Systems Engineering and Mechanical Engineering

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This treatment opens with a brief overview of subdisciplines of mechanical engineering. The interested reader seeking a more thorough study on Mechanical Engineering (ME) is referred to Sagdeh and Worek (2017) and other references identified below. As stated by Hibbeler (2015), “Mechanics is a branch of the physical sciences that is concerned with the state of rest or motion of bodies that are subjected to the action of forces. In general, this subject can be subdivided into three branches: rigid-body mechanics, deformable-body mechanics, and fluid mechanics.” It is with those branches that this summary begins, before delving into thermodynamics, controls, and mechanical engineering design and the relationship between SE and ME.

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Contents

Rigid-Body Mechanics and Deformable Body Mechanics

Mechanical engineering and civil engineering structural analysis bear much in common, as both fundamentally seek to create structures to satisfy a design need. While the bridge designer may prioritize material selections that hold up under constant use and varying weather conditions, the race car designer may prioritize light weight while maintaining crash worthiness. In the process of structural analysis, one applies Newton's laws to analyze loads at joints and calculates internal forces, shear, and moment on structural elements. By understanding the loads a joint or structural element must withstand, one can select materials with appropriate properties to prevent failure. A structural element that changes its shape under load is known as a deformable body, whereas a body for which the distances between points on the body remain constant regardless of loading is known as a rigid body. The study of static structures, solid mechanics, and materials are typically foundational in a mechanical engineering undergraduate curriculum (e.g. (Hibbeler 2015), (Philpot and Thomas 2020), and (Callister and Rethwich 2019)).

Dynamics

A subset of mechanics is dynamics. Eloquently summarized by Greenwood (1965), "[t]he science of mechanics is concerned with the study of the interactions of material bodies. Dynamics is that branch of mechanics which consists of the study of the motions of interacting bodies and the description of these motions in terms of postulated laws." In static rigid-body mechanics, with structures that are not accelerating, we write Newton's second law as $\Sigma F=0$. In dynamics we utilize $\Sigma F=ma$ and leverage conservation of energy and momentum in analyzing systems. Simple dynamics problems typically involve the swinging of a pendulum or a spring-mass-damper system and evolve in complexity to modern suspension systems, orbital dynamics, and the multi-body challenges one might see when landing a rescue helicopter on the deck of a Coast Guard vessel.

Fluid Mechanics

Fluid mechanics includes experimental, computational, and analytical modeling of forces on a body moving in a liquid. Models of fluid dynamics often utilize the Navier-Stokes equations, a collection of partial differential equations arising from conservation of mass and momentum. For inviscid flows, the Navier-Stokes equations can be simplified to the Euler equations. The Euler equations can be further simplified to Bernoulli's equation in the special case of steady, incompressible, irrotational flow along a streamline. Common dimensionless parameters to characterize a flow include Reynolds number, Froude number, and Mach number. Reynolds number is a measure of the inertial forces to viscous forces, Froude number characterizes the ratio of inertial forces to gravitational forces, and Mach number provides a ratio of flow speed to the speed of sound. A comprehensive introductory text on fluid mechanics is Batchelor (2000).

Thermodynamics

Mechanical engineering thermodynamics involves products where heat is a primary consideration in the generation or transfer of energy – examples include engines, refrigeration systems, and nuclear reactors. At a broad level, the study of thermodynamics is captured by the following laws:

- *Zeroth law:* "[W]hen two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with one another." (Moran and Shapiro 1998).
- *First law:* "[T]he value of the net work done by or on a closed system undergoing an adiabatic process between two given states depends solely on the end states and not on the details of the adiabatic process." (Moran and Shapiro 1998). In short, energy can be neither created nor destroyed.
- *Second law:* "It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter

body." (Moran and Shapiro 1998). Notably, the first and second laws together are what render a perpetual motion machine physically impossible.

- *Third law:* "[T]he entropy of a pure crystalline substance is zero at the absolute zero of temperature..." (Moran and Shapiro 1998).

Relating thermodynamics to the mechanics topics described above, in a comprehensive summary paper, Graham Baker quotes Clifford Truesdell stating "As mechanics is the science of motions and forces, so thermodynamics is the science of forces and entropy." (Baker 2005).

Controls

Controls refers to "the process of causing a system variable to conform to some desired value, called a reference value." (Franklin et al. 1994) In application, this requires assimilating knowledge of the above disciplines to devise a system to achieve a desired outcome; e.g. measuring room temperature and using that as feedback to control an HVAC system, or measuring orientation and angular velocity to ideally time the firing of a spacecraft thruster to achieve a target orbit.

