Preface

There are men whose head is full
Of nothing, if not their science;
There are the learned of all trades.
I tell you without pretension:
Rather than learning too much,
Go and learn what really matters.

Hernández, J., 1872, *Martín Fierro,*
Editorial de la Pampa, Buenos Aires (current text
in the original Spanish taken from the 1982 edition
by Bruguera Publishers, Barcelona).[1]

The need to provide instructors and students with a textbook on the classical principles and the modern methods of analysis, modeling and simulation of mechanical systems gave rise to *The Dynamic Response of Linear Mechanical Systems*. I came across this need myself when I was assigned, in the late eighties, the teaching of the undergraduate *Dynamics of Vibrations* course at McGill University's Department of Mechanical Engineering, while one of the instructors was on sabbatical. This was an interesting challenge, as I had never taken an undergraduate vibrations course as such. In fact, I came from the 5-year *Electromechanical Engineering* Program at the National Autonomous University of Mexico (abbreviated UNAM, from its name in Spanish), where the teaching of vibrations was included in the 1-year course on *Applied Mechanics*; this course comprised both kinematics and dynamics of machines. Vibrations being the last topic in the syllabus, the instructor usually rushed through it, the final examination hardly including a question on vibration dynamics. In my senior year the curriculum underwent a radical updating, with courses offered in semesters. This change gave me the opportunity to take a one-semester course on Electromechanical Energy Conversion, which was about my first and only exposure to the discipline of dynamics of systems as an undergraduate.

[1] Verses 6923–6928, translated by the author.

My first task as a designated instructor of undergraduate vibrations was to search for the right textbook. I was overwhelmed by the vast bibliography on the subject. To my surprise, with rare exceptions, all textbooks I consulted observed the same pattern, which was originally set by Thomson's classical book, first published in 1948.[2] As I was familiar with system theory, given that this was the minor I took in my graduate studies of Mechanical Engineering (M.Eng., UNAM) and Applied Mechanics (Ph.D., Stanford), I tried to make the connection between these two closely related disciplines. I knew Cannon's book [2], which makes such a connection, this book thus appearing as the right choice. Given the size of the book and its unusually broad scope, however, the students were intimidated, which forced me to look for an alternative, more focused textbook, as I continued teaching that course for several years afterwards. I found other books that somehow integrated system theory with the dynamics of vibration,[3] but I thought that there was more to it that was not as yet in the textbooks. For one thing, I did not like the idea of having to solve a *generalized eigenvalue problem* to find the natural frequencies and the natural modes of a multi-degree-of-freedom system, as the generalized problem does not necessarily lead to real, non-negative eigenvalues. Inman's book had an interesting idea along these lines that I decided to pursue.

I thus undertook an in-depth research on a more intuitive, yet rigorous approach to the teaching of vibration and, for that matter, mechanical-system analysis, that would (a) exploit the mathematical knowledge required from the students, as spelled out in the prerequisites (linear algebra and basic engineering mechanics); (b) connect the theory of vibrations with the more general theory of systems; and (c) resort to well-known graphical techniques of solving engineering problems. This is how I decided to take a departure from traditional approaches to the teaching of vibration dynamics. Features of the book along these lines are listed below:

- Modeling is given due attention—most books appear to take modeling for granted. In doing this, a seven-step procedure is introduced that is aimed at structuring the rather unstructured process of formulating mathematical models of mechanical systems. I always insist in the need for a creative approach to modeling, as no two engineers will always come up with the same model of the same situation. Modeling, while based on sound science, is also an art, that can only be developed by practice.
- A system-theoretic approach is adopted in deriving the time response of the linear mathematical models of the systems under study. In this regard, first what is known in system-theoretic terminology as the *zero-input response*—dubbed the *free response* in vibration analysis—is obtained; next, the *zero-state response* is derived by relying on the impulse response of the system under analysis. The time response of a system to arbitrary excitations is then naturally derived in convolution form upon resorting to a black-box approach that is applicable to all

[2]The book has gone through many revisions, e.g., [1], but it keeps its original basic contents.
[3]These were Meirovitch [3] and Inman [4].

linear, time-invariant dynamical systems. The fundamental concept of linearity, which entails superposition and additivity, is stressed throughout the book.

