Adaptive Structures - An Overview

Stefan Hurlebaus*, Lothar Gaul**
*Department of Civil Engineering, Texas A&M University, College Station, TX, 77843-3136, USA
**Institute A of Mechanics, University of Stuttgart, Pfaffenwaldring 9, 70550 Stuttgart, Germany

ABSTRACT

This paper gives an overview of research in the area of adaptive structures. A general description of smart material systems is given. Particular focus is given to the following fields of application: semi-passive concepts, energy harvesting, semi-active concepts, active vibration control, and active structural acoustic control. The use of adaptive structures in structural health monitoring applications and for shape adaptation is also considered.

1 Introduction

Passive measures for reducing noise and vibration or for ensuring optimal structural performance have reached certain limits. For this reason, adaptive structures are becoming increasingly important. As funds have become available to pursue research in this area, terminologies have been introduced to define the field of study. The terms adaptive structures, intelligent structures, smart structures, active structures, adaptronics, and structronics all refer to the same field of study. All these terms refer to the integration of actuators, sensors in structural components, and the usage of some kind of control unit or enhanced signal processing with a material or structural component (Fig. 1). The goal of this integration is the creation of a material system having enhanced structural performance, but without adding too much mass or consuming too much power. Due to its nature, the field of adaptive structures depends on interdisciplinary research since numerous disciplines (e.g. material science, applied mechanics, control theory, etc.) are involved in the design of a adaptive structure system solution.

The materials used in adaptive structures often have interesting and unusual properties. Electrostrictive materials, magnetostrictive materials, shape memory alloys, magnetorheological fluids, polymer gels, and piezoelectric materials, for example, can all be used to design and develop structures that can be called adaptive. However, the materials themselves are not adaptive. "Adaptivity" refers to the exploitation of material properties to better serve a design function than would be possible through conventional structural design.
2 Semi-passive Damping

Piezoelectrics have the ability to efficiently transform mechanical energy to electrical energy and vice versa. It is this dual transformation ability which makes them useful as structural dampers. Hagood and von Flotow [1] presented a passive damping mechanism for structural systems in which piezoelectric materials are bonded to the structure of interest. Their work is based on the papers of Forward [2] and Edwards and Miyakawa [3] who first presented this type of passive piezoelectric damping for applications on resonant structures. According to the “shunted piezoelectric” approach, the electrodes of the piezoelectric are shunted with an electrical impedance. Electricity generated in the piezoelectric as the host structure deforms, is dissipated as heat in the resistive part of the shunted electrical network. The shunted piezoelectric principle is depicted in Fig. 2. As shown, the piezoceramics are connected to the resistors $R_s$.

Hagood and von Flotow [1] established the analytical foundation for general systems with shunted piezoelectrics. Their work characterizes the electromechanical interactions between a structure and the attached piezo network, and offers some experimental verification. Davis and Lesieutre [4] extends previous studies by using the modal strain energy approach to predict the structural damping produced by a network of resistively shunted piezoceramic elements. Using this approach, the amount of added damping per mode caused by an individual ceramic element can be computed. It was also demonstrated that increased damping could be achieved in several modes simultaneously via proper placement of the piezoceramics. Fig. 3 demonstrates the effectiveness of shunted piezoelectricity for three different resistance values. For the case in which the PZT element is shunted using an optimal value, the acceleration is decreased by 5.9 dB [5].

Fein and Gaul [6] further developed the shunted piezoelectric approach by replacing the shunt resistors with digital potentiometers and adding sensors to the structure. Based on information about excitation frequency, a feedback controller was used to switch the resistance of the digital potentiometers. This technique is more flexible than previous techniques since optimal damping of different modes is possible.

A structural vibration control concept using piezoelectric materials shunted with real-time adaptable electrical networks has also been investigated. Instead of using variable resistance only, they implemented variable resistance and inductance in an external RL circuit as control inputs. They created an energy-based parametric control scheme to reduce the total system energy while minimizing the energy flowing into the main structure. Furthermore, they proved stability of the closed loop system and examined the performance of the control method on an instrumented beam. The experiment demonstrated effective suppression of the total system energy and vibration amplitudes. The shunted piezoelectric technique has been applied to improve the performance of sports equipment, including tennis rackets, skis, and snowboards. In the case of tennis rackets, piezoelectric fibers built into the frame have been used to enhance the structural damping. This results in a preciser serve and a decreased risk for injuries such as tendonitis.

