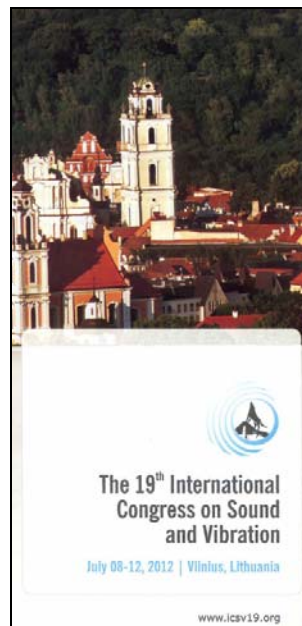


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EASYMOD: A MATLAB/SCILAB TOOLBOX FOR TEACHING MODAL ANALYSIS

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Teaching experimental modal analysis (EMA) to engineering students needs a basic knowledge and it is rarely possible to illustrate it with commercial software packages which are often presented as a black box following a specific industrial demand. These tools are naturally not adapted to education as they hide most of their fundamentals. This paper presents the development of an educational *MatLab* toolbox called *EasyMod* designed for determining the modal parameters of a structure by analysing frequency response functions (FRFs) obtained experimentally. Various Single-Input Single-Output methods, on increasing complexity, have been implemented in this toolbox: the peak picking/mode picking, circle-fit and line-fit methods use interesting properties of FRFs with emphasis on estimating eigenfrequencies, damping ratios and compliances. More complex methods are also proposed, for instance the least square complex exponential method (multi-input multi-output method), for a progressive adaptation of the student to EMA theories. This method has the significant advantage of revealing the limits of simple methods. The matrix formulation and graphic features proposed by *MatLab* offer an interesting framework for illustrating the possibilities of this toolbox. Since the purpose of *EasyMod* is to be open source, an adaptation to *SciLab* software is also presented. Typical illustrative examples are given, ranging from a cantilever beam to a 11-*dof* model analysis.

1. Introduction

Experimental modal analysis (EMA) is a fundamental technique which has been developed rapidly the last 30 years. It embraces a wide range of disciplines, and was considered, from the start, as a useful tool to study and illustrate the dynamic characteristics of a structure, since its scope is considerable [1]. It covers a large area of expertise, based on academic fundamentals, such as experimental testing and data acquisition, modal behaviour and other associated engineering applications [2]. Unfortunately, the mathematical techniques, especially the process of modal parameters identification, are most often hidden in the commercial software programs. Those tools are developed with the concerns of calculation power, user-friendliness and efficiency but represent a human and financial investment that the industry cannot afford if the application is not inside its core business. For example, simple identification methods, like peak peaking (PP) and circle-fit (CF), considered as excellent methods for teaching the basis of experimental modal analysis, have been disappeared in favour of more efficient multi-input multi-output approaches like least-square complex exponential (LSCE) method or polymax estimator [3], which are considered as “industry-standard” time and frequency domain estimation methods, respectively.

Teaching modal analysis to engineering students responds to a growing industrial demand. At the undergraduate level, modal analysis courses treat the structural dynamics in the modal base, which presents the undeniable advantage to decouple motion equations, emphasizing the structure modal

properties, by using the mathematical basis of deriving the eigenfrequencies and the eigenvectors for time domain response data. Although the commercial tools provide a support for illustrating these mathematical concepts, they often mask a number of features which are important for a good understanding. It is therefore difficult to estimate the importance of measurement methods, the choice of a given frequency range or the selection of relevant coordinates. Moreover, the number of identification methods is limited for the purpose of simplicity. For example, the LSCE method is ideal for rapidly identifying the mode shape of a structure to study, but the fundamentals are rarely understood by the student users ... but also by the major of engineer users. A progressive approach could be preferred, from simple to recent algorithms. Obviously, the latter are essential for deriving better models of large and complex tested structures, only if the user well understand what he does.

