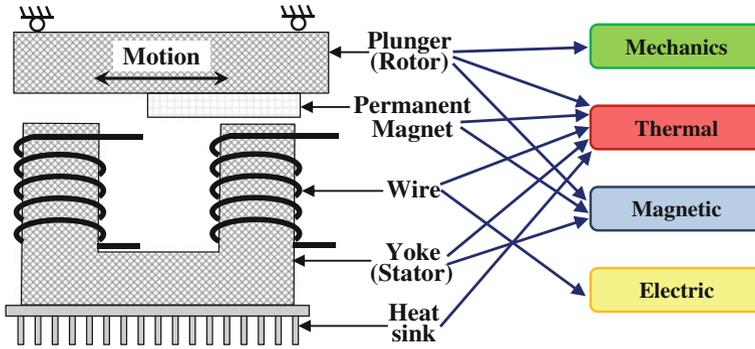


Fig. 2.6 Conceptual schematic view of a simple linear actuator. The featured components of the device (i.e., permanent magnet, wire, etc.) are common to not only actuators, but electric motors

that acts on the plunger. Consequently, the electric energy supplied to the wires is converted into mechanical energy at the plunger through the magnetic energy surrounding the device. During this energy conversion processes, thermal energy is produced due to power loss in the electrical wires and magnetic materials (i.e., yoke and plunger). Logically, a heat sink (or cooling jacket) is then attached for thermal management of the device.

The physical interactions that occur in motors and actuators are very similar to those present in magnetic components with the exception of the mechanics-related physics. Low-frequency electromagnetic field coupling is again a fundamental phenomenon that must be considered in the performance prediction of motors and actuators. The heat generation effect due to Joule and hysteresis losses (i.e., temperature rise due to heat dissipation) is identical to the effect explained in relation to magnetic components. The main difference is that motors and actuators are devices that generate force (or torque) and thus mechanical power. Therefore, it is necessary to understand the dynamics, structural, and vibration characteristics related to the plunger (or rotor) movement. Also, this mechanical behavior may have cascading effects and influence the electromagnetic characteristics. Thus, the coupled electromagnetic-thermal-mechanical problem needs to be addressed in the analysis and design of motors and actuators.

An active research area with regard to motors and actuators is the development of methods for simultaneously increasing power density (i.e., generated power amount per unit device size) and efficiency (i.e., mechanical energy output per consumed electrical energy input). The enhancement of these two performance metrics is required in order to improve the mobility of motors and actuators. Many extensive research studies have been conducted, and one technical approach is the development of new materials based on nano-technologies. Such materials hold promise to offer better material properties (e.g., permanent magnets that have higher residual magnetic flux density or iron that has higher magnetic permeability with low electric conductivity). Improving electric power conversion devices such as inverters and converters

is a second potential approach to achieve high power density and efficiency, where engineers seek an optimal electrical energy input waveform. Lastly, design optimization based on multiphysics simulation, as addressed in this book, may also be an effective technique for motor and actuator performance enhancement.

Simulation methods that consider electromagnetics and force generation, relative to power density and efficiency, have been extensively studied; see for example [1, 2, 19, 21]. Thus, related governing equations for the multiphysics analysis of motors and actuators will be provided in Chap. 3 along with several design example studies in Chap. 5. However, it should be mentioned that understanding thermal and vibration performance is another critical piece of the puzzle in the analysis and design of motors and actuators. Fully coupled simulation methods that handle electromagnetics, force generation, heat transfer, and structural dynamics are not yet mainstream due to their inherent complexity, although future research into motors and actuators may address all of these effects.

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