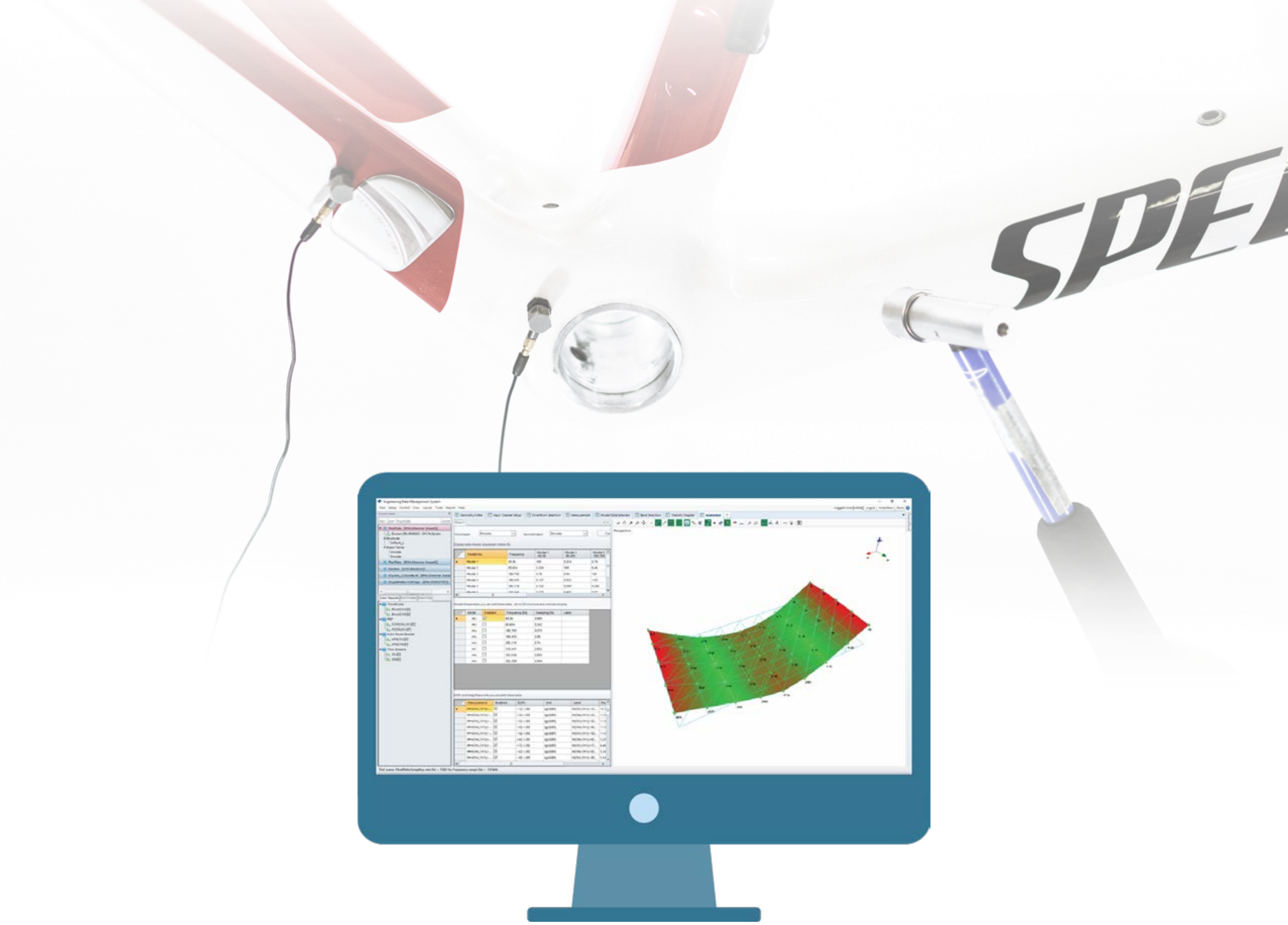
Experimental Modal Analysis Overview

Application Note 043



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Contents

Introduction

Experimental Modal Analysis (EMA) has developed into a major technology for the study of structural dynamics in the past several decades. Through Experimental Modal Analysis, complex structure phenomena in structural dynamics can be represented using decoupled modes consisting of natural frequency, damping, and mode shapes. The collection of these modal parameters is referred to as Modal Model. Experimental Modal Analysis is commonly referred to as Modal Analysis.

Structural vibration has been a significant focus for the dynamic testing and analysis group. Whether the object is a turbine blade rotating at high speed, or a bridge sustaining traffic and strong winds, Modal Analysis can be applied to provide insightful solutions.

