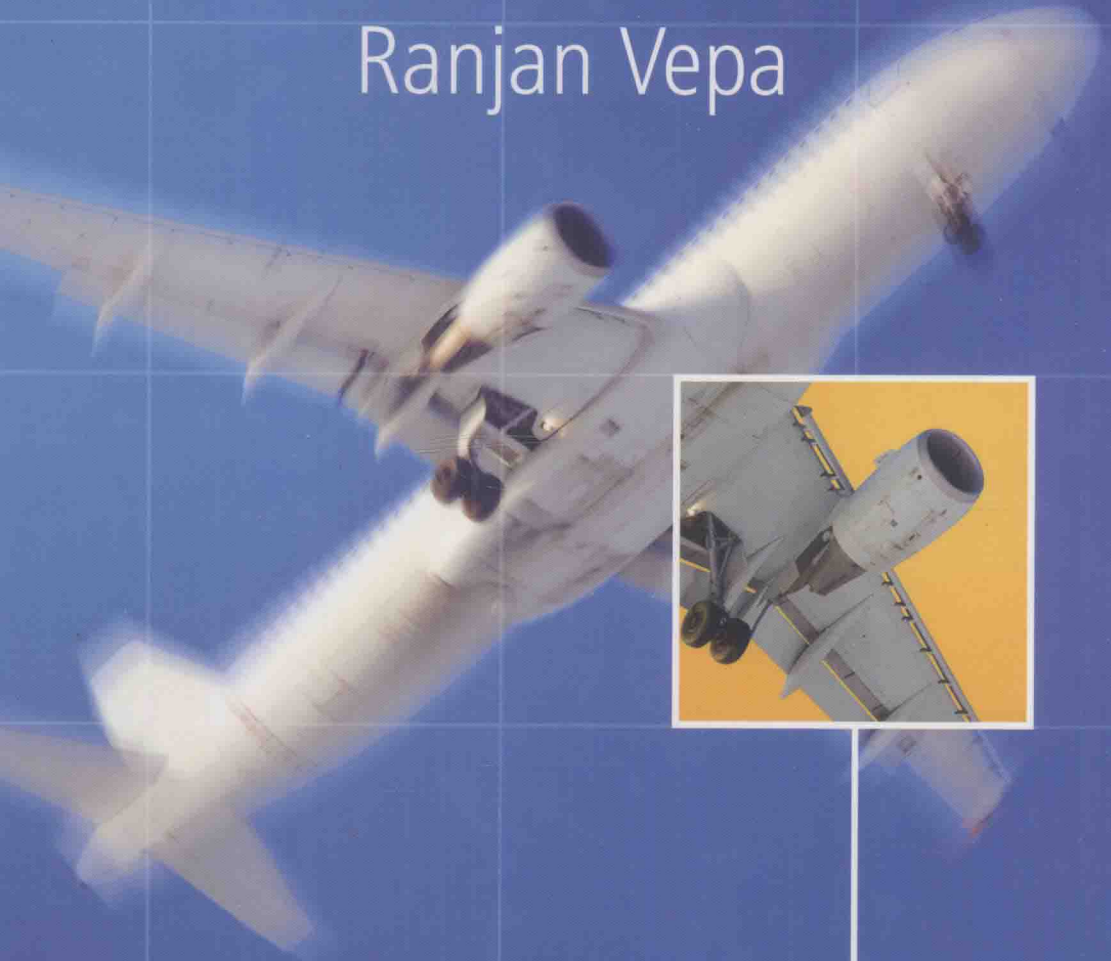
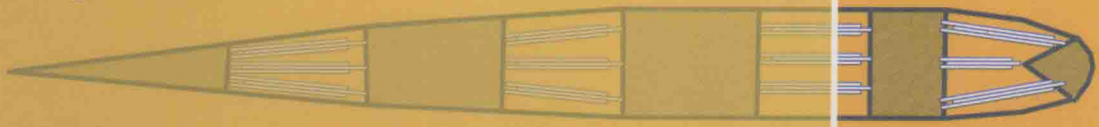


Dynamics of Smart Structures

Ranjan Vepa



 WILEY



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Dr. Ranjan Vepa



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DYNAMICS OF SMART STRUCTURES

To my brother Kosla

Preface

The dynamics of smart structures has evolved over the years and has now matured into an independent and identifiable subject. The objective of this text is to provide an introduction to the fundamental principles of dynamics of smart structures. The goal is to provide a practical, concise and integrated text on the subject matter.

