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Overview of Smart Materials Used For Vibration Control

Dr. Jitendra R. Chaudhari[1], Prof. Avinash V. Patil[2], Prof. Girish P. Bhole[3] Dr. Shrikant U. Chaudhari[4]

[1,3,4]Asst. Professor, [2]Asso. Professor.
SSGB COE & T, Bhusawal 425201,

jitendra.rc1@gmail.com

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Abstract – *"Smart Structures refer to engineered systems capable of sensing, processing, and responding to environmental conditions. These conditions encompass stress, pressure, temperature, electric fields, and incident photons. Smart Structures find applications across various engineering domains, including aerospace, automotive, civil, marine, electronics, and robotics. The field of Smart Structures is rapidly advancing, driven by supporting technologies—particularly optics and electronics. Innovations like piezoelectric actuators, fiber optic sensors, shape memory alloys, magneto-restrictive materials, and electro-rheological fluids are under development. Additionally, we explore aspects such as structural integrity, sensor fusion, and data interpretation."*

Keywords*- Smart Structures, Smart Materials, Piezoelectric, Shape Memory Alloy*

1. INTRODUCTION

Smart Materials, Intelligent Structures, and Biomimetics represent a rapidly growing interdisciplinary field that encompasses materials, structures, sensor systems, and information processing. Advances in each of these areas independently have led to the emergence of this interdisciplinary technology. Inspired by nature, biomimetics explores external features—such as DaVinci's bird-inspired flying machines, fish-inspired ship hulls, and turkey vulture-inspired airplane stabilizers. With advancements in electronics and photonics, our mimicry of nature continues to evolve, aiming to replicate the remarkable features found in the most intelligent of creatures—humans.

The School of Mechanical and Production Engineering at NTU has harnessed expertise across various aspects of foundational technologies, allowing us to delve into this Strategic Research Area. While Smart Materials and Structures fall within the Sensors and Actuators Strategic Research Programme, they serve as the driving force behind our group. In this article, we explore smart structures and the diverse smart materials employed for vibration control within this Strategic Research Area.

Currently, the engineering community is focused on developing a new generation of high-performance structural and mechanical systems. These systems integrate sensing, diagnostics, and control capabilities. Within active structural applications, several smart/intelligent materials—such as piezoelectric materials, shape memory alloys, electrorheological materials, and electrostrictive materials—are in use. Thanks to advancements in computer hardware and efficient software, we can study and simulate material and mechanical properties, as well as their behavior and control capabilities, using approximate numerical methods. The widely employed method for such studies is the finite-element method. Researchers have applied this method to explore the response of various smart materials and to simulate the sensor and actuator

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functions of smart structures, often comparing the results with experimental data.

II - SMART MATERIALS AGE

Throughout history, materials technologies have profoundly shaped human civilization. Historians even define eras based on dominant materials—think Stone Age, Bronze Age, and Iron Age. Today's Synthetic Materials Age, featuring plastics and composites, serves as a precursor to the upcoming Smart Materials Age. In this new era, synthetic materials will merge with emerging technologies, creating smart materials with nervous systems, brains, and muscular capabilities. Innovations in nanotechnology, biomimetics, neural networking, artificial intelligence, materials science, and molecular electronics will drive this evolution. These smart materials will impact civilization significantly, enabling autonomous functions, embedded sensors, and even self-repair. Industries—from aerospace to medicine—will harness their unique capabilities.

III -SMART STRUCTURES

The definition of smart structures sparked debate from the late 1970s to the late 1980s. To establish common terminology, a special workshop convened by the US Army Research Office in 1988 identified sensors, actuators, control mechanisms, and timely response as the four defining features of any smart system or structure. The workshop formally adopted the following definition for smart systems/structures: 'A system or material with built-in or intrinsic sensors, actuators, and control mechanisms capable of sensing a stimulus, responding predictably and promptly, and returning to its original state once the stimulus is removed.

In conjunction with smart or intelligent structures, Rogers introduced additional terms to further classify smart structures based on sophistication. These classifications are as follows:

- **Sensory Structures**: Equipped with sensors for determining or monitoring system states/characteristics.
- **Adaptive Structures**: Feature actuators that allow controlled alteration of system states or characteristics.
- **Controlled Structures**: Result from the intersection of sensory and adaptive structures, integrating both sensors and actuators in feedback architecture for precise control.
- **Active Structures**: Combine sensors and actuators seamlessly into the structure, providing not only control but also structural functionality.
- **Intelligent Structures**: Essentially active structures with highly integrated control logic and electronics, offering cognitive capabilities through distributed or hierarchical control architecture.