3 Energy Harvesting

Energy harvesting research has been driven by the need for remote electrical power supplies for applications ranging from structural health monitoring to walking-powered electronics. Portable systems which make use of power harvesting techniques do not have to depend on traditional methods for providing power, such as the battery, which has a limited
operating life. The general idea underlying energy harvesting research is the extraction of electrical energy from the operating environment. Potential sources of energy include solar, thermal, mechanical, chemical, or some combination thereof. For example, piezoelectric materials can be used to transform ambient motion into electrical energy that may be stored and used to power other devices. Recent studies, experiments, and patents indicate the feasibility of using piezoelectric devices as power sources. Umeda et al. [7] use a free falling ball to impact a plate which has a PZT wafer attached to its underside. An equivalent circuit model was developed to predict the electric energy which is generated by the mechanical impact. They also investigated the energy storage characteristics for the electrical system composed of the PZT, a bridge rectifier, and a capacitor. Goldfarb et al. [8] presented a linearized model of a PZT stack and analyzed its efficiency as a power generation device. It was shown that the maximum efficiency occurs in a low frequency region which is much lower than the structural resonance of the stack. It was also found that the efficiency depends on the amplitude of the input force, a fact which is attributable to hysteresis in the piezoelectric material. Clark and Ramsey [9] investigate the performance of piezoelectric generators whose force inputs are parallel and transverse to the poling direction. Their work showed that the $d_{33}$ mode has a mechanical advantage in converting applied pressure to working stress for power generation. They concluded that a 1 cm$^2$ piezoceramic wafer can power a MEMS device in the microwatt range. Sodano et al. [10], consider methods for storing the electrical energy generated by piezoelectric devices. Their research is motivated by the fact that the power generated by PZT is far smaller than that required for the normal operation of most electronics in real field applications. Additionally, the time required by a PZT generator to charge a power storage device is too long for certain applications. In their study, the energy produced by a PZT generator was stored in two different ways: using a capacitor, as in previous studies, or using a nickel metal hydride battery. The battery charging method was found not only to increase the level of output power, but it also allowed electrical energy to be stored for a longer period of time.

Lesieutre et al. [11] describe an approach in which electrical energy is harvested from a mechanically loaded piezoelectric structure, and simultaneously, structural damping is introduced. The harvesting system consists of a full bridge rectifier with a filter capacitor, a switching DC-DC step-down converter, and a battery. This system has two modes of operation: at low excitation levels, the rectifier charges the battery directly, and at higher excitation levels, the DC-DC converter is placed between the rectifier and the battery. At higher levels of excitation, the DC-DC converter delivers more than four times the power to storage as compared to directly charging the battery from the rectifier. Under harmonic forcing conditions, the effective modal loss factor depends on the piezoelectric system coupling coefficient and the ratio of the operating rectifier output voltage to its maximum open circuit value. The loss factor is comparable to that achieved using resistive shunting (see Section 2), but it does not have the corresponding strong frequency dependence.

4 Semi-active Concepts

The concept of semi-active damping was formally proposed by Karnopp et al. [12]. The concept involves the use of control theory to augment the damping properties of a passive element in real-time. Sometimes referred to as active-passive damping, the technique offers considerable advantages in performance over passive damping elements, and with only a slight increase in system cost/complexity. On the other hand, semi-active damping cannot deliver the level of performance of a fully active system. However, semi-active damping requires much less energy than active control (since one is only changing a passive damping level), and it can usually be implemented with less weight and cost. As energy can only be dissipated, spillover phenomena are avoided.

There are several means of realizing semi-active damping, see for example those suggested by Karnopp [13]. The most common implementation is the viscous dashpot with a variable (controlled) orifice. This technique has been explored extensively in the field of semi-active automotive suspension. Moreover, the use of semi-active damping in flexible structure control was first studied by Karnopp and Allen [14] and later also by Davis et al. [15]. Another way of achieving semi-active damping is through the use of electro-rheological fluids whose viscosity can be controlled through application of an electric field. This technology has been applied in semi-active suspension and flexible structure control [16, 17].

