

EXPERIMENTAL MODAL ANALYSIS OF COMPONENTS OF THE LHC EXPERIMENTS

Kurt Artoos, Michael Guinchard, Andrea Catinaccio, Keith Kershaw, Antti Onnela,
CERN, Geneva, Switzerland

Abstract

Experimental modal analysis of components of the LHC experiments is performed with the purpose of determining their fundamental frequencies, their damping and the mode shapes of light and fragile detector components. This process permits to confirm or replace Finite Element analysis in the case of complex structures (with cables and substructure coupling). It helps solving structural mechanical problems to improve the operational stability and determine the acceleration specifications for transport operations. This paper describes the hardware and software equipment used to perform a modal analysis on particular structures such as a particle detector and the method of curve fitting to extract the results of the measurements. This paper exposes also the main results obtained for the LHC Experiments.

INTRODUCTION

Experimental modal analysis provides a dynamic characterisation of structures under real mechanical conditions (with cabling, supports, etc...). Each structure has its own natural frequencies (where the amplitude of the system's response is much greater than the amplitude of the excitation) and natural modes of vibration (or mode shapes, the manner in which it deforms).

CERN's specialised structures such as particle detectors are built to have high rigidity, low weight and are very fragile. A second characteristic of CERN's application is the low accessibility of excitation and measurement points. These particularities of CERN structures increase the difficulty of experimental modal analysis.

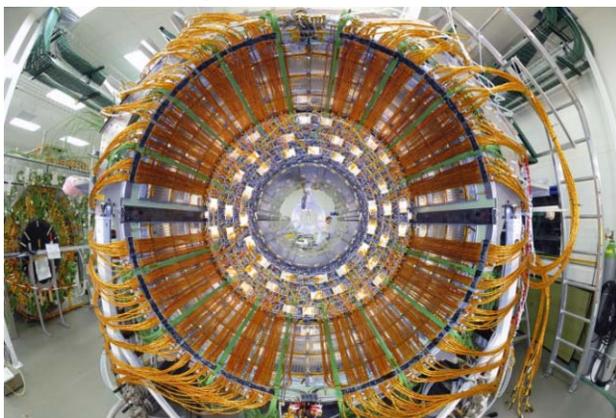


Figure 1: Tracker Outer Barrel of the CMS Experiment.

This type of analysis is essential to ensure that machine and detector sub-assemblies operate according to their design. The necessary micrometric precision of a detector

could be compromised by the vibration of neighbouring equipment such as pumps, ventilation systems, cryogenic systems.

Experimental modal analysis is also a key element for successful transport and handling operations around the CERN infrastructure. Modal analysis serves to identify the critical points of the structures, where accelerometers are then positioned during transport: It is important to focus the real time spectral analysis on mode shapes determined by experimental modal analysis. For instance, excitations produced by the environment must not coincide with one of the structures natural modes of vibration. Results of experimental modal analysis are used to select a vibration absorption system for handling and transport operations.

METHODS

Modal analysis is the method used to determine the structure's dynamic characteristics; such as resonant frequencies, damping values, and the associated pattern of structural deformation called mode shapes. A series of frequency response functions are measured at various geometric locations using either an instrumented impact hammer or an electro-dynamic shaker to supply an input force. Responses are measured in the X, Y, and Z directions with motion sensors, typically accelerometers. A frequency response function is the response per unit force over the frequency range of interest. Modal analysis software curves these data into a matrix and determines the mode shapes and the damping associated with each of the resonances. Test data can be used as additional input to structural modification software to investigate the effectiveness of potential corrective actions such as absorption systems prior to actually implementing such a modification.

Supporting the structure

With CERN's specific applications, it is generally not possible to fully achieve the free-free conditions. In this case, it is important to evaluate the impact of the rigid body modes on the first mode of the structure. However, if a sufficiently soft support system is used, the rigid body frequencies will be much lower than the frequencies of the flexible modes.

Geometry

In order to determine the mode shapes of a structure, it is necessary to create a virtual structure with all measurement points. The geometry resolution depends on the highest frequency mode shape. In practice, on particle detector structures, the geometry resolution is often

limited by the accessibility of measurement points. After the post-processing, each transfer function (magnitude, phase and direction) is associated with each point of the virtual geometry.