Comprehensive Modal Analysis includes both data acquisition and the subsequent parameter identifications. From its inception till now, Modal Analysis has been widely applied in mechanical and structural engineering for designing, optimizing, and validating purposes. It has been widely accepted for broad applications in automotive, civil engineering, aerospace, power generation, musical instruments, (etc.), industries.

Overview

Experimental Modal Analysis emerged in the late 1950's and gained steady popularity since the late 1960's. During that time period, researchers tried to solve a major structural issue referred to as the self-excited aerodynamic flutter problem, which is considered a critical issue for the aerospace industry. Nowadays, ground vibration testing (GVT) is still carried out on the prototype of every new airplane model designed.

Another challenging task during that time period was normal mode tuning. A large amount of testing equipment was required in addition to the necessity of a highly skilled test team.

More commonly used than normal mode testing was the modal survey, which was conducted on a structure under test using a small hydraulic actuator or an electro-mechanical exciter to understand the characteristics of the structural modes. The measurement research effort of the late 1960's and early 1970's focused on generating a modal model from a set of measured FRFs.

Over the next several decades, the acquisition of FRFs followed by modal parameter identification based on FRF models proved to be the dominant methodology. Using this method, the FRFs are measured first, followed by parameter identification of the modal frequencies, damping factors and mode shapes.

The origin of modal analysis is traced back far into history. For instance, the Fourier series and the study of spectrum analysis laid a solid foundation for the development of modal analysis. Fourier, based on earlier mathematical wisdom, claimed that any arbitrary periodic function with a finite interval can always be represented by the summation of simple harmonic sinusoidal functions.

The Fast Fourier Transform (FFT) algorithm invented by James Cooly and John Tukey in 1965 paved the way for application of experimental techniques in structural dynamics. With FFT, Frequency Response Functions of a structure under test can be computed from the measurement of given inputs and resultant outputs. The modal analysis theory helps establish the relationship between measured FRFs and the modal data of the structure under test. Research efforts were focused on identifying modal data from measured FRF signals. Since then, numerous parameter identification methods have been proposed, from Single DOF to Multiple DOF, time domain methods to frequency domain methods, single reference to multiple reference, etc. Many of these methods have since been computerized, including methods based on responses of a structure instead of its frequency response functions.

Theoretical modal analysis is closely identified with the wave equation, which describes the dynamics of a vibrating string. From the solution, we can determine its natural frequencies and mode shapes. Forced responses can then be computed using the modal model. This stage of modal analysis, developed during the 1990's, was largely dependent upon mathematics to solve partial differential equations which describe different continuous dynamic structures. The elegance of the solution is evident while the scope of the solvable structures is limited.

The concept of discretization of an object in space and the introduction of matrix analysis brought about a climax in analytical modal analysis. It was theorized that a structural dynamic analysis of an arbitrary system can be carried out when knowing its mass and stiffness distribution in matrix forms. However, this theory could only be realized when powerful computers became available. In this aspect, analytical modal analysis is very much a numerical method, which is one of the more popular Finite Element Analysis (FEA) applications.

Experimental modal analysis development also helped advance the theory of modal analysis. Traditional analytical modal analysis based on the proportional damping model was expanded into the non-proportional damping model. The theory of complex vibration modes was developed. Inverse structural dynamic problems such as force identification from measured responses were actively pursued. Nonlinear dynamic characteristics were studied experimentally.

Today, Experimental Modal Analysis has entered nearly all the fields of engineering and science. Its applications range from automotive engineering, aerospace engineering to bio-engineering, medicine and science. Analytical Modal Analysis (FEA dynamic analysis) and Experimental Modal Analysis have become part of the foundations of structural dynamics.

Figure 1.1

Modal Testing

Modal testing is the experimental technique used to measure system characteristics, assuming the system is linear and time-invariant. The theoretical basis of this technique is secured upon establishing the relationship between the vibration response at one location and an excitation at the same or different location as a function of the excitation frequency. This relationship, which is often a complex mathematical function, is known as the Frequency Response Function or FRF in short. Combinations of the excitation and response at different locations lead to a complete set of frequency response functions (FRFs) which are collectively represented by an FRF matrix of the system. This matrix is usually symmetric, reflecting the structural reciprocity of the structure under test.

The practice of modal testing involves measuring the FRFs of a structure. The FRF measurement is simply taken by asserting a measured excitation force at one location of the structure in addition to measuring vibration responses at one or more location(s). The modern excitation technique and recent developments of modal analysis theory permit more complicated excitation mechanisms. The excitation can be of a selected frequency band, stepped sinusoid, transient, white noise, or periodic random types. It is usually measured by a force transducer or impedance head at the driving point while the response is measured by accelerometers or other probes. Both the excitation and response signals are fed into a dynamic signal analyzer which is an instrument responsible for computing the FRF data.

