CHAPTER 1
INTRODUCTION

Vibration is a very important phenomenon in machinery and structures. In some cases vibration causes breakdown, malfunction or discomfort. In other cases vibration is the principal means of operation. In many systems, from ships to musical instruments, quality and performance are closely related to vibration. In those cases it is very important to understand and control vibration.

To understand and control vibration of a structure, first it is necessary to *characterize* the vibrational properties of the structure, i.e. to have certain knowledge of how the parts of the structure vibrate. Vibration characterization is essential in anticipating the vibration levels or determining what actions to be taken if the vibration is to be controlled. However, the quest for the ultimate control of vibration has advanced to the extent that active forces are now used to counteract the vibration. This relatively new vibration control method is called active control of vibration. This method requires *sensing* of the vibration in real time. Regardless of the active control strategy, either feedback or feedforward, sensing is necessary.

This dissertation was conceived of an aspiration to contrive a system that performs both the characterization and the sensing of vibration of machinery or structural components. This system operates on the basis of adaptive processing of signals from distributed sensor arrays. This chapter will give the reader an idea of the basic concepts, purpose, and expected results of the research endeavor to develop the system.

1.1 Modal Analysis and Modal Coordinates

Vibration of a multi-degree-of-freedom system can be expressed in terms of the motion of the systems along several coordinates. The equations governing the motion of the system can be relatively simple or relatively complicated depending on the choice of the coordinate system. Some coordinate systems result in coupled equations of motion. Coupling means that one cannot solve any of the individual equations without involving the others.

The choice of coordinate system determines the “degree of coupling” among the equations. As a rule, the more coupling exists among the equations, the more complicated the solutions are. In controlling the vibration of a multi-degree-of-freedom system, a coordinate system that leads to no coupling among the equations also allows simple control schemes. In many cases, it is possible to choose a coordinate system that results in no coupling among the equations of motion. The coordinates in such a coordinate system are called the *principal coordinates*. These coordinates are also called the *natural coordinates*.

The natural coordinates provide a basis on which to express mathematically the vibration of a structure. On this basis, the vibration of a structure can be viewed as a summation of products of a spatial function and a temporal function.

$$w(x,t) = \sum_{m=1}^{M} \phi_m(x)\eta_m(t), \tag{1.1}$$

where x is position and t is time. The spatial function ϕ is the mode shape of the structure, which is a characteristic of the structure. The temporal function η is called *modal coordinate*.

Real-time monitoring of modal coordinates is very important in active vibration control of continuous structures. The use of modal coordinates in feedback control can prevent control spillover, a phenomenon that results in degradation of performance or in instability (Balas, 1978). Feedback control problems of continuous structures using modal coordinates can be viewed as a problem of controlling single-degree-of freedom (SDOF) systems in parallel, with no interaction among the systems (Meirovitch and Baruh, 1982). Decades ago, Porter and Crossley (1972) published a book dedicated to this control method, which is called modal control. Modal control has been developed for several control applications such as vibration control of large space structures (Davidson, 1990).

Several control theories have been developed using the modal control concept for various control problems including LQG optimal control (Bai and Shieh, 1995). Positive Position Feedback (Baz and Poh, 1996), and neural-network-based control (Chen et al., 1994). Modal control theory has also advanced beyond linear structures (Slater and Inman, 1995). Modal coordinates are not just useful in feedback control. Clark (1995) developed a feedforward control strategy that relies heavily on the availability of modal coordinates. Modal control experiments have been done on various structures such as plates (Clark ,1991, Zhou, 1992, Gu et al., 1994, Miller et al., 1996), cylinders (Sumali and Cudney, 1991, Finefield et al., 1992, Clark and Fuller, 1993), and highway bridges (Shelley et al., 1991).

All of the above modal control methods require monitoring of modal coordinates. Sensing modal coordinates in real time is so important that many researchers have developed a special area within structural control dedicated to obtaining modal coordinates in real time (Meirovitch and Baruh, 1985, Ouyang, 1987, Shelley, 1991). This area is called modal sensing. A short description of some previous work in modal sensing is presented below.

1.2 The Quest for Modal Coordinate Sensors

Many researchers have developed techniques to create sensors that can produce modal coordinates in real time. The proposed research work in this dissertation adopts the concepts of spatial filtering, segmentation, and adaptive signal processing. This section will mention a selected sampling of previous work especially related to those concepts.

1.2.1 Modal Filtering in Time Domain

Monitoring modal coordinates of a vibrating structure can be done by processing signals from sensors in time domain. Several researchers claimed that this processing can be done by filtering sensor outputs with a bank of filters, each of which admits only certain frequency and filters out other components of the signal. Balas (1978) introduced this modal filtering concept. Ouyang (1987) developed a realization of this concept with a bank of special filters where each filter only passes a single frequency that coincides with a natural frequency of the structure (See Fig. 1.1). Davidson (1990) conceptually designed an electronic circuit that implements Ouyang's filters with a set of phase-locked loops (PLL's) built with voltage-controlled oscillators (VCO's) that generates pure sinusoidal signals. Davidson performed numerical simulation of a scenario where his VCO-based modal filters are used to control many hundred modes of a large space structure.

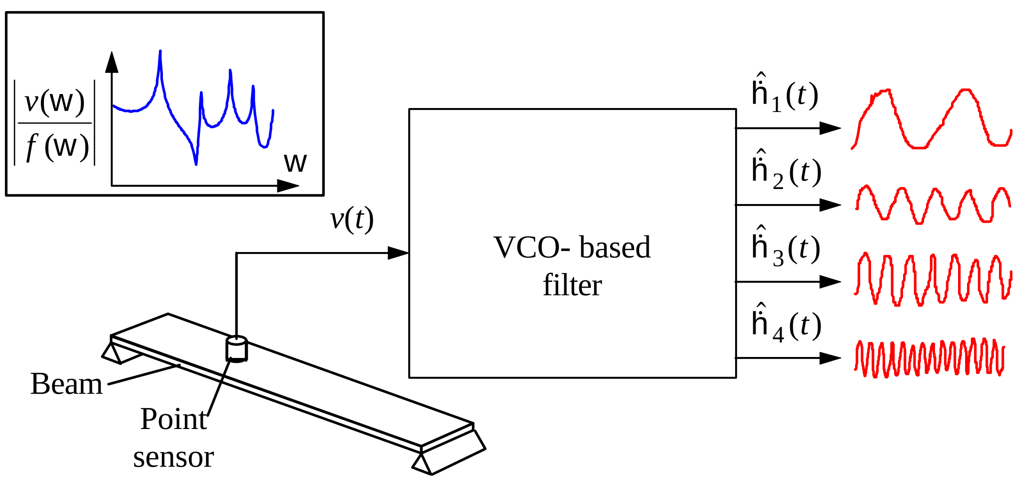

Figure 1.1 Modal filtering in time domain.

