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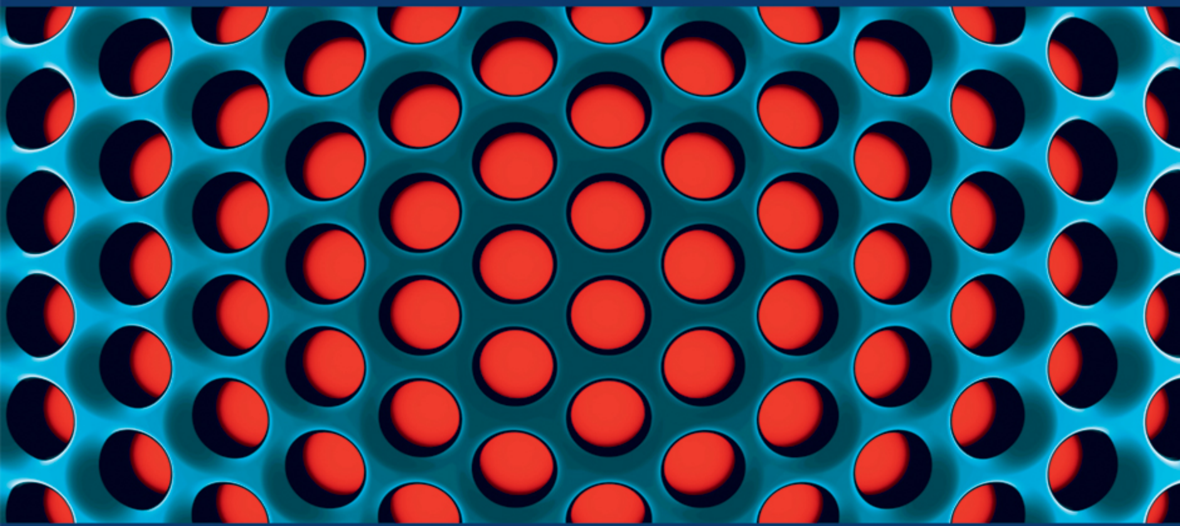

Experimental Mechanics of Solids and Structures

Jérôme Molimard

iSTE

WILEY

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Foreword

Mechanics is an ancient discipline that has been through major changes in recent decades with the advent of the finite element method. The possibility of calculating the spatial distribution of variables such as displacements, strains, and stresses, using adapted models for geometries and complex loading conditions, had initially led to the purely experimental aspects related to characterization of the mechanical behavior of materials and structures to be pushed into the background. Even though the final validation tests have always remained necessary to validate geometries or choice of materials, the number of preliminary tests carried out on the structural elements has naturally decreased the calculations which enable us at least to significantly "refine" the designing of systems and structures, if not to propose near-optimal solutions. Material characterization tests, though still indispensable for providing the calculation codes with finer laws, have for a long time remained somewhat rigid in well-established procedures, along with the measurement methods which have also changed very little over a long period of time – since the release of "classic" sensors such as point displacement sensors or strain gauges.

In recent years, however, there has been an increased interest in experimental mechanics. The emergence and rapid dissemination of new investigative methods, such as kinematic measurement systems, have enabled access to spatially continuous information, at least on the surface of tested specimens. Several heterogeneities were thus brought to light in the fields of displacements and deformations which were only partially seen using classical instrumentation based on point measurements. However, with the numeric sizing calculations improving over time, it has become necessary to provide experimental information also in line with the improved calculation results. Though the above-mentioned full field measurement methods are effective, the proliferation of conventional sensors distributed over large structures requires optimal management of the information collected. Finally, the increasing overlap between numerical models and elaborately instrumented test results has led to the emergence of identification strategies for material and structural properties in contrast with conventional procedures which are well-established, but unsuitable for mining of data available in large volumes.

It is in this context that this book written by Jérôme Molimard is presented to us. Its content covers many of the issues mentioned above in a language particularly adapted for technicians or engineers. First, the author briefly reviews the principles of "classic" standardized tests. He then addresses the performance of the usual force, displacement, and deformation sensors, with particular attention drawn to the metrological performance that users can expect. The author then continues with the main techniques, whether purely geometric or interferometric, for measuring kinematic fields; and finally, discusses the consideration of uncertainties related to measurement procedures. The book includes the description of experimental designs to provide the reader with a rigorous framework to address the optimal management of a large volume of data and unknowns.

