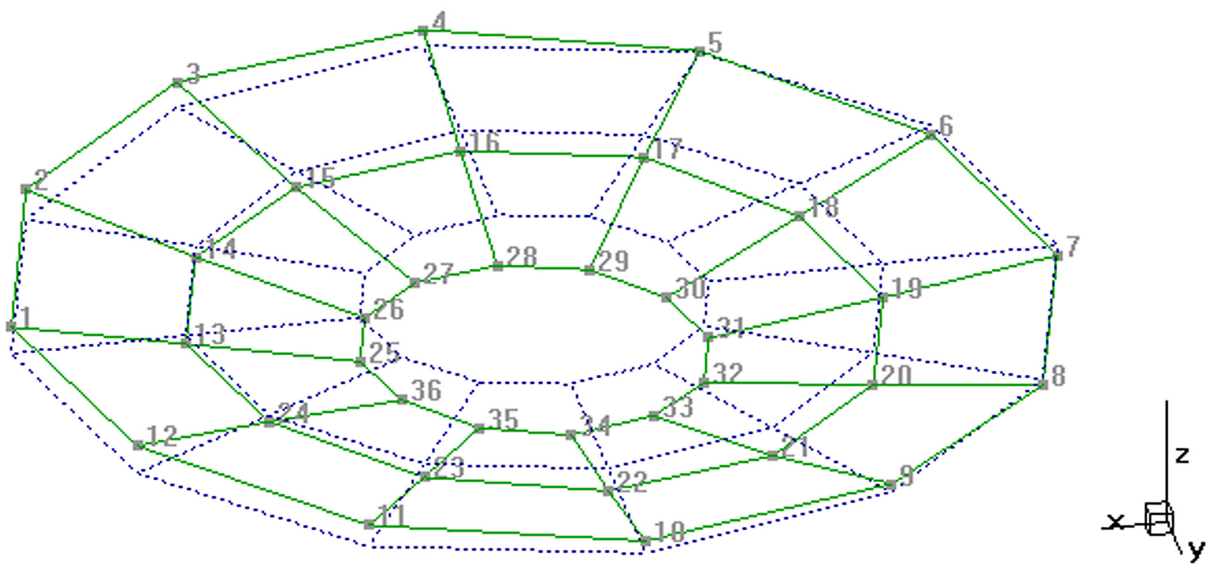
Application Note

Normal Mode Tuning

Introduction

Modal testing is performed to characterise a structure's dynamic properties in terms of resonant frequency, damping and modeshape.

- Resonant frequencies amplify input force so they need to be controlled to ensure vibration problems do not result. For example, a serious vibration problem will result from helicopter blade pass frequencies coinciding with structural modes.
- The damping quantifies how much dynamic amplification will occur. This can be expressed in different ways including damping ratio, loss factor and Q.
- The modeshape describes the amplitude and phase at each measurement point on the structure. A bi-product is the familiar computer animation of deflections, as shown below:



These properties are measured by 'exciting' the structure with external forces. m+p international support all the established methods, as follows:

- Hammer excitation
- Step relaxation
- Single-point random
- Multi-point random
- Single-point sine
- Multi-point sine

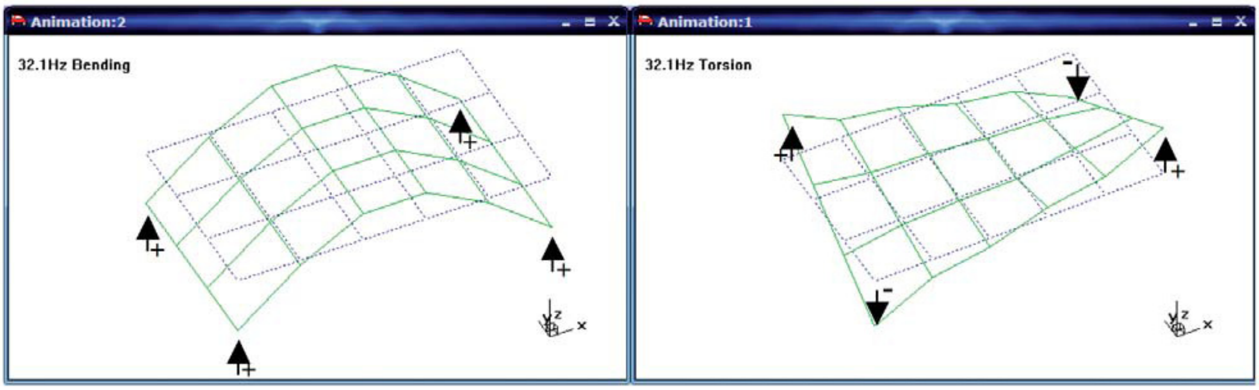
Background

Each method has a different application depending on the objective of the test and the time available. For example, impact testing with a hammer, which is quick and easy, is ideal for studying a car's exhaust system's vibration problems but is wholly unsuited to the safety requirements of the aircraft industry where the objective is more likely to be correlation of an FE model and clearance to fly.