A practical consideration of modal testing is the quantity of FRF data needed to be acquired to adequately derive the modal model of the structure under test. When performing a simple hammer test, a fixed response location is used while alternately roving force excitation points. The measured FRF data constitutes a row of the FRF matrix. The data would theoretically suffice for deriving the modal model. For a simple shaker test, a fixed force input location is used while alternately moving response collection points or simultaneous acquiring responses from points. The measured FRF data constitutes a column of the FRF matrix. Again, the data should suffice theoretically. With sufficient measured FRF data, the parameter identification process will derive modal parameters by ways of curve fitting. This process is known as experimental modal analysis. The identified modal parameters will form the modal model of the structure under test. Parameters can be extracted either from individual FRF curves or from a set of FRF curves, namely a local or global method. (Figure 1.1)

The hammer impact test is typically carried out on a simple structure or is used as a quick survey prior to the more complex modal shaker test. It involves relatively less equipment, namely a sensor without the attachment of the shaker to the structure. In general, it takes little time to set up and carry out the FRF measurements. However, this could be time consuming when hundreds of measurement points need to be covered. In addition to the roving hammer method, the roving measurement method is also widely used. The selection of the driving point needs some consideration for the hammer impact test. The objective is to select the driving

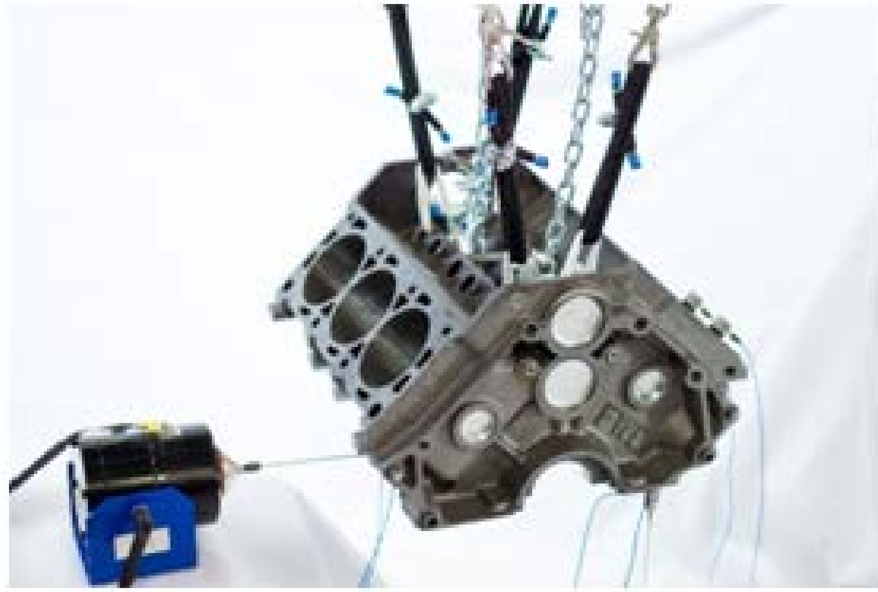

Figure 1.2

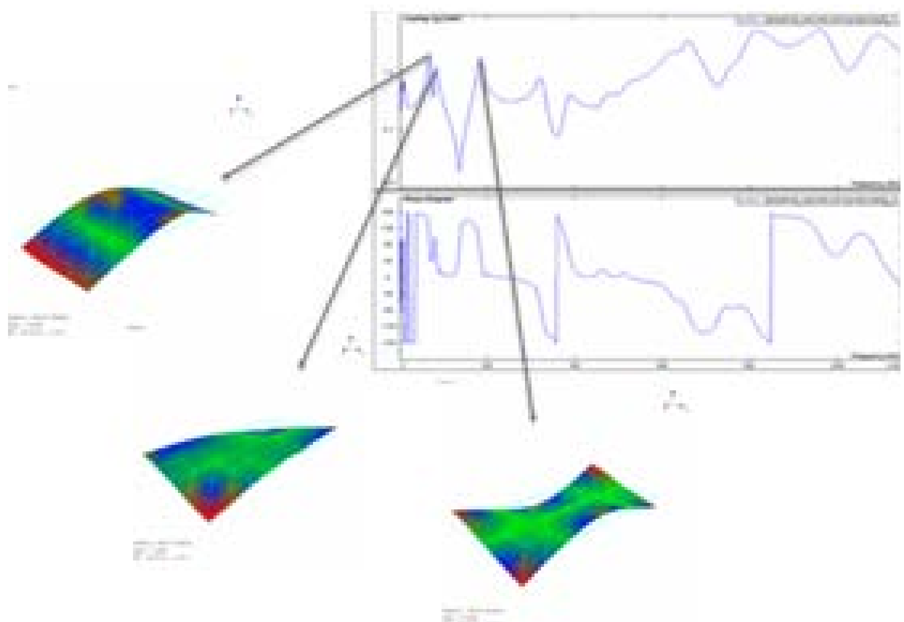

Figure 1.3

point from which all the modes will show up in the FRF with a valley in between. This driving point selection method can yield useful information for modal shaker testing. (Figure 1.2)

