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Experimental modal analysis in research

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Abstract: Experimental modal analysis has grown steadily in popularity since the advent of the digital FFT spectrum analyser in the 1970's. This days impact testing has become widespread as a fast and economical means of finding the vibration modes of a machine or structure. Its significantly use ascending roles can be seen also in the civil engineering industry [6]. This paper reviews the main topics associated with experimental modal analysis including making FRF measurements, modal excitation techniques, and modal parameter estimation from a set of FRFs.

Keywords: experimental modal analysis, FRF function, vibration modes, testing.

1. Introduction

Modes are used as a simple and efficient means of characterizing vibrations. The majority of structures can be made to resonate. That is, under the proper conditions, a structure can be made to vibrate with excessive, sustained, oscillatory motion [1,9].

Vibrations are caused by an interaction between the inertial and elastic materials properties within a structure. Resonant vibration is often the cause, or at least a contributing factor to many of the vibration related problems that occur in civil engineering structures.

To better understanding a structural of vibration problems, the resonances of a structure need to be identified and quantified. A common way of doing this is to define the structure's modal parameters [4].

2. Vibration types

All vibration is a combination of both forced and resonant vibration. Forced vibration can be due to:

- internally generated forces,
- unbalances,
- external loads,
- ambient excitation.

Resonant vibration occurs when one or more of the resonances or vibration natural modes of a structure is excited. Resonant vibration typically amplifies the vibration response far beyond the stress level, and strain caused by static loading.

3. Modes and operating definition shape description

Modes 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 [2,10].

At or near the natural frequency of a mode, the overall vibration shape (operating deflection shape) of a building structure will tend to be dominated by the mode shape of the resonance.

An operating deflection shape (ODS) is defined as any forced motion of two or more points on a structure. Specifying the motion of two or more points defines a shape. Stated differently, a shape is the motion of one point relative to all others. Motion is a vector quantity, which means that it has both a location and a direction associated with it. Motion at a point in a direction is also called a Degree Of Freedom, or DOF [3,6].

That is, experimental modal parameters are obtained by artificially exciting a structure, measuring its operating deflection shapes (motion at two or more DOFs), and post-processing the vibration data.

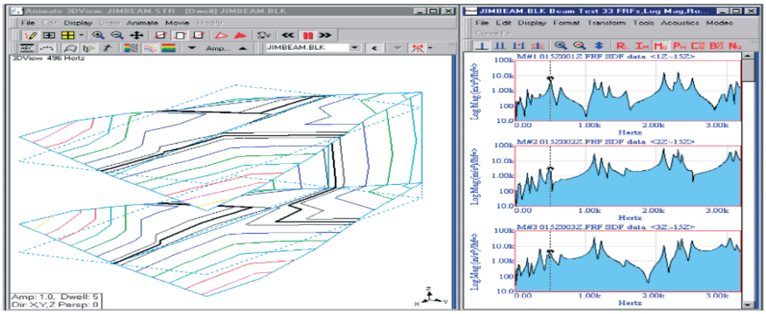

Fig. 1. Frequency Domain ODS From a Set of FRFs

The figure above shows an ODS being displayed from a set of FRF measurements with the cursor located at a resonance peak. In this case, the ODS is being dominated by a mode and therefore is a close approximation to the mode shape.

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 [5,6].

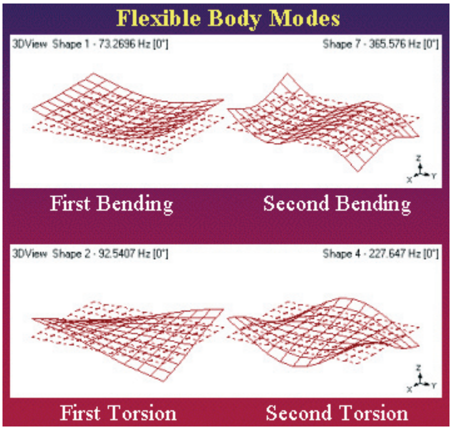

Fig. 2. Flexible Body Modes

Many vibration problems are caused, or amplified by the excitation of one or more flexible body modes. Figure 2 shows some of the common fundamental (low frequency) modes of a plate [6].

4. FRF measurements

The Frequency Response Function (FRF) is a fundamental measurement that isolates the inherent dynamic properties of a structure. Experimental modal parameters (frequency, damping, and mode shape) are also obtained from a set of FRF measurements.

The FRF describes the input-output relationship between two points on a structure as a function of frequency, as shown in Figure 3. Since both force and motion are vector quantities, they have directions associated with them. Therefore, an FRF is actually defined between a single input DOF (point & direction), and a single output DOF[1,3,6].

