Modal Analysis A Tool for Design and Optimization

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ABSTRACT
The magnitude of change in natural frequencies is a function of the severity and of the location of deterioration in structures. Ratios of changes in natural frequencies normalizes with respect to the largest frequency change are independent of severity for small deterioration and can serve to indicate the location of deterioration directly. Specific deterioration events have an associated characteristic ensemble of ratios of natural frequency changes that may be compiled in advance to form a data base for later interpretation of observed modal parameter changes. The modal analysis method is holds promise as a condition monitoring tool for bridges, rotating machineries and other skeletal structures. High speed impellers, motors, engines and similar can fail due to fatigue caused by vibration especially at resonance, a condition wherein the excitation frequency equals one of the natural frequencies of the system inducing very large deformations. Because of the requirements on geometric, kinematic, and dynamic similarity, real or working models are quite expensive and difficult to construct and to test. FEA is a powerful technique to obtain satisfactory results, also reducing time of the testing or analysis.

The review on nondestructive inspection of structures by modal analysis of vibration response is studied in this paper.

Keywords
Modal Analysis, FEA, Damping, Structural Dynamics, Mode Shape

1. INTRODUCTION
Effective control of noise and vibration, whatever the application, usually requires several techniques, each of which contributes to a quieter environment. For most applications, noise and vibration can be controlled using four methods: (1) absorption (2) use of barriers and enclosures (3) structural damping and (4) vibration isolation. Although there is a certain degree of overlap in these classes, each method may yield a significant reduction in vibration and noise by proper analysis of the problem and application of the technique, but for current industrial applications the remedy after the problem arises is of old age, it requires the prediction of any problem before the production to reduce or eliminate the need of prototype or destructive testing where the FEA is a reliable tool during the stages of design and optimization [1].

The majority of structures can be made to resonate, i.e. to vibrate with excessive oscillatory motion and the small forces can result in critical deformation, and possibly, damage can be induced in the structure. Resonant vibration is mainly caused by an interaction between the inertial and elastic properties of the materials within a structure. Resonance is often the cause of, or at least a contributing factor to many of the vibration and noise related problems that occur in structures and operating machinery. To better understand any structural vibration problem, the resonant frequencies of a structure need to be identified and quantified. Today, modal analysis has become a widespread means of finding the modes of vibration of a machine or structure. In every development of a new or improved mechanical product, structural dynamics testing on product prototypes and finite element modal analysis is used to assess its real dynamic behavior.

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Many software packages e.g. NASTRAN, ABAQUS, RADIOS, ANSYS, OPTISTRUCT etc. are available for modal analysis, of which ANSYS and ABAQUS are mostly preferred by industries.

1.1 Modal Analysis for Rotor System Dynamics
Modal analysis in FEM is normally used to determine the natural frequencies, mode shapes and the location of nodal plane. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. These are also necessary if a spectrum analysis or a mode superposition harmonic or transient analysis is supposed to be implemented [1].

Condition monitoring of rotating machinery is a critical subject in most industries. It can prevent catastrophic failure of machines, production losses and reduces the downtime for maintenance. The vibration analysis technique consists mainly of vibration measurement its interpretation and modal or harmonic analysis. The interpretation of the results is mainly done by relating the measured frequencies with their relevant causes such as unbalance, misalignment, bearing defects, resonance etc [2].

Rotordynamics, a branch of dynamics applied to Turbomachinery, differentiate between static and dynamic natural frequencies which occur at specific geometric vibrational modal shapes. The centrifugal force influences the stiffness of the impeller or rotor which in turn changes the natural frequencies and modal shapes into their dynamics counterparts. The latter are functions of mass, mass distribution and speed which is why a vibration analysis of high speed rotors has become essential to obtain higher speeds while reducing weight [3]. The main purpose of the system's dynamics characteristics analysis is to determine the dynamic natural frequencies as well the modal shapes along with their impact over a range of tip speeds. In this analysis the impeller or rotor's natural frequencies and modal shapes must be obtained before going into the dynamic part. Accordingly modal analysis is performed for the first ten to twenty modes assuming no external forces [4].

