1. INTRODUCTION

- A structure is an assembly of mechanical components that serves an engineering function.

- **Examples** of Structures or Structural Systems

  - **Civil Structures**
    - Buildings
    - Bridges
    - Towers
    - Roads, etc.

  - **Aerospace Structures**
    - Aircrafts
    - Helicopters
    - Satellites, etc.

  - **Naval Structures**
    - Ships
    - Submarines, etc.

  - **Ground Vehicles**
    - Automobiles
    - Trains, etc.

  - **Weapons and Missiles**
    - Machine Guns
    - Guided Missiles, etc.
1. Appliances

2. Commercial Electronic Products

3. Energy Producing Structures
   - Power Plants
   - Wind Turbines, etc.

4. Sensors
   - Accelerometers
   - Load Cells, etc.

Elements of large structures or structural systems are also structures or structural components.

Examples:
- Wings of an aircraft
- Blades in a jet engine (see figure below)
- Casing of a missile
- Recoil spring of an automatic weapon
- Cooling fan of a laptop processor
- Body-in-white of an automobile (see figure below)

Kanatçık

Türkiye Diski
Traditionally structural design involves selection of load-bearing components of a structure.

- Dimensions and materials are selected considering failure modes such as:
  - yielding,
  - rupture,
  - buckling,
  - excessive deformations,
  - fatigue, etc.
- Design involves using materials which are natural such as wood, metals or synthetic such as plastics and composites.

In a traditional sense, structures are passive, that is they only perform the intended function under the expected conditions but cannot respond actively to external stimulus in a way to continue performing its original function.

With the discovery and development of active or smart materials with unusual properties such as changing the material behavior by triggering change in the phase of the material (shape memory alloys), by poling direction (piezoelectric materials), and the level of electric field (electrorheological fluids) opened up a new area of research in which “smartness” can be integrated into structural design.

Smartness in the context of structures an ability to perform a function also for a structure to sense, and/or react, and/or adapt to its environment.

- Example:
  - Aircraft wing with a sensor system to listen for acoustic waves caused by cracking.
  - These type of sensors can produce warnings before critical failures saving lives and also reducing maintenance costs.
  - There are practical applications of such systems in Wind turbine crack monitoring.

A more advanced level of smartness may be the ability of structures to report, learn and perhaps self-repair any possible damage.

Sometimes called intelligence, thus making the structure an “Intelligent structure”.

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ME 493 Introduction to Smart Structures and Materials, FALL 2011-2012, METU, Ankara
Dr. Gökhan O. ÖZGEN
1.1. Smart Materials

- Common characteristic of smart materials is that they have one or more properties that can be altered using thermal, optical, electrical, and magnetic fields.

  - *Piezoelectric Materials*
  - *Electrorheological And Magnetorheological Fluids*
  - *Electrorheological And Magnetorheological Elastomer*
  - *Shape Memory Alloys*
  - *Fiber optics*
  - *Carbon Nanotubes*

Some Others NOT studied in this course

- *Magnetorestrictive materials*
- *Self Healing Materials.*
1.5

**Piezoelectric Materials**
- These materials can be deformed when a voltage is applied across them or in the reverse manner can produce electric charge when mechanically deformed by external forces.
- This unique property can be utilized to produce very effective solid state sensors and actuators.
- They can be integrated into structures as embedded sensors and actuators to come up with active or smart structures.
- They are available in natural form (Quartz) or can be manufactured as sintered ceramics (Lead Zirconate Titanate or PZT) in pellet, wafer or fiber forms.
- There are also piezoelectric polymers such as Polyvinylidene Fluoride (PVDF)
  - Low stiffness and low actuation capacity.

Source: NATO AVT-086 COURSE, presented by Afzal SULEMAN
- **Electrorheological And Magnetorheological Fluids**
  - Electrorheological - (ER), Magnetorheological - (MR)
  - ER/MR fluids use electric/magnetic field to change the effective viscosity (or rheological behavior) of a fluid.
  - ER/MR fluids contain fine particles (1-10 μm size) of dielectric/magnetic materials.
  - The fluid must be nonconducting.
  - Electric/magnetic field caused the dielectric/magnetic particles to align (see figure).