In terms of the form, the author shares his knowledge from extensive experience in mechanical testing through many short exercises that appear throughout the book, and a final chapter dedicated entirely to case studies.

In conclusion, the work of Jérôme Molimard is well-timed to respond, in a clear and concise manner, to the queries raised by traditional tools and methods of experimental mechanics, but also related to recent changes within this discipline. Amply illustrated, the book will certainly help the reader to find examples of application close to their own interests, complemented with insightful background information on the experimental mechanical techniques and methodologies found in the book.

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February 2016

Introduction

I.1. Experiments for solid and structural mechanics

The modern mechanics of solids and structures relies heavily on the numerical solution of a mechanical problem. Since the early 1970s, the Finite Element Method was widely used for very complex cases. In the present day, a Computer-Aided Design software which generally integrates a small calculation module predicts the behavior of complete mechanical systems, something impossible as few as twenty years ago. The training of a mechanical technician or engineer today largely incorporates this tool, sometimes abandoning the practical work altogether. However, the numerical calculation only responds, in a more or less accurate manner, to an inevitably idealised mathematical problem. It is therefore necessary to *validate the simplifying assumptions* introduced in the modeling. Furthermore, the *values used* in the calculation should be *well-known* (structural damping, binding strength, or boundary conditions). This all requires experimental work which is sometimes difficult, even in the case of a relatively simple behavior that can be easily modelled. Firstly, numerical codes have to be fed with *experimental data*. For example, the current development of elaborate composite parts requires characterization of the anisotropic stiffness tensor (9 parameters), whereas the contemporary practice reflects only the properties of the plate (4 to 6 parameters) where one dimension is negligible in the face of others. Furthermore, the boundary conditions, either restraint or contact, are often subject to strong assumptions that an experimental approach can improve, by defining a recessed stiffness, for example.

But mechanical design is based on various functioning patterns of the proposed device. There is of course normal functioning, very often under static loading, but also a dynamic functioning linked to possible shocks, abrupt load changes (e.g. emergency stop), or a challenging external environment with variations in temperature or humidity. Moreover, any mechanical device must guarantee a certain lifetime. In a conventional design approach, it is possible to size the apparatus by numerical method for some cases and then *experimentally test the prototype* with the objective of validation, whereas other cases will only be studied experimentally.

Finally, even though Mechanics is an ancient discipline, the formalism is sometimes lacking. It is then necessary to return to the basic approach of experimental science and conduct *experiments for understanding*. These situations beyond the mathematical formalism are very common in everyday life: in the study of interaction between two solids in contact – tribology – friction and wear are beyond the scope of intrinsic material properties and modeling of infinitesimal elements, as is usually done in mechanical modeling. More recently, mechanicians were interested in the mechanics of powders, where the material studied is neither a liquid nor a solid. The recent interest in biomechanics also raises the question of the nature of the medium studied; the skin, for example, could be considered as a linear elastic material, or hyper-elastic, anisotropic, viscoelastic, poro-elastic… Therefore, presently, a well-conducted experimental study is the only reasonable approach to this category of problems.

These different types of experiments rely on common concepts such as data processing, choice of sensors, or experimental modelling. However, the strategies are quite different, depending on whether we can or cannot rely on a reliable formalism. The three following examples will illustrate the experimental approaches for different purposes, directly related to the degree of knowledge of a system.

I.1.1. *Study of a bicycle wheel; an example of a complete structural validation*

This work was conducted as part of a technology transfer from a university lab to an SME, in the form of a doctoral thesis [MOU 98]. The objective was to provide the company with a software to assist the designing of bicycle wheels. In particular, the software should be able, via a Finite Element analysis, to recognize and analyze the natural modes of a wheel.

The program was written in MATLAB© using a graphical interface and numerical analysis facilities. This solution enables the SME not to invest human and financial resources in a generic finite element software; the developed application can be used by the technicians of the research department without any special knowledge of the calculation method.