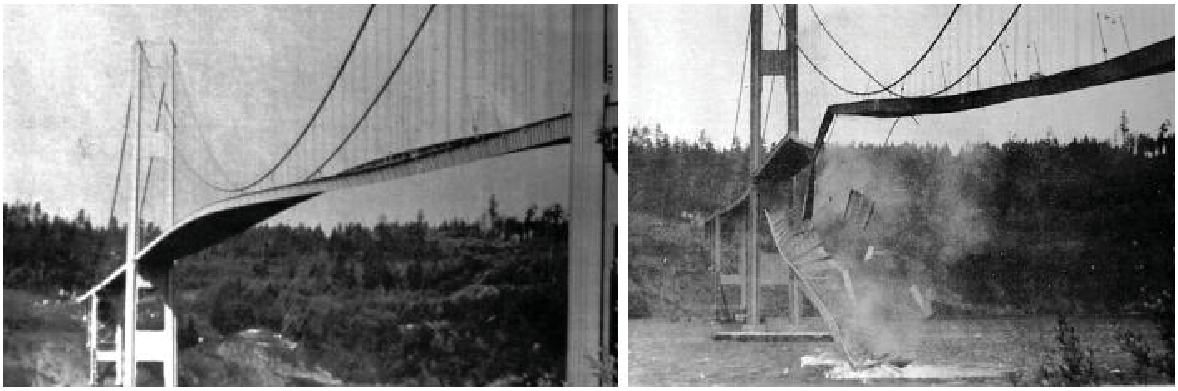

Fig.1 Tacoma Narrows Bridge Disaster

1.2 Modal Analysis for Civil Structures/ Aircraft and Bridge System Dynamics:

The Tacoma Narrows bridge disaster is a typical example of resonance in structures. On November 7, 1940, the Tacoma Narrows suspension bridge collapsed due to wind induced vibration (i.e. resonance or flutter). Situated near the Washington, the bridge had only been open for traffic four months ago. Wings of airplanes can be subjected to similar flutter phenomena during flight. Before an airplane is released, flight flutter tests have to be performed to detect possible onset of flutter. The classical flight flutter testing approach is to expand the flight envelope of a airplane by performing a vibration test at constant flight conditions, curve-fit the data to estimate the resonance frequencies and damping ratios, and then to plot these frequencies and damping estimates against flight speed or Mach number. The damping values are then extrapolated in order to determine whether it is safe to proceed to the next flight test point. Flutter will occur when one of the damping values tends to become negative. Before starting the flight tests, ground vibration tests as well as numerical simulations and wind tunnel tests are used to get some prior insight into the problem [9, 11].

1.3 What are Modes?

Modes (or resonances) are inherent properties of a structure. Resonances are determined by the material properties (mass, stiffness, and damping properties), and boundary conditions of the structure. Each mode is defined by a natural (modal or resonant) frequency, modal damping, and a mode shape. If either the material properties or the boundary conditions of a structure change, its modes will change. For instance, if mass is added to a vertical pump, it will vibrate differently because its modes have changed. At or near the natural frequency of a mode, the overall vibration shape (operating deflection shape) of a machine or structure will tend to be dominated by the mode shape of the resonance [7].

1.4 Two Kinds of Modes

Modes are further characterized as either rigid body or flexible body modes. All structures can have up to six rigid body modes, three translational modes and three rotational modes. If the structure merely bounces on some soft springs, its motion approximates a rigid body mode [5].