EasyMod toolbox is presented as an alternative for studying EMA. It consists of several *MatLab* functions, allowing to establish step by step a complete modal analysis from experimental data. This tool has the advantage to be open source, and can consequently be adapted by the engineering community according to educational purposes. This paper presents the adopted philosophy allowing an easy use. The toolbox structure is revealed and the illustration of theoretical concepts is shown. Some comments are given on the toolbox translation towards the *SciLab* alternative. Finally, two examples are presented whereby some of the toolbox capacities are evidenced together with a discussion around the educational experience.

2. EasyMod: Easy Modal Analysis

2.1 Structure of the toolbox

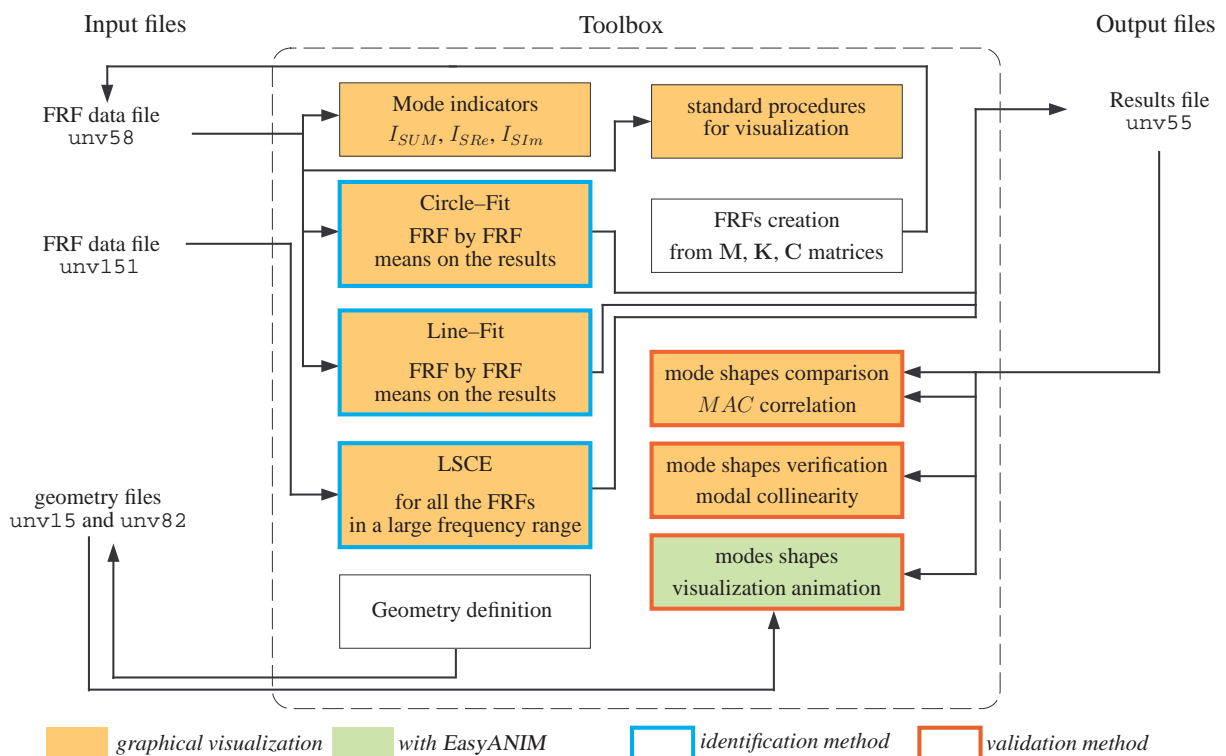


Figure 1. Schematic operating diagram of toolbox *EasyMod*

The structure of *EasyMod* functions is presented in Figure 1. Both identification and validation methods are implemented: circle-fit, line-fit and LSCE methods are present, as well as MAC (modal assurance criterion) and modal collinearity. By using the matrix abilities offered by *MatLab*, operations on frequency response function (FRF) are well made easier. Among others, the generation of

FRF from mass, damping and stiffness matrices is summarized into one function only. Notice that other *MatLab*-based solutions exist, as for example *SDTools* [4] or *ModalTools* [5] but above all dedicated to commercial EMA and dynamic simulation for vibration problems.