**Source:** Recent Developments in Smart and Nanscale Materials 2009, University of Cincinnati, 2009.

![Magnetorheological(MR) Fluid: Before and After a magnetic field is applied.](image-1)

**Source:** Recent Developments in Smart and Nanscale Materials 2009, University of Cincinnati, 2009.

**MR Fluid-based dampers**

![MR Fluid-based dampers](image-2)

**Transmission Clutches Damper**

**Vehicle Suspension Damper**
• **Electrorheological And Magnetorheological Elastomers**
  o Counterparts of ER/MR fluids.
  o Particles are dispersed in a solid elastomer.
  o Particles are dispersed in liquid form of elastomer and exposed to electric/magnetic fields to orient the dielectric/magnetic particles while the curing of the elastomer is performed.
  o In the final configuration, modulus of the material can be altered by applying electric or magnetic field.

**EXAMPLE**

• Development of an adaptive tuned vibration absorber with magnetorheological elastomer

(Hua-xia Deng, Xing-long Gong1 and Lianhua Wang)

• **Shape Memory Alloys**
  o These materials can change their phase at critical temperatures in a reversible manner (Nitinol, a Nickel - Titanium alloy).
  o Capable of very high strains and high actuation forces but have low bandwidth (slow response time) due to time needed for heating and cooling.
- **Fiber optics**
  - Uses Bragg gratings etched into the fiber or a gap to reflect light. The change in the wavelength of light is proportional to the strain in the fiber.
  - 100 times better resolution compared to typical piezoresistive strain gauges.
  - Can measure up to 8% strain.
  - Large bandwidth (up to 50 tera Herz)

- **Carbon Nanotubes (CNT)**
  - CNT is a synthetic material constructed of 2-dimensional sheet of graphite honeycomb lattice rolled into a seamless tube.
  - May be produced in Single-Walled or Multi-Walled configurations with Single wall CNT diameter as small as a few nanometers.
  - These materials are high strength and also exhibit actuation and sensing properties with charge injection.
  - Boron Nitride Nanotubes also show piezoelectric and pyroelectric properties.
Others which will not be studied in this course:

- **Magnetorestrictive materials**
  - Magnetorestriction is the deformation of a ferromagnetic material when it is subjected to a magnetic field.
  - Such materials are called magnetorestrictive elements.
  - This effect may be subtle for most such materials but for certain materials in ceramic configuration and after proper treatment, magnetorestrictive capabilities can be elevated enabling this active characteristic to be used for smart structure applications.

- **Self Healing Materials**
  - Polymer composites which can trigger polymerization using catalyst and polymerization agents to fill in internal cracks that cannot be observed or reached externally.

![Impregnated Epoxy Capsules](image-url)
1.2. Smart Structures

- A proper definition for a smart structure is given in the textbook as follows:
  
  “Smart structures have the capability to sense, measure, process, and diagnose at critical locations any change in selected variables, and to command appropriate action to preserve structural integrity and continue the intended functions.”

1.2.1. Need for Smart Structures

(Source: NATO AVT-086 COURSE, presented by Eswar PRASAD)

- Optimizing response of large, complex systems
  - Adaptive response will cope with unforeseen circumstances
  - Enhance the range of survivability conditions
  - Early warning systems

- Perform enhancements otherwise not possible
  - Minimizing a satellite antenna’s surface distortion – increase precision
  - Control of pointing accuracy under thermal or other disturbances

- Functionality
  - Light weight
  - Preventive maintenance
  - Performance optimization
1.2.2. Smart Structure Classification
(Source: NATO AVT-086 COURSE, presented by Eswar PRASAD)

- **Passively Smart**
  - Structures have the ability to respond to a stimulus in a useful manner, without assistance of electronic controls or feedback systems.
    - Example: A helicopter blade in which composite layers are arranged to tailor the stiffness of the blade to produce twisting when the blade bends (bend-twist coupling). The coupling is used to reduce aerodynamic loads on the blade when it bends.