1.2.2 Modal Filtering in Spatial Domain

Another method to obtain modal coordinates in real time from sensor outputs is by filtering the sensor outputs in space. Basically this means assigning different weights to different sensor outputs depending on which mode to be sensed. Sumali and Cudney (1991) performed some experiments using this method. One set of weights produce one modal coordinate. This method can be illustrated with the beam in Fig. 1.2. Assume that the exciting force is such that the response is limited to combinations of the first four modes. In practice, this rather simplistic assumption might be realized by several methods such as low-pass filtering the excitation. We know that for the simple boundary conditions the mode shapes of the Euler-Bernoulli beam are sinusoidal. We use four point sensors to sense displacements at strategically assigned positions on the beam, based on our knowledge of the mode shapes.

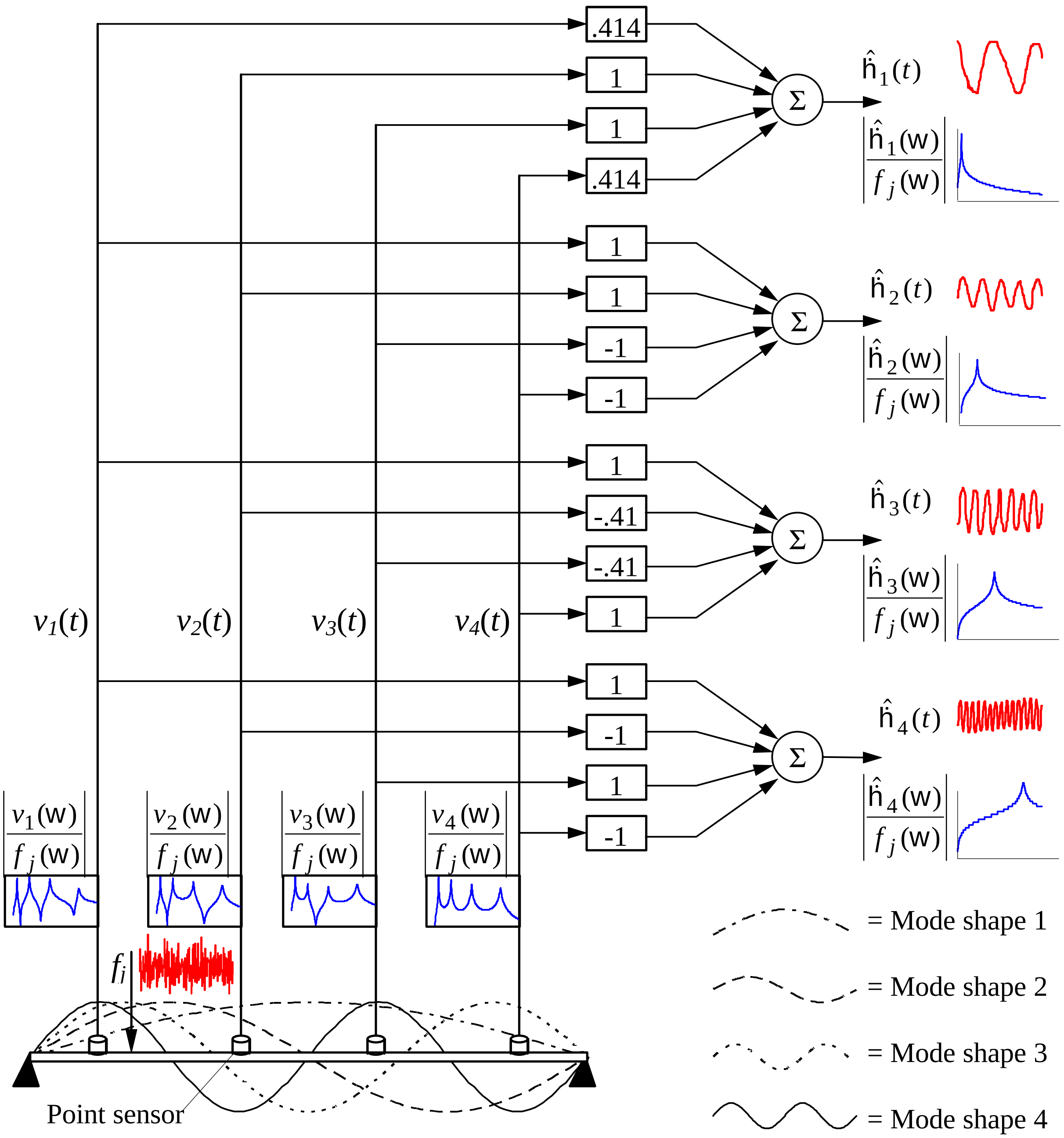

Figure 1.2 Modal filtering in spatial domain.

This method can be described well with simulation results. The frequency response functions (FRF's) from the force to the velocities at the four point sensor locations are shown in Fig. 1.3. By combining the outputs of the four sensors with the right mixture as shown in Fig. 1.2, we can obtain sensor outputs that are proportional to the individual modal coordinates, as shown in Fig. 1.4. The gains in Fig. 1.2 constitute a matrix that transforms the sensor coordinate system to the modal coordinate system. It will be shown later that these gains are closely related to the modal matrix (or eigenvector matrix) of the structure.

