1 Introduction

1.1 Background

The field of ultrasonic guided waves has created much interest this past decade. The number of publications, research activities, and actual product quality control and in-service field inspection applications has increased significantly. Investigators worldwide are considering the possibilities of using ultrasonic guided waves in nondestructive testing (NDT) and structural health monitoring (SHM), and in many other engineering fields. Tremendous opportunities exist because of the hundreds of guided wave modes and frequencies that are available for certain waveguides. Researchers have made tremendous advancements in utilizing mode and frequency selection to solve many problems, for example, in applications for testing pipe, rail, plate, ship hull, aircraft, gas entrapment detection in pipelines, and even ice detection and deicing of rotorcraft and fixed-wing aircraft structures. These have become possible by examining special wave structures that are available via certain modes and frequencies that are capable of effectively carrying out these special work efforts.

Ultrasonic guided waves in solid media have become a critically important subject in NDT and SHM. New faster, more sensitive, and more economical ways of looking at materials and structures have become possible when compared to the previously used normal beam ultrasonic or other inspection techniques. For example, the process of inspecting an insulated pipe required removing all the insulation and using a single probe to check with a normal beam along the length of the pipe with thousands of waveforms. Now, one can use a guided wave probe at a single location, leave the insulation intact, and perhaps inspect the entire pipe by examining just a few waveforms. The knowledge presented in this book will lead to creative ideas that can be used in new inspection developments and procedures.

The tremendous advances made in ultrasonic guided wave technologies in the past three decades are possible because of the tremendous computational power that has evolved over the past two decades and our improved ability to interpret and understand those mathematical guided wave computational results. Many of the problems solved today couldn't have been tackled ten or twenty years ago because the computations would have taken weeks, if they were possible to complete at all.

The finite element methods available today are absolutely amazing. Scientists can study so many problems impossible to solve decades ago. Special structural symmetries and specific loading functions are not necessary. Any configuration can be evaluated.

Wave propagation studies are not limited to NDT and SHM, of course. Many major areas of study in elastic wave analysis are under way, including:

(1) transient response problems, including dynamic impact loading;
(2) stress waves as a tool for studying mechanical properties, such as the modulus of elasticity and other anisotropic constants and constitutive equations (the formulas relating stress with strain and/or strain rate can be computed from the values obtained in various, specially designed, wave propagation experiments);
(3) industrial and medical ultrasonics and acoustic-emission NDT analysis;
(4) other creative applications, for example, in gas entrapment determination in a pipeline, ice detection, deicing of various structures, and viscosity measurements of certain liquids; and
(5) ultrasonic vibration studies that combine traditional low-frequency vibration analysis tools in structural analysis with high-frequency ultrasonic analysis.

Typical problems in wave propagations as waves reflect and continue propagating from boundary to boundary in a long time solution, compared to the short time transient solution, lead to an ultrasonic vibration problem.

Note that ultrasonic bulk wave propagation refers to waves that encounter no boundaries, like waves traveling in infinite media. On the other hand, guided waves require boundaries for propagation as in plates, rods, or tubes, for example. Elastic-wave propagation theory, for example, handles both transient response and the steady-state character of vibration problems.

Historically, the study of wave propagation has interested investigators (engineers and scientists) in the area of mechanics. Early work was carried out by such famous individuals as Stokes, Poisson, Rayleigh, Navier, Hopkinson, Pochhammer, Lamb, Love, Davies, Mindlin, Viktorov, Graff, Miklowitz, Auld, and Achenbach. K. F. Graff presents an interesting history in *Wave Motion in Elastic Solids*. I have included a number of other useful references on history and the basics of wave propagation at the end of this chapter. A detailed literature survey is not presented in the text. With today's tremendously sophisticated information-gathering technology, surveys are easy to perform. Key references enhancing the basic material presented in this text are given throughout the book.

Investigators all over the world now face the challenges of technology transfer and product development in the ultrasonic guided wave field. The basic theory presented in this text prepares us for a theoretically driven approach to sensor, system, and software design. The feedback from field experience and encounters, though, has led to the development of many new problem statements and considerations to meet these challenges effectively. The work presented in this textbook represents a starting point. Hundreds of papers and other work being done today are tremendously useful in meeting our current challenges. The breakthroughs in guided wave application will continue. A paradigm shift from bulk wave ultrasonics in NDT to SHM is triggering this growth in the creative utilization of ultrasonic guided waves. Guided waves will play a critical role in sensor development in the coming decades to improve safety and economics of inspection via self-diagnostics in SHM.

