Interactive lecture notes for structural dynamic analysis in frequency domain

Apuntes de clase interactivos para el análisis de la dinámica estructural en el dominio de la frecuencia

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HIGHLIGHTS

- A numerical tool for learning awkward mathematical background of structural dynamic analysis
- Understanding frequency domain analysis of structures through numerical experiments
- Application of modern live script tools to learn traditional frequency domain analysis

TITULARES

- Herramienta para el aprendizaje los fundamentos matemáticos de la dinámica estructural..
- Entendiendo el análisis en el dominio de la frecuencia a través de la experimentación numérica
- Aplicación de herramientas interactivas al aprendizaje clásico del dominio de la frecuencia.

ABSTRACT

Dynamic and experimental analysis of structures are two of the most abstract and complex disciplines in structural engineering, because of its awkward mathematical and physical background and due to the multidisciplinary knowledge needed to go over the whole analysis (from the acquisition of measures up to the final interpretation of results). In particular, Fourier analysis (frequency domain analysis) in discrete time, which is routinely used in the dynamic analysis, is not usually well-understood and even is not well computed in discrete time. Frequently, students lose motivation trying to decrypt difficult mathematical developments, which do not let them to interpret properly complex concepts which are extremely important for current analysis in discrete time such as: Fourier transforms, aliasing, leakage, filtering, windowing, etc. For this reason, the authors has implemented a new teaching tools based on the numerical experiments and interactive learning that transform the learning experience into a more pleasant process than in the pass. In this way, recently-developed tools as "MATLAB Live Editor" allows professors to create interactive lecture notes, which students can easily follow, modify and simultaneously run during classes, developing its own intuitive interpretation of the knowledge. This tool is been successfully employing to teach dynamic analysis of structures in frequency domain with excellent feedback from the students.

Keywords: *Learning based on experiments; Active learning technologies; Interactive lecture notes; Dynamic analysis of structures; Fourier analysis*

RESUMEN

El análisis experimental y dinámico de estructuras son dos de las disciplinas más complejas y abstractas de la ingeniería estructural debido a la complejidad de los fundamentos que se manejan y al conocimiento multidisciplinar necesario para llevar a cabo el proceso completo de análisis (desde la toma de datos hasta la interpretación final de los resultados). En particular, el análisis de Fourier (análisis en el dominio de la frecuencia), el cual se usa continuamente en el análisis dinámico, no siempre se entiende adecuadamente e incluso no se aplica correctamente en el dominio discreto. Con frecuencia los estudiantes pierden la motivación intentando comprender los desarrollos matemáticos asociados, lo que no les permite interpretar adecuadamente conceptos más complejos y a la vez importantes como: la transformada de Fourier, "aliasing", "leakage", filtrado, ventanas de ponderación, etc. Por ello, los autores han implementado una nueva herramienta basada en la experimentación numérica y en el aprendizaje interactivo, haciendo del mismo un proceso más llevadero que en el pasado. Así, herramientas recientes como "MATLAB live Editor" permiten que los profesores creen clases interactivas que los estudiantes pueden de forma sencilla, seguir, modificar y ejecutar durante las clases, desarrollando un conocimiento más intuitivo del problema. Los autores están empleando esta herramienta exitosamente en el análisis dinámico de estructuras en el dominio de la frecuencia con muy buenos comentarios por parte de los estudiantes.

Palabras clave: *Aprendizaje basado en experimentos; Tecnologías activas de aprendizaje; Material docente interactivo; Análisis dinámico de estructuras; Análisis de Fourier*

1. INTRODUCTION

Structural Engineering traditionally has been an eminently practical field, however, certain disciplines as dynamic and especially, experimental analysis of structures differ slightly from this conception. This is mainly due to the confluence of several mathematical, physical and engineering concepts and tools such as signal processing, digital analysis, partial differential equations, numerical methods etc. [1]

This fact is especially reflected in some master-course lectures, when the professor must address difficult and awkward background concepts (especially those are not clearly related to civil engineering). Frequently, students get lost when they have to face cumbersome mathematical developments and lose easily motivation since they do not find any eminent practical application (Fig. 1). Nowadays, a more intuitive, friendly and practical way of understanding is demanded by students.

A clear example of such a difficult mathematical background is the frequency domain analysis of signals, which results to be capital when understanding dynamic behavior of structures [2].