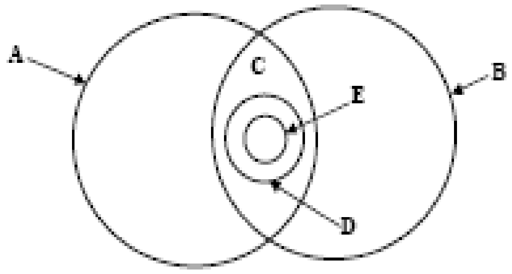

Figure 1 Classification of Smart Structures

IV-ACTIVE AND PASSIVE SMART MATERIALS

Smart materials can be categorized as either active or passive. Active smart materials have the ability to modify their geometric or material properties when subjected to electric, thermal, or magnetic fields, thus enabling energy transduction. Examples of active smart materials include piezoelectric materials, shape memory alloys (SMAs), electrorheological (ER) fluids, and magnetostrictive materials. These materials serve as force transducers and actuators. For instance, SMAs exhibit a substantial recovery force (approximately 700 MPa or 105 psi), making them suitable for actuation. Similarly, piezoelectric materials, which convert electric energy into mechanical force, fall into the 'active' category.

On the other hand, passive smart materials lack inherent energy transduction capabilities despite their 'smart' characteristics. An example of a passive smart material is fibre optic material. While these materials can function as sensors, they do not serve as actuators or transducers.

Smart Materials: Future Applications

Experienced researchers frequently share forward-thinking concepts related to the future of smart materials during conferences and seminars. The following advancements could potentially occur in the field of smart materials and structures:

a) **Damage Arrest Materials**: These substances have the remarkable ability to hinder the propagation of cracks by automatically generating compressive stresses around them.

b) **Shock Absorbers**: Imagine materials that can discern between static and shock loading, responding by producing substantial forces to counteract shock stresses.

c) **Self-Healing Materials**: These remarkable materials possess the capability to repair themselves over time, healing any damages incurred.

d) **Thermal Mitigation Materials**: Designed for extreme conditions, such as those encountered by space shuttles re-entering Earth's atmosphere from outer space, these materials can adapt their composition to withstand ultra-high temperatures.

Additionally, smart materials find application in vibration analysis and control.

V- PIEZOELECTRIC MATERIALS

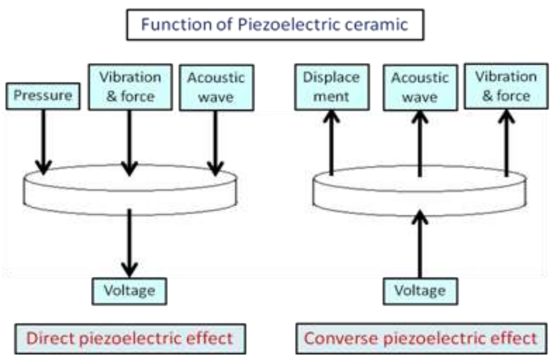

Figure 2 Functions of Piezoelectric Ceramics

Piezoelectricity, a fascinating phenomenon, refers to a material's ability to generate an electrical charge when subjected to mechanical strain (known as the direct piezoelectric effect). Conversely, it can also develop mechanical strain in response to an applied electric field (the converse piezoelectric effect), as illustrated in Figure 2.

The remarkable coupling of mechanical and electrical properties in piezoelectric materials makes them well-suited for specific applications:

1. **Sensors**: Utilizing the direct piezoelectric effect, these materials act as sensors. When the dynamic host structure undergoes deformation, it generates an electric charge, resulting in an electric current within the sensing circuit.

2. **Actuators**: Employing the converse piezoelectric effect, piezoelectric devices serve as actuators. By applying a high voltage signal, they deform and transmit mechanical energy to the host structure.

Two common types of piezoelectric materials are:

- **Lead Zirconate Titanate (PZT) Ceramics**: These ceramics are brittle and stiff.

- **Polyvinylidene Fluoride (PVDF) Polymers**: Known for their toughness and flexibility.