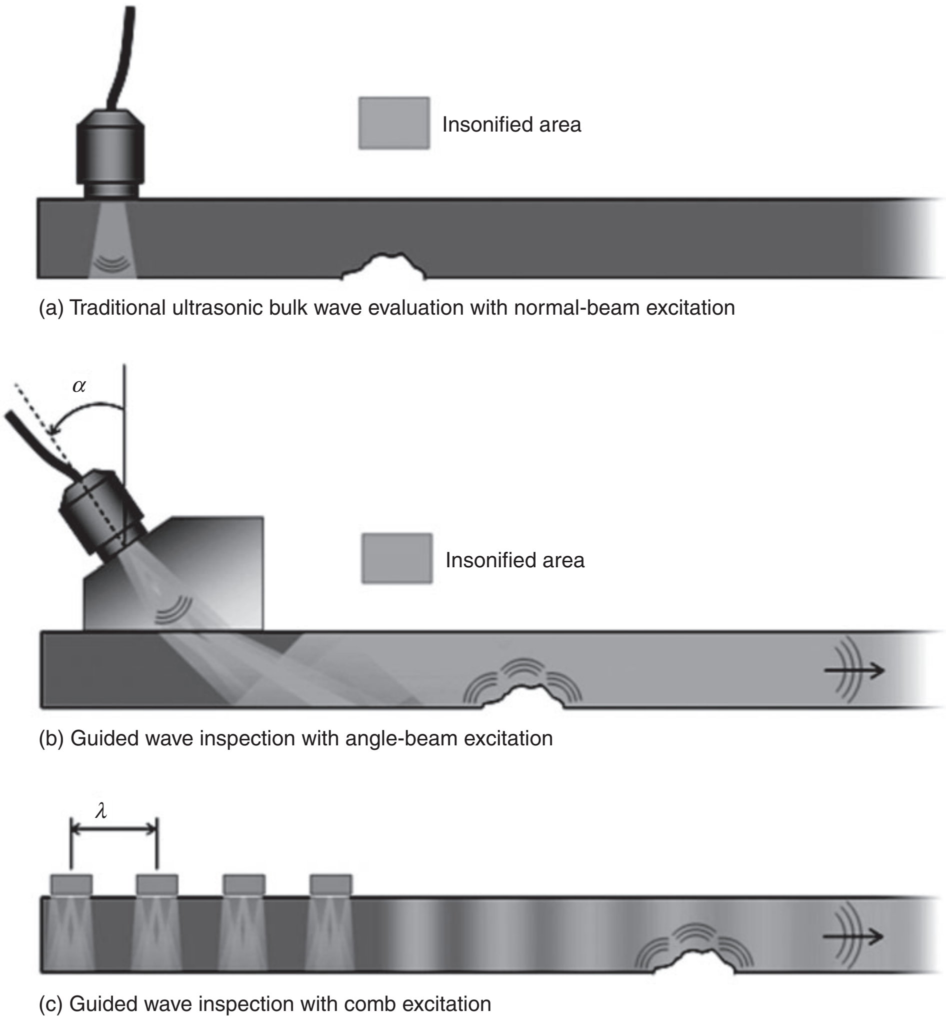

Figure 1.1. Comparison of bulk wave with two guided wave inspection methods.

1.2 A Comparison of Bulk versus Guided Waves

A brief comparison of bulk wave and guided wave ultrasonic inspection is illustrated in Figure 1.1. Note the coverage volume of a structure is huge compared to a local region for a bulk wave. The guided waves cover the total thickness of the structure over a fairly long length compared to a localized area covered in ultrasonic bulk wave studies just below the transducer. Hence, in bulk wave inspection, the transducer must be moved along the surface to collect data, whereas with guided waves the structure can be inspected from a single probe position.

The two guided wave methods shown cover a large area of the structure. Note that the angle beam method could be used in bulk wave evaluation with waves reflecting back and forth inside the structure. Whether a bulk wave or guided wave is generated depends on the frequency used. Lower frequency with larger wavelengths λ would be used in guided wave generation. Wavelength λ would generally be greater than the structural thickness if guided waves are generated.