In this book fundamental principles are stressed. The treatment in detail on structures assembled from specific smart material types is based on the need to illustrate basic principles and to introduce the properties of a variety of commonly used smart structure prototypes. The text extends considerably beyond the needs of a single specific two-semester or one-year course. There are two compelling reasons for this: the first being the need for flexibility in structuring a course, which might be based on this text, while the second is due to a desire to achieve a degree of completeness that makes the text a useful reference to contemporary practising engineers. The result is a text that should meet the needs of a senior undergraduate or postgraduate course. It will also be possible to offer two one-semester courses based on the text: the first on the dynamics of smart structures, covering substantial portions of the first four chapters in the book, and the second on the active control of smart structures where review of the earlier chapters is covered with a control flavour followed by the remaining chapters. Relevant application examples from across the book may be included in each course.

The first chapter provides an introduction to make a smooth transition from a general review of smart materials to smart structures. The second chapter addresses the dynamical issues related to smart sensors and actuators. The topics covered are transducers and sensors for smart structures, piezoelectric actuators, shape memory alloy actuators and fibre-optic sensors, as well as other conventional transducers. The last section of this chapter is dedicated to fibre-optic transducers, as these transducers are expected to play a key role in the evolution of smart structures. The next chapter introduces the basic concepts of structural control. Only the basics of control theory and topics that are relevant to structural control are presented here. As the fundamentals of acoustic waves and transmission lines play a basic role in understanding the latter concepts, the fourth chapter begins with this topic. Following an introduction to waves in solids, the dynamics of continuous structures, particularly the mechanics of elastic media and waves in elastic media, are covered. The focus of the fifth chapter is vibrations in plates and plate-like structures. The sixth chapter is devoted to the dynamics of piezoelectric media. After providing an introduction to piezoelectric crystalline media, the topics covered are wave propagation in piezoelectric crystals, vibrations in piezoelectric plates, transmission line modelling, discrete element modelling of transducers and the generation of acoustic waves in piezoelectric media. The next chapter deals with mechanics of composite laminated media and flexural vibrations in laminated composite plates. The modelling of flexible laminated plates employing one of several theories such as the classical theory of Kirchhoff, and the theories of Reissner and Mindlin, with the inclusion of the shear, as well as the more recent theories of composite zig-zag laminates, are extensively discussed. Furthermore, the chapter covers the mechanics of composite laminated media, failure of fibre composites, flexural vibrations in laminated composite plates, dynamic modelling of flexible structures, including the finite element method and equivalent

circuit modelling, and active composite laminated structures. The eighth chapter covers the dynamics of thermo-elastic and magneto-elastic media and includes sections on fundamentals of thermoelasticity, creep in materials, the shape memory effect, thermal control of shape memory alloys, constitutive relations, dynamics of hysteretic media and the modelling and control of shape memory alloy-based actuators. The last chapter is devoted entirely to the design of active controllers for flexible structures, and the sections include controller synthesis for structural control, optimal design of structronic systems, the analysis of structures with repeated components and application case studies.

The last chapter is particularly important, as this chapter is the one that brings together the concepts, techniques and systems presented in the earlier chapters. Rather than present the general principles of control engineering, this chapter focuses on the application of control theory to problems related to the active feedback control of flexible structures. Thus, it is assumed that the reader is familiar with the basic principles of control engineering and no attempt is made to provide an in-depth explanation of these basic tools. The validation of controller designs could be achieved by the application of advanced validation tools, which is covered in most advanced textbooks on control systems design. These topics are not covered here. However, the reader is also assumed to be familiar with the matrix analysis package for the PC, MATLAB/Simulink (MATLAB[®] and Simulink[®] are registered trademarks of the The Mathworks Inc., MA, USA) and some of its tool boxes.