When dealing with a large or complicated structure under test, a modal shaker can be used to provide the excitation. The attachment of the modal shaker location can be determined using the results from the previously mentioned driving point selection method. A random type of excitation waveform is usually implemented to drive the modal shaker. Pure random (white noise) excitation would require windowing due to the leakage issue. Burst random, on the other hand, can be leakage free with the right burst rate selected. If this is the case, uniform window (no window) can be used. With pseudo random or periodic random, the same block of waveform will be repeat several times, with a few as delay blocks. Thus, the structure will settle down to a periodic response stage and the measured block will be leakage free. This will not require windowing. Furthermore, the multiple numbers of cyclic averages using the same block of excitation will reduce the noise further and yield highly accurate measurement results. Thus, the cost of increased test time will result in the FRF measured using the periodic type of excitation to have an improved accuracy.

When the structure under test has some structural symmetry, it may require multiple modal shakers to provide multiple inputs to the structure under test. There will be repeated modes or highly coupled modes on these structures under test. Using more than one modal shaker will excite these modes and provide enough information to identify these repeated or highly coupled modes.

Civil engineers working on bridges, buildings, stadiums, (etc.), are not always able to excite the test object. For testing these types of structures, the responses will only be available for measurements. Based on the measured responses, the so-called Operational Modal Analysis can be applied to identify the modal parameters of the structure under test.

In summation, experimental modal analysis involves three constituent phases: test preparation, frequency response measurements, and modal parameter identification. Test preparation involves the selection of a structure's support, type of excitation force(s), location(s) of excitation, hardware to measure force(s) and responses, determination of a structural geometry model (which consists of points of response to be measured), and identification of mechanisms (which could lead to inaccurate measurement). During the test, a set of FRF data is measured and stored, which is then analyzed to identify modal parameters of the tested structure.

Modal Parameter Identification

Modal parameter identification is heart of the modal analysis. It is the process of determining the dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes, and using them to formulate a modal model for its dynamic behavior. The formulated mathematical model is referred to as the modal model of the system and the information for the characteristics are known as its modal parameters. (Figure 1.3)

The dynamics of a structure are physically decoupled into the modes, represented by a natural frequency, damping factor and mode shape. This is clearly evidenced by the analytical solution of partial differential equations of continuous systems such as beams and strings. Modal analysis is based upon the fact that the vibration response of a linear time-invariant dynamic system can be expressed as the linear combination of a set of simple harmonic motions called the modes of structure. This concept is parallel to the use of a Fourier combination of sine and cosine waves to represent a complicated waveform. The natural modes of vibration are inherent to a dynamic system and are determined completely by its physical properties (mass, stiffness, damping) and their spatial distributions. Each mode is described in terms of its modal parameters: natural frequency, the modal damping factor and characteristic displacement pattern, namely mode shape. The mode shape may be real or complex. Each corresponds to a natural frequency. The degree of participation of each natural mode in the overall vibration is determined by properties of the excitation source(s) and by the mode shapes of the system.

There are different types of modal parameter identification algorithms. The SDOF method is applicable for lightly coupled modes identification and the MDOF method is applicable for heavily coupled modes identification. The local method may be used for non-stable measurements, while the global method is used for stable measurements. To identify modal parameters from the Multiple Input Multiple Output testing data, the Poly-reference method would be required.

The categories of modal analysis fall into the frequency domain and the time domain based on the domain of the curve fitting process. One popular time domain method is the Complex Exponential (CE), which is a local type; and the Least Square Complex Exponential (LSCE), a global type. In the case of MIMO FRF data, the equivalent poly-reference version poly-reference Frequency Domain (PTD) will be used. As for the frequency domain, many polynomial methods are developed.

With the help of a Mode Indicator Function (MIF), the natural frequencies can be labeled. The popular MIF functions are Multivariate, Complex, Real, and Imaginary Sum MIFs. The MIF indicators assist in the identification of repeated roots (repeated poles) and closely-spaced distinct roots. Nowadays, a stability diagram is commonly used for modal parameter identification. It employs the iteration process by increasing modal orders and stable poles (including the modal frequency and damping information) that can be clearly labelled. The physical poles sought are stable (as opposed to ‘computational poles’ sometimes produced by the process) and can be selected from the stability diagram for mode shape calculation using the residual data in addition to the identified poles. This two-stage modal parameter identification method is a common practice for experimental modal analysis.

The resulting mode shape table can be saved and used for mode shape animation. Modal Assurance Criterion (MAC) function and FRF synthesis is also available. These methods provide a means for modal parameter validation.

References

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