If we increase the number of sensors, we get a higher spatial resolution. In the limit, for an infinite number of sensors, the sensor gain matrix becomes continuous functions, each row representing a mode. This modal sensing concept was invented by Lee (1987) for strain sensors such as piezoelectric film. The width of the film is varied along the beam as a function of the modal sensor weight. For a mode 3 sensor, such a sensor is shown in Fig. 1.5. Theoretically, this sensor is an ideal mode 3 sensor, insensitive to any other mode. Lee and Moon (1990) successfully applied this type of spatially distributed modal filter to vibration control. Many other researchers have implemented Lee's modal filters in various forms, for example: Structure-borne acoustic sensors (Clark, 1992), one-dimensional modal sensors on plates (Zhou, 1992), one-dimensional modal sensors on cylinders (Sumali, 1992; Clark and Fuller, 1993) sensors for feedforward modal control of structures (Clark, 1995), acoustic sensing by volume-velocity (Guigou et al., 1995). Burke and Hubbard (1990) explained the concept of spatial filtering sensors and applied the techniques to control distributed parameter systems in general.

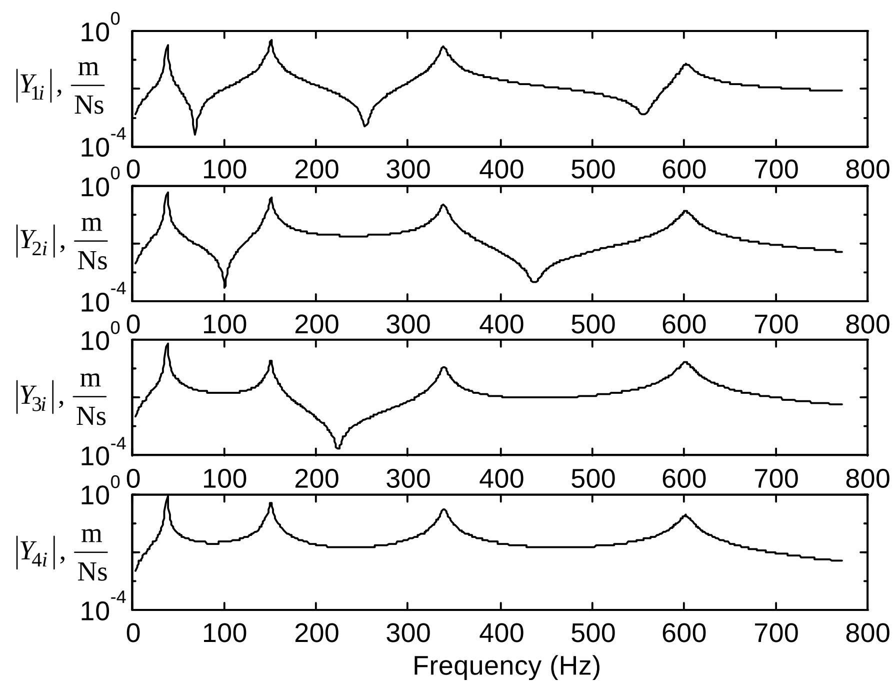

Figure 1.3 Mobility magnitude, $|Y_{ij}| = \left|\frac{v_i(\omega)}{f_j(\omega)}\right|$, at four points.

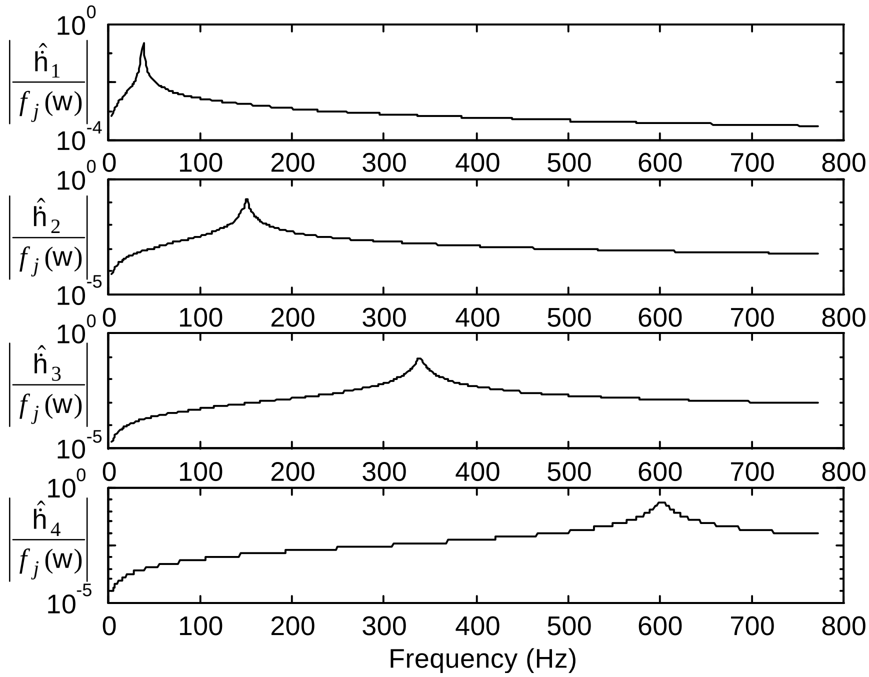

Figure 1.4 Modal mobility magnitudes, $\left|\frac{\hat{h}_i(w)}{f_j(w)}\right|$, for modally combined sensors.

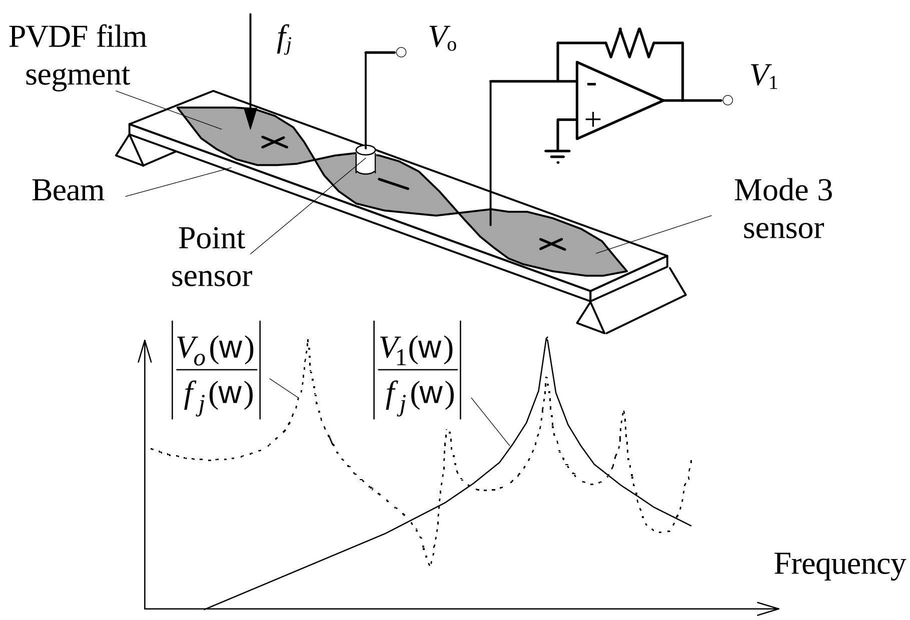

Figure 1.5 Modal sensor in continuous spatial domain.