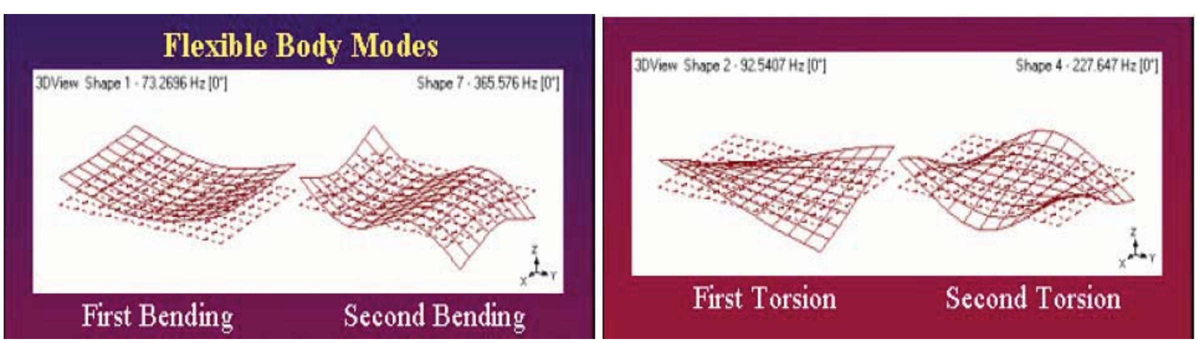

Fig. 2 Flexible Body Modes

1.5 Why Are Modes Dangerous?

Figure 3 shows why modes cause structures to act as "mechanical amplifiers". At certain natural frequencies of the structure (its modal frequencies), a small amount of input force can cause a very large response. This is clearly evident from the narrow peaks in the FRF. (When a peak is very narrow and high in value, it is said to be a high Q resonance.)

If the structure is excited at or near one of the peak frequencies, the response of the structure per unit of input force will be large. On the other hand, if the structure is excited at or near one of the anti-resonances (zeros or inverted peaks), the structural response will be very small per unit of input force [6].

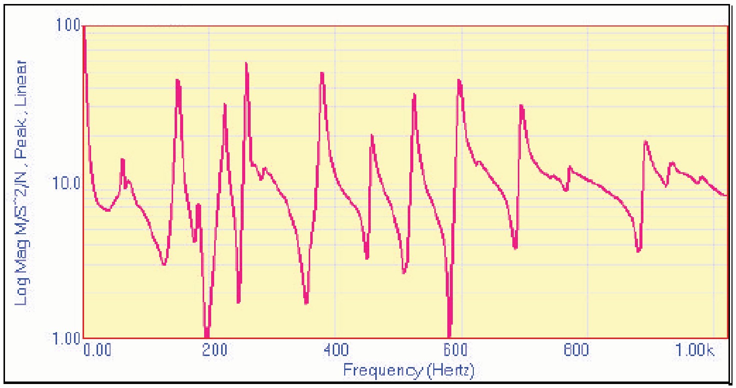

Fig. 3 High Level Resonance Peaks

2. LITERATURE STUDY

Roller bearings are intense sources of vibration in the low frequency range, where they form a discrete part of the spectrum, and in the high frequency range. B. I. Zubrenkov and V. V. Sen'kina [1] investigated the eigen frequencies and forms of oscillation of rotary machines on radial ball bearings, their study compared the frequency characteristics of oscillatory systems, by means of the spectral forms of the exciting signals and the responses of the structural element. Their proposed method of investigating the elastic properties permitted the reduction in the vibration of asynchronous motors by factor of 3–5.

S. Kolla, Y. Anil Kumar,S. Rajesh [2], have worked on noise reduction of air blower casing using composites. In his paper the various sound pressure values at different frequencies of both metal and composite blower were analyzed, natural frequency analysis was carried out by the authors, and the noise level was simulated using SYSNOISE software and concluded that the noise was reduced to 9.7% when composite material is used.

V. Hariharan and P. S. S. Srinivasan [3] performed experimental studies on a rotor dynamic test apparatus to predict the vibration spectrum for shaft misalignment. A self designed simplified 3 pin type flexible coupling was used in the experiments. The rotor shaft accelerations were measured using dual channel vibration analyzer (ADASH) under the misalignment condition. The experimental and numerical (ANSYS) frequency spectra were obtained. The experimental predictions are in agreement with the ANSYS results. Also it is found that if twice the shaft running speed (2X) is at or close to one of the system natural frequencies, the misalignment effect can be amplified and a high acceleration level at 2X shafts running speed is pronounced in the frequency spectrum.

3. THE "MODAL" MODEL:

Modes are inherent properties of a structure, and are determined by the material properties (mass, damping, and stiffness), and boundary conditions of the structure. Each mode is defined by a natural (modal or resonant) frequency, modal damping, and a mode shape (i.e. "modal parameters") [8]. If either the material properties or the boundary conditions of a structure change, its modes will change. For instance, if mass is added to a structure, it will vibrate differently.

No structural constraint is used for the modal analysis. This produces a simulation of an unrestrained model or assembly. This state is similar to the state of physical testing where the structure rests on the table with no restriction [9].