2.2 The use of universal file

The so-called universal file format (UFF) is presented as an interesting way to initialize a project. UFF is the industry standard format for storage of geometry, DOF information and measurements, supporting both ASCII and binary format. Originally developed by the Structural Dynamics Research Corporation in the late 1960s, they facilitate the data transfer between test measurements and dedicated engineering software programs. Although some restrictions are still pointed out and the format is considered obsolete by the original developer, it presents a certain degree of universality [6] and remains a standard for the experimental dynamics community, especially in the area of modal analysis. In ASCII format, all file types present the same structure (Figure 2). A number, at the script heading, is dedicated to a specific content: geometries, FRF data or results. For example, the format 58 is associated to the FRF measurement. The format defines a header that contains general information about the data contained in the file (function type, response direction,...) and channel specific information (channel name, units, data type,...).

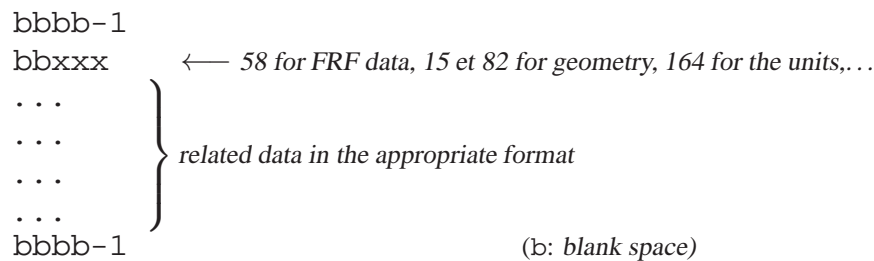


Figure 2. Structure of universal files

The proposed approach is clearly academic but the toolbox makes a link with commercial software with the help of UFF files. Any structural analysis can be performed with both approaches. For example, the software called *EasyAnim*, initially developed for teaching multibody simulation [7], has been adapted to visualize mode shapes associated to analyses issued from *EasyMod* and/or from other commercial software supporting the UFF format (*Test.Lab*, *Cada-X*, *ME'scope*,...).

2.3 Proposed functions and utility of matrix manipulations

Identification functions are proposed, not only with a growing degree of complexity, but also for SISO/SIMO/MIMO comparison. SISO (single-input single-output) methods allow to well emphasize the contribution of a single mode of a structure, supposing that one term in the series form of the frequency response function H_{ij} dominates the whole expression

$$H_{ij} = \frac{X_i}{F_j} = \sum_{k=1}^{\infty} \frac{B_{ijk}}{\omega_k^2 - \omega^2 + j\eta_k\omega_k^2} \quad (1)$$

where ω_k (natural circular frequency), η_k (loss factor) and B_{ijk} (modal constant) are the modal parameters of mode k . These methods exploit interesting properties of a FRF like the circularity in the immediate vicinity of resonance or the linearity of inverted FRFs, which are associated to important statement in modal analysis theory [8]. SIMO (single-input multi-output) and MIMO (multi-input multi-output) represent a natural step towards industrial applications. The rapidity and precision

(multi-output) as well as the distinction between two close modes in frequency (multi-input) are underlined through the use of an advanced method like LSCE. In this case, the use of indicators may turn out useful. The validation will be performed with collinearity properties, MAC and visualisation techniques.

The matrix manipulation offered by *MatLab* presents the important advantage to easily analyse a FRF in any requested format through a user-friendly interface. For example, peak picking/mode picking method, which is certainly the oldest identification technique, does not require any specific procedure (curve-fitting, minimization, . . .) and modal parameters can be simply obtained from FRF's Bode diagram and imaginary amplitude in *MatLab* GUI.