1.2.3 Polyvinylidene Fluoride (PVDF) Film Sensors

Throughout the research work, the material used for vibration sensor is thin film of a piezoelectric polymer polyvinylidene fluoride (PVDF). The use of this material in the structural dynamics community was promoted mainly by Lee (1987). This material is particularly suited for the structural modal sensing applications because it offers many advantages, including the following.

PVDF is lightweight. Compared to accelerometers (even very small ones), PVDF film has negligible mass-loading effects, even on light structures. The polymer is also very compliant. This feature enables us to neglect the changes in structural parameters due to stiffening by the film.

Another attractive feature of the PVDF film sensor is its strain-integrating nature. Unlike point sensors, segments of piezoelectric film can be cut into shapes that convolve the strain on the structure's surface with a specified function (Lee and Moon, 1990, Collins et al., 1992). The function can be selected such that the convolution results in a low-pass filtering effect in the wave number domain. This effect results in the reduction of *spatial aliasing*, which is an important property that we will address later in this dissertation.

PVDF film segments are much cheaper than accelerometers or other vibration transducers such as strain gages, laser, or fiber optic transducers. The signal conditioning circuit for a PVDF sensor is also much cheaper than the signal conditioning circuits for the other sensors. The simplicity to attach large numbers of PVDF segments on structures is also very important in creating highly distributed sensor arrays.

PVDF has a strong piezoelectric effect compared to most other piezoelectric materials (Lee, 1987). The material is also robust, both physically and chemically. It has been used also as protective coatings against harsh environment, for instance, as vat liners for chemicals (Collins et al., 1990). It endures time, temperature (up to about 120^{o} C), and mechanical shock (up to several hundred g's). The (mechanical) bandwidth of the film is very high (up to about 10^7 Hz). With appropriate signal conditioning circuit, no dynamics is introduced by the sensor.

1.2.4 Segmentation of Modal Filtering Sensors

The idea of dividing the piezoelectric film layer into segments emerged primarily because a piezoelectric sensor layer covering the whole host structure fails to detect anti-symmetric modes (Cudney, 1992). Several researchers have investigated the use of segmentation in piezoelectric film sensors. Tzou and Fu (1992, 1992b) developed a theory for applying the segmented sensors and actuators to vibration control of plates. Clark (1992) developed an adaptively-computed sensor array gains to apply to segmented PVDF film sensors so that the sensor array emulates vibration sensors and structural acoustic sensors. Sumali and Cudney (1993) developed a technique to create modal sensor from an array of segmented piezoelectric film sensors. Callahan and Baruh (1994) developed another method to create modal sensors from the same segment array configuration. Sullivan (1993) developed a special kind of distribution calculus to calculate the responses of piezoelectric sensor patches of general shapes and to calculate the actuation of arbitrarily shaped strain-induced actuators on multidimensional structures. Sullivan also developed a sensor array that is weighted spatially according to a linearly varying function developed by Burke and Hubbard (1990).

1.2.5 Modal Filtering Using Adaptive Algorithms

At least two methods have been developed to create modal sensors using adaptive signal processing. The first method (Shelley et al., 1992) uses the sensor configuration shown in Fig. 1.6. The outputs of the sensors are input to a linear combiner with some gain vector. The gain vector is computed on-line using the LMS algorithm. The structure is excited with a random force excitation. The output of the sensors are used to adjust the gain matrix iteratively until the output of the linear combiner matches the output of a pre-programmed second-order digital filter. The natural frequency and damping of the digital filter are pre-programmed based on the knowledge of the natural frequency, modal damping, and residue of the desired mode. These parameters must be known in advance. The advantage of this method is that knowledge of the mode shapes of the structure is not required in computing the gain matrix. An example of the application of this method is shown below. The details of a simulation of the adaptive modal filter are given in Appendix A.

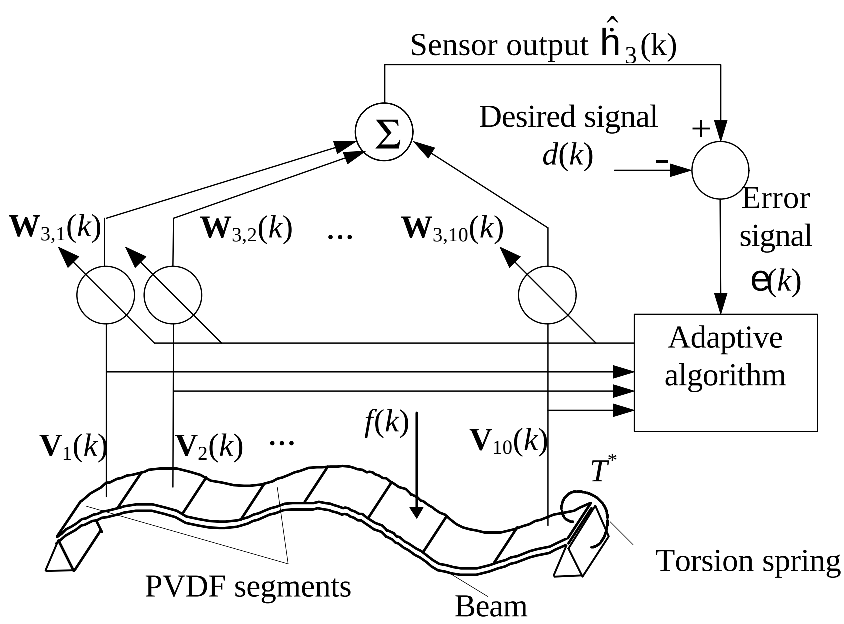

Figure 1.6 Using an adaptive algorithm to create a modal filter.