An FRF is a measure of how much displacement, velocity, or acceleration response a structure has at an output DOF, per unit of excitation force at an input DOF.

Figure 3 also indicates that an FRF is defined as the ratio of the Fourier transform of an output response (X(ω) divided by the Fourier transform of the input force (F(ω) that caused the output [2,6].

X(ω) - X(ω)   F(ω) - F(ω)

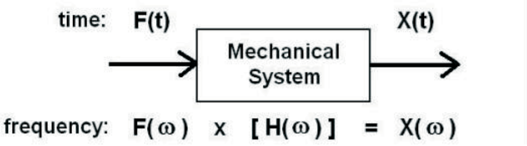

Fig. 3. Block Diagram of an FRF

Depending on whether the response motion is measured as displacement, velocity, or acceleration, the FRF and its inverse can have a variety of names:

- Compliance ⇔ (displacement / force)
- Mobility ⇔ (velocity / force)
- Inertance or Receptance ⇔ (acceleration / force)
- Dynamic Stiffness ⇔ (1 / Compliance)
- Impedance ⇔ (1 / Mobility)
- Dynamic Mass ⇔ (1 / Inertance)

An FRF is a complex valued function of frequency that is displayed in various formats, as shown in Figure 4.

Figure 5 points out another reason why vibration is easier to understand in terms of modes of vibration. It is a plot of the Log Magnitude of an FRF measurement (the solid curve), but several resonance curves are also plotted as dotted lines below the FRF magnitude. Each of these resonance curves is the structural response due to a single vibration mode [6,8].

The overall structural response (the solid curve) is in fact, the summation of resonance curves. The overall response of a structure at any frequency is a summation of responses due to each of its modes. It is also evident that close to the frequency of one of the resonance peaks, the response of one mode will dominate the frequency response.

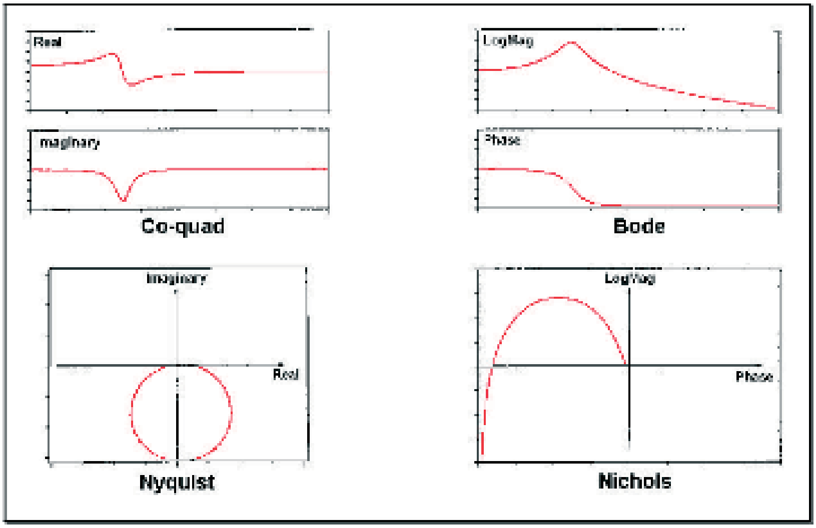

Fig. 4. Alternate Formats of the FRF

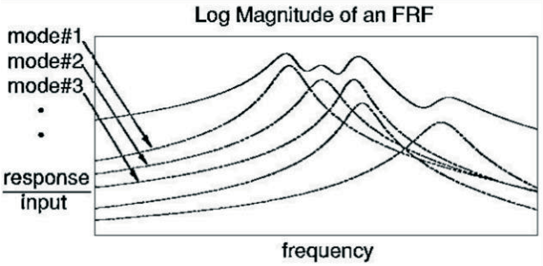

Fig. 5. Response as Summation of Modal Responses

FRF CALCULATION

Although the FRF was previously defined as a ratio of the Fourier transforms of an output and input signal, is it actually computed differently in all modern FFT analyzers. This is done to remove random noise and non-linearity's (distortion) from the FRF estimates.

Tri-Spectrum Averaging

The measurement capability of all multi-channel FFT analyzers is built around a tri-spectrum averaging loop, as shown in Figure 6. This loop assumes that two or more time domain signals are simultaneously sampled. Three spectral estimates, an Auto Power Spectrum (APS) for each channel, and the Cross Power Spectrum (XPS) between the two channels, are calculated in the tri-spectrum averaging loop. After the loop has completed, a variety of other cross channel measurements (including the FRF), are calculated from these three basic spectral estimates.