I would like to thank my wife, Sudha, for her love, understanding and patience. Her encouragement was a principal factor that provided the motivation to complete the project. Finally, I must add that my interest in the subject of structural dynamics was nurtured by my brother Kosla, when I was still an undergraduate. His encouragement and support throughout my academic life motivated me substantially in this fascinating project.

R. Vepa

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1

From Smart Materials to Smart Structures

1.1 Modern Materials: A Survey

One of the most challenging and intellectually satisfying endeavours of materials scientists during the last decade has been the application of the well-developed methodologies of materials science research to the study of smart materials. Smart materials may be described as materials that can sense an external stimulus (e.g. stress, pressure, temperature change, magnetic field, etc.) and initiate a response. Passively smart materials can only sense an external stimulus. Actively smart materials have both sensing and actuation capabilities. Smart materials, like materials themselves, may belong to one of four classes: metals or alloys, polymers ceramics, or composites (Figure 1.1). Metals and alloys of different metals are the classical materials. It is other materials that are unusual and most important as smart materials (Askeland and Phule, 2003).

1.1.1 Polymers

Polymers are chained molecules that are built up from simple units called monomers (Schultz, 1974; Hearle, 1982). Polyethylene is an archetypal example of a polymer. Polyethylene is produced from ethylene molecules by an addition reaction. The unsaturated double bond in ethylene (C_2H_4) is broken, and this acts as an active agent, attracting self-similar units at either end to produce a chain molecule. Some examples of polymers are silicone, polydimethyl siloxane, polyurethane, polyethylene (PE), polyvinylchloride (PVC), hydrogels, polyester, polytetrafluoroethylene (PTFE), acetal, polyethylene, polymethyl methacrylate (PMMA), polylactic acid, polyglycolic acid, nylon and ultra-high molecular weight polyethylene (UHMWPE).

1.1.2 Structure and Classification of Polymers

PMMA is an example of a hydrophobic linear chain polymer. It is known by the trade names Lucite and Plexiglas and possesses excellent light transmittance properties. It is therefore used for the manufacture of intra-ocular and hard contact lenses. Polypropylene is another polymer that possess high rigidity, good chemical resistance, good tensile strength and excellent stress cracking resistance. PTFE, known by the trade name Teflon, is a very hydrophobic polymer with good lubricity and low wear resistance.

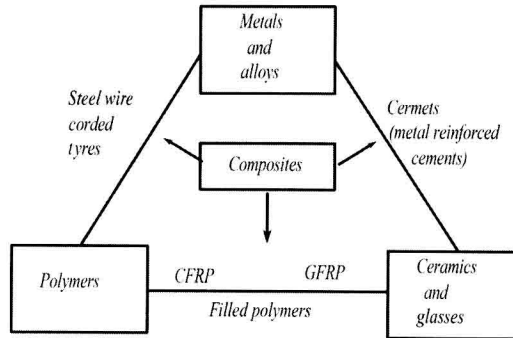


Figure 1.1 Classification of smart materials

Polyethylene is a polymer that can be compacted to a high density (HD) form with an ultra-high molecular weight and has good toughness and high wear resistance. Polyethylene terephthalate (PET), known by the trade name Dacron, is a high-melting crystalline polymer with a very high tensile strength and is therefore used in fabrics for various applications. Polylactic glycolic acid (PLGA) is a random copolymer used in medical applications.

A polymer chain layout has a macroscopic structure to it and two types of structures, amorphous and crystalline, are common. The molecular structure could be chained, linear, branched, cross-linked or networked. Polymers may also be classified as homopolymers, with all repeating units in the chain of the same type (PE, PVC, PTFE, PMMA, PET and nylon), or copolymers, which consists of two or more dissimilar 'mer' units along the chain or branches (Acrylonitrile, Butadiene, and Styrene or ABS, dimethylsiloxane). Copolymers can be random, alternating, graft or block type.