Piezopolymers, in particular, are excellent candidates for sensing due to their low stiffness, which minimally affects the host structure. On the other hand, **piezoceramics** are better suited for actuation because of their higher elastic modulus, facilitating effective mechanical coupling.

Piezoelectric materials are lightweight and can be easily attached or embedded in structures. They find applications as distributed sensors and actuators. As technology advances, mechanical systems and components are shrinking—especially in the electronic and computer industries. However, conventional vibration testing techniques become inadequate at smaller scales due to the mass loading effect of traditional transducers.

One ongoing project explores using piezoelectric materials for **buckling control of structures**. By bonding piezo-ceramics to surfaces, lateral forces can alter the initial straight profile of a beam, creating an anti-symmetrical second mode shape. Researchers conduct finite element analysis and experimental verification to understand boundary conditions, ply orientation, and actuator positioning.

In summary, piezoelectric materials remain at the forefront of research within the Sensors & Actuators program, particularly for vibration analysis and control.

VI- SHAPE MEMORY ALLOYS

The Shape Memory Effect refers to a material's remarkable ability to regain its original shape after being plastically deformed, all thanks to heating. This phenomenon primarily occurs during solid-phase changes in metals, specifically in the martensitic transformation. Notably, two types of alloys exhibit a strong shape memory effect: Copper Alloys (such as Cu-Zn-Al and Cu-Al-Ni) and Nitinols (composed of Nickel and Titanium).

The key advantage of Shape Memory Alloys (SMAs) lies in their ability to achieve complex movements using minimal components. Remarkably, they accomplish this with only a small temperature change, despite hysteresis effects.

Here’s how SMAs work:

- When heated beyond their transformation temperature, SMAs memorize and recover their original shape.
- During this transformation, they can generate substantial forces or deformations, which find application in actuation.

Nitinol, the most commonly used SMA, deserves special mention. It can:

- Recover up to 8% strain or generate around 500 MPa stress if constrained during recovery.
- Survive millions of cycles when strains are kept below 2%.

However, SMA-based actuators have a comparatively slow response time due to their reliance on heating and cooling for actuation. As a result, they are better suited for low-frequency and quasi-static response control rather than high-frequency applications.

Applications of SMAs span a wide range:

- Successful examples include SMA-made eyeglass frames and mobile phone antennas.
- SMAs are also used in vibration dampers and isolators, leveraging their high internal friction.
- More advanced applications involve robotics (such as artificial hands/arms), passive/active control systems (like buckling control), smart/adaptive structures (for vibration control), and composite structures (for shape control).
- Nitinol’s excellent bio-compatibility has led to its use in medical instruments, including vascular stents and filters.
- An active endoscope utilizing a Nitinol coil spring has been designed and tested.

VII - ELECTRO / MAGNETO-STRICTIVE MATERIALS

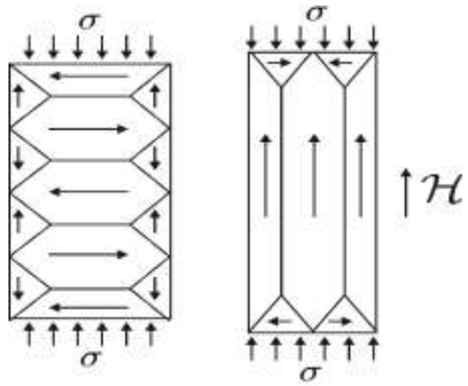

Figure 3 Preloaded Magnetostrictive Material

Magnetostriction, a fascinating phenomenon, occurs when a ferromagnetic material undergoes a shape transformation in the presence of a magnetic field. Most ferromagnetic materials exhibit measurable magnetostriction. Interestingly, if an external force strains a magnetostrictive material, its magnetic state changes—a remarkable bi-directional magnetomechanical coupling that finds applications in both actuation and sensing devices.
Here’s how it works:

- Internal Strains: The rotation of small magnetic domains within the material induces internal strains, resulting in expansion along the field direction.
- Magnetic Alignment: As the magnetic field strengthens, more domains align with it until magnetic saturation is reached.
- Reversed Field: Even when the field reverses, the domains change direction, but the strains still lead to expansion.