For the more onerous requirements of the aircraft and space industry m+p international have implemented 'Normal Mode Tuning'. This method uses Multi-point sine excitation but with an added ingredient: strategic choice of the exciter locations and tuning of the sinusoidal inputs. The objective is to excite a 'pure normal mode' which means the resonant frequency has to be strongly excited and not influenced by adjacent modes or repeated roots at an identical frequency.

Imagine a plate whose bending and torsional (twisting) resonances occur at the same frequency. These modes can be extracted independently using a 2-stage process:

- Measurement whilst forcing the bending mode with in-phase forces (left)
- Measurement whilst forcing the torsional mode with out-of-phase forces (right)

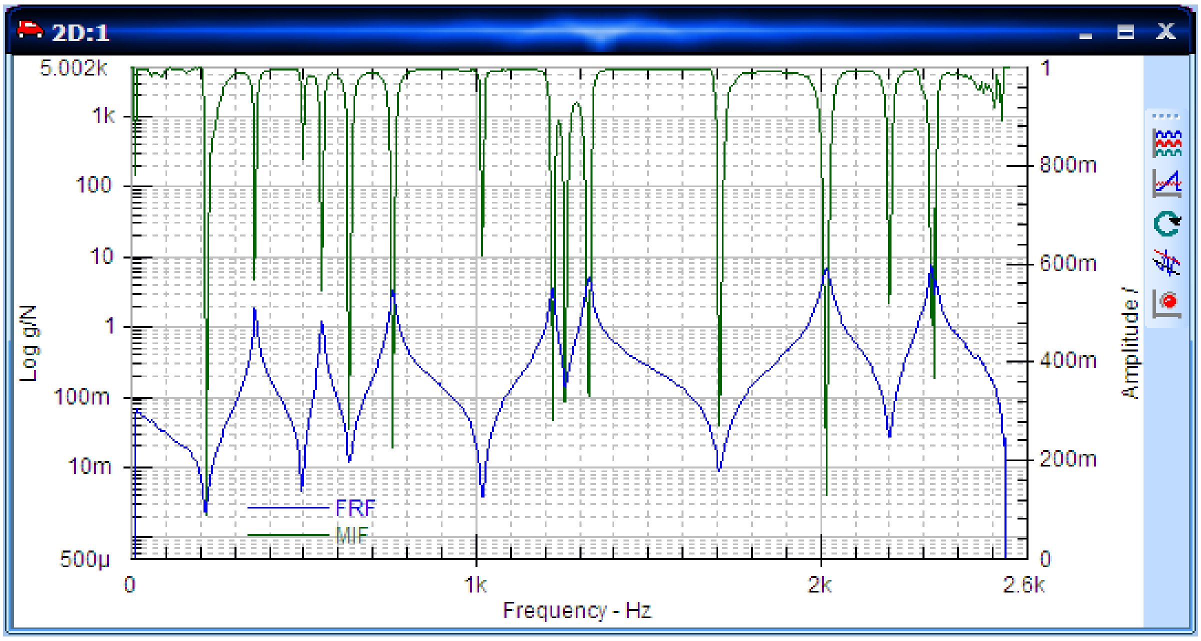


In reality the measurement is made whilst the frequency is swept or stepped through the resonance so that least squares methods can be used to improve the estimation of the modal parameters. The stepped technique is more rigorous than sweeping as it allows settling of the structure and then averaging of the data.

The preference usually is to measure all response locations simultaneously. This is why normal mode tuning systems tend to have a large number of accelerometers, possibly 100s or even 1000s. When testing with random inputs it is common to have less accelerometers and move them around the structure until measurements have been made at all points of interest.