Table 1.1. Ultrasonic bulk versus guided wave propagation considerations

	BULK	GUIDED
Phase Velocities	Constant	Function of frequency
Group Velocities	Same as phase velocities	Generally not equal to phase velocity
Pulse Shape	Nondispersive	Generally dispersive

In the case of a comb transducer excitation, element spacing is wavelength λ, associated with the frequency used to generate the guided waves. Multiple elements are pulsed whose multiple oscillations lead to the generation of guided waves.

You can easily visualize for guided waves an outcome that is strongly dependent on frequency and impinging wave angles of propagation inside the structure and the resulting complex wave interference phenomenon that occurs in a guided wave situation. The strongly superimposed results are actually points that end up on the wave mechanics solution of the phase velocity dispersion curve for the structure that will be introduced later in this book. Elsewhere there is strong cancellation on destructive interference.

The principal advantages of using ultrasonic guided waves analysis techniques can be summarized as follows.

- Inspection over long distances, as in the length of a pipe, from a single probe position is possible. There's no need to scan the entire object under consideration; all of the data can be acquired from the single probe position.
- Often, ultrasonic guided wave analysis techniques provide greater sensitivity, and thus a better picture of the health of the material, than data obtained in standard localized normal beam ultrasonic inspection or other NDT techniques, even when using lower frequency ultrasonic guided wave inspection techniques.
- The ultrasonic guided wave analysis techniques allow the inspection of hidden structures, structures under water, coated structures, structures running under soil, and structures encapsulated in insulation and concrete. The single probe position inspection using wave structure change and wave propagation controlled mode sensitivity over long distances makes these techniques ideal.
- Guided wave propagation and inspection are cost-effective because the inspection is simple and rapid. In the example described earlier, there would be no need to remove insulation or coating over the length of a pipe or device except at the location of the transducer tool.

A general comparison of bulk and guided waves can be seen in Table 1.1. Key elements of the differences between isotropic and anisotropic media are listed in Table 1.2. *Isotropic* refers to materials with properties independent of direction and *anisotropic* refers to materials with properties dependent on direction like composite materials. Methods of determining characteristic equations for anisotropic waveguides can be found in the literature. See also Rose (1999).

Note that all metals are not isotropic. For example, columnar dendritic centrifugally cast stainless steel is anisotropic. This must be considered in any wave propagation studies.

Table 1.2. Ultrasonic wave considerations for isotropic versus anisotropic media

	ISOTROPIC	ANISOTROPIC
Wave Velocities	Not function of launch direction	Function of launch direction
Skew Angles	No	Yes

Table 1.3. A comparison of the currently used ultrasonic bulk wave technique and the proposed ultrasonic guided wave procedure for plate and pipe inspection

Bulk Wave	Guided Wave
Tedious and time consuming	Fast
Point-by-point scan (accurate rectangular grid scan)	Global in nature (approximate line scan)
Unreliable (can miss points)	Reliable (volumetric coverage)
High-level training required for inspection	Minimal training
Fixed distance from reflector required	Any reasonable distance from reflector acceptable
Reflector must be accessible and seen	Reflector can be hidden

A further practical comparison of the use of bulk and guided waves is presented in Table 1.3, in particular for plate and pipe inspections.

1.3 What Is an Ultrasonic Guided Wave?

Let us go beyond bulk waves traveling in infinite media, *infinite media* meaning that boundaries have no influence on wave propagation, to an explanation of ultrasonic guided waves that require boundaries for propagation. The waves interact with boundaries in a very special way so that boundary conditions can be satisfied. The boundaries could even be the surface of a very thick structure where the structure is considered as a half-space or a semi-infinite media. In this case, Rayleigh surface waves can propagate over the surface of a thick steel plate, for example, or over any thick structure where the frequency is such that the wavelength is very small compared to the thickness of the structure. The Rayleigh surface wave velocity in metals can be estimated as a function of Poisson's ratio, which for steel, as an example, is around 2,900 meters per second. Guided waves can also propagate in many different kinds of waveguides including thin plates, rods, tubes, and multilayered structures. In this case, the ultrasonic waves reflect back and forth inside the waveguide, leading to interference phenomena. Imagine pumping ultrasonic energy into a plate with an initial starting angle and a specific frequency. As the waves reflect back and forth, mode conversion occurs, whereby each time an interface is encountered both longitudinal and shear waves are reflected and/or refracted as in the case of multilayered media. For the particular angle and frequency chosen, the interference phenomena could be totally constructive, destructive, or intermediate in nature. There will be certainly hundreds of solutions of constructive interference points leading to a whole set of incident angles and frequencies that could represent solutions to the guided wave problem. To solve a guided wave problem, we could consider a governing wave equation in solid media, Navier's equations subjected to specific boundary conditions, for example, in a plate with stress-free boundary conditions. Utilizing the theory of elasticity in wave mechanics along with Navier's equation, subsequent strain-displacement equations, and a constitutive equation such as the generalized Hooke's law, with assumed harmonic solutions in satisfying the boundary conditions, one could come up with all of the constructive interference points leading to the dispersion curves for the structure. These constructive interference points can be plotted to produce a wave velocity dispersion curve of phase velocity versus frequency. The relationship between incident angle and phase velocity is simply expressed by Snell's law, so incident angle or phase velocity could be plotted against frequency. As a consequence, each natural waveguide, plate, tube, and so forth has its own unique phase velocity dispersion curve.