Given the situation, a new teaching philosophy based on pleasant ways of interpreting the knowledge must be developed, as graphical representation or numerical experimentation. These techniques allow the students to learn the tricky theoretical background easier and faster than in the past. These also enable the professor to focus the lectures on the applicability of this knowledge.

On the one hand, there have been different attempts to explain frequency domain analysis providing kind interpretations of the knowledge and making use of several amusing learning tools [3]. For instance, new high-quality graphical and animated interpretations have been shared at massive web platforms as You Tube by many content creators as “Three Blue one Brown”, “Khan Academy” or “Eugene Kutoryansky” [4].

On the other hand, modern ways of teaching this complex background knowledge at university level can be found in the literature. These relatively new strategies make use of friendly concepts as music [5] robotics [6] or digital image processing [7], in order to provide an interesting applicability to the taught knowledge.

Among all the above-mentioned learning techniques, the integration of specific software for mathematical analysis as MATLAB [8], Mathematica or Maple having been using as an essential tool for engineering teaching [9]. Even though, this software is becoming more relevant nowadays, the benefits of classical lectures and student notetaking processes are widely recognized.

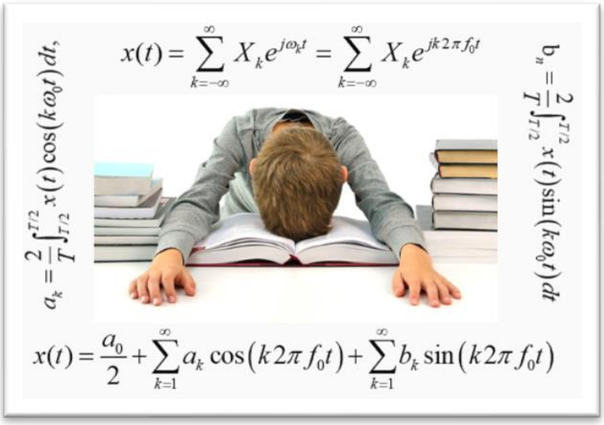


***Fig. 1**: Fourier analysis becomes a nightmare for professors and an esoteric discipline for students*.

From all the above-mentioned aspects, it is capital to update/upgrade the way of imparting lectures. This means that modern interactive tools for the students that enables them combining software analysis tools with an organized set of lecture notes, all in the same platform, are undoubtedly interesting. This would ease their notetaking process through complementing it with short code scripts, which they can use for understanding concepts by means of testing and numerical experimentation [10].

This paper presents this teaching methodology as applied to discrete frequency domain analysis for structural dynamics. That is, the "Structural Engineering Group" from ETSI Caminos Canales y Puertos of UPM has started to implement it within two master courses: *Experimental Analysis of Structures* and *Dynamic and Seismic Analysis of Structures*. The authors have created a set of interactive notes using the recently developed tool of the MATLAB Software package called "MATLAB Live Editor". Finally, making use of these notes, and through guided experiments, the students have been able to perceive the advantages of the proposed method.

2 DESCRIPTION OF THE METHODOLOGY

The described learning methodology is based on two fundamental aspects.

The first one, is to take advantage of the new technologies available nowadays that could facilitate the learning experience. Currently, university students have free access to lots of mathematical and engineering software products. Among them, MATLAB stands out: it combines comprehensive math and graphic the only benefits that MATLAB could offer. MathWorks have recently developed a new programming environment "MATLAB Live Editor" [11] where computation, results and graphics are displayed together with the code that produced them, in a single document. Inside this smart document the user can add formatted text, mathematical equations, images and