2.4 On the use of SciLab

To be completely open source, the framework must be available entirely for free, for, at least, avoiding any software dependence to the student. Contrary to *MatLab*, *SciLab* is an open source high-level computational package and a numerical educational tools but available for commercial use also. It was created in 1990 by researchers from the French national research institution and Ecole nationale des ponts et chaussées (France). It is one of several open source alternatives to *MatLab*. It can be used for high-level programming, 2D/3D visualization, numerical computation, data analysis and signal processing. As its syntax is similar to *MatLab*, *SciLab* includes a source code translator for assisting the conversion of scripts and functions from *MatLab* to *SciLab*. Due to the openness of the software, some user contributions have been integrated into the main program.

The choice of this kind of support is motivated by the fact that the toolbox is offered to the mechanical engineering community and this community can contribute to the toolbox development, without any financial benefit, in contrast to the “cathedral–building style” [9]. The long-term interest is to dispose of a large tool set including relevant and interesting frequency and time-domain modal analysis approaches. Obviously, to be included in the toolbox, the function debugging must be performed in both supports.

3. Example 1: a cantilever beam

The cantilever beam is probably the most popular system for illustrating the modal analysis. The main advantage for studying this illustrative exercise is the progressive approach, that we have adopted in the course “Dynamics of mechanical systems and vibrations” in the third year of bachelor's degree in engineering (University of Mons). The students are indeed encouraged to learn the principles of vibrations, through analytical, numerical and experimental analyses. A specific configuration of the cantilever beam is imposed (with fixed geometrical dimensions, with or with lumped mass at the end) to each student. In this regard, it is much harder to learn experimental modal analysis with a “black box” software with complex methods. An open approach is thus preferred for illustrating the properties of FRFs, through the CF et the LF methods, in comparison with:

- the analytical approach, by resolving the Euler-Bernoulli theory for the one-dimensional structure,
- the numerical software, using a commercial finite element software and home-made routines on *MatLab* (again this platform!), allowing to establish mass and stiffness matrices of the structure.

The experimental modal data serve to validate these aforementioned approaches.

Figure 3 and 4 display examples of results obtained with *EasyMod*. The information provided by the circle–fit method gives interesting findings (Figure 3), by illustrating the circularity around the analysed natural frequency, and its dependency with the number of samples. If the structure is low-dampened, the limitation of this method is clearly revealed. The damping estimation by further

