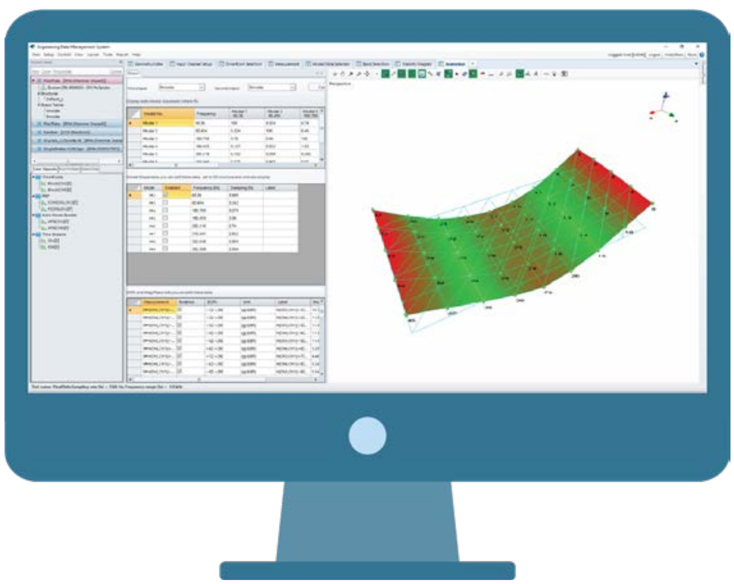
Applications of Experimental Modal Analysis

Application Note 045



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Introduction

Experimental Modal Analysis (EMA) has developed into a major technology for studying 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. (Figure 1.1)

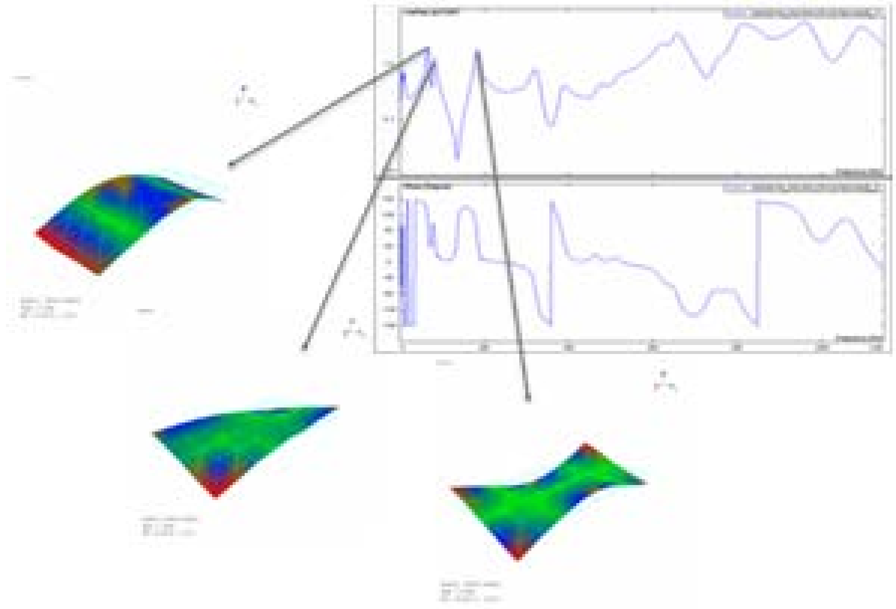

Figure 1.1

Structural vibration has been integral for the field of dynamic testing and analysis. Whether the object is a turbine blade rotating at high speed or a bridge sustaining the impact of traffic, Modal Analysis can be applied to provide insightful solutions.

Complete Modal Analysis includes both data acquisition and subsequent parameter identifications. From its inception to present day, Modal Analysis has been applied widely in mechanical and structural engineering for designing, optimizing, and validating purposes. It has been widely accepted for broad applications in industries such as automotive, civil engineering, aerospace, power generation, musical instruments, etc.

With modal analysis results, quite a large number of applications are performed for a variety of industries. This note will discuss popular applications that are performed by engineering in industries such as aerospace, automotive, (etc.)

Applications of Experimental Modal Analysis

Experimental Modal Analysis ultimately yields the modal model of a structure under test. Compared to measured FRFs or vibration responses, the modal model explicitly depicts the dynamic characteristics of a system in a decoupled fashion. Therefore, applications of modal analysis are closely related to utilizing the derived modal model in design, problem solving, and analysis.

Once the modal model of the structure under test is derived, a number of applications can be performed. Some applications of modal analysis involve direct use of modal data from measurement while others use the data for further analysis. Applications of modal analysis are reviewed in the following paragraphs.