From the mechanical point of view, the numerical modelling is as follows:

– the spoke beams are highly slender structures with negligible flexural rigidity and compression. Their behavior has a geometric nonlinearity. So we have:

$$\in_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2\right] \quad [I.1]$$

– given the number of spokes and considering the thickness of the rim relative to its diameter, it is approximated as a simple beam element (not a curve). The section of the rim is complex, such that the beam element is a strong approximation required to maintain a reasonable calculation time;

– the hub is considered infinitely rigid;

– the connections are assumed to be perfect; the point of application of stress of the spokes is shifted with respect to the torsion center of the rim.

The main elements of the research method of eigenvalues and eigenvectors are:

– a search for solutions to the dynamic equation in a pseudo-modal base which enables a reduced calculation time;

– numerical method of resolution of the nonlinear behavior of the wheel is the incremental Newton–Raphson method. The change of state is divided into n steps, for which the stiffness matrix is updated at each step; the total change is the sum of individual changes.

The software developed is used to find the static behavior, frequency response, and the time response of a bicycle wheel with defined assembly.

This software has been validated by an experimental approach, particularly for the frequency response. The assembly is reproduced in Figure I.1.

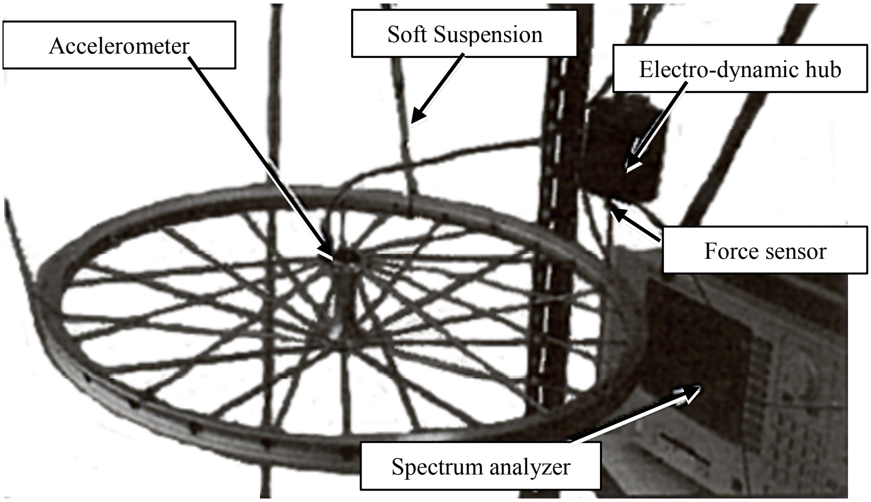


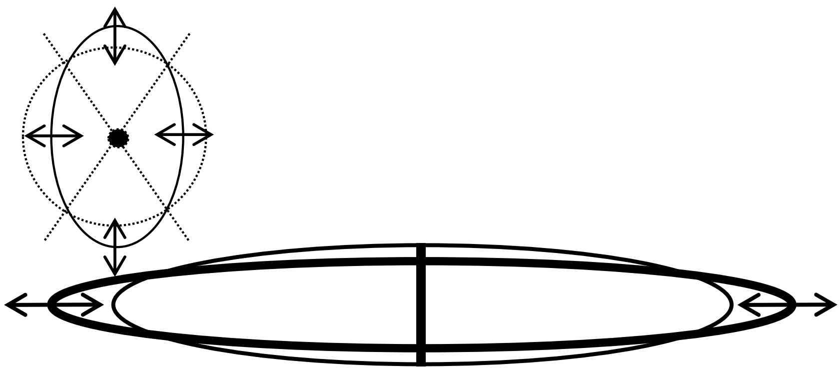
Figure I.1. *Assembly for frequency analysis of a bicycle wheel (according to [MOU 98])*

The wheel is mounted on flexible supports simulating free-free boundary conditions. An accelerometer is placed on the upper side of the hub. The excitation takes place on one side of the rim. This excitation requires movement off the periodic plan.