Based on their thermal characteristics, polymers may be classified as thermoplastics, which are linear or branched polymers that can be melted and remelted with heat, or thermosetting plastics, which are cross-linked or networked and are therefore rigid structures that cannot be remelted and degrade on heating. Thermoplastics are recyclable, e.g. polyethylene, while thermosets are not recyclable, e.g. polyurethane.

Based on the chain structure, polymers could be classified as linear, branched or cross-linked. In linear polymers, the mer units form a single continuous chain. The mer units in the chain are bonded together by weak van der Waals forces. In the case of branched polymers, additional side branches result from further reactions that occur during synthesis. A consequence of the existence of the side branches is that the packing efficiency of the polymers is reduced, resulting in a lower density (LD). In cross-linked polymers, the side branches join up with adjacent branched chains. These bonds are essentially covalent bonds formed during the synthesis of the polymer or at elevated temperatures, and the net result is a cross-linked chain polymer. A typical example is vulcanized rubber.

1.1.3 Characteristic Properties of Polymers

Polymers are generally elastic at relatively low temperatures below the melting point, although they are not as stiff as metals and are viscous fluids near the melting point. At intermediate temperatures they are viscoelastic. Some other key characteristics of polymers are good thermal stability, high tensile strength, high impact resistance, excellent ultraviolet resistance and extremely high purity. Thermosetting plastics are liquid or low-melting-point solids that 'cure' with heat, which is an irreversible process. Thermoplastics soften to viscous fluids when heated and regain the solid state when cooled. This process is reversible. The main properties of polymers that set them apart from other materials are molecular

weight, glass transition, crystallinity, melting point, mechanical behaviour and viscoelasticity, fatigue and fracture resistance, and crazing. The glass transition temperature is one below which all segmental motion of polymer chains ceases. The glass transition temperature varies from polymer to polymer because it is a function of compound chemistry. Due to the alignment and ordering of chain segments in thermoplastics, 100% crystallinity is seldom achieved; polyvinylidene fluoride (PVDF) is typically 50–60% crystalline. The extent of crystallinity achieved is dependent on the complexity of side groups and leads to higher densities: $\rho(\text{HDPE}) = 0.97 \text{ g/cc}$; $\rho(\text{LDPE}) = 0.92 \text{ g/cc}$.

Elastic deformation is due to stretching of the constituent chains in the polymer. Viscoelasticity refers to instantaneous elastic strain followed by time-dependent strain. Mechanical deformation is highly time, rate and temperature dependent. The fatigue strength of polymers is more sensitive to load characteristics/temperature than metals/ceramics. Thermosets exhibit brittle fracture, while thermoplastics can exhibit either brittle or ductile fracture. Ductile to brittle transition is possible in thermoplastics, e.g. PMMA is brittle at 4°C and completely ductile at 60°C. Crazing refers to the narrow zones of highly deformed and voided polymer. Typically a 'craze' contains from about 20% to about 90% voids.

1.1.4 Applications of Polymers

An unusual ferroelectric polymer is PVDF, which is a highly crystalline polymer that belongs to a class of materials based on the vinylidene fluoride monomer $[-\text{CH}_2-\text{CF}_2-]$. Depending on the structure, in some crystal lattices, the centres of the positive and negative charges do not coincide even in the absence of an external electric field. In these cases, there exists spontaneous polarization in the crystal, which is referred to as ferroelectricity. When the polarization of the material can be altered by an electric field, it is said to be ferroelectric. Ferroelectric crystals are spontaneously polarized only below a certain temperature known as the Curie temperature. A ferroelectric polymer such as PVDF is one with groups of molecules linked as orderly crystallites. The crystallites form in an amorphous matrix of chemically similar, but differently structured, material. The piezoelectric behaviour of the material, which refers to the generation of charge due the application of mechanical stress, is determined by the relative population of crystallites.