This adaptive method seems to result in an impressive modal filtering effect. Figure 1.7 shows the difference between the sensor output and the ideal modal coordinate. This error converging to zero means that the sensor output converges to the desired modal coordinate.

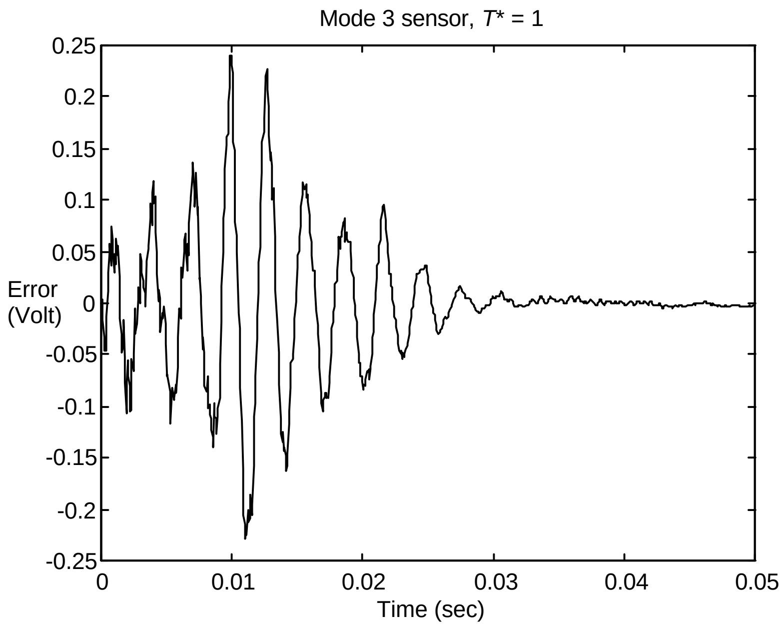

Figure 1.7 Error signal history of adaptive modal filter.

Despite the impressive modal filtering effect, a more critical examination of Appendix A reveals the fact that this technique is not likely to be of practical utility. Figures A.1 and A.2 in the appendix show that the key element in this modal filter is the filter that generates the "desired signal" $d(k)$. This filter must be programmed with the natural frequency, modal damping, and modal residue. Therefore, this method still requires complete knowledge of the natural frequencies, modal damping, and residues of the modes of the structure. If one knows these parameters and hence the filter coefficients, then there is no need for the adaptive linear combiner. The filter alone can be used to generate the desired signal $d(k)$, which is precisely the modal coordinate. The real utility of this method would be in obtaining the mode shape.

The second method uses a parallel bank of second-order recursive digital. This method is based on the modal decomposition of the multi-degree-of-freedom structure into a parallel bank of single-degree-of-freedom systems as in Eq. (1) (Horvath, 1976). Wimmel and Melcher (1992) used adaptive recursive filter algorithms developed by White (1975) and Hsia (1981). Part of this method, namely modeling a multi-degree-of-freedom (MDOF) system as a parallel bank of second-order filters, will be adopted in this research work for the purpose of simulating a structure with already-known modal properties with digital filters.

1.3 Conventional System Characterization and Mode Shape Extraction

From the above discussion, we know that modal filtering requires knowledge of the characteristic of the structure: either mode shapes or natural frequencies and damping ratios. In fact, the most important step in virtually all vibration analyses is to obtain the natural frequency or eigenvalues and mode shapes or eigenvectors of the system. The importance of eigenvalues and eigenvectors can not be overemphasized. In all but the simplest structures, the modal properties of the system must be obtained numerically or experimentally. The most popular methods to obtain the modal properties of a structure by experiments can be easily classified into two broad categories. Each category is different from the other in many ways: tradition and historical development, mathematical foundation, and experimental knowledge base. Even the purposes of the different categories are different. The first category is commonly called "System Identification", the second, "Experimental Modal Analysis" (EMA). In this section we will discuss the concepts and efforts involved in computing mode shapes from experimental data using the two categories of computation methods.

System identification, or more specifically "Control-Model Identification" (Juang, 1994) has developed since the mid-sixties out of the necessity to control sophisticated systems such as guidance and controls of aerospace structures. The main objective of this type of analysis is to obtain the block diagram of the system to be controlled so that the control engineer can design the controller, observer, sensors, and actuators. Modal properties of the structure can be obtained easily from the resulting dynamic model of the structure. However, obtaining modal properties is only a small part of system identification and often not an essential part. Much theoretical work has been generated by many researchers on system identification (see for example the bibliography of Juang, 1987).

EMA originated partly from such testing practices as "Resonance Testing" and "Mechanical Impedance Methods" in the 1940's (Ewins, 1986). Development in electronics in the 1960's and Cooley and Tukey's Fast Fourier Transform (FFT) algorithm created a revolution in signal processing (Mitchell, 1986). Unlike Control-Model Identification, Modal Testing is especially geared towards obtaining the modal properties of structures. The resulting estimates of modal properties are used not mainly in active control of aerospace structures, but in various other tasks, such as design modification and passive vibration control.

EMA is very commonly used in obtaining vibration modes to verify finite element or theoretical models. Once the model is validated, it can be used to predict the responses to complex excitations such as shock, or to proceed to more further stages of analysis. A validated model can be used as a basis for further modeling and analysis. Modal Testing is often used to produce a mathematical model of a component which may then be used in a structural assembly. Mode shapes obtained from EMA can be used to modify the design of a component to improve its vibrational characteristics, such as lower dynamic stresses, less acoustic radiation, relocation of points of large vibration, etc.

In terms of knowledge requirements, Modal Testing requires a thorough integration of 1) Vibration theory 2) Accurate measurement, and 3) Signal processing. The area of Modal Testing is very rich in experimental knowledge and intuitive rules that complement, sometimes even circumvent, the mathematics. On the other hand, Control-Model Identification requires the mathematics of modern control systems theory. In particular, most Control-Model Identification algorithms rely on Singular-Value Decomposition (SVD). The state-space is the standard domain of Control-Model identification.

