Structural Health Monitoring (SHM) systems for future structures and vehicles would involve a process of damage identification and prediction of certain quantities of interest that concerns the function and safety. This process provides SHM systems the ability to not only save cost but also enhance the service life, safety and reliability of the structures and vehicles. Integrated SHM system (ISHM) is an advancement of SHM system that has additional capability of predicting the component life/failure. ISHM system development involves detailed understanding of diagnostic waves, hardware components, signal processing paradigms and intelligent use of algorithms. Diagnostic waves like the guided waves are the elastic waves that propagate in a direction defined by the material boundaries. These waves have the capability of traveling large distance probing the entire thickness in plates/shells. Thus, they are widely used by SHM systems in monitoring the plate structures. Piezoelectric transducers are often employed in the interrogation using guided waves. Most SHM systems employing guided waves are designed for specific structures. Current paradigms of SHM systems are unable to enable the transition from simple or ideal structures to realistic and complicated structures. This is due to the challenges at the fundamental level involving transducer, wave propagation and phenomena of guided wave scattering with damages to evaluate the possible solutions through mathematical modeling and signal analysis capability required by ISHM systems.

This thesis aims to develop understanding of these problems at a fundamental level. Complex system level understanding is still needed which is left out as open problem.

A primary requirement in designing SHM system is the proper understanding of wave characteristics such as number of modes, wavelength and dispersiveness. Although three-dimensional elasticity solution and simplified theories are available to understand them, their applicability in SHM problem requires a much more detailed look. Effort toward this direction has led to the development of simpler models. However, mathematical models are not available for understanding the wave characteristics in complex structures involving stiffeners and adhesive joints. This problem is addressed in this thesis. There is a fair amount of understanding developed regarding transducer characteristics. This is accomplished by analytical and finite element models of transducers in the past. However, simplified transducer model that are computationally fast to suit SHM system requirements needs to be developed. The development of such model is presented in this thesis. Apart from modeling the transducers and wave scattering due to damage, signal correlation and calibration are needed for practical implementation in SHM. Characterization studies reported in published literature are limited to quasi-static and low frequencies applications. However, SHM of aerospace structures employ guided waves typically in the frequency range of 100-500 kHz. Methods to characterize the transducers at this frequency range needs to be developed, which is addressed in this thesis.

Another major requirement of SHM system is the design and development of sensor-actuator network and appropriate algorithm. Techniques developed earlier involving transducer arrays in this regard have limitation due to complexity of geometry and signal interpretation that needs to be addressed. The network with suitable algorithm should ideally monitor large area including the critical areas of failure with minimum number of transducers. ISHM systems further require some capability to estimate the useful life of the damaged structure in order to take suitable decisions. Efficient techniques to achieve these are not developed. Overall, there is a need to improve highly interdisciplinary areas involving mathematical modeling, transducer design, fabrication and characterization, damage detection and monitoring strategies. In this thesis, various novel techniques to combine mathematical model with experimental signals to enhance the damage detection capability are presented.

In this thesis, developments in the three main aspects of SHM systems are focused upon. They are (1) development of mathematical models of sensors/actuators, wave propagation and scattering due to damage (2) characterization and calibration of transducers and (3) development of technique to monitor wide variety of damages within the scope of ultrasonic guided wave based SHM. The thesis comprises of ten chapters. First chapter is devoted to the background and motivation for the problem addressed in this thesis. In second chapter, brief overview of available mathematical models and conventional damage monitoring strategy is presented. The significant contributions reported in the subsequent chapters in this thesis are outlined below

In chapter 3, a reduced-order model of guided wave propagation in thick structures with reduced-order approximation of higher-order elasto-dynamic field is formulated. The surface normal and shear tractions of the thick structure are satisfied in a closed form. The time-frequency Fourier spectral finite element is developed and is validated using detailed and computationally intensive finite element simulations. Natural frequencies obtained from the developed spectral finite element and the detailed finite element simulations are compared. Transient response due to broad frequency band and narrow frequency band excitations given in the form of surface tractions are validated by comparing with the detailed finite element simulations. Using the developed spectral finite element, wave scattering from a free edge and a notch are simulated and validated by comparing with the detailed finite element simulations.