- **Actively Smart**
  - Structures utilize feedback loops which accelerate the recognition and response process.
    - Example: A helicopter blade with piezoceramic patch sensor that detects that vibrations of the blade and active fiber composite actuators that are controlled to suppress vibrations of the blade.

- **Very Smart (or Intelligent)**
  - Structures utilize nonlinear properties of the sensor, actuator, memory and/or feedback systems to tune the response behavior.
1.2.3. Smart Structure Application Areas

- Some Widely Pursued General Applications for Smart Structures are:
  - **Active Vibration Control**
  - **Active Noise Control**
  - **Active Shape Control**
  - **Active Health Monitoring**

- Also there are potentials for applications such as:
  - **Self Healing Structures**
  - **Biological Sensor Systems**
  - **Novel Actuator Systems**

- Aerospace
  - Damage detection
  - Vibration control
  - Shape control

- Defense
  - Firing accuracy of weapons
  - Vibration and noise reduction in submarines
  - Fuel savings through adaptive wings for aircraft and missiles
  - Early detection of damage

- Automotive
  - Passenger comfort
  - Vibration control (active engine mounts)
  - Health monitoring (smart sensors)

- Industrial
  - Manufacturing (machine tool chatter)
  - Air conditioning and ventilation (noise control)
  - Exhaust systems (noise control)
  - Foundation Isolation (vibration control)
  - Operator comfort in heavy machinery (noise and vibration control)
  - Rotor critical speed control

- Civil
  - Bridges
  - Earthquake protection

- Spacecraft:
  - Pointing accuracy of large antennas maintained through an elaborate network of sensors and actuators.

- Medical devices
  - Smart sensors
  - Surgical Micro robots
  - Surgical tools
    - Micromotor capsules that unclog arteries
1.2.4. Components of a Smart Structure

- Two functions are important for smart materials:
  - Sensing and Actuation.
  - **Sensing:** structural displacement, strains, vibrations, and wave propagation. Can be used to control or performance monitoring or for determining the integrity of the structure. Called Structural Health Monitoring (SHM).
  - **Actuation:** used to suppress vibration or to change the shape of structures to improve their performance.
    - **Examples:**
      - Morphing wings to improve aerodynamic performance of an aircraft.
      - Active noise reduction in a helicopter cabin.

General Components of a Smart Structure

- **Sensor(s):**
  - Monitor environmental changes and generate signals proportional to the changing measured parameters.

- **Actuator(s):**
  - Used to change the properties of the smart structure in order to achieve desired response.

- **Control system(s):**
  - Continually monitors the sensor’s signal, processing the information in order to determine if action is required. If an action is required, then a signal is applied to the appropriate actuator(s).

Source: NATO AVT-086 COURSE, presented by Eswar PRASAD

- In a general sense, the following generic **Component Schematic** can be drawn for a Smart Structure:

- We will be focusing on
  - Materials that can be integrated to the structure as actuators and sensors.
  - How the combined structure can be modeled?

- Control system design is another area of study that needs further effort.
1.3. Potential Applications for Smart Structures

- **Morphing Aerial Structures**
  
  *Source: Recent Developments in Smart and Nanscale Materials 2009, University of Cincinnati, 2009.*

- **Smart systems for application in aircraft**
  
  *Source: NATO AVT-086 COURSE, presented by Eswar PRASAD*
• Instead of using rotating rigid fins to maneuver the missile, flexible fins constructed of “smart” materials can warp to appropriate shape.

*Source: NATO AVT-086 COURSE, presented by Eswar PRASAD*

• Warping is **NOT** a new concept.