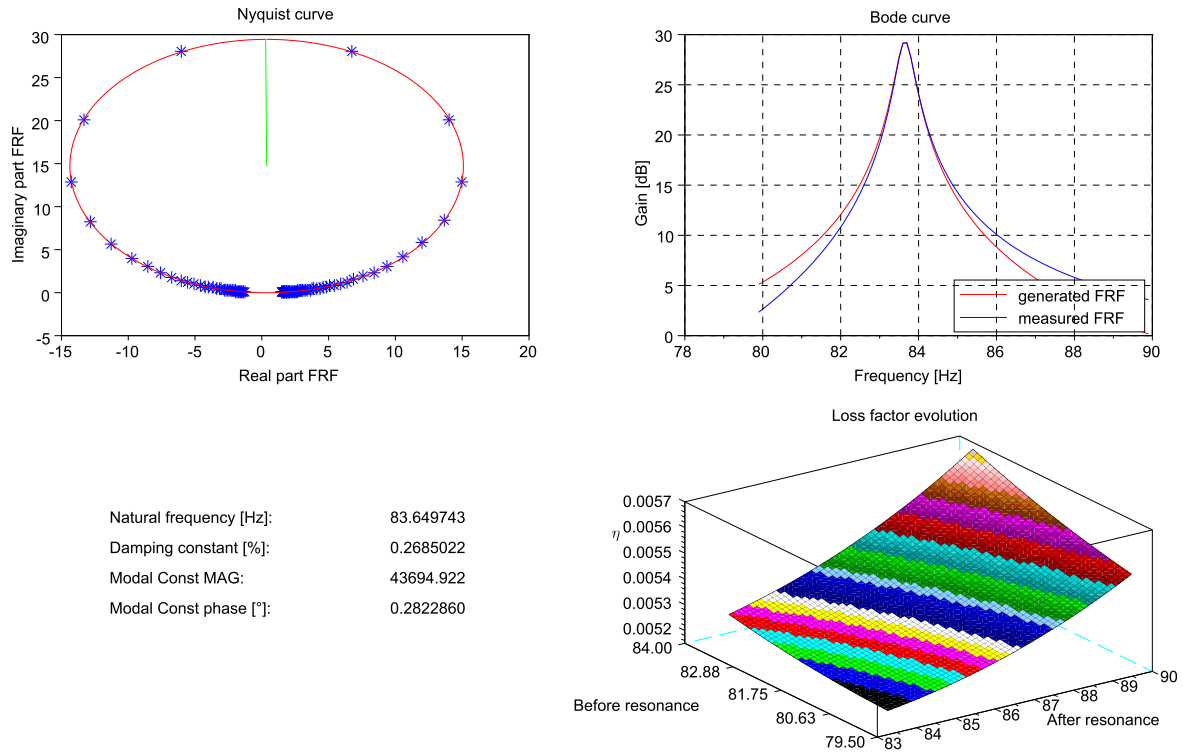


Figure 3. Information provided by the circle-fit method

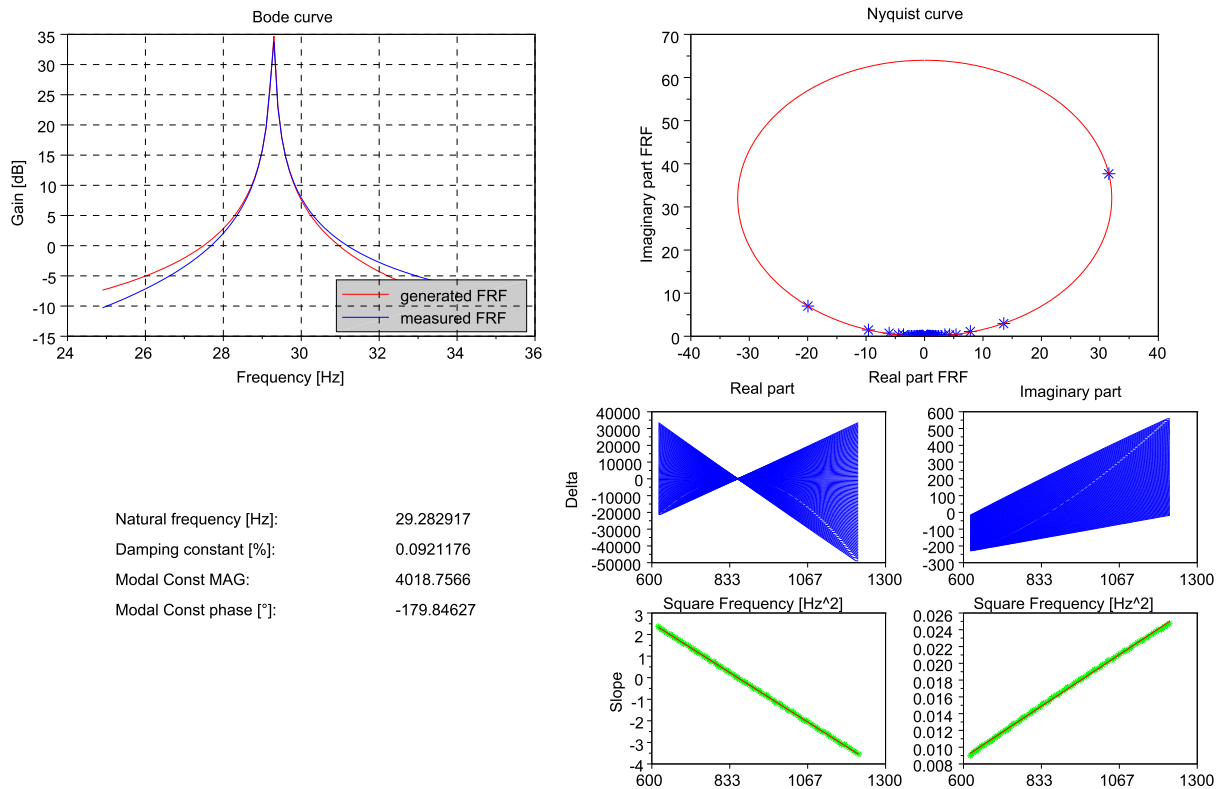


Figure 4. Information provided by the line-fit method

examination of the spacing of the FRF points is also analysed, through the effect of the generalized version of the half-power points formula and its sensitivity with the selected points before or after resonance. Figure 4 shows the same analysis with the LF method, where the linear property of the inverted FRF is taken into account.

4. Example 2: a 11-dof model

The second system is a noise-free 11-dof system [10] excited by three incoherent random sources at points 1, 2 and 9 and schematically illustrated on Figure 5. This example is typically well adapted to the course of “Techniques in vibration engineering” in the first year of master’s degree in mechanical engineering, since the main purpose is to put emphasis on the MIMO advantages, all the while varying the structure damping for a convenient analysis. Table 1 gives the dynamic data associated to this system as well as the modal parameters obtained by solving the eigenvalue problem

$$\det([\mathbf{K}] + \lambda[\mathbf{C}] + \lambda^2[\mathbf{M}]) = 0 \quad (2)$$

where \mathbf{M} , \mathbf{C} and \mathbf{K} are the mass, damping and stiffness matrices of the system. This operation is trivial on *MatLab* or *SciLab*. *EasyMod* provides functions for generating FRFs from these matrices and for saving it in UFF files. Therefore, it is possible to produce sets of data for the students as if they have been measured in the “virtual system”, while defining variants by changing the damping level of the model. The matrix formulation allows, by working with a single matrix \mathbf{H} containing all the selected FRFs

$$\mathbf{H} = \left\{ \begin{array}{c} \vdots \\ H_{ij}(\omega) \\ \vdots \end{array} \right\}, \quad (3)$$

to easily select the response to analyse et to compare the contribution of relevant FRFs.