An interesting turn of events now takes place. Virtually hundreds of solutions to an inspection problem are available from the phase velocity dispersion curves. How do we pick the best solution? Often, the solution is built into a specific test instrument for a particular application. Every point on a dispersion curve has a different particle velocity vibration characteristic across the thickness of the structure. As an example, maximum in-plane vibration could occur on the surface of a structure at a particular phase velocity and frequency value. If this point were selected as a solution and the structure were placed under water, the water would have almost no influence on the wave propagation characteristics as energy leakage into the fluid would not take place. Let's consider one additional example to get a conceptual understanding of the potential of guided wave inspection. Suppose we wanted to examine a weak interface in a multilayer structure; we would have to search the phase velocity dispersion curve space to seek out a special wave structure across a thickness of a multilayer structure in such a way that we would obtain, for example, a maximum shear stress at the interface under consideration. This phase velocity and frequency value would then have excellent sensitivity to the weak interface situation at the particular layer being designated. Each guided wave problem could be approached in a similar fashion in searching for a particular variable with appropriate sensitivity in a certain problem. Upon selection of a particular point in the phase velocity dispersion curve space, it becomes possible to design an ultrasonic transducer that excites that particular point. Precise excitation is often difficult, however, because of the existence of a phase velocity spectrum and a frequency spectrum. These are concerns, though, for another day. The sensor design could be an angle beam transducer with an excitation line at a constant phase velocity value on the dispersion curve. As frequency is swept across the frequency axis, the specific modes and frequencies will be generated. An alternative probe design could be a comb transducer or an inter-digital design where the excitation line goes from the origin of the phase velocity dispersion curve at an angle of wavelength as the excitation line crosses many modes in the phase velocity dispersion curve space. Again, as the frequency is swept along the frequency axis, the modes crossed by the excitation lines will be generated. The comb spacing will be wavelength, which is the actual slope of the excitation line in the phase velocity dispersion curve space. Note that it becomes possible to move freely over the entire phase velocity dispersion curve space by changing angle in the horizontal excitation line approach or by changing element spacing in the sloped line of slope wavelength from the origin in the phase velocity dispersion curve space.

Table 1.4. Natural waveguides

- Plates (aircraft skin)
- Rods (cylindrical, square, rail, etc.)
- Hollow cylinder (pipes, tubing)
- Multilayer structures
- An interface
- Layer or multiple layers on a half-space

Let's now consider the long time solution to a wave propagation problem simply to add to our understanding of a wave propagation problem versus a vibrations problem. In the bulk wave case, because waves are traveling in infinite space, there is no vibration aspect of the problem to be considered because there are no wave reflection and transmission factors.

When you think about it, many structures are really natural waveguides provided the wavelengths are large enough with respect to some of the key dimensions in the waveguide. If the wavelengths are very small, then bulk wave propagation can be considered. Development of ultrasonic guided wave technology moved slowly until recently because of a lack of understanding and insufficient computational power. One very interesting major difference of many associated with guided waves is that many different wave velocity values can be obtained as a function of frequency, whereas for most practical bulk wave propagation purposes the wave velocity is independent of frequency. In fact, tables of wave velocities are available from most manufacturers of ultrasonic equipment that are applicable to bulk wave propagation in materials, showing just a single wave velocity value for longitudinal waves and one additional value for shear waves. See Table 1.4.

1.4 The Difference between Structural Health Monitoring (SHM) and Nondestructive Testing (NDT)

It seems worthwhile at this point to introduce the strategies of SHM and NDT. NDT is difficult as you carry equipment to a site and are asked to find defects in often very complex structures. For SHM, on the other hand, a baseline is available that can often handle very complex structures. See Table 1.5 for a summary.