Keeping the backgrounds of Control-Model Identification and Modal Testing in mind, we can now make a reasonable judgment of the two categories of methods in terms of an important goal in this dissertation: Computing *mode shapes*. Then we propose a *new* method of computing mode shapes, which also results in a means of obtaining modal coordinates in real time. The advantages of this new method over Control-Model Identification and the classical Modal Testing will be discussed later.

For an explanation of the Control-Model Identification procedure, Juang (1994b) is an excellent reference, on which the following paragraphs are based. The purpose of describing the Control-Model identification procedure here is only to give an idea of the computational process. Figure 1.8 shows a typical sequence of variables to calculate in Control-Model identification of a structure. Knowledge of SVD-based procedures such as one described in Appendix C is desirable for further understanding of the rest of this section.

From the identification procedure in Appendix C, we learn that obtaining mode shapes from experimental data using Control-Model Identification requires at least the following operations:

1. Fast Fourier Transform (FFT) to transform force and response signals into the frequency domain. This process does not only require the application of Fourier transform algorithms, but also other procedures to ensure good results, e.g. windowing, coherence computation and checking, averaging, sometimes zooming, and so on.
2. FRF Computation from all input forces to all sensor outputs. This complex operation requires multiplication and division. FRF computation must be done to all time data. In a highly distributed sensor system with a high number of input channels, FRF computation requires significant computing power.
3. Inverse FFT to transform the FRF back into time domain to obtain Markov parameters.
4. Singular value decomposition (SVD). Equations (C.4) through (C.7) in Appendix C show that SVD is a key step in the identification process. This process is a lengthy sequence of matrix operations (see, for example Golub and Van Loan, 1989).
5. Eigenvalue and eigenvector computation. This is another computationally extensive operation.
6. Transformation of eigenvalues from the discrete *z*-plane to the continuous *s*-plane (Eq. (C.19)). This transformation requires evaluation of logarithms, a computation process that is much less elementary than addition or multiplication. In the implementation of real-time algorithms, this nonlinear operation may take many computation steps.

7. Raising a matrix to the -1/2 power (Equation (C.9)). This process obviously needs extensive computation.
8. Matrix inversion (Eq. (C.21)) and several multiplications. This is another computationally extensive process.

From the above discussion, we can conclude that a typical Control-Model Identification process is computationally extensive. If mode shapes are to be obtained and modal filtering are to be performed in real time, this type of analysis must be done with tremendous computing power. Less computing power may do the job if the computation is done with recursive methods. Recursive algorithms are available mainly for single-input-single-output (SISO) systems. (Ljung (1989) is an excellent reference.) The algorithms are mostly based on Recursive Least Squares (RLS) or Kalman filter theories. These methods are not suitable for obtaining mode shapes because they do not address the distributed nature of sensors required in mode shape computation.

EMA is perhaps the best category of methods to obtain mode shapes. However, the current procedures to compute mode shapes are not designed for on-line computation. Figure 1.9 shows typical steps of modal testing and the computation steps to obtain mode shapes. The first steps in EMA are identical to their counterparts in Control-Model Identification. The procedure shown in the picture requires the first three operations performed in Control-Model Identification. EMA programs use circle-fit, least-squares curve-fitting, and other averaging and error-minimizing techniques. Like the processes in Control-Model Identification, those processes also require too much computing power to apply in real time.

The foregoing discussion was not meant to argue that the current state of the art is full of disadvantages and inefficiency. The argument is that the current practices of system identification are not geared towards real-time application. Recent advances in adaptive algorithm have created a trend towards streamlining the computational procedure by using recursive adaptive algorithms. (See, for example, Ljung (1989b)). However, most of the current advances can be traced back to SVD, least-squares curve-fitting including recursive least-squares error minimization and Kalman-filtering-type algorithms, mainly because those are standard procedures. A typical system identification expert is well-trained in, and feels comfortable with, those standard procedures. Building on the current techniques can only improve the speed within the bounds inherent to the nature of the underlying concepts.

The LMS algorithm (Widrow, 1985) is a notable exception to the above statements although the underlying concept is least-squares error minimization. This algorithm is simple, versatile, and requires very little computation, hence a lot of practical applications. The drawbacks of this algorithm are, among others: Slow convergence, inability to take advantage of knowledge about the system, lack of guaranteed stability. In terms of adaptive modal filtering, the application of this algorithm is not very promising, mainly because it requires some kind of “desired” signal, as discussed earlier.