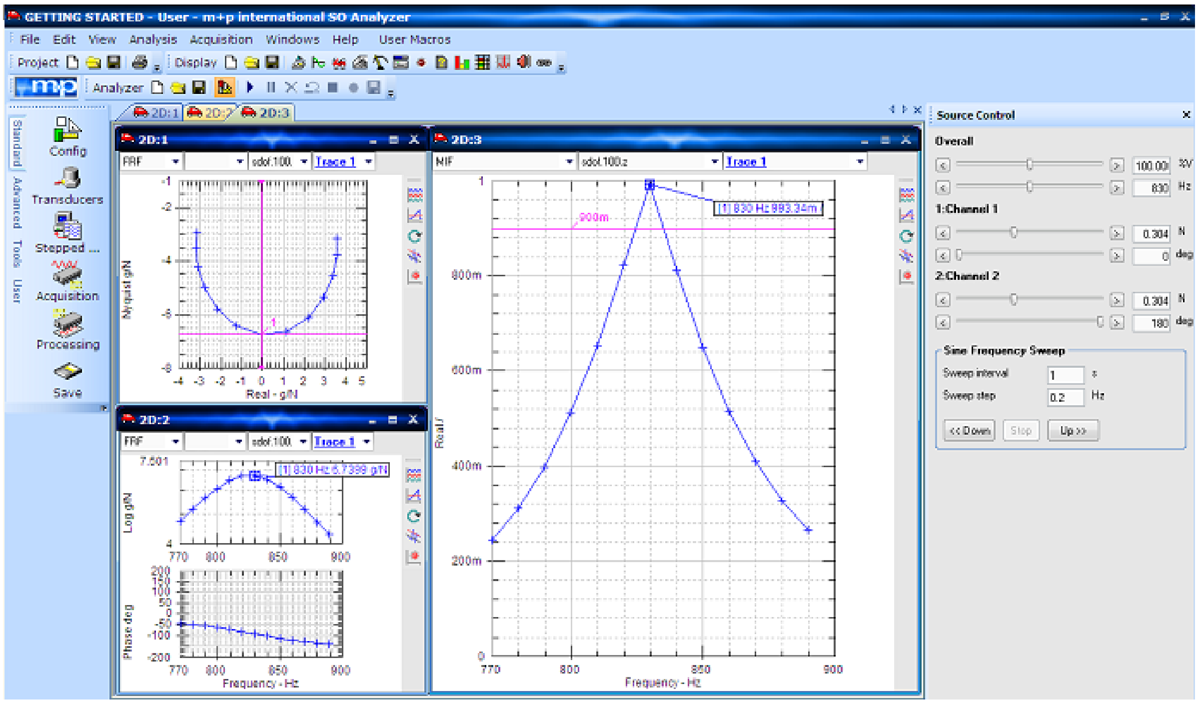
An FE model predicts normal modes with no interaction between them and this is why Normal Mode Tuning is ideal for correlation. It could be said that the test structure is being forced to behave like the FE model.

A measure of the 'normality' of a resonance has been developed called the Mode Indicator Function (MIF) and it exploits the fact that the phase of a normal mode will be 90 degrees at resonance. When the phase is exactly 90 degrees it follows that the imaginary component will be a maximum and the real component will be zero. The MIF essentially sums all the real components and plots them against frequency. In reality the MIF approaches zero but never reaches it because of compromises in exciter location, measurement error, frequency resolution, noise, etc. An MIF which is less than 0.1 is generally considered adequate. It can be clearly seen in the following comparison that peaks in the FRF coincide with dips in the MIF:



Normal Mode Tuning

The following screenshot shows m+p's Normal Mode Tuning user interface. A great deal of emphasis has been placed on interactivity to maximise the potential of SO Analyzer's real-time displays. In this example the MIF has been inverted (1-MIF) so that a value greater than 0.9 is the objective.



The following features can be seen in the above plot:

- The MIF (right-hand chart) is plotted real-time to determine the purity of the mode.
- The frequency can be adjusted to maximise the MIF.
- The force and phasing can be adjusted real-time. In this example
  Force Channel 1 = 2 Newtons @ 0 degrees and
  Force Channel 2 = 2 Newtons @ 180 degrees.
- The forces are under closed-loop control.
- Once the frequency and forcing has been optimised the frequency can be stepped through the resonance in an upward or downward direction.
- The centre frequency whilst stepping through the frequency range will be the exact frequency which produced the best MIF result.
- The upper left plot shows the real-time FRF represented using a nyquist plot in the Argand plane (real versus imaginary).
- The lower left plot shows the same data but plotted as amplitude and phase versus frequency.

It is common to perform a linearity check at this stage to determine how natural frequency and damping vary with force level. In general an increase in force results in a lower natural frequency and a higher damping as the structure's joints are more highly exercised.