Because magnetostriction has a molecular origin, its response is exceptionally fast. Figure 3 illustrates preloaded magnetostrictive material.
!Figure 3: Preloaded Magnetostrictive Material
In practical applications:

- Mechanical Bias: Magnetostrictive materials are typically mechanically biased during normal operation. A compressive load forces the domain structure to orient perpendicular to the applied force.

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- Magnetic Field Introduction: When a magnetic field is introduced, the domain structure rotates, producing maximum strain in the material.
- Terfenol-D: Among commercially available materials, Terfenol-D (an alloy of $Tb_xDy_{1-x}Fe_2$) exhibits significant magnetostrictive effects. Under mechanical bias, it strains up to 2000 microstrain in a magnetic field of 2 kOe at room temperature.
- Dependence on Bias Conditions: Terfenol-D's properties depend on magnetic and mechanical bias conditions. Increasing compressive prestress requires larger field bias and drive field values.
- Electrostriction: This property, observed mainly in materials with high dielectric coefficients (such as PMN—Lead Magnesium Niobate), relates the strain of a ferroelectric material to even powers of the applied electric field. PMN exhibits an electrostrictive strain of up to 0.1%.

VIII- ELECTRO / MAGNETO-RHEOLOGICAL FLUIDS

Magnetorheological (MR) fluids and electro-rheological (ER) fluids exhibit intriguing behavior when subjected to applied magnetic or electric fields, resulting in significant changes in their rheological properties. This behavior can be described as semi-smart because the external field (whether electric or magnetic) influences a classical coupling (specifically, viscosity), yet there is no reciprocal effect.

Here's a closer look at these fascinating fluids:

1. MR Fluids:
    - These are non-colloidal suspensions of polarizable small particles.
    - Their remarkable characteristic lies in their ability to transition from a free-flowing, linear viscous liquid to a semi-solid state with controllable yield strength within milliseconds when exposed to a magnetic field.
    - In the absence of an applied field, MR fluids behave reasonably well as Newtonian liquids.
    - The magneto-rheological response occurs due to polarization induced in the suspended particles by the external field.
    - Resulting induced dipoles cause the particles to align, forming chain-like structures parallel to the applied field (as depicted in Figure 4).
    - These chain-like structures restrict fluid motion, leading to an increase in apparent viscosity.
    - The mechanical energy required to break these structures rises with the applied field strength.
2. Applications and Advantages:
    - Controllable fluids offer simple, quiet, and rapid-response interfaces between electronic controls and mechanical systems.
    - They serve as fast-acting fluid valves without any moving parts in semi-active vibration control systems.
    - Notably, MR fluids can achieve a maximum shear stress approximately 20 times greater than that achievable with ER fluids.

In summary, these materials hold promise for various applications, bridging the gap between electronic control and mechanical functionality.

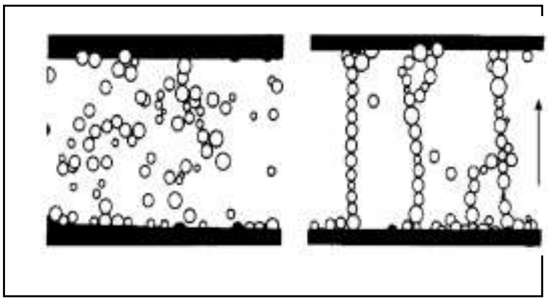

Figure 4 Particles Alignment Due to an Applied Field

9. CONCLUSION

The School of Mechanical and Production Engineering at NTU is actively engaged in diverse research endeavors. Here's a glimpse into their current focus areas:

Sensor and Actuator Designs for Smart Composite Materials:

Researchers delve into creating innovative sensors and actuators tailored for smart composite materials.

They explore the impact of embedding these components on the overall structural integrity of the materials.

Analysis and Control of Vibration:

Understanding sensor and actuator systems is a fundamental aspect of their work.

The team investigates how these systems interact with vibrations and contribute to control mechanisms.

Specific Sensor and Actuator Technologies:

Piezoelectric and Fiber Optic Sensors have garnered significant attention due to their established histories.

Additionally, they explore the potential of MR (Magnetorheological) and ER (Electro-rheological) fluids, as well as Shape Memory Alloys, which offer niche applications and complement existing techniques.

Advanced Materials and Processing:

Non-destructive testing and micro-electromechanical systems (MEMS) play pivotal roles.

These areas collectively shape the future of Smart Materials and Structures.

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