

CHAPTER 7

CONCLUSIONS AND FUTURE DIRECTIONS

7.1 Conclusions

Looking back to Eq. (1.1) in the Introduction, we recall that knowledge of mode shapes and real-time monitoring of modal coordinates are very useful in vibration measurement and control. For that reason, we have developed the concepts of adaptive modal filtering and real-time mode shape extraction. Some of the accomplishments of the research work documented in this dissertation can be summarized as follows.

1. A new distributed sensor configuration:

We devised a sensor system consisting of segments of strain-sensing film connected to adjustable gains. This adaptive distributed sensor system can be programmed to perform as various types of sensors. A proof-of-concept experiment showed very promising potential to create adaptable distributed modal sensors from this configuration.

2. An adaptive modal filter:

The sensor system is programmed to produce modal coordinates of a vibrating structure in real time. This system does not require knowledge of the modal properties of the structure. If the modal properties of the structure changes slowly with time, the system can adapt to keep acting as a modal filter.

3. Adaptive eigenvector computing algorithms:

We developed two new algorithms to compute the sensor gain matrix that transforms the segment outputs into uncorrelated modal coordinates. The new algorithms use recursive averaging, zero-order correlation matrices, and Jacobi rotation matrices in computing the eigenvectors of real symmetric matrices. The algorithms compute the eigenvector matrices recursively over many time steps, so as to lower the computational load. One of the algorithms takes advantage of performance feedback in the form of non-zero correlation between different sensor outputs.

4. A mode shape extraction formula:

We developed a simple method to extract the mode shapes of the structure from the adaptively computed sensor gain matrix. This method is based on Lagrange interpolation formula.

7.2 *Future directions*

The experiment with the segmented strain-sensing film and the signal conditioning circuits for the sensor system showed that their outputs agree with the theoretical prediction. The transducers and the associated signal conditioning circuit have then proven to be promising hardware for future development. The intentions are to build a prototype of the adaptive modal filter, including the signal processing hardware and the associated software. At this point, the signal processing part has only been simulated on a computer. While a digital signal processing board appears to be the most practical first try, the hardware implementation would utilize hard-wired dedicated electronic circuits in the future if the concept of adaptive modal sensing and mode-shape analysis becomes common. Much further development of the adaptive modal sensing theory is necessary before a prototype can be constructed.

A natural extension to the completed work includes the following :

1. Study the sensitivity of the sensors to errors in sensor parameters, such as:
 - a. The piezoelectric constants of the sensor material.
For example, a deviation in the e_{31} value (Eq. (2.30)) from the theoretical value will result in a proportional deviation in the segment output voltages and the estimated modal coordinates.
 - b. The positions of the segments on the beam.
For any set of segment dimensions and positions, the adaptive algorithms will converge to the correct gain matrix to make sure that the outputs of the sensor are uncorrelated. Therefore, the positions of the segments on the beam should not introduce any unnecessary coupling between the modal sensor outputs. However, the mode shape extraction technique in Chapter 7 assumes perfect knowledge of the segment dimensions and positions. The accuracy of the mode shape estimates depends on the accuracy of the segment positions and dimensions.
2. Study the effects of segment resolution on sensor performance.

As mentioned in subsection 2.3.3, even a hypothetical gain matrix derived from a perfect modal matrix will not always result in exact modal coordinates. The reason for the error is modal truncation. Although the adaptive modal filter described in this work requires almost no information about the modal properties of the structure, it still requires information on *how many modes* contribute significantly to the structural vibration within the specified frequency range. It was shown in Subsection 3.1.2 that contribution from modes that are not accounted for in the sensor design will falsely be sensed as lower mode (spatially aliased) coordinates.

The number of modes to be included in the design of a modal filter determines the minimum number of segments. This number of modes can be obtained by several kinds of tests. One of the simplest test is to sweep the structure with a point vibration transducer to locate nodes. The number of modes is closely related to the upper limit of the frequency range, which is in turn related to the sampling rate, the excitation frequency range, anti-aliasing filter range, etc. The relationships among these parameters are simple but very important. The development of a comprehensive set of simple rules is a necessary step towards the implementation of the adaptive modal sensors.

The number of segments also determines the accuracy of the mode shape estimates. As mentioned in Chapter 6, the mode shape estimates are polynomial functions that cannot be identical to the actual mode shape functions. The difference between the estimates and the actual mode shapes can be small only if the orders of the polynomial functions are sufficiently high. The order of the polynomial can only be as high as the number of segment output voltages plus the number of known boundary conditions. Thus, the accuracy of the mode shape estimates depends on the number of segments. Further study is necessary to quantify the relationship between the number of segments and the error in the mode shape estimates.

3. Study the effects of spatial aliasing and devise methods to reduce those effects.

As mentioned in Subsection 3.1.2, spatial aliasing is a serious problem in the discretized modal filters. One of the advantages of a strain-integrating film segment over a point sensor is that the film segment can acquire strain information over its entire area. This integrating feature can be exploited to reduce spatial aliasing. Shaping a segment with a function that has a low-pass characteristic in the wavenumber domain reduces the sensitivity of the segment to modes with high wavenumbers, thereby reducing spatial aliasing. The relationship between spatial shaping functions and their spatial aliasing reduction effects are important in the development of the segmented modal filtering sensors.

4. Study the effects of noise and develop methods to reduce those effects.

Random, uncorrelated noise in the segment output signals is filtered out by the averaging process in obtaining the segment output correlation matrix. However, other kinds of noise that contaminates the segment output correlation matrix will introduce errors in the modal matrix

and the sensor gain matrix. Statistical analysis should be done to determine the effects of noise on the modal filters. Furthermore, methods should be developed to reduce these effects.

5. Refine the adaptive algorithms to eliminate their limitations.

As mentioned in Section 5.5, naturally arbitrary scaling of eigenvectors and unpredictable ordering of the modal sensor outputs are some of the problems of the adaptive modal sensors. Further development of the algorithms may resolve these problems.

At its current stage, the adaptive modal filtering theory has only been applicable to self-adjoint structures with orthogonal mode shapes, such as the beam used as the example structure throughout the dissertation. To create modal sensors for plates, the theory has to be modified. The mode shape functions of plates with most boundary conditions cannot be shown to be orthogonal (Blevins, 1984b). Another problem with the segmented sensor on plates is that the segment output voltage is caused by flexure in two directions. For each individual segment, it is impossible to separate the segment output voltage into the part generated by curvature in one direction from the part generated by curvature in the other direction. In the cases where the adaptive modal filter theory can be applied to plates, point sensors are easier to use than strain-sensing segments.

Future modifications to the algorithms we developed may reduce the computational requirements. For example, Eqs. (5.4) and (5.5) show that Jacobi rotation of a matrix is a very efficient operation because this matrix transformation only affect two rows (or columns) of the matrix to be transformed. On the other hand, Eq. (5.15) shows that Algorithm B requires transformations with a modal matrix, which is almost always less sparse than the Jacobi rotation matrix. The transformation is therefore computationally more demanding than a simple Jacobi rotation. An encouraging fact is that the symmetry of the matrices allows us to work with only the upper triangular half of the matrices.

The writer hopes that this research work helps inspire efforts to devise other novel techniques to perform modal filtering and mode shape identification adaptively in real time. Advances in digital signal processing will then help make the concept of real-time adaptive modal analysis a reality in the near future.