The concept of semi-active friction damping has been studied for use in flexible structure control and semi-active automotive suspension systems. The concept uses control theory to vary the normal force, and thus the friction force, in response to sensory feedback. Semi-active friction damping was first considered by Anderson and Ferri [18]. The concept was also mentioned by Karnopp [13] as one of several ways of developing semi-active damping forces. Karnopp’s idea was based on an antilock braking system (ABS). In the case of ABS braking, it is important to avoid sticking surfaces at a frictional interface, and in the case of semi-active damping, it is important to dissipate energy as quickly as possible. While the two objectives are related, especially since a sticking interface cannot dissipate energy, the control systems that maximize these two objectives are different.

About 90 percent of the damping in structures occurs in the joints. It is most logical, therefore, to actively influence the damping in a structure at the joints. This is achieved by controlling the joint clamping forces and hence the relative interfacial slip.

In 2000, Gaul [19] patented a semi-active friction joint (Fig. 4). Application of a voltage to the piezoelectric stack results
in controllable normal force at the friction interface. For modeling the nonlinear behavior in the friction joint, one possibility is the so-called LuGre model which was reviewed among others in [20]. This model is capable of predicting relevant friction phenomena, such as presliding displacement, stick-slip motion, and the Striebeck effect. The model describes the friction interface as a contact between bristles (Fig. 5). The internal state variable \(\varphi\) represents the average deflection of the bristles, and it is governed by a first order differential equation.

This model was designed to reproduce all observed friction phenomena over a wide range of operating conditions. It is given by

\[
F_t = (\sigma_0 \varphi + \sigma_1 \dot{\varphi} + \sigma_2 v) F_N = \mu(\varphi, \dot{\varphi}, v) F_N \tag{1}
\]

\[
\dot{\varphi} = v - \sigma_0 \frac{|v|}{F_c + F_\Delta} \exp\left(-\frac{(v - v_s)}{2}\right) \varphi, \quad \varphi(0) = \varphi_0 \tag{2}
\]

where \(F_t\) is the friction force, \(v\) is the relative sliding velocity at the friction interface, and \(F_N\) is the normal force. The internal friction state \(\varphi\) represents the average deflection of the bristles which simulate the rough surface asperity contact (Fig. 5). The parameter \(F_c\) is the Coulomb friction level, and the sum \(F_c + F_\Delta\) corresponds to the stiction force. The so-called Striebeck velocity is \(v_s\) [21]. The stiffness of the bristles is described by \(\sigma_0\), and the two parameters \(\sigma_1, \sigma_2\) describe the dynamic dependence of friction on velocity. The function \(\mu\), which is defined in (1), can be interpreted as a state-dependent friction coefficient.

Gaul and Nitsche [22, 23], presented a nonlinear feedback design method based on Lyapunov techniques for linear mechanical systems with nonlinear semi-active joint connections. The feedback maximizes the energy dissipation in an instantaneous and local sense. Since the control law requires the knowledge of an internal variable from the LuGre friction model, they considered the design of appropriate observers. Specifically, they considered an operating point observer and a Kalman filter. Moreover, they presented an effective disturbance estimation method for improving estimation accuracy when considerable disturbances are present. The proposed feedback and observer design methods are suitable for use with a computer, and the method is applied to a flexible two-beam system containing a semi-active joint.

Another approach for controlling a semi-active friction joint employs LQR theory [24]. The cost function is an infinite time integral of a weighted sum of system energy and control effort. Ferri and co-workers [24] have compared controllers in which the input is constrained during and after optimization. In the latter case, the controller may call for negative normal forces. An ad hoc modification of this controller which requires \(F_N \geq 0\), where \(F_N\) is the normal force in the friction interface, is called clipped LQR control. Both the optimal and clipped controllers are shown by simulation to perform favorably in comparison to a control law in which \(F_N = k|v|\), where \(v\) is the relative sliding velocity at the damper, and \(k > 0\) is a constant. The velocity proportional controller does however prevent the damper from sticking and thereby ensures energy dissipation (a sticking damper does not dissipate energy).

Gaul et al. [25, 26] suggested a method for optimal placement of semi-active joints for vibration suppression of large lightweight structures. At optimal locations, they replaced conventional rigid connections of a large truss structure by semi-active friction joints. They implemented two different concepts for the control of the normal forces in the friction interfaces. In the first approach, each semi-active joint has its own local feedback controller (SISO control), whereas the second concept uses a global, clipped-optimal controller (cLQG control). Simulation results for a 10-bay truss structure demonstrate the potential of the proposed semi-active concept. A model of the truss structure is shown in Fig. 6. The response of the system for three control strategies are compared in Fig. 7. In the figure, LQG denotes fully active control. The fully active system performs only slightly better than the semi-active cLQG controller. However, the semi-active approach requires only a fraction of the control power required by the active control approach.
Figure 6: Model of the orbital truss structure (SAJ=semi-active joint).