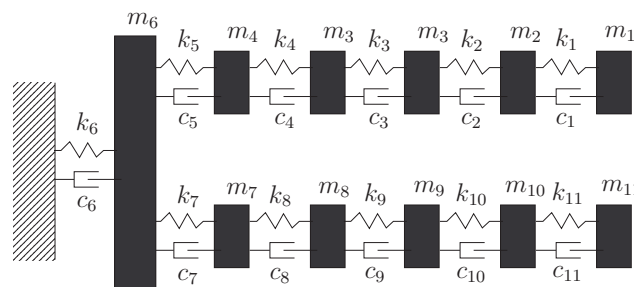


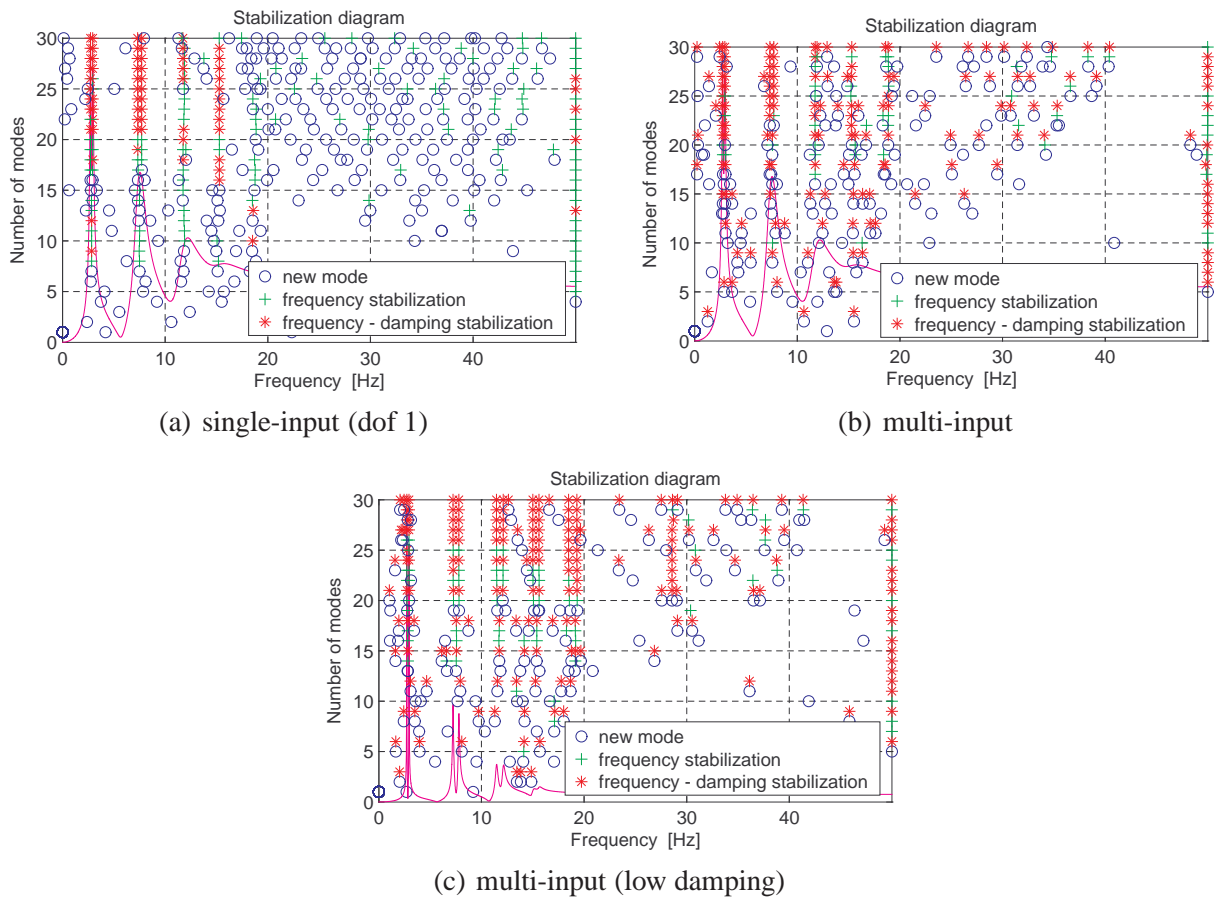
Figure 5. 11-dof discrete model

Circle-fit and line-fit methods are not adapted for this example and this can be proved by using these methods for some FRFs, especially for close frequency modes. Multi-input methods are preferred. Figure 6 shows stabilization diagrams obtained by the LSCE method, by considering various configurations. Single- and multi-input excitation are displayed in Figure 6(a) and Figure 6(b), and the particular case of low damping, by dividing the damping matrix by 10, is presented in Figure 6(c). The following observations are noteworthy:

- The MIMO advantages are clearly depicted in the first two diagrams. That avoids the case of a excitation on a point node and the distinction of modes strongly coupled is more emphasized. In the presented example, the stabilization of modes 9 and 10 do not operate while multi-excitation data provide more acceptable results.