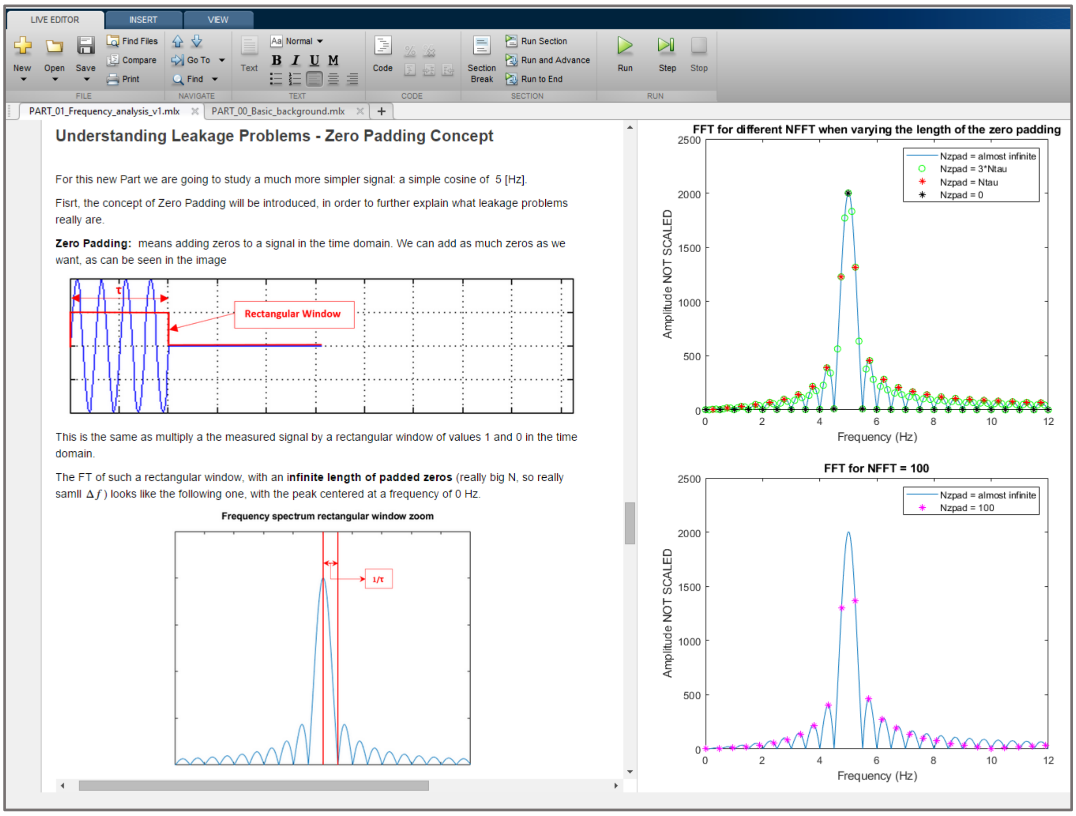


***Fig. 2**: MATLAB Live Editor environment. Example of the interactive notes given to the students*.

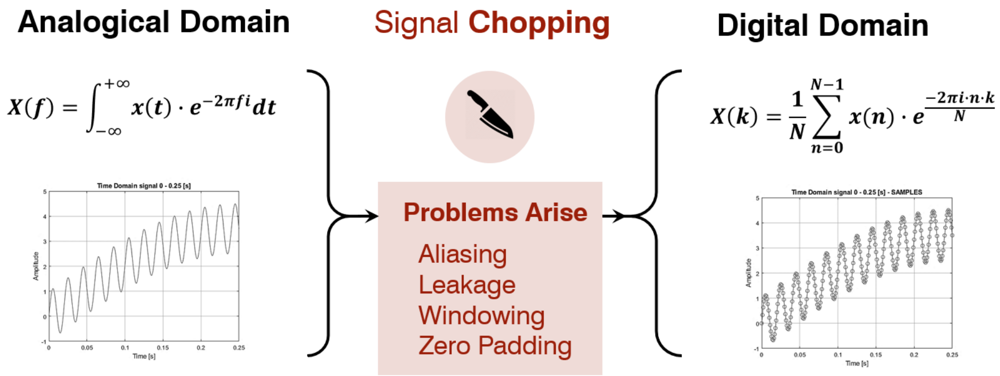


***Fig. 3**: Analog signal chopping involves many new mathematical challenges.*

hyperlinks within the code to create an interactive and clear narrative. Fig. 2 shows an example of Live Editor script focused on explaining leakage problems. functions with a powerful high-level language, which can be learned easily. But those are not

The second key aspect is "Numerical experimentation". Once professors have this excellent state-of-the-art technology at their disposal. How should they use it? One option is to develop a guided experimental learning process that starts with simple examples and ends up with more complex problems. This way of thinking fit the Anglo-Saxon approach based on education practitioners.

When combining these two aspects: a friendly and innovative environment, interactive tools and a self-learning approach based on numerical experiments, the concept of "game" might arise. As it was said before, the main objective is to transform a pretty tough learning experience of the student into an enjoyable game.