• **Smart Piezo materials to achieve “stealthiness” for underwater vehicles**

*Source: NATO AVT-086 COURSE, presented by Eswar PRASAD*
1.4. Actual Applications of Smart Structures

• **Smart Shock absorber.**  
  *Source: NATO AVT-086 COURSE, presented by Eswar PRASAD*

  ![Smart Shock absorber diagram](image1)

• **Earthquake protection of civil structures**

  *Source: NATO AVT-086 COURSE, presented by Afzal SULEMAN*

  ![Earthquake protection diagram](image2)
3-dimensional Adaptive Aircraft Wing

Source: NATO AVT-086 COURSE, presented by Eswar PRASAD
- Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings (TÜBİTAK Project)

Prof. Dr. Yavuz YAMAN, Prof. Dr. Serkan ÖZGEN, Assist. Prof. Dr. Melin ŞAHİN, Assist. Prof. Dr. Güçlü SEBER, Mr. Evren SAKARYA (MSc.), Mr. Levent ÜNLÜSOY (MSc.), Mr. E. Tolga İNSUYU (MSc.), METU, Aerospace Engineering Department, Structures Lab.
• Medical Application of Piezoelectric Ceramics
  
  **Source:** Recent Developments in Smart and Nanoscale Materials 2009, University of Cincinnati, 2009.

  • Use of piezoelectric materials inside human body to replace or support damaged or weakened muscles in appendages such as fingers or toes.

  - Piezoelectric materials will be mounted to bones, actuate to move joints
  - Controlled via brain impulse
  - Extra power will be required, possibly harvested using piezoelectric materials other places in the body
• Piezoelectric-material based Inchworm Actuator
  
  Source: NATO AVT-086 COURSE, presented by Eswar PRASAD
• **Smart Strut Member (utilizing piezoelectric material based actuator)**  
  *Source:* NATO AVT-086 COURSE, presented by Eswar PRASAD

• The smart strut member was designed to replace some of the conventional strut members that are components of current passive support structures.
• The smart strut has the ability to vary its length depending on the requirements of the truss structure.

• **Applications**
  - Heavy load positioning and handling
  - Smart structure research
  - Dynamic loading
  - Instrumentation
  - Robotics
  - Civil engineering
• Smart Truss Structure (utilizing piezoelectric material based sensors and actuators)
Source: NATO AVT-086 COURSE, presented by Eswar PRASAD
• **Morphing Wings (Trailing Edge)**  

  - Elastic Hinge
  - Shape Memory Alloy (SMA) actuators pull on structure to create curvature.

• **Morphing Wings (Skin)**  

  - Allow shape changing of wing skin.
  - Shape Memory Polymer (SMP) is used as the active element.
• **Structural Health Monitoring**  

![Active diagnostic of inconel pipe for rocket engines. Comparison of baseline signal to signal with induced surface crack in direct path. 4mm, 10mm in length. Crack could not be detected at 50kHz, barely at 200kHz.](image)

- The Tachi Laboratory at the University of Tokyo has developed many applications of retro-reflective projection technology, or RPT.
- Using their projection method, an image is projected onto a retro-reflective material worn by a person in the light of the projector.
- The problem in using this type of camouflage is the fact that this is good for a stationary object and not a movable object as the projector has to be stationary itself.

• **Cloaking Systems**  
• Active Vibration Control of a Beam (Smart Beam)
  METU, Aerospace Engineering Department, Structures Lab.

Aluminum beam-like structure
(Smart Beam)

Frequency responses of the open loop and closed loop systems of the smart beam within excitation of
(a) 5–8 Hz (b) 40–44 Hz
Active Vibration Control of a Plate (Smart Fin)
METU, Aerospace Engineering Department, Structures Lab.

Comparison of the open-loop and closed-loop frequency responses of the smart fin for the SISO model for
(a) 70 m/sec (b) 83 m/sec
Some Resources on the Topics of Smart Materials and Structures

- The Journal of Intelligent Material Systems and Structures, SAGE Press
- Smart Materials and Structures, Institute of Physics

Manufacturers of Active Materials Web Pages:
- Etrema Products, http://etrema-usa.com/
- Cymer Active Control Experts, http://www.acx.com/
- Biomimetic Products, Inc., http://www.biomimetic.com/
- CeraNova, http://www.ceranova.com/
- Lord Corp., http://www.frictiondamper.com/

www.piezo.com
http://www.physikinstrumente.com/
References

9. Introduction to Smart Structures, Course Notes, University of Cincinnati, 2002.