Troubleshooting

The modal model from Experimental modal analysis can be used for troubleshooting purposes in order to gain an insight into a problematic dynamic structure. This is one of the most popular applications of experimental modal analysis since its emergence. Troubleshooting relies on experimentally derived natural frequencies, damping factors and mode shapes of the structure. This data provides a fundamental understanding of the structural characteristics and often reveals the root causes of dynamic problems the system encounters in real life.

Correlation Analysis with Finite Element Analysis

Many structural dynamics applications rely upon having an accurate mathematical model for a dynamic structure. Such a theoretical model can be derived from the finite element analysis. The solutions from an FEA model, which is in the form of mass and stiffness matrices, can be essential for further applications, i.e., sensitivity analysis and prediction per proposed structural changes. However, due to the complexity and uncertainty of the physical structure, it is not practical to expect such an FEA model to be very accurate.

The feasible approach is to carry out an experimental measurement of the structure, derive its modal model, use it to correlate with the FEA model, and then update it. The philosophy behind this model correlation is that the modal model derived from measurement, though incomplete due to lack of sufficient numbers of vibration modes and measured locations, truly represents the structure's dynamic behavior. Thus, it can be used to 'correct' the FEA model, should any discrepancies occur between them.

Structural Dynamic Modification

Structural dynamic modification makes changes on mass, stiffness or damping of a dynamic structure. These physical changes will certainly alter the dynamic behavior of a system. A simulation and prediction of "what if' can be conducted by using the modal model of the structure derived from the EMA. The effect of hypothetical physical changes on the dynamic behavior can be derived without another complete analysis or the actual structural changes. For instance, if a lumped mass is to be added to part of the system, then the existing modal model and the mass together should predict a new modal model with the structural modification. This is particularly useful in an early design stage to optimize the dynamic characteristics of a new design, or to improve a structure's dynamic behavior after its modal model is derived from a prototype.

Reduction of FEA model

In FEA modeling of a dynamic structure, the number of elements and nodes used determines the size of the FEA model. Although employment of more nodes does not necessarily translate into greater accuracy of the modeling results, it is often helpful. However, when only the low frequency range dynamic behavior of the modeled structure is of interest, a highly reduced mathematical model will be preferred. Such a reduced model can be derived either from a modal model of the structure, or from the original FEA model using various modeling reduction algorithms. In both cases, the modal model is essential in the process of model reduction or for the evaluation of the results.

Forced Response Prediction

Another application of modal analysis is the prediction of vibration responses to a given force. With an established modal model, structural dynamic responses to a defined force input can be computed. For instance, upon knowing the modal model of a vehicle, the measurement of test track vibrations can be used to predict the vehicle's response on the track before it is driven. Using the superposition principle, a response due to several forces can also be predicted. The difficulty associated with this application often lies in accurately estimating or measuring the forces. An experimentally derived modal model usually provides damping factors of a structure which are crucial in determining an accurate response prediction. Once the modal model of a structure is adequately determined, it becomes possible to predict the structural response for any combination of input forces. This will provide a scientific basis for studying the structural integrity with a known dynamic environment. When the structural vibration responses are in the form of dynamic strain, the response prediction could be keen in forecasting the fatigue life of the structure.

Force Identification

Force identification is an inverse problem which determines the applied forces from system response measurements, assuming the modal model is known. In practice, forces which induce vibration of a system are not always measurable. However, it is possible to identify them using the response measurement and the modal model of the system. The identification of forces inducing severe vibration is highly significant for some applications. For instance, a loosened bearing inside a turbine engine may breed an excitation force that introduces excessive vibration. This sort of excitation force has the potential of causing a catastrophic structural failure.

Sub-structural Coupling

It is often required to predict the dynamic behavior of a whole structure from the knowledge of the behavior of its components. This process is known as sub-structure coupling. There are several practical reasons why the behavior of the whole structure is not measured or modeled directly. One reason is to break a complex dynamic problem into manageable parts. Many algorithms of sub-structure coupling are based on the modal parameters from components or sub-structures. Sub-structure coupling can also be effectively used in finite element analysis when the model of a structure is too complex for computer capacities.

Active Vibration Control

A traditional control problem depends upon a reliable plant model to derive control laws from its observers. For active vibration control of a structure as a plant, it is imperative that an accurate mathematical model exists, which delineates its dynamic characteristics. Experimental modal analysis is the ideal tool to serve this purpose. An excellent example is the active vibration control of a tall building under wind loading. By combining an accurate modal model of the building with proper filtering techniques, it is possible to devise actuators and sensors while forming a feedback control loop so that the selected vibration modes will be brought under control.

Practical Applications of Modal Analysis

The past several decades have yielded reports of numerous modal analysis applications covering wide areas of engineering, science, and technology. The application scope of modal analysis is expected to undergo a significant expansion in the coming years as it follows a trend of growth. Practical applications of modal analysis are largely related to advances in experimental technology.