Table 1. Data related to the 11-dof discrete model

data †				modes		
i	m_i [kg]	k_i [N/m]	d_i [-]	k	f_{ok} [Hz]	ξ_k [-]
1	1	2421	0.04	1	2.74	0.022
2	1	2989	0.05	2	2.95	0.026
3	1	3691	0.06	3	7.34	0.064
4	1	4556	0.07	4	7.72	0.080
5	1	5625	0.08	5	11.75	0.078
6	1	18000	0.09	6	11.91	0.154
7	1	5625	0.10	7	15.28	0.096
8	1	4556	0.11	8	15.35	0.202
9	1	3691	0.12	9	18.84	0.198
10	1	2989	0.13	10	18.85	0.128
11	1	2421	0.14	11	28.53	0.170

 † d_i so that $c_i = 2d_i\sqrt{k_i m_i}$

Figure 6. Stabilization diagrams provided by the LSCE method

- By knowing a priori the modal parameters, it is therefore more convincing to put emphasis on the abuses of LSCE method, for which some mathematical modes appear. The use of mode indicators beforehand allows to concentrate the analysis on specific frequency ranges.
- The effect of damping on the time domain method efficiency can be studied when damping is or is not taken into account, knowing the benefit of frequency domain in the case of high-

dampened systems. To be complete, the toolbox should contain on the long view a MIMO method based on the frequency domain.

5. Conclusion

In this paper, a modal analysis toolbox has been presented for which students can visualize and illustrate the base fundament of the modal theory. With the continuous development of engineering software, simple methods like CF or LF have made space for advanced mathematical method, more efficient but less open to deal with the students in a course of modal analysis. *EasyMod* is not yet-another EMA software. It does not claim to outclass and replace the present commercial software. It provides some interesting functions for teaching EMA. As it is presented as an open-source framework, all the engineering community can develop they own contribution, in the scope of modal analysis teaching. The use of UFF files allows to make the link with commercial data acquisition software or modal parameter extraction programs, for a general-purpose use. Ultimately, students adopt rigorous reaction in view of vibration problems, while still keeping an up-to-date training with the rapid development in this engineering field.

The toolbox can be downloaded in our web site where the interested reader can find additional information (<http://mecara.fpms.ac.be/EasyMod>).

REFERENCES

- ¹ D. J. Ewins. Modal analysis as a tool for studying structural vibration. In S. G. Braun, editor, *Mechanical Signature Analysis*. Academic Press, London (UK), 1986.
- ² N. A. J. Lieven and D. J. Ewins. The context of experimental modal analysis. *Phil. Trans. R. Soc. Lond. A*, 359:5–10, 2001.
- ³ P. Guillaume, P. Verboven, S. Vanlanduit, H. Van der Auweraer, and B. Peeters. A poly-reference implementation of the least-squares complex frequency-domain estimator. In *IMAC 21, the International Modal Analysis Conference*, Kissimmee (USA), 2003.
- ⁴ SDTools. SDT Structural Dynamics Toolbox. <http://www.sdtools.com>, 2012.
- ⁵ Acticut AB. VibraTools. <http://vibratools.eu>, 2012.
- ⁶ A. W. Phillips and R. J. Allemang. Development of a long term viable dynamic data archive format. In *Modal Analysis Topics, Volume 3, Proceedings of the 29th IMAC, A Conference on Structural Dynamics*, Kissimmee (USA), 2011.
- ⁷ O. Verlinden, G. Kouroussis, and C. Conti. EasyDyn: A framework based on free symbolic and numerical tools for teaching multibody systems. In *Multibody Dynamics 2005*, Madrid (Spain), 2005. ECCOMAS Thematic Conference.
- ⁸ D. J. Ewins. *Modal Testing: Theory and Practice*. John Wiley & Sons, Great Yarmouth (UK), 1991.
- ⁹ E. S. Raymond. *The Cathedral and the Bazaar*. O'Reilly, Sebastopol (USA), 2001.
- ¹⁰ N. Niedbal and E. Klusowski. Optimal exciter placement and force vector tuning required for experimental modal analysis. In *ESA SP-321 (Volume 1), Spacecraft Structures and Mechanical Testing, Proceedings of the International Conference Held at ESTEC*, Noordwijk (The Netherlands), 1991.