PVDF is a piezoelectric polymer material used for vibration sensing. PVDF, which is known by the trade name Kynar[®], is a high molecular weight, semi-crystalline, semi-opaque and white thermoplastic polymer that is melt processable. It belongs to a class of materials based on the vinylidene fluoride monomer $[-\text{CH}_2-\text{CF}_2-]$. In practice, both uniaxial and biaxial mechanical orientation is used in applications. A process known as poling or subjecting the material to high electric field in a heated condition gives a different balance of piezo/pyroelectric properties. Poled PVDF has excellent corrosion and chemical resistance and outperforms other piezoelectric materials in many applications up to 300°F (149°C). PVDF has a glass transition temperature of about -35°C . It is suitable for chemical processing applications because of its unique combination of properties. Poled PVDF possesses excellent chemical resistance, is tough and durable, and is easily fabricated into finished parts.

Large applied AC fields ($\sim 200 \text{ MV/m}$) can induce non-linear electrostrictive strains of the order of $\sim 2\%$. Co-polymerization of trifluoroethylene (TrFE) with VDF produces a random co-polymer, P(VDF-TrFE), a PVDF polymer that has been subject to electron radiation and has shown electrostrictive strain as high as 5% at lower-frequency drive fields ($150 \text{ V}/\mu\text{m}$). These polymers belong to a class known as electroactive polymers (EAPs) and may be used in the construction of actuators.

1.2 Ceramics

Ceramics (Boch and Niepce, 2005) are inorganic and non-metallic materials, the term 'ceramics' originates from the Greek word 'keramikos' or 'burnt stuff'. Ceramic materials are intrinsically hard,

strong and stiff, but brittle, as determined by their atomic structure. Ceramics are different from metals, which are characterized by metallic bonding, and polymers, which are characterized by organic or carbon covalent bonding. Most ceramics usually contain both metallic and non-metallic elements (with a combination of ionic and covalent bonding).

The structure of a ceramic depends on the structure of the constituent metallic and non-metallic atoms, and the balance of charges produced by the valence electrons. Examples of ceramics are glass ceramics that are based on a network of silica (SiO_2) tetrahedrons, nitride ceramics (TiN) and other silicate ceramics such as quartz and tridymite. A classic example of a ceramic is cement. There are a number of different grades of cement, but a typical Portland cement will contain 19–25% SiO_2 , 5–9% Al_2O_3 , 60–64% CaO and 2–4% FeO.

1.2.1 Properties of Ceramics

Ceramics are characterized by some unique properties due to the coupling of their chemistry with the mechanics of cracking. These properties include thermo-electrical properties, non-linear optical properties and ferroelectric (piezoelectric) properties as well as several others. A typical ceramic ferroelectric is barium titanate, BaTiO_3 . Lead zirconate titanate (PZT) powders are processed in rolling mills to form a visco-plastic dough. The dough may be extruded or processed by calendaring or lamination. PZT powder is manufactured by calcinating an appropriate mix of at least three different lead oxides, titanium and zirconium oxide. PZT with the formula $\text{PbZr}_{1-x}\text{Ti}_x\text{O}_3$ is available in several forms. Particle size has a direct influence on both the direct and the inverse piezoelectric response. The latter effect, the inverse piezoelectric effect, refers to the generation of stress by the application of an electric field. Complex dielectric properties are also controlled by adding dopants. In typical examples of acceptor doping Fe^{3+} replaces $\text{Ti}^{4+}/\text{Zr}^{4+}$ or Na^+ replaces Pb^{2+} , while in the case of donor doping Nb^{5+} replaces $\text{Ti}^{4+}/\text{Zr}^{4+}$ or La^{3+} replaces Pb^{2+} .

Ceramics and polymers do not exhibit piezoelectric properties in their natural state but only after the temporary application of a strong electric field. The process of making polycrystalline ceramics and polymers piezoelectric is called poling. It has been described as a process analogous to magnetizing a permanent magnet. Several ceramics exhibit the piezoelectric property when poled. These include barium titanate, PZT, lead metaniobate, bismuth titanate, sodium potassium niobate and lead titanate.