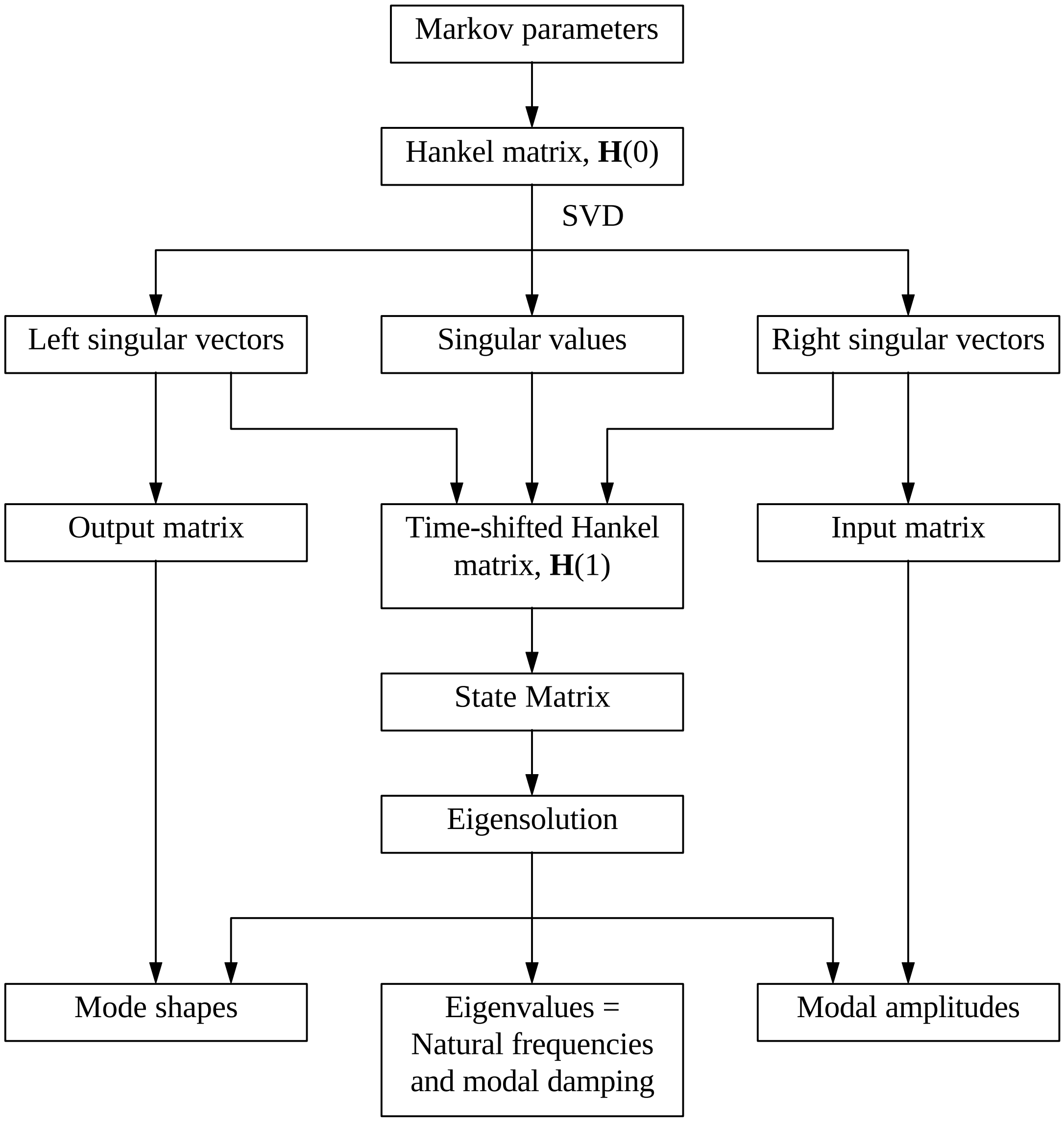

Figure 1.8 Typical Control-Model Identification. (Adapted from Juang, 1994b)

1.4 On-line Modal Analyzer: a Novel Concept

The proposed research work is to develop a structural vibration sensor system that obtains the mode shapes of the structure in real time and performs modal filtering. This sensor system will be called the *modal analyzer*. This novel system does not require discrete Fourier transform (DFT or FFT), FRF computation, SVD, or matrix inversion. The modal analyzer works in time domain using adaptive algorithms. This method is based on correlation and computation of eigenvectors.

Therefore, it still needs eigenvector computation (step 5 in the Control-Model Identification procedure described above.) This step is computationally extensive. However, the proposed system performs this step recursively, improving the estimates of the eigenvectors gradually with each iteration. Adaptive algorithms will be developed to perform this operation.

Comparison between Fig. 1.9 and Fig. 1.10 shows that the new modal analyzer bypasses many computational steps between data acquisition and the computation of mode shapes and modal coordinates. The modal analyzer does not compute natural frequencies and modal damping. However, it performs modal filtering concurrently with mode shape computation. The conventional methods require that the mode shapes be obtained first, and then the modal filter constructed accordingly. If the structure's parameters change, for example, due to temperature change or drift in boundary conditions, then the fixed-parameter modal filter will no longer be accurate. The modal analyzer, on the other hand, will track changes in structural parameters, and adaptively adjust the modal filter so that the outputs are the correct modal coordinates.

1.5 Overview of Dissertation

Although a proof-of concept experiment will be conducted, most of the theory developed in this dissertation will be tested on a simulated structure. This structure and its discrete-time simulation will be described in chapter 2. Throughout the dissertation it is assumed that that the structure is linear and self-adjoint, that the modes are real, and that the mode shapes are orthogonal. Most of the theory developed here will apply only under those assumptions.
The sensor system is physically constructed from an array of piezoelectric polyvinylidene fluoride (PVDF) film segments connected to electronic signal conditioning circuits. The design and modeling of the sensor array are also described in chapter 2.

Numerical simulation of the structure-sensor system is presented in chapter 3. In this chapter we also present an experiment to verify that the simulation procedure, indeed, represents the physical system and to prove that the concepts used in the development of the adaptive sensor array are physically realizable.

In chapter 4, we reveal the fundamental principle that we will use to develop a new algorithm to perform adaptive mode shape calculation and modal filtering simultaneously. Numerical simulation is presented to demonstrate the effectiveness of using this fundamental principle. The development of the adaptive algorithms is presented in chapter 5. In chapter 6 we utilize a simple formula to extract mode shapes from sensor gain matrices. Conclusions are presented in chapter 7. Also in this last chapter we discuss the possibility of constructing a hardware prototype of the modal analyzer.