1.5 Text Preview

A brief outline and discussion of the material included in this text is presented next. We begin with a discussion of dispersion principles in Chapter 2. Note that in guided wave propagation, basic dispersion concepts are encountered whenever wave velocity becomes a function of frequency or angle of propagation. The phase and group velocities change significantly as a result of the studying of the boundaries of the waveguide, which leads to many possible modes of wave propagation. Criteria must be established for selecting a particular mode and frequency for solving a particular problem. The basic formulas from physics and basic wave mechanics are outlined in Chapter 2.

Chapter 3 outlines wave propagation principles in unbounded isotropic and anisotropic media. Even though this is a subject in bulk wave propagation at this

Table 1.5. The difference between SHM and NDT

NDT	SHM
• Offline evaluation	• Online evaluation
• Time-based maintenance	• Condition-based maintenance
• Find existing damage	• Determine fitness for service and remaining useful time
• More cost and labor	• Less cost and labor
• Baseline not available	• Baseline required
	• Environmental data compensation methods required

point, the concepts will be extended to guided wave analysis in later chapters. The classic Christoffel equations are reviewed in detail to show the steps involved for studying wave propagation in anisotropic media. The wave velocity is no longer independent of angle, as it is in an isotropic material and, in fact, often changes quite drastically with angle. As a result, the interference phenomena as the wave propagates in a waveguide change drastically, affecting the group velocity of the waves in different directions, as well as producing skew angle effects that occur as the wave propagates through the material. Detailed mathematical treatment and sample problems are discussed.

Another subject directed toward bulk wave propagation that becomes critical in guided wave analysis is presented in Chapter 4, with emphasis on reflection and refraction factor analysis as waves encounter an interface. The initial emphasis is on isotropic media, followed by Snell's law and mode conversion. A variety of different models and boundary conditions are used to tackle the various wave propagation problems in different structures and in anisotropic materials, a topic that will be discussed in later chapters while still utilizing some of the concepts presented here.

Chapter 5 treats the more general problem of reflection and refraction analysis for oblique incidence including the study of slowness profiles and critical angle analysis. The energy partitioning into the different modes is treated here. Again, this is a topic presented from a bulk wave ultrasonic wave propagation point of view, the concepts of which are extended to guided wave analysis in later chapters and also considered in current research activity.

Chapter 6 covers the classic problem of wave propagation in a plate, where the Rayleigh–Lamb wave propagation problem is covered in detail. Some of the most significant aspects of guided wave analysis are covered in this chapter, which illustrates the development of the dispersion curves associated with phase velocity and group velocity, along with wave structure computation to show how the choice of mode and frequency changes the problem being investigated quite significantly in having different sensitivity, resolution, and penetration power for certain defects in different structures.

Chapter 7 covers various aspects of surface and subsurface waves in detail. These waves treat a wave traveling in a half-space. Surface waves of course have been used for years, and have often been covered in the more traditional books on ultrasonics. They are covered here as a guided wave problem because of the boundary involved and the similar treatment of guided waves in general.

In Chapter 8, an introduction to and pertinent details of finite element analysis are presented to help us move forward with wave propagation studies in guided waves. The finite element analysis tool is a significantly powerful one that allows us to do many interesting things in guided wave analysis. The computational efficiency available today makes this a unique and extremely useful tool for advancing the state of the art in ultrasonic guided wave analysis. Quite often, when combined with analytical tools to get us started in what we call a hybrid analytical FEM approach to the problem, the analytical work allows us to come up with the phase and group velocity dispersion curves and wave structures from which mode and frequency selection can take place, which leads to an actuator design and eventually a problem and systems solutions. The finite element analysis can take over from the analytical studies because the actuator design serves as the boundary conditions used in the finite element problem. We can then evaluate our choice of mode and frequency to solve a particular problem by looking at the wave propagation in the structure and the potential response from certain defects. All sorts of anomalies encountered in field application can be modeled with FEM assisting greatly in a final system design.

In Chapter 9, a fairly new concept is presented associated with a semi-analytical finite element (SAFE) method that allows us to calculate the wave structures and dispersion curves for a particular structure. It also provides an alternative to calculating dispersion curves for almost any waveguide in going beyond the global matrix technique presented in Chapter 6 for the traditional problem of waves in a plate. The SAFE technique is a very powerful computational process that can assist us greatly in studying and understanding unusually shaped waveguides like a rail or a multilayered anisotropic structure.