In chapter 4, two-dimensional plane wave and flexural wave scattering models for more complicated features such as stiffener with delamination and stiffener with bolt failures in a stiffened panel are derived using ultrasonic ray tracing based approach combined with wave-field representation. Dispersion relations are reformulated for the base plate where it is bolted with the stiffener. Surface conditions due to contact stiffness and contact damping are modeled by introducing springs and dampers. Scattering coefficients for the bonded and bolted stiffeners are derived. The scattering coefficients are evaluated for various different frequencies. Results are compared for different stiffener parameters.

In chapter 5, a simplified analytical model of a piezoelectric actuator with uniform electrodes is modeled. The problem is to determine the launched guided wave characteristics in the structure. The analytical model is derived considering two-dimensional elasticity based approach and Airy's stress function. The actuator model is used to specify the displacement boundary conditions in the detailed finite element model. The radiated wave patterns in a plate due to actuation from transducers of different shapes are obtained and validated with experiments. Phased array actuators are modeled in the detailed finite element model using the displacements estimated from the actuator model.

The radiated wave pattern from the detailed finite element simulations are validated with experiments.

Chapter 6 is devoted to the design and characterization of transducers for ultrasonic guided wave applications. The characterization techniques involve the estimation of voltage response for the induced strain by the guided wave at various different frequencies. First, a novel removable bonding technique and a calibration technique are demonstrated and related advantages are discussed. Performance of the piezoelectric thin film under quasi-static, dynamic and transient impact loadings are analyzed first. Next, a guided wave technique is developed to characterize piezoelectric thin film sensors and actuators at ultrasonic frequencies. The transducers with inter digital electrodes are characterized for frequency tuning and directional sensitivity. This characterization study enables in the selection of optimal frequency bands for interrogation. Further, the characterization of transducers with thermal degradation is presented.

In chapter 7, a novel guided wave technique to calibrate the thin film sensors for ultrasonic applications is presented. Calibration procedure involves the estimation of the piezoelectric coefficient at ultrasonic range of frequencies. Calibration is done by the measurement of voltage generated across thin films when guided waves are induced on them. With the proposed technique, piezoelectric coefficient can be estimated accurately at any frequency of the propagating wave. Similarly, the measurement of piezoelectric coefficient of thin films with inter digital electrodes is presented. The estimation of piezoelectric coefficient at various different directions using laser Doppler vibrometer is presented. Lastly, the degradation of piezoelectric coefficient is studied for increasing thermal fatigue.

In chapter 8, toward SHM methodology development, a guided wave based technique to detect and monitor cracks in a structure is presented. To establish the methodology, a detailed study is carried out on the effect of crack and specimen size on the guided wave propagation characteristics. Using the wave characteristics, an analytical way of modeling Lamb wave propagation in the specimen with plastic zone is proposed. The feasibility to determine plastic zone and fatigue crack propagation with integrated piezoelectric transducers is demonstrated experimentally and the results are verified analytically. A method is further established to detect damage at initial stage and crack-tip plastic zone size along with crack length for a given stress amplitude or vice-versa. An approach to estimate fatigue life from the transducer signals is also proposed.

In chapter 9, a compact circular array of sensor-actuator network and an algorithm is presented to monitor large plate structures. A method based on the wavelet transforms of transducer signals is established to localize and estimate the severity of damages. Experiments are conducted to demonstrate the capability of the circular array based method in the localization and quantification of various types of damages like debonding of stiffeners, failure of bolted joints, corrosion and hole-enlargement. A damage index is then computed from wavelet time-frequency map that indicates the severity of damage.

Chapter 10 ends with the concluding remarks on the work done with simultaneous discussion on the future scope.

The work reported in this thesis is interdisciplinary in nature and it aims to combine the modeling and simulation techniques with realistic data in SHM to impart higher confidence levels in the prediction of damages and its prognosis. The work also aims in incorporating various mathematical models of wave propagation and ray tracing based algorithm to optimize the detection scheme employed in SHM. The future direction based on this study could be aimed at developing intelligent SHM systems with high confidence levels so that statistical machine learning would be possible to deal with complex real-world SHM problems.