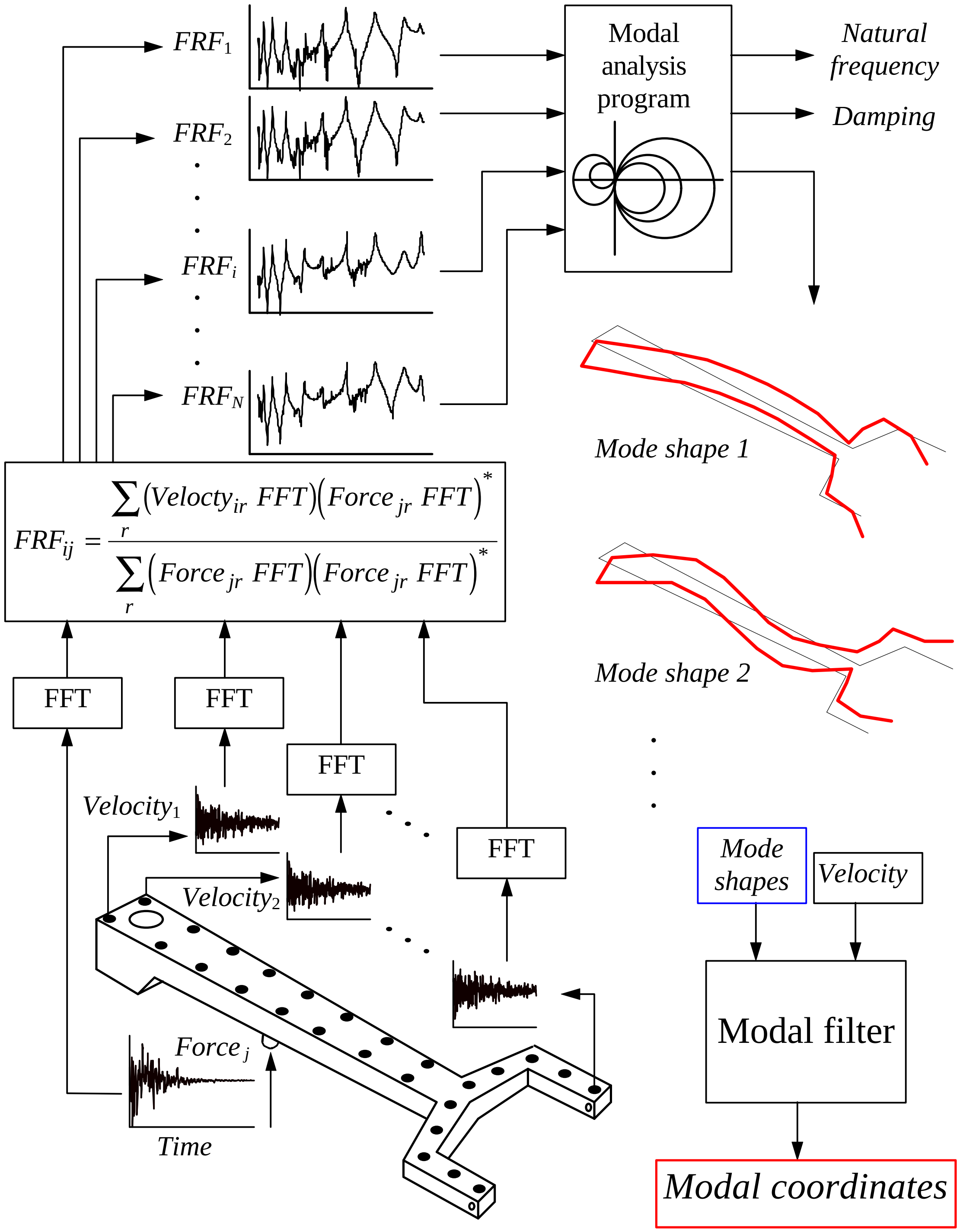

Figure 1.9 Typical experimental modal analysis and modal filtering with conventional methods.

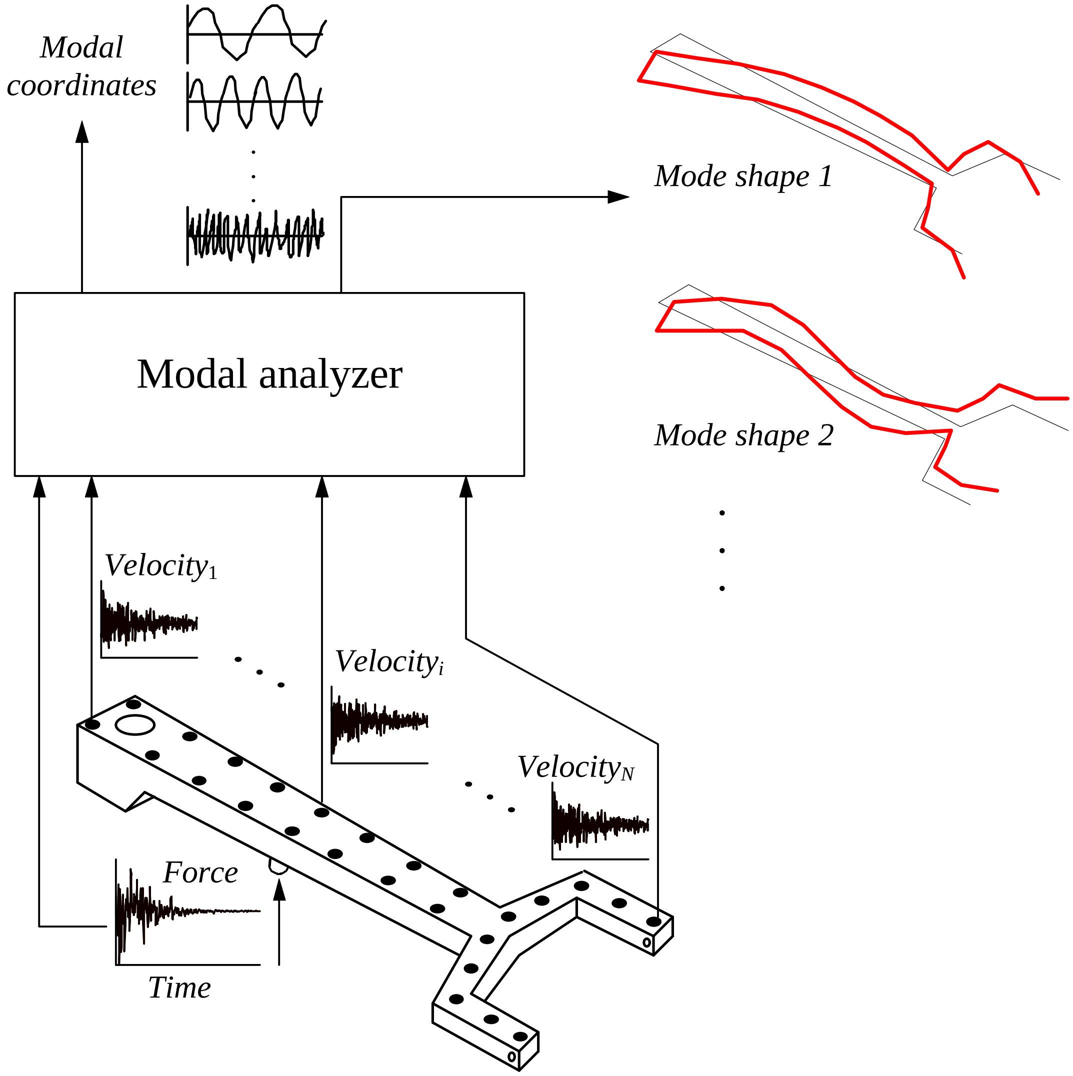

Figure 1.10 Modal analysis and modal filtering with the new modal analyzer.