Excitation of the structure

Excitation of the structure is the most critical point of experimental modal analysis. The choice of excitation source is determined by the time available and the fragility of the test object. Main excitation sources are shaker and impact hammer. The advantage of the impact hammer is the low amplitude level of the energy applied to the structure: In fact, all the energy of impact is spread through the whole frequency band. At the resonant frequency of the structure, the energy of impact is less than the energy of a shaker in burst sine mode. The stiffness of the contacting surfaces affects the shape of the force pulse, which in turn determines the frequency content. It is not feasible to change the stiffness of the test object; therefore the frequency content is controlled by varying the stiffness of the hammer tip.

For the main applications such as the CMS experiment beam pipe or ATLAS Inner detector, the impact hammer was used. All these structures are fragile and the highest vibration magnitude allowed is around 1 ms^{-2} . These limitations impose the use of impact hammer but with a high sensitivity (10 mV/N) and with a very soft hammer tip in order to avoid risks of structure degradation.

Response measurements

The applications require measurement of very low levels of response to excitation. Tri-axial accelerometers are used to measure the dynamic response of the structure with high sensitivity (about 100 mV/g) and a frequency range between 0.3 Hz and 6 kHz. The mass of each transducer is only 10g to reduce the mass loading effects.

Transfer function measurement

Excitation and response signals are acquired in a spectrum analyser. Impact testing has potential signal processing problems associated with it; these problems are solved with windowing techniques (force or exponential window).

A spectrum analyser includes an averaging process in order to reduce the statistical variance of measurement and also reduce the effects of nonlinearity. For the main CERN applications, the results show that an average of three impacts reduces these effects.

Analysis

Having acquired the transfer functions, the next major step of the process is the use of parameter estimation techniques named 'Curve fitting' to identify the modal parameters. The frequency and damping for each mode can be estimated from any combination of these measurements.

The first and most critical step of modal parameter estimation is to determine how many modes have been excited in the frequency band of a set of transfer function

measurements. Mode indicator methods are used to help identify the number of modes in a band. Many methods are available but for the present application, the modal peak function seems the most appropriate. The modal peak function is calculated by summing together the real parts, imaginary parts or magnitudes of all transfer functions in the data block file that is being curve fitted.

After frequency and damping determination for each mode, the last step is to determine the mode shapes. The curve fitting software applies a mathematical function, such as a polynomial function on each transfer function around the frequency of the mode shape and searches the best coefficients for the polynomial function.

After curve fitting is completed, the modal parameters are stored in a shape table. Mode shapes can then be displayed in animation on a structural model directly from the shape table. Finally, the modal mass and stiffness can be determined from these parameters and all these results can be exported to Finite Element analysis software.

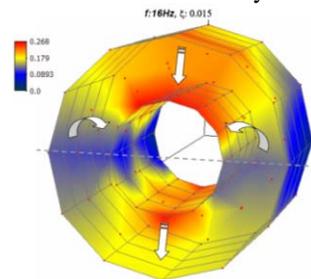


Figure 2: First vertical mode shape of Tracker Outer Barrel of CMS Experiment.

APPLICATION TO LHC EXPERIMENTS

Main results

Modern experimental modal analysis techniques have been performed on components of the LHC Experiments such as light and fragile detector components or beam pipes. The main results are shown in the following table:

Inner Detector of the LHC experiments (*)		
Mode Shape	Frequency	Damping
First longitudinal mode	8 to 10 Hz	4.3 to 5.5%
First vertical mode	16 to 17 Hz	1.5 to 3.2%
First breathing mode	18 to 21 Hz	1.5 to 3.1%

(*): Tracker Outer Barrel of CMS experiment and SCT-TRT Barrel of ATLAS experiment.