The unique situation that the professors have had to face up when this new methodology was proposed to the students, is that not all of the students were familiar with MATLAB's code language. Even though most of them have notions of programming. Fortunately, due to the high-level properties of MATLAB's programming language, those students are able to learn it easily in a specific lecture prepared for them about "MATLAB Basic Background". This introductory Lecture has been also imparted with smart live scripts created inside the own MATLAB Live Editor, which resulted to be extremely efficient. As a result, the feedback obtained from unexperienced students has been quite positive.

3 APPLICATION EXAMPLE: FREQUENCY DOMAIN ANALYSIS

As stated above, the "Structural Engineering Group" has applied this philosophy to teach background mathematical and physical concepts with certain degree of complexity. The first implementation was done last year (2018-2019), for explaining "Frequency domain analysis of vibration signals" in the master courses *Experimental Analysis of Structures* and *Dynamic and Seismic Analysis of Structures*.

Frequency domain analysis of signals is one of the most difficult tricky and problematic fields in engineering, due to the extensive mathematical knowledge required to perform certain calculations correctly. This discipline commonly becomes awkward for the student when changing from the continuous and ideal domain of mathematical functions, to the discrete and real domain of chopped signals (Fig. 3 illustrates this fact). This simple step involves many new mathematical challenges as "leakage", "aliasing", "signal windowing", "zero padding" or "filtering" [2]. Hence, the student needs to assimilate and get used to the discrete frequency domain, in order to face and overcome the mentioned challenges, for finally process properly any vibration signal.

In this regard, in order to provide a first pleasant introduction to such a topic (not closely related to classical structural engineering) professors decided to made use of these interactive tools to not demotivate the students. In addition, frequency domain analysis seemed to be a good field for making a first trial with this new methodology, as its understanding relies a lot on an appropriate graphical interpretation of the analyzed signals.

This part of the course was structured in three main lectures: first, an introduction to MATLAB, second, an introduction to frequency domain analysis, and third, its applications in experimental and dynamic analysis of structures.

3.1 Example: teaching aliasing with MATLAB Live Editor

The objective of this first lecture was to provide an understandable knowledge about discrete frequency domain analysis of signals, and the main problems that can arise when performing it. Thereby, certain basic concepts were explained