- The modal analysis and the time response of two-degree-of-freedom (two-dof) systems is eased by invoking the standard, symmetric eigenvalue problem. Of the many authors of books on vibrations, only Inman seems to have made a point on the benefits of a symmetric eigenvalue problem, as opposed to its generalized counterpart, in which the matrix in question is not symmetric. My approach requires obtaining the positive-definite square root of the 2×2 mass matrix, which is eased by resorting to (a) facts from linear algebra pertaining to the analytic functions of matrices and (b) a graphical method that relies on the *Mohr circle*, an analysis tool that is learned in elementary courses on solid mechanics. The concept of *frequency matrix*, first found in Inman's book, although not by this name, is introduced here, which helps the student use the Mohr circle in conducting the modal analysis of the systems at hand. This concept was published in a tutorial paper [5].
- The time response of first- and second-order mechanical systems is derived in a *synthetic*, i.e., *constructive* manner. What this means is that I do not follow the classical math-book approach, under which the general response is derived as the sum of a general solution, with undetermined coefficients, and a particular solution. The downside of this approach is that it does not take into account the *causality* of dynamical systems. I exploit causality by deriving the general time response as a sum of the zero-input and the zero-state responses. The former is derived, for first- and second-order systems, by means of an infinite series; this is obtained in turn by successively differentiating the mathematical model at hand, and reducing every higher-order derivative to a multiple of the first derivative of the variable of interest for first-order systems; for second-order systems, every higher-order derivative is reduced to a linear combination of this variable and its first derivative. By evaluating these derivatives at the initial time, numerical values for the coefficients of the series expansion are derived in terms of the initial values of the problem at hand.
- The time response of n-dof systems with a positive-definite stiffness matrix is introduced rather informally, by resorting to the intuitive notion that the response of these systems should be formally analogous to that of single-degree-of-freedom systems. The analogy is achieved by means, again, of the concept of frequency matrix. The time response of n-dof *undamped* systems is then informally derived by replacing the natural frequency of single-dof systems with the frequency matrix of n-dof systems. The underlying informality is then justified by proving that the time response thus obtained is indeed *the integral* of the system of governing ordinary differential equations (ODEs). The foregoing proof is conducted by resorting to a basic concept of system theory: the response thus obtained verifies *both* the ODEs and the initial conditions.

- The time response of n-dof *damped* systems, unfortunately, does not allow for a *straightforward* derivation similar to that applicable to their undamped counterparts. In this light, the time response of these systems is done first by simulation, then by means of the Laplace transform and the concept of *impulse response*.
- Examples and exercises rely on modern computational toolboxes for both numerical and symbolic computations; the powerful capabilities of readily available commercial software for plotting are fully exploited.
- Great care has been taken in producing drawings of mechanical systems, so as to convey the most accurate information graphically. This feature should be appreciated by students and instructors, as inaccurate information in a technical document invariably leads to delays in the completion of a task.
- Emphasis is placed on the logic of computations, and so, wherever needed, procedures that can be implemented with commercial software are included.

While novel techniques are introduced throughout the book, classical approaches are given due attention, as these are needed as a part of the learning process.

A common trend in the literature on the field is to be highlighted: with the aim of bringing computers into the teaching of vibration analysis, many a textbook includes code to calculate the time response of the systems of interest. The problem here is that this code is, more often that not, nothing but the verbatim casting of the time response formulas in computer language, thereby doing away with the actual possibilities offered by computing hardware and software. An alternative approach found in the literature is the numerical integration of the underlying systems of linear ordinary differential equations (ODEs) using a Runge–Kutta algorithm. While there is nothing essentially wrong with this approach, the use of such algorithms is an unnecessary complication. Indeed, Runge–Kutta methods are suitable for the integration of nonlinear ODEs; they do not exploit the linearity of the systems encountered in a first course on dynamics modeling, analysis, and simulation, thereby complicating the issue unnecessarily. We depart from these practices by resorting to the concept of *zero-order hold* and by casting the numerical integration of the underlying mathematical models in the context of discrete-time systems. The outcome is that the problem is reduced to simple operations—additions and multiplications—of arrays of numbers, i.e., vectors and matrices.

The book is accompanied by some Maple™ worksheets that illustrate: (a) the discrete-time response of single-, two-, and three-degree-of-freedom systems; and (b) the use of the Mohr circle in the derivation of the time response of undamped two-dof systems. The worksheets are available at the *Springer Extras* website: http://extras.springer.com/.

A *Solutions Manual* that includes solutions to selected problems accompanies this book; it is made available to instructors.

Before closing, I would like to stress the philosiphy behind this book: knowledge being such a complex, *experiential* phenomenon [6]—it cannot be *downloaded*, contrary to popular belief—it cannot be reduced to a set of ad-hoc rules; it can be transmitted, though, via its underlying *principles*. This is probably what the *gaucho* Martín Fierro had in mind when giving wise advice to his son in the verses quoted above.

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Montreal Jorge Angeles

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