In a multi-channel analyzer, tri-spectrum averaging can be applied to as many signal pairs as desired. Tri-spectrum averaging removes random noise and randomly excited nonlinearity's from the XPS of each signal pair. This low noise measurement of the effective linear vibration of a structure is particularly useful for experimental modal analysis [2,4,6].

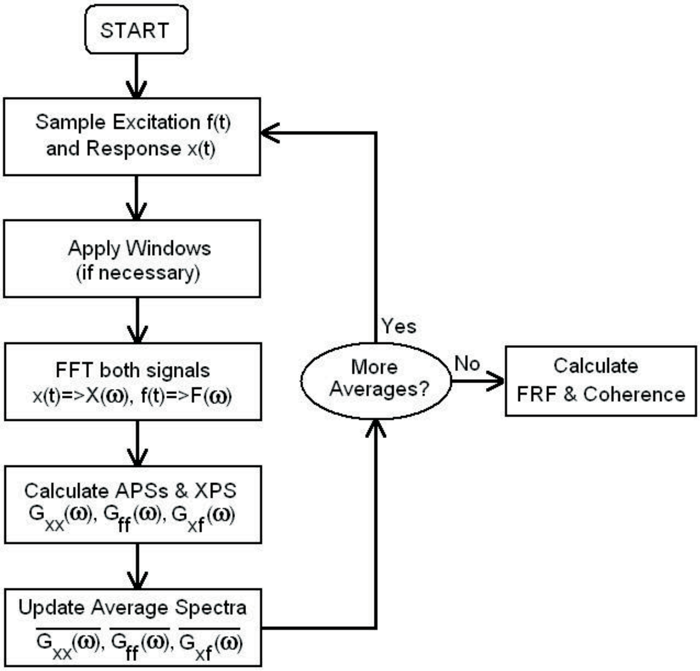

Fig. 6. Tri-Spectrum Averaging Loop

THE FRF MATRIX MODEL

Structural dynamics measurement involves measuring elements of an FRF matrix model for the structure, as shown in Figure 6. This model represents the dynamics of the structure between all pairs of input and output DOFs [6].

The FRF matrix model is a frequency domain representation of a structure's linear dynamics, where linear spectra (FFTs) of multiple inputs are multiplied by elements of the FRF matrix to yield linear spectra (FFTs) of multiple outputs.

FRF matrix columns correspond to inputs, and rows correspond to outputs. Each input and output corresponds to a measurement DOF of the test structure.

Modal Testing

FRF measurements are usually made under controlled conditions, where the test structure is artificially excited by using either an impact hammer, or one or more shakers driven by broadband signals. A multi-channel FFT analyzer is then used to make FRF measurements between input and output DOF pairs on the test structure [6,7,8].

Measuring FRF Matrix Rows or Columns

Modal testing requires that FRFs be measured from at least one row or column of the FRF matrix. Modal frequency & damping are global properties of a structure, and can be estimated from any or all of the FRFs in a row or column of the FRF matrix. On the other hand, each mode shape is obtained by assembling together FRF numerator terms (called residues) from at least one row or column of the FRF matrix.

Impact Testing

When the output is fixed and FRFs are measured for multiple inputs, this corresponds to measuring elements from a single row of the FRF matrix. This is typical of a roving hammer impact test.

Shaker Testing

When the input is fixed and FRFs are measured for multiple outputs, this corresponds to measuring elements from a single column of the FRF matrix. This is typical of a shaker test.

Single Reference (or SIMO) Testing

The most common modal testing type is done with either a single fixed input or a single fixed output. A roving hammer impact test using a single fixed motion transducer is a common example of single reference testing. The single fixed output is called the reference in this case.

When a single fixed input (such as a shaker) is used, this is called SIMO (Single Input Multiple Output) testing. In this case, the single fixed input is called the reference.

Multiple Reference (or MIMO) Testing

When two or more fixed inputs are used, and FRFs are calculated between each of the inputs and multiple outputs, then FRFs from multiple columns of the FRF matrix are obtained. This is called Multiple Reference or MIMO (Multiple Input Multiple Output) testing. In this case, the inputs are the references [6,9,10].

When two or more fixed outputs are used, and FRFs are calculated between each output and multiple inputs, this is also multiple reference testing, and the outputs are the references.

Multi-reference testing is done for the following reasons:

- the structure cannot be adequately excited from one reference,
- all modes of interest cannot be excited from one reference,
- the structure has repeated roots, modes that are so closely coupled that more than one reference is needed to identify them.