Figure 7: Deflection of the mast tip in y-direction.

5 Active Vibration Control

One of the earliest studies of active vibration control was completed by Swigert and Forward [27]. They conducted a theoretical and experimental study that involved electronic dampers. In that study, a system of electromechanical transducers made from lead zirconate titanate (PZT) were implemented to control the mechanical vibration of an end-supported mast. The output signals from the sensors were amplified and appropriately shifted in time to provide control inputs for actuators positioned symmetrically on the surface of the mast. Bailey and Hubbard [28] developed the first smart structure using polyvinylidene fluoride (PVDF). The PVDF was used as an active element for active vibration control of a cantilever beam. By implementing both constant gain and constant amplitude controllers, they experimentally demonstrated that the PVDF actuator could significantly increase the measured loss factor (i.e. the system damping) when the structure was subjected to an initial displacement. In a later study, Fuller et al. [29] described a systematic approach for active control of vibration. They summarized the principles underlying active vibration control and its practical applications by combining material from vibrations, mechanics, signal processing, and control theory. Today, two main approaches exist in vibration control: feedforward and feedback control.

The feedforward approach makes use of adaptive filtering methods such as x-filtered LMS algorithms [29]. The main advantages of these control systems are that no model of the structure is needed and that they can be employed at high frequencies. The major drawback of the feedforward method is that a reference signal is required, which is somehow correlated with the disturbance.

Feedback methods can further be divided into two parts: active damping and model-based control techniques. In the active damping approach, sensors and actuators are located at the same position. Feedback control is guaranteed to be stable if ideal sensors and actuators are used. The active damping method has the advantage that it does not require a model of the structure. However, it has the major drawback that it works only near structural resonances.

There exists a large variety of model-based feedback methods, including LQR, H\textsuperscript{∞}, and modal feedback methods. Modal feedback control has been successfully implemented for the reduction of plate vibrations [30]. The modal parameters for plates can be determined using analytical solutions to the governing plate equation or by using finite element (FE) calculations. For structures with more complex geometry, such as a car body, an analytical solution does not exist, and even a FE calculation is complicated and time intensive. As an alternative, Stöbener and Gaul [31] used an experimental
modal analysis to extract modal parameters (eigenfrequencies, mode shapes) from measurements made on a car body. The sensors and actuators are laid out based on information about the experimental mode shapes. After the optimal actuator and sensor positions and dimensions were determined, the modal input and output matrices for a modal state-space controller were computed.

6 Active Noise Control / Active Structural-Acoustic Control

The concept of active noise control is not new. Leug [32, 33] received a patent for a system implementing active control of sound in a duct. The sound field is first detected using a microphone. The microphone signal is then used to produce a canceling wave which is emitted from a loudspeaker in the downstream duct. Superposition of the two waves results in destructive interference at a reference location. In 1953, Olson and May [34] developed a different active noise control system. In this system, sound is detected with a microphone, and the signal is fed through a controller to a loudspeaker located near the microphone. Good local sound reduction at the microphone over a range of frequencies from 20 to 300 Hz was demonstrated.

The classic studies by Leug and Olson illustrate two distinct control approaches used in active noise control. Leug’s approach is a feedforward approach, since a priori knowledge about the disturbance is obtained using an upstream microphone. Olson and May’s approach is a feedback approach since the detection microphone is located close to the active source.

The feedforward approach for active noise control was first formally introduced by Connover [35], who studied the active control of sound radiated from large electrical transformers. The noise radiated from large electrical transformers is dominated by sinusoidal tones which are even multiples of the line frequency and which can be correlated with the electrical line signal. Connover proposed that a reference signal, formed from the line signal, could be used as a control input rather than a detection microphone. The reference signal could then be passed through an electronic controller to the control loudspeakers. Connover also introduced the concept of an error sensor with which the radiated sound field from the transformer was monitored. The signal from the error sensor was used to adjust the controller so as to minimize the radiated sound.