CMS End cap Beam Pipe		
Mode Shape	Frequency	Damping
First bending mode	11 Hz	0.1%
Second bending mode	41 Hz	0.3%
Third bending mode	90 Hz	0.7%

Comparison with Finite Element calculation

Finite element calculations and experimental modal analysis were performed for an earlier prototype structure

of the CMS Tracker Outer Barrel (TOB) [1, 2]. For the lowest mode shapes the calculations and measurements agreed and the lowest fundamental frequencies were in rather good agreement: 1st mode 23.8 Hz calculated and 16.6 Hz measured; 2nd mode 24.8 Hz calculated and 18.3 Hz measured. As the prototype structure was still not equipped with the final detector elements, cooling and cabling it was loaded with steel bars, distributed in the structure as for the final weights, thus simulating the full structural mass. The lowest fundamental frequencies of the loaded structure were measured to be 6.1 Hz and 8.3 Hz.

With the TOB prototype the time spent on finite element calculation and experimental modal analyses were comparable, about 3 man-weeks for each activity. The time needed for calculations stayed reasonably low as a suitable FE-model of the structure had already been created for static analysis, and also the structure was empty of any detectors, pipes and cables that would have been difficult to approximate into a reliable calculation model. In addition the prototype was already built (following a multi man-year effort), so the 3 man-weeks was only for preparing and performing the experimental modal analysis itself.

Based on the results from the prototype calculations and measurements it was expected that the final TOB would have its lowest fundamental frequencies between 5 and 10 Hz. Due to geometrical requirements and limited options for material choice there were no ways of substantially influencing the modal characteristics of the detector assembly. It was therefore decided to wait until the detector assembly was ready and then measure it [3].

A two man-week campaign, with 3 days of actual measurement work, was enough to perform the experimental modal analysis of the final TOB, and to provide useful and directly applicable data for the transport and operation of the detector.

Interest for the transport of a delicate object

The characterization of the conditions (transient signal) during the transport and installation of the fragile ATLAS Inner Detectors was set as a main requirement in order to verify their integrity.

For this purpose, we performed a dummy load transport with the real trolley frame and a simulated mass (dummy) representing the detectors. In that configuration, a direct reading of the accelerometer data on the dummy mass was meaningless, because the rigid dummy mass would not have responded as the MDOF (Multiple Degree Of Freedom) real detector structure. Thus, only transient load entries at the detector support positions on the base frame were recorded.

Based on the results of the experimental modal analysis, a powerful method to predict the peak response of our structures under transient loads at the base was found in the SRS (Shock Response Spectrum) analysis. The SRS [4, 5]. represents the maximum response of the system, to a given transient load, for varying eigen-frequencies. The shock response spectrum is a calculated

function based on the acceleration time history. It applies an acceleration time history as a base excitation to an array of single degree-of-freedom (SDOF) systems, as shown in Figure 3. Each system is assumed to have no mass-loading effect on the base input

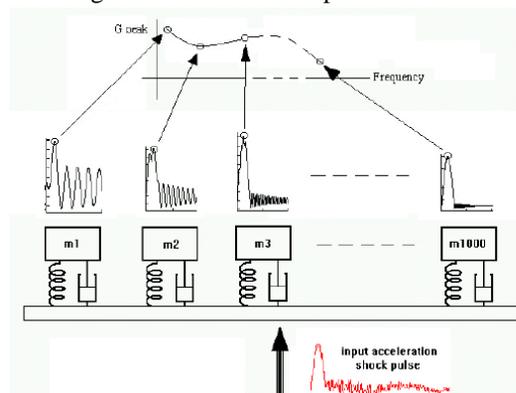


Figure 3: The SRS (Shock Response Spectrum) concept.

An SRS analysis was performed on two “worst case reference shocks” and detector parts were analyzed and considered safe under those peak events.

The derived acceptable SRS became then our specification. Based on recordings during real transport we determined, by calculating the SRS, whether it was less than or equal to the acceptable SRS.

The verification above is possible also on line by directly mounting and monitoring of accelerometers on the detector relevant points. When input accelerations can only be monitored at the base, then the on-line verification requires the implementation in the acquisition software of an SRS routine or the alternative method based on the FFT.

CONCLUSION

Experimental modal analyses have been successfully performed at CERN to obtain useful data for safe transportation and operation of various systems of the LHC.

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