5. Exciting modes with impact testing

With the ability to compute FRF measurements in an FFT analyser impact testing was developed during the late 1970's, and has become the most popular modal testing method used today. Impact testing is a fast, convenient, and low cost way of finding the modes of machines and structures [6,8].

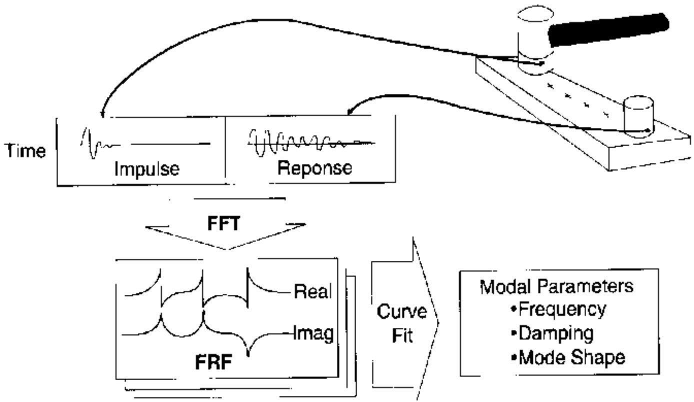

Fig. 7. Impact Testing

Impact testing is depicted in Figure 7. The following equipment is required to perform an impact test:

- an impact hammer with a load cell attached to its head to measure the input force,
- an accelerometer to measure the response acceleration at a fixed point & direction,
- a 2 or 4 channel FFT analyzer to compute FRFs,
- post-processing modal software for identifying modal parameters and displaying the mode shapes in animation.

A wide variety of structures and machines can be impact tested. Of course, different sized hammers are required to provide the appropriate impact force, depending on the size of the structure; small hammers for small structures, large hammers for large structures. Realistic signals from a typical impact test are shown in Figure 8.

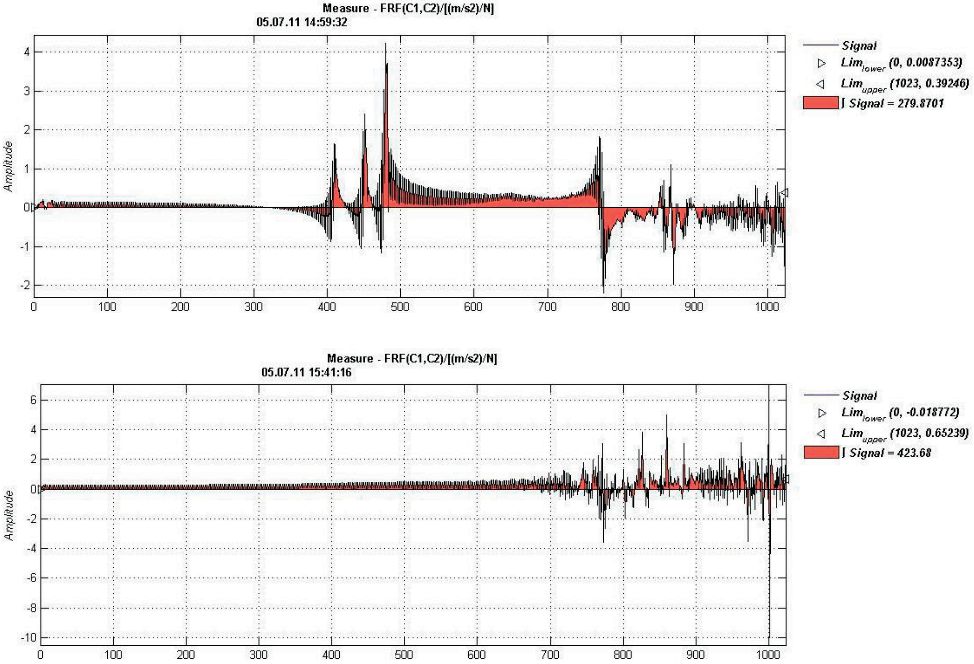

Fig.8. Realistic FRF signals form an impact test of wall bricks

6. Conclusions

Modern experimental modal analysis techniques have been reviewed in this paper. The three main topics pertaining to modal testing; FRF measurement techniques, excitation techniques, and modal parameter estimation (curve fitting) methods were covered. FRF based modal testing started in the early 1970's with the commercial availability of the digital FFT analyser, and has grown steadily in popularity since then. The modern modal testing techniques presented here are just a brief summary of the accumulation of the past 30 years of progress.

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