Although the potential of active noise control had been demonstrated in these early studies, the practical implementation of multichannel systems only became feasible with advances in digital signal processors in the 1980’s. However, the noise control systems still relied on loudspeakers for actuation. The noise control concepts were successfully implemented in a wide variety of applications, including control of cabin noise in an aircraft [36] and control of road noise in cars [37]. It was later shown that actuators directly coupled to the structure in coupled structure-acoustic problems yield a higher noise reduction. This approach is termed active structural acoustic control (ASAC). Over the last several years, various control techniques have been established in the field of active noise control and active structural acoustic control: adaptive filter techniques, robust control techniques, and modal control techniques.

7 Active Vibration Isolation

Isolating a piece of delicate equipment from the vibration of a base structure is of practical importance in a number of engineering fields. Passive anti-vibration mounts are widely used to support the equipment and to protect it from severe base vibration. Although conventional passive mounts offer good isolation at high frequencies, they suffer from vibration amplification at the mounted resonance frequency. Generally, the best isolation performance is achieved by using an active system in combination with a passive mount, whereby the fundamental mounted resonance can be actively controlled without compromising the high frequency performance.

A good overview of active vibration isolation techniques can be found in [29]. Various control strategies are discussed, including feedforward and feedback concepts for systems under periodic as well as random vibrations.

Stöbener and Gaul [38] modeled a piezoelectric stack actuator with finite elements and investigated the response of a one degree of freedom vibration isolation system having such a stack actuator built in. To validate the FE formulation and to evaluate the performance of the vibration isolation system with the stack actuator, they designed and tested an experimental setup. They examined both feedforward control and feedback control techniques to enhance the isolation effect. Huang et al. [39] presented a theoretical and experimental investigation of an active vibration isolation system. In that study, decentralized velocity feedback control was employed, whereby each electrodynamic actuator is operated independently by feeding back the absolute equipment velocity at the same location. They obtained good control and robust stability both experimentally and theoretically for the multichannel control systems.

Preumont et al. [40] compared the force feedback and acceleration feedback implementation of a sky hook damper used to isolate a flexible structure from a disturbance source. They showed that the use of a force sensor always produces alternating poles and zeros in the open-loop transfer function between the force actuator and the force sensor, thus
guaranteeing stability of the closed loop. On the contrary, the acceleration feedback produces alternating poles and zeros only when the flexible structure is stiff compared to the isolation system.

Riebe and Ulbrich [41] presented the model of a parallel robot with six degrees of freedom for the use in real time computation of the inverse dynamic. They modeled the frictional behavior, and the parameters describing the friction model are identified and optimized. Furthermore, they presented a comparison between the measured and the simulated actuation forces.

Müller et al. [42] and Beadle et al. [43] investigate a four mount, six degree of freedom system for active vibration isolation and suppression. The system itself is based on a decentralized analog velocity feedback controller. Fig. 8 depicts the active vibration isolation system which was investigated. The governing equations of motion are obtained by using the balance of linear and angular momentum. The parameters necessary to describe the system’s behavior were experimentally determined by comparing measured transfer functions to those calculated using an updated model. Finally, two different active control strategies, specifically SISO (single input, single output) and MIMO (multiple input, multiple output) control schemes, are considered. The predicted transmissibility curves for the uncontrolled and MIMO-controlled vibration isolation system are depicted in Fig. 9. Transmissibility of the receiver isolation is defined here as the displacement amplitude ratio of the receiving upper surface of the vibration isolation system divided by the base structure source amplitude.

Fig. 8: Active vibration isolation system.  

Fig. 9: Simulated transmissibility curves for a passive and an active vibration isolation system.

8 Shape Adaptation

In avionics active shape control of aerodynamic surfaces is one of the most challenging issues. The aerodynamic forces acting on the aircraft depend directly on its geometry. Therefore, an ideal aircraft with full geometric adaptability would fly with extreme efficiency and reliability due to the extensive influence on aerodynamics. At the current state of the art, there is no design concept which allows extended adaptability in conjunction with the stringent lightweight requirements of aircraft design. Geometric adaptability is reduced to very few degrees of freedom. The unlimited shape adaption is realized through relative motion of rigid surfaces. In order to realize extensive geometrical adaptability new structural concepts are needed. In these concepts flexibility as well as actuator forces are no longer concentrated but distributed. This approach allows not only a lightweight-optimized design but also shows advantages concerning maintenance and reliability through structural redundancy.