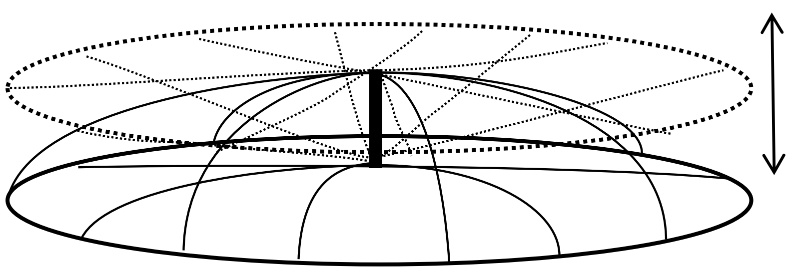
Just as the digital model is questionable due to various assumptions and required approximations, a test like this is only an approximation of the real situation. This is an *experimental model*, simplifying the structure, the boundary conditions and the load. The experimental model also offers only a few measuring points, based on *a priori* judgment of the designers of this model, which gives a limited view of the examined physical reality. Finally, the modifications of the experimental model in relation to the physical reality it explores leads to distortion of the obtained solution.

In this specific case, an accelerometer weight sensor is generally likely to alter the natural modes of the wheel. Likewise, the positioning of the accelerometer may also affect the observation of certain occurrences. Therefore, an accelerometer placed at the node of a mode does not allow its identification.

It may be noted, according to these rules, that the choice of positioning is especially important: in an infinitely rigid zone, the accelerometer does not change the stiffness matrix. With regard to assumed or calculated modes, it can be predicted that the accelerometer will be sensitive to different degrees. For example, Figure I.2 shows the “2Φ–plan” mode which is barely visible and the “umbrella” mode that should be easily identifiable.



2Φ—plan mode



Umbrella Mode

Figure I.2. *Examples of vibration modes of a bicycle wheel (according to [MOU 98])*

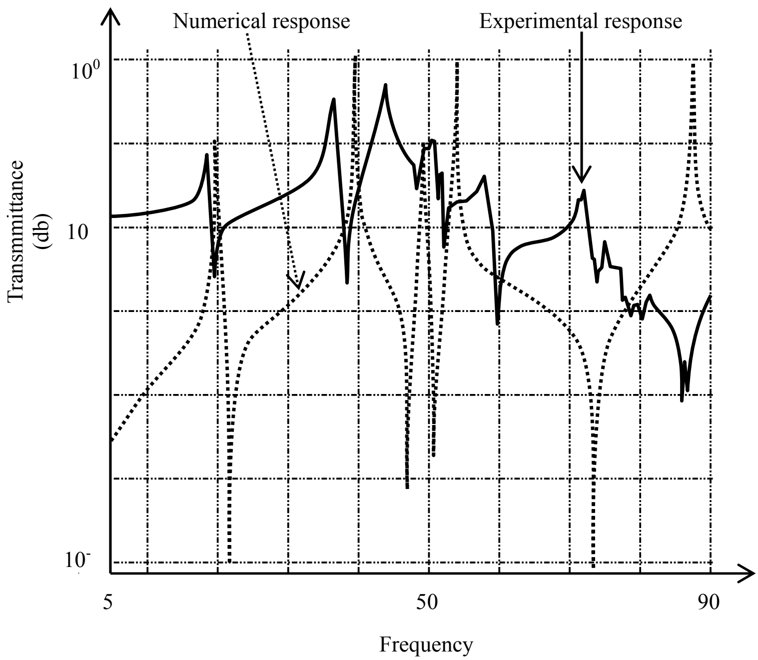


Figure I.3. *Numerical and experimental response of a bicycle wheel (according to [MOU 98])*

Comparison of numerical and experimental approaches gives the results shown in Figure I.3. The first resonance, which corresponds to the "2Φ off-plan" mode shows a very good theory/experiment correlation. In contrast, the frequencies corresponding to other modes differ more and more, until the error reaches 15%. Even if the prediction model works well, this variance is a representative of many modal analyses: the approximations are manifested especially when the frequency is high.

On the other hand, the theoretical and experimental values of the transmittances are somewhat similar. But these values, which are directly related to damping (structural damping, spoke connections), show the acuteness of the natural frequency to be taken into account: with zero damping, the structure will break; with a critical damping $(c = 2\sqrt{km})$, the natural frequency will be in noise.