The majority of practical application cases being reported have been from the fields of aerospace engineering, automotive engineering, and mechanical engineering in particular. This does not discredit the growth of interdisciplinary applications of modal analysis.

In automotive engineering, the enormous commercial and safety aspects associated with redesigning a vehicle obligate a thorough understanding of dynamic properties regarding vehicular structures and the repercussion of any design changes. Keen interest has been placed on combining both experimental modal analysis and finite element analysis in the study of automotive components. Modern vehicle structures must be low in weight and high in strength. A combination of both analytical and experimental modal analysis enables improvement in the design of automotive components and enhancement of a vehicle's dynamic properties.

Experimental modal analysis as a troubleshooting tool also plays a crucial role in the study of vehicle noise and vibration harshness (NVH). A simple modal analysis of a body-in-white or a sub-frame structure is a typical application. More sophisticated applications have also been achieved, such as those involved in modal sensitivities of vehicle floor panels and structural optimization for vehicle comfort. Further examples include vehicle fatigue life estimation, vehicle suspension with active vibration control mechanism, the condition monitoring of the vehicle engine, and a diagnostic system for the vehicle engine.

Another prominent modal analysis application is the study of vehicle noise. Modal analysis is used as a tool to understand structure-borne noise from vehicle components. It analyzes airborne sound transmission into vehicle cabins through door-like structures and the path noise takes to transmit itself in vehicles. A more advanced application of modal analysis involves interior noise reduction through structural optimization or redesign. Overall, modal analysis has been an effective tool in automotive engineering for improving a vehicle's NVH performance.

The rapid development in the aerospace industries has challenged many disciplines of engineering with diverse technological difficulties. The structural dynamics of both aircraft and spacecraft structures have been a significant catalyst to the development of modal analysis. Aircraft and spacecraft structures impose stringent requirements on structural integrity and dynamic behavior, which are shadowed by rigorous endeavors to reduce weight. The large dimension of spacecraft structures also asserts a new stimulus for structural analysts. Establishing an accurate mathematical model is often a required task for aircraft and spacecraft structures. Experimental modal analysis has provided to be an indispensable means of verifying a mathematical model derived from computer modeling.

Modal testing has reportedly been carried out on structures ranging from a scaled down aircraft frame and a whole satellite to an unmanned air vehicle. This asserts a special significance in terms of damping properties, nonlinearities, accurate force, and response estimation – which computer modeling alone often finds itself powerless to deal with. In fact, a majority of early publications in the 1980s on updating finite element models using experimental data originated from aeronautical industries. Large amplitudes of force and response experienced by aircraft and spacecraft structures stretched the linearity assumption of modal theory to its very limit. The necessity to enter the twilight zone of nonlinear dynamic behavior became real. The complexity and dimension of aircraft structures was also responsible for the rapid theoretical development of sub-structural coupling and synthesis. In some multi-disciplinary topics such as fluid induced vibration and flutter analysis, modal analysis has also been found to be a useful tool. Light and large-scale on-orbit space structures impose a control problem for structural engineers. The research in this area has led to notable advances in recent years on blending modal analysis and active control of space structures.

Modal analysis has also found increasing acceptance in the civil engineers' community where structural analysis has always been a critical area. The concern of dynamic behavior of civil structures under seismic and wind loading warrants the application of modal analysis. Civil structures are usually much larger than mechanical and aeronautical structures for which modal testing was originally developed. A wide range of applications are concerned with the prediction of responses in civil construction due to ambient vibration or external loadings. This response prediction endeavor relies on an accurate mathematical model which can be derived by modal analysis. Examples of such applications range from tall buildings, soil-structure interaction to a dam-foundation system. The real-life force inputs involved in civil structures are earthquake waves, wind, ambient vibration, traffic load, etc.

Recent years have seen an upsurge of modal testing on bridges to complement traditional visual bridge inspection and static testing. Modal testing has been used as an effective non-destructive testing technique to promptly locate the presence of critical defects. This can provide invaluable information for bridge maintenance and budgetary decision making. Such modal testing can be done using either traffic loading, a shaker or impact input, depending on the span and size of the bridge. Bridge testing is strongly related to the research of structural damage detection using modal test data.

Modal analysis has been successfully used across all types of engineering fields. A good example is acoustics and musical instruments. Acoustic modal analysis has been used to analyze the dynamic characteristics of speaker systems. This analysis provides crucial information in the design of new speakers with improved sound quality. Experimental modal analysis has been used to study a number of musical instruments, such as violins and guitars. These experiments help decipher the mystery behind the generations of craftsmanship and provide manufacturers of musical instruments with useful scientific data for improving product quality. Moreover, it assists in establishing an effective procedure of scientifically evaluating a musical instrument.

References

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