As a typical example Fig. 10 illustrated the concept of active shape adaption of a wing structure. Typically, a wing structure consists of spares, spokes, a belt and the skin. Embedded piezoelectric material can replace some of these components (e.g. spokes) in order to directly induce the desired variation in geometry. Controlled extension of the now active spokes results in induced forces / moments. Consequently, the shape of the wing can be adapted, as demonstrated in Fig. 10. This can be done with an actuating system using shape memory alloys as shown in 10. The main aerodynamic advantages of shape adaption can be summarized as follows (Fig. 11): increase of aerodynamic efficiency, increase of the lifting force, and reduction of wing root bending moments. This results in a reduction of fuel consumption and structural weight. Furthermore, it improves maneuverability and operational flexibility.
9 Structural Health Monitoring

Nearly all in-service structures require some form of maintenance for monitoring their integrity and health condition. Appropriate maintenance prolongs the lifespan of a structure and can be used to prevent catastrophic failure. Current schedule-driven inspection and maintenance techniques can be time consuming, labor-intensive, and expensive. Structural Health Monitoring (SHM) on the other hand involves autonomous, in-service inspection of a structure. The first instances of structural health monitoring date back to the late 1970’s and early 1980’s. The aerospace community used SHM techniques in conjunction with the development of the space shuttle, and the civil engineering community applied SHM techniques to bridges. SHM consists of both passive and active sensing monitoring. Passive sensing monitoring is used to identify the location and force-time-history of external sources, such as impacts or acoustic emissions. Active sensing monitoring is used to localize and determine the magnitude of an existing damage. An extensive literature review of damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics is given by Doebling et al. [45].

9.1 Passive sensing diagnostics

For a passive sensing system, only sensors are installed on a structure. Sensor measurements are constantly taken in real-time while the structure is in service, and this data is compared with a set of reference (healthy) data. The sensor-based system estimates the condition of a structure based on the data comparison. The system requires either a data base, which has a history of prestored data, or a structural simulator which could generate the required reference data.

The input energy (external loads, temperature, pressure, etc.) to a structure is typically random and unknown. Passive sensing diagnostics are primarily used to determine unknown inputs from changes in sensor measurements [46]. Choi and Chang [47] suggested an impact load identification technique using piezoelectric sensors. They used a structural model and a response comparator for solving the inverse problem. The structural model characterizes the relation between the input load and the sensor output. The response comparator compares the measured sensor signals with the predicted model. An extension of this work is given in Tracy and Chang [48]. Their work is not only applied to beams, but also to composite plates. They developed a computer code which automatically identifies the impact load and location.

Only a few studies deal with dispersive waves in structures in conjunction with time-frequency analysis. Kishimoto et al. [49] developed a tool for determining the impact location of a beam using the wavelet transform (WT). Here, they restricted their analysis only to beams. Inoue et al. [50] experimentally validated the method suggested by Kishimoto et al. [49]. In that study, a simply supported beam was impacted with a sphere, and strain gauges were used to measure the strain caused by the flexural waves.
The experimental setup of a representative passive sensing diagnostic system is depicted in Fig. 12. The system consists of a freely suspended steel plate which is impacted by a pendulum. Four piezoelectric film sensors (PVDF) have been attached at the plate corners. The force-time-history at the impact location is directly measured using a laser vibrometer and is compared to the force-time-history reconstructed from the PVDF sensor signals. Specifically, the vibrometer is used to measure the velocity, and therefore the velocity-proportional impact force, at the impact site. A signal processing procedure using the wavelet transform was developed to reconstruct the force-time-history from the PVDF sensor signals [51, 52]. The maximum value of the wavelet transform was used to indicate the arrival time of the flexural wave at a given PVDF sensor. The impact location and the group velocity of the flexural waves were then determined from these arrival times. Based on the measured strain-history and impact location, the force-time-history at the impact location was reconstructed [53, 52]. Fig. 13 shows the force-time-history measured with the vibrometer and the force-time-history reconstructed from the PVDF sensor signals. The same localization procedure has also applied for acoustic emission signals [54].