Shaker Location

A test for the normal modes typically requires 2, 3 or 4 shakers. Finding the optimum locations is critical to meeting the test's objectives. Here are some of the ways in which the shaker locations may be determined:

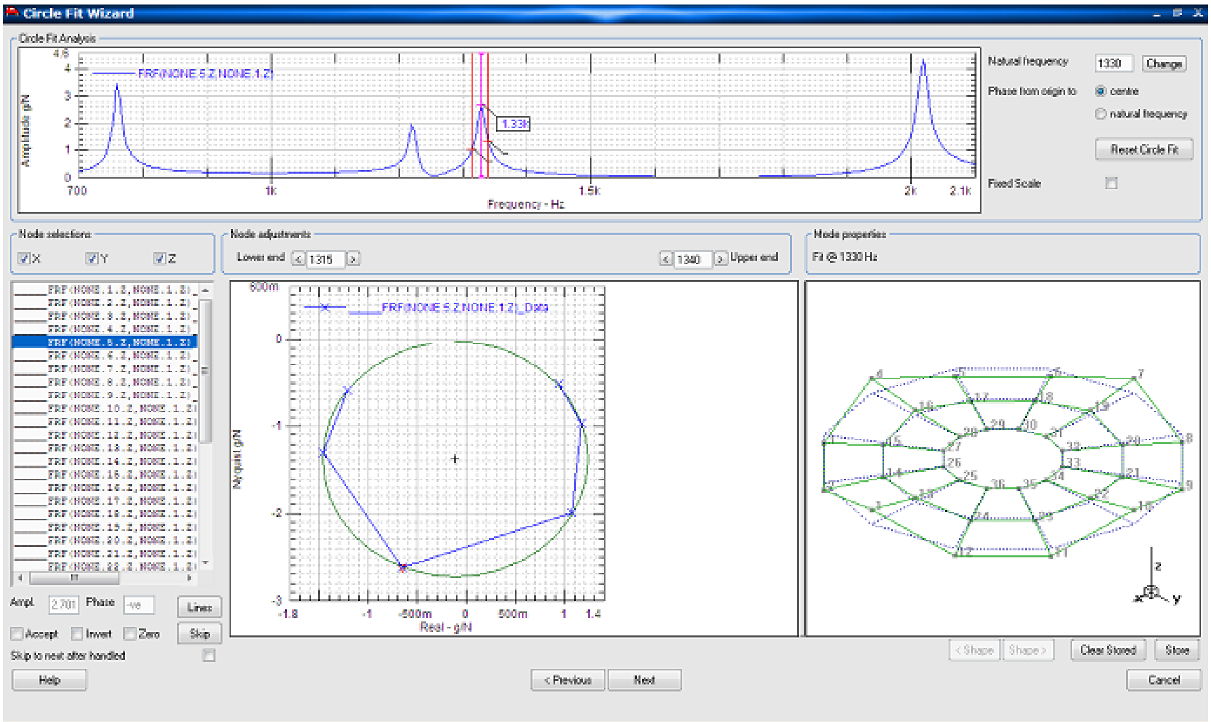
- Preliminary testing with an impact hammer
- Preliminary testing with single-point random and sine excitation
- Inspection of the FRFs, MIFs and modeshapes resulting from the above
- Force appropriation, a mathematical approach which automates the above
- Guidance from the FE process
- Experience
- Engineering judgement

Mode Shape Extraction

m+p international have implemented a wide range of curve-fitting algorithms to extract the modal parameters. These include single-degree-of-freedom (SDOF) methods which extract individual modes and multi-degree-of-freedom (MDOF) methods which have the advantage of analysing a wide frequency and separating closely spaced or coincident modes. Because Normal Mode Tuning was developed in the 1960s, before the widespread use of computers, it relied on the forerunner of modal extraction techniques: circle fitting. This method relied on the fact that a resonance plotted in the Argand plane (real versus imaginary components) results in a circle. The diameter of the circle represents the amplitude and its orientation represents the phase.

Even though this method has been superseded by automated and faster techniques its benefit is in the ability to manually process each measurement at each natural frequency and gain an added insight into the structure's behaviour. Additionally, it's an excellent tool for spotting suspicious measurements which might result from a faulty cable or a loose accelerometer.

The following plot shows an example of circle-fitting in a modern context.



Summary

In summary, m+p international have taken an important yet very traditional test approach, Normal Mode Tuning, and brought it into the 21st century with real-time interactivity and real-time displays to improve data quality and consistency whilst reducing test time.

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