Design

In design, one combines knowledge of these specific fields to develop products of need by a customer or society. The Accreditation Board for Engineering and Technology (ABET) definition of design is agnostic to engineering discipline; specifically, they state "Engineering design is a process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances." (ABET n.d.) In the design process, mechanical engineers use their knowledge of these disciplines to address societal needs. Furthermore, a key aspect of mechanical engineering design is the decision-making process. As such, decision theory is a key component to the study of design. (Tebay et al. 1984). Approaches to mechanical engineering design vary from waterfall (sequential) style to agile (parallel) methods, with waterfall methods more likely to be governed by a design spiral leading to a single point design whereas agile methods are iterative. Set-based design has become increasingly common in recent years, gaining benefit from increased flexibility by pursuing a broad design space, eliminating options over time as data and validation of underlying assumptions warrant. (Scaled Agile n.d.)

Application to Related Subdisciplines

These fundamental knowledge areas provide core skills for deeper knowledge in numerous subdisciplines, often taught as standalone multi-disciplinary fields. For example:

Aerospace Engineering

Aircraft and spacecraft require command of each of these core areas. For example fluid-dynamics permits understanding the forces of lift and draft on a body. Thermodynamics allows modeling thermal effects on engines, craft operating at high speeds, or subject to large thermal load fluctuations in space. Application of knowledge of dynamics and control allows engineers to develop safe, operable vehicles with performance traits tailored to design need. Expertise in mechanics and materials allows one to develop light weight structures. And ultimately, the design process enables the development and refinement of prototype and production vehicles. Aircraft provide numerous examples of the ties between mechanical engineering and systems engineering. For example, a Boeing 747 has approximately 6 million parts, provided by over 550 suppliers (Boeing 2013), relying on supply chain management. Furthermore, an airline fleet becomes a system of aircraft with the air traffic network constituting a system of systems.

Naval Engineering

Naval engineers function in many ways as systems engineers. Recognizing, for example, the wide range of engineering complexities involved in designing, building, and operating an aircraft carrier – from hull, mechanical, and electrical system design, to hydrodynamics and maneuvering, to integrated warfare systems, to aircraft operations, to hotel services for crew, the modern naval combatant is a highly complicated system of systems. A representative reference is provided in Lamb (2003).

Codes and Standards

The American Society of Mechanical Engineers (ASME) has been involved in the development of codes and standards for mechanical engineering systems since its first standard, "Code for the Conduct of Trials of Steam Boilers" released in 1884. (ASME n.d.a) As a testament to the complexity of mechanical engineering systems, in the present day, ASME standards are used in more than 100 countries and cover topics as diverse as elevators to nuclear plants with guidance under development for additive manufacturing and robotics, amongst other fields. (ASME n.d.)

Relationship between Mechanical and Systems Engineering

ME emphasizes design, development, and research on dynamic systems, be it turbines, prosthetics, or autonomous vehicles. Mechanical engineering products often form the building blocks for systems of systems; for example, a materials scientist designs the fan blade that goes into another mechanical engineer's turbine engine design which resides on an aerospace engineer designed fighter jet, operating off an aircraft carrier designed by naval and systems engineers. One of the best examples of the relationship between ME and SE is with regard to human systems integration, in which multidisciplinary teams assess topics such as ergonomics, health, safety, user interface design, and human performance in designing mechanical systems. Systems engineers often lead such assessments. A comprehensive reference on human systems integration is Booher (2003).

Relatively junior mechanical engineers often focus heavily on the individual subdisciplines of ME, such as those described earlier in this article. They might, for example, conduct a structural analysis of an individual physical assembly. As mechanical engineers gain experience and take on more senior roles, they often become concerned with the larger context in which mechanical components fit and hence take on many of the roles that systems engineers perform but with a focus on the mechanical subsystems. This becomes quite evident when looking at advertisements for senior mechanical engineers. For example, in a May 2022 listing of 20 senior mechanical engineer positions on one online job site, responsibilities included such systems engineering activities as reviewing mechanical documents for areas of conflict with all disciplines, resolving discrepancies between the employer and customer requirements, working with external partners and projects to ensure interoperability of internal and external components, driving internal development methodology, owning the full life cycle for parts, and managing the quality of deliverables while coordinating with other project disciplines.

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< Previous Article | Parent Article | Next Article >
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