By performing modal analysis the modal parameters can be found, and a complete dynamic model of the system can be produced. This allows discovery of potential vibration problems at an early stage in the design. And the effect of subsequent mass, stiffness, and damping modifications, designed to solve any problems, can be investigated [5].

4. TROUBLE-SHOOTING NOISE AND VIBRATION PROBLEMS:

First we find the source of the problem by using vibration measurements on the structure under operating conditions. If the problem is caused by a structural resonance (in fact a structural weakness), we can apply modifications to the dynamic model and find alternative ways to remedy the structural weakness. Adequate damping would be needed for the structure to go smoothly through its critical operational conditions [2].

5. DESIGN OPTIMIZATION:

Analysis in FEA and prototype testing of structures allow us to optimize designs by simulating the response of the prototype and results of analysis, and making modifications to the dynamic model. In some cases it may require to design and redesign of a structure to achieve a degree of stabilization considering the criteria of vibration and noise [3].

6. STRUCTURAL MONITORING:

The modal parameters can be used to monitor the condition of structures. As defects imperfections such as cracks develop, one or more of the modal parameters of the Structure will change [4].

7. VERIFYING ANALYTICAL MODELS:

We can use analytical models (derived through theoretical as opposed to experimental techniques) extensively in, the early design stage of aircraft, spacecraft, and most other vehicles. These models usually obtained through the finite element technique, are also used for simulation and optimization. Once we have built a prototype structure we do a modal test and compare the resulting model with the analytical model. This comparison then allows us to verify or improve the analytical model [5].

7.1 Structural Damping:

Structural damping reduces both impact generated and steady state noises at their source. It dissipates vibrational energy in the structure before it can build up and radiate as sound. Damping, however, suppresses only resonant motion. Forced, non resonant vibration is rarely attenuated by damping, although application of damping materials sometimes has that effect because it increases the stiffness and mass of a system [4]. A damping treatment consists of any material (or combination of materials) applied to a component to increase its ability to dissipate mechanical energy. It is most often useful when applied to a structure that is forced to vibrate at or near its natural (resonant) frequencies, is acted on by forces made up of many frequency components, is subject to impacts or other transient forces, or transmits vibration to noise-radiating surfaces [8]. Although all materials exhibit a certain amount of damping, many (steel, aluminum, magnesium and glass) have so little internal damping that their resonant behavior makes them effective sound radiators. By bringing structures of these materials into intimate contact with a highly damped, dynamically stiff material, it is possible to control these resonances. Of the common damping materials in use, many are viscoelastic; that is, they are capable of storing strain energy when deformed, while dissipating a portion of this energy through hysteresis.

Several types are available in sheet form. Some are adhesive in nature and others are enamel-like for use at high temperatures [9].

7.2 Vibration Isolation:

This method reduces the transmission of vibrational energy from one system to another. Common vibration isolators are steel springs, rubber pads or bellows. These devices are available in many shapes and are capable of isolating masses weighing from a few pounds to thousands of pounds. An automobile suspension is a good example of damped isolation. Shock absorbers dissipate energy by pumping a fluid through orifices that offer a predetermined resistance to high-velocity flow. Many isolation systems use elastomeric materials to provide both the spring force and damping. Some rubbers are capable of achieving useful damping at certain frequencies, although at low frequencies most exhibit loss factors less than 0.2, or roughly 10 percent of critical damping [7].

8. SUMMARY

The bottom line in noise and vibration control, as in virtually all other engineering efforts, is cost effectiveness, which translates into achieving workable, inexpensive solutions to complex problems. Maximum advantages of reducing noise and vibration at the source can be achieved by careful planning, thoughtful design, and proper choice of materials and structures specifically engineered for the task. There is the engineering judgment in selection of damping materials and systems to make it possible to design products that operate more quietly, with lesser vibration and greater precision, without being necessarily more expensive or difficult to build.

The FEM model is a computer approximation of an actual structure. The error of this approximation will depend on the consideration of all the system components, their accurate properties, correct selection of the elements and refinement of the model.

The condition monitoring, protection and fault diagnostics system is inherent module in the failure prevention technology of modern machines. This paper is dedicated to study of dynamics, condition monitoring, fault diagnosis and modeling of high speed machinery and structural mechanical failure. Also the use of modal analysis technique found to be having competitive advantage with better performing products and a source of prediction of vibration modes.

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