Chapter 10 describes the subject of waves in hollow cylinders. The emphasis here is on tubes and pipelines. This probably treats one of today's most popular practical applications in using guided waves in pipeline inspection. A hollow cylinder or tubular structure is a superb waveguide as the energy wraps around on itself and hence the propagation distances can be very large. The basic theoretical concepts presented in this chapter are classic in allowing us to study all of the different axisymmetric longitudinal and torsional modes along with the flexural modes for each that can propagate in a hollow cylinder.

Chapter 11 deals with circumferential guided waves, an important subject dealing with waves over a curved surface. The dispersion curves and wave structures are calculated with a description of a sample problem in advising us how to come up with mode and frequency choice for solving a particular problem, of optimizing coating detection on a pipe.

Chapter 12 covers guided waves in layered systems, which include multilayer structures along with interface waves and a layer on a half-space problem. Classic problems like Stoneley wave and Love wave propagation are discussed in this chapter. The computational methods are presented along with a description of the practical aspects of wave propagation in these layered systems.

Chapter 13 examines source influence on guided wave excitation in detail. This very important subject illustrates what happens when a finite source is used to load a waveguide compared to the theoretically popular analytical approach considering a plane infinite wave excitation. In this case, beyond the frequency spectrum that is considered for a pulse traveling in a structure, there is also a phase velocity spectrum, often with side lobes that can occur. The computational procedures associated with excitation and the phase velocity spectrums are covered. The work here allows us to efficiently get onto specific points on a dispersion curve for best possible sensitivity and penetration power in a particular waveguide. Note that, quite often, in guided wave analysis the signals appear noisy, but the noise is really associated with coherent guided wave propagation because of multiple mode wave propagation, and is not random in nature. This chapter outlines the ability to get onto a specific portion of a dispersion curve.

Chapter 14 tackles the subject of horizontal shear waves. This considers shear activation, but only in a platelike structure. It turns out this is one of the closed-form solution possibilities for calculating phase and group velocity in a waveguide, along with the wave structures and cutoff frequencies. Horizontal shear waves have not received much attention in past years because of experimental wave generation difficulties, but with so many new generation possibilities now realized by way of special shear-type transducers, including, for example, magnetostrictive or electromagnetic acoustic transducers (EMAT), the waves are becoming more popular and have very special applications in ice detection, in deicing, and in structures where water loading or accumulation is a problem in NDT and SHM.

Chapter 15 considers guided waves in anisotropic media. Dispersion curves become a function of direction. This is where the Christoffel equations allow us to look at wave-skewing influences in anisotropic media in certain anisotropic waveguides. Single-layer isotropic and multilayer isotropic structures are treated.

Chapter 16 discusses guided wave phased array focusing in piping. With the onslaught of phased array technology, where electronics are used for scanning and beam steering, tremendous interest is being generated on this subject. So beyond the bulk phased array analysis that relies primarily on simple line of sight computation from the source to the focal point in question, a technique is presented to allow focusing to occur in a pipe. The problem here is more complex than in a simple infinite media or even in a plate. In a plate, of course, you have to deal with the specific modes that you would like to use to produce focusing and appropriate sensitivity, for example, as is the case with piping. But in this case, in piping, a convolution concept is introduced to look at the summation of all the waves that turn around on themselves that cause the superposition and constructive interference phenomena to occur at the focal point. The details are presented on how to calculate the time delays associated with the particular elements around the circumference of the pipe, along with sample results on controlling the focused beam as it travels in the pipe. An understanding of flexural modes is critical to accomplish this focusing.

Chapter 17 consists of a discussion of guided waves in viscoelastic media. The overall viscoelastic approach will be introduced for bulk waves and for waveguides. The emphasis will be placed here on looking at a viscoelastic composite material along with a viscoelastic coating on a structure.

Chapter 18 presents a fairly new subject associated with ultrasonic vibration. The ultrasonic vibration approach goes beyond traditional vibrations studies utilizing vibrations under 20 kHz, but many of the concepts associated with the resonance and modal vibration character of the structure are similar. It turns out, though, that with ultrasonic vibrations the mode and modal pattern depend strongly on the loading function that is taken from transient ultrasonic guided wave analysis, beyond which, after multiple reflections occur, an ultrasonic vibration problem is introduced.