After a ceramic has been fired, the material will be isotropic and will exhibit no piezoelectric effect because of this random orientation. Before polarization, the ceramic material is thus a mass of minute, randomly oriented crystallites. The ceramic may be made piezoelectric in any chosen direction by poling, which involves exposing it to a strong electric field. Following poling and the removal of the field, the dipoles remain locked in alignment, giving the ceramic material a permanent polarization and a permanent piezoelectric property.

This poling treatment is usually the final stage in the manufacture of a piezoelectric ceramic component. The manufacturing process involves the dry mixing and ball milling of the components, calcining above 900°C , followed by milling to a powder, spray drying and the addition of a binder. The dried, calcined powder with the binder added is then compacted. In this state it is still 'chalky' and in a soft condition. The binder is then burnt out by heating to between 600 and 700°C . It is then machined if necessary and sintered at 1800°C . During the sintering or firing process, high energy is provided to encourage the individual powder particles to bond or 'sinter' together, thus removing the porosity present in earlier compaction stages.

During the sintering process, the 'green compact' shrinks by around 40% in volume. The shrinkage is predictable and can be accommodated. In the final stages of manufacture, after cutting, grinding and polishing as required, electrodes are applied either by screen printing or by chemical plating or vacuum deposition. Poling then is carried out by heating in an oil bath at 130 – 220°C , and applying an electric field of 2–8 kV/mm to align the domains in the desired direction.

1.2.2 Applications of Ceramics

Ferroelectric ceramics are very promising for a variety of application fields such as piezoelectric/electrostrictive transducers and electro-optics. PZT is a piezoelectric ceramic that is suitable for incorporation in composites in the form of ceramic fibres. PZT fibres are an active piezoelectric ceramic material and are particularly suitable for actuating and sensing applications for vibration control in smart and adaptive structures. Innovative fabrication technologies, which enable the realization of very high volume fraction fibre composites, have been developed for the manufacture of high-performance active and novel flexible composites for smart structure applications (Srinivasan and McFarland, 2000).

1.3 Composites

A composite is a combination of two or more materials (reinforcement, resin, filler, etc.) (Agarwal and Broutman, 1990; Vijaya and Rangarajan, 2004; Daniel and Ishai 2005). The component materials may differ in form or composition on a macroscale. A unique feature of composites is that the materials retain their identities, i.e. they do not dissolve or merge into each other, and act cooperatively. The components can be physically identified and exhibit an interface between each other. A typical composite is a two-phase composite consisting of a matrix, which is the continuous phase, that surrounds a second phase known as reinforcement, which in turn is a dispersed phase that normally bears the majority of stress.

There are several ways to classify composites and a broad classification of composites is shown in Figure 1.2. Based on the classification certain main types of composites can be identified:

1. micro- and macrocomposites
2. fibre-reinforced composites
3. continuous fibre composites
4. short-fibre composites
5. fibre-matrix composites.

1.3.1 Micro- and Macrocomposites

Micro- and macrocomposites can be considered as polymer combinations, metal combinations and ceramic combinations. Typical examples of polymer combinations are polymer-polymer fibre-reinforced

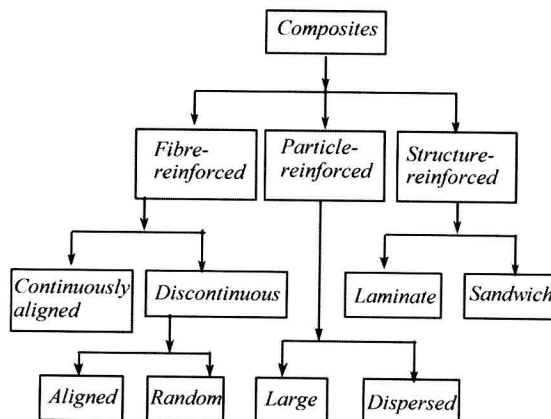


Figure 1.2 Classification of composites