9.2 Active sensing diagnostics

Another important topic in structural health monitoring is damage detection. Boller and Biemans [55] gave an overview of structural health monitoring on aircraft. They found that the size of a delamination must be at least 10 % of the component’s surface if it is to be reliably detected using vibration-based damage detection. Local or wave-propagation-based structural health monitoring is therefore advantageous since much smaller defects can be detected. Chang [46] concentrates his research on wave-propagation-based structural health monitoring. He developed Lamb-wave based techniques for impact localization/quantification and damage detection. Wilcox et al. examined the potential of specific Lamb modes for detection of discontinuities [56]. They considered large, thick plate structures (e.g. oil tanks) and thin plate structures (e.g. aircraft skins). They showed that the most suitable Lamb mode is strongly dependent on what the plate is in contact with. Furthermore, they showed that the properties of the system to be inspected determine which modes can be used, and that this then dictates the type of transducer required. Lemistre and Balageas [57] presented a robust method for damage detection based on diffracted Lamb wave analysis by a multiresolution wavelet transform.

Benz et al. [58] and Hurlebaus et al. [54] developed an automated, noncontact method for detecting discontinuities in plates. Laser ultrasonic techniques are used to generate and detect Lamb waves in a perfect plate and in a plate that contains a discontinuity. The geometry of the examined plate is depicted in Fig. 14. The measured signals are first transformed into the time-frequency domain using a short time Fourier transform (STFT) and subsequently into the group-velocity-frequency domain (see Fig. 15). The discontinuity is then located through the use of a correlation in the group-velocity-frequency domain. Figure 16 shows the correlations for a perfect plate and a notched plate. A ratio of the correlations is formed to enhance any features that are present in the notched plate correlation, but not in the perfect plate correlation. As shown in Figure 16, the correlation ratio has a single dominant peak at $\Delta d = 40$ mm ($\Delta d$ corresponds to the round trip distance between source and receiver), which is in excellent agreement with the actual location of the discontinuity [52].
Figure 14: Geometry of the notched plate with source and receiver locations (dimensions in mm).

Figure 15: Group-velocity-frequency representation for the notched plate.

Figure 16: Correlation curves for the perfect plate, notched plate, and a division of both curves.

Figure 17: Smart Layer (left) and real and identified defect in the aluminum plate (right)
A further SHM technique involves the use of a smart layer for damage detection. The smart layer approach is particular useful for monitoring the so-called 'hot spots' of a highly loaded structure. The smart layer developed by Hurlebaus et al. \cite{59, 5} contains an embedded network of distributed piezoelectric polymers. The smart layer was used to identify an 'artificial' damage in an aluminum plate (150 x 150 x 15 mm$^3$). The artificial defect is created by milling out some bottom sections at the backside of the aluminum plate. The depth of the milled section is about 2 mm. The boundary of the milled section is shown in Fig. 17 by the solid lines. On top of the aluminum plate, a smart layer is attached using couplant material. The smart layer is shown in Fig. 17. The electrical connections were obtained using printed circuit techniques. The dark square regions mark a 10 x 10 array of PVDF transducers. The side length of each PVDF element is 10 mm, and the distance between sensors is 2 mm. The transducers are used both as senders and receivers. Fig. 17 shows a C-scan of the aluminium plate. The identified defect is much larger than the actual defect. However, this is a consequence of the size and quantity of PVDF transducers which are used. If one would use a large array of smaller PVDF transducers, the resolution of the identified defect would be finer and smoother.

10 Conclusions

This paper addresses several fields of application of adaptive structures. First, semi-passive concepts used to enhance the damping behavior of structures were summarized. Then energy harvesting technologies are discussed, and their combination with the shunted piezoelectric concept is highlighted. Semi-active concepts are also considered, particularly in the context of control of large lightweight space structures. Next, active concepts are discussed. In addition to active vibration control and active noise control, this paper deals also with the field of active vibration isolation and suppression. Finally, the implementation of adaptive structure technologies for in-service monitoring is addressed. Three concepts of structural health monitoring are discussed in more detail: passive sensing diagnostics, active sensing diagnostics, and self-healing structures. Various adaptive structure technologies have been developed; The growing use of these technologies in many potential application areas can be expected: automotive engineering (e.g. cars, trucks), aerospace engineering (e.g. space shuttle, airplanes), and civil engineering structures (e.g. bridges, tunnels). Avoiding failure of adaptive structures during structural life is an important prerequisite and a future challenge.

References


\cite{5} S. Hurlebaus, Smart Structures - Fundamentals and Applications, Lecture Notes, Zachry Department of Civil Engineering, Texas A&M University, 2005.


\cite{9} W. Clark, M. J. Ramsay, Smart material transducers as power sources for mems devices, in: International Symposium on Smart Structures and Microsystems, Hong Kong, 2000.