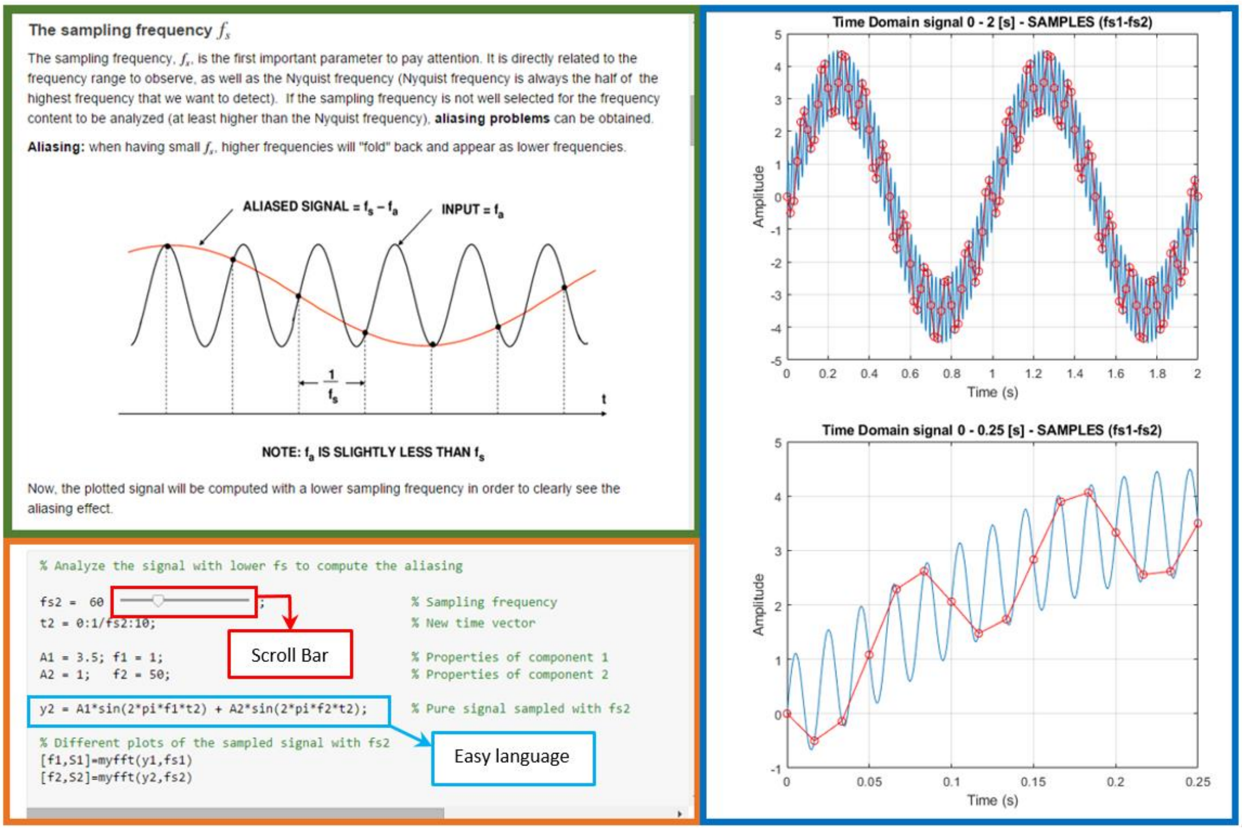


Fig. 4: MATLAB Live Editor environment. Explaining aliasing through interactive notes.

providing always an interactive graphical interpretation.

A clear example that could portray this new way of teaching properly is the explanation of the concept of "aliasing". Aliasing expresses a misunderstanding of the high frequency content of an analogic signal, when the sampling rate applied to digitalized is too low [1]. This may be seen a complex concept, but when addressed graphically, it turns to be much simpler.

Fig. 4 shows an example of a script used for teaching. As said above, the same document involves formatted text and images, for a first theoretical approach that introduces what is going to be discussed (inside the green area). Secondly, MATLAB code that students can modify to explore and experiment in real time, during the class (orange square). In order to facilitate this sort of testing game, some friendly tools can be introduced inside the code, as for example scroll bars for varying some governing parameters. Finally, in the blue area it can be found the results from calculations and graphical outputs that change whenever the student runs the program.

Hence, numerical experimentation and simple guided tests performed by the students during the class lead him to a deeper and richer comprehension of the knowledge, as Fig. 5 depicts.

3.2 Concepts explained in master-course lectures

Many other ideas were explained to the students following the same procedure, as for example: Fourier Transform, and its discrete version, the Discrete Fourier Transform, including certain notions about algorithms that can be used to perform it, as the Fast Fourier Transform (Fig. 6).

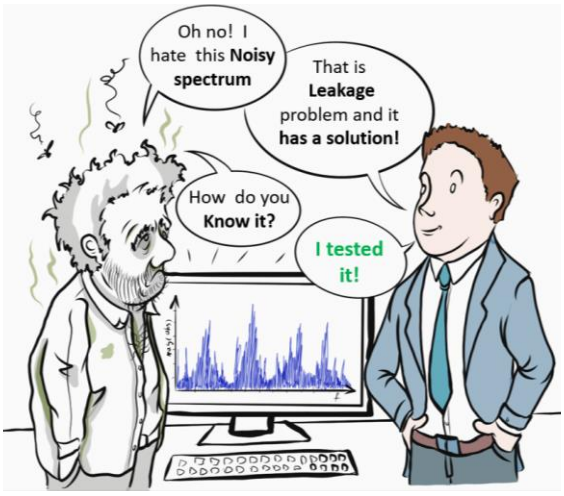


***Fig. 5**: Numerical experimentation and testing are capital when facing awkward mathematical concepts.*

In this context, the first lecture finished with an illustrative example about the relation of the concepts of "Zero padding" and "Leakage" [1], which has band seen presented above in Fig. 2. Finally, the second lecture was dedicated to applications of the discrete frequency domain analysis in dynamic experimental analysis of structures.

Professors continued with the same structure for the lectures:

- Short and simple theoretical introductions to complex mathematical concepts, describing the main formulas in a qualitative way, and introducing some representative examples.
- Guided numerical experiments through simple tests in which students vary the key governing parameters which describe a certain phenomenon.
- Theoretical justification of the observed behavior in previous experiments. Here, students share their conclusions and the professor completes the explanation.

In this manner, the definition of Frequency Response Function [2] and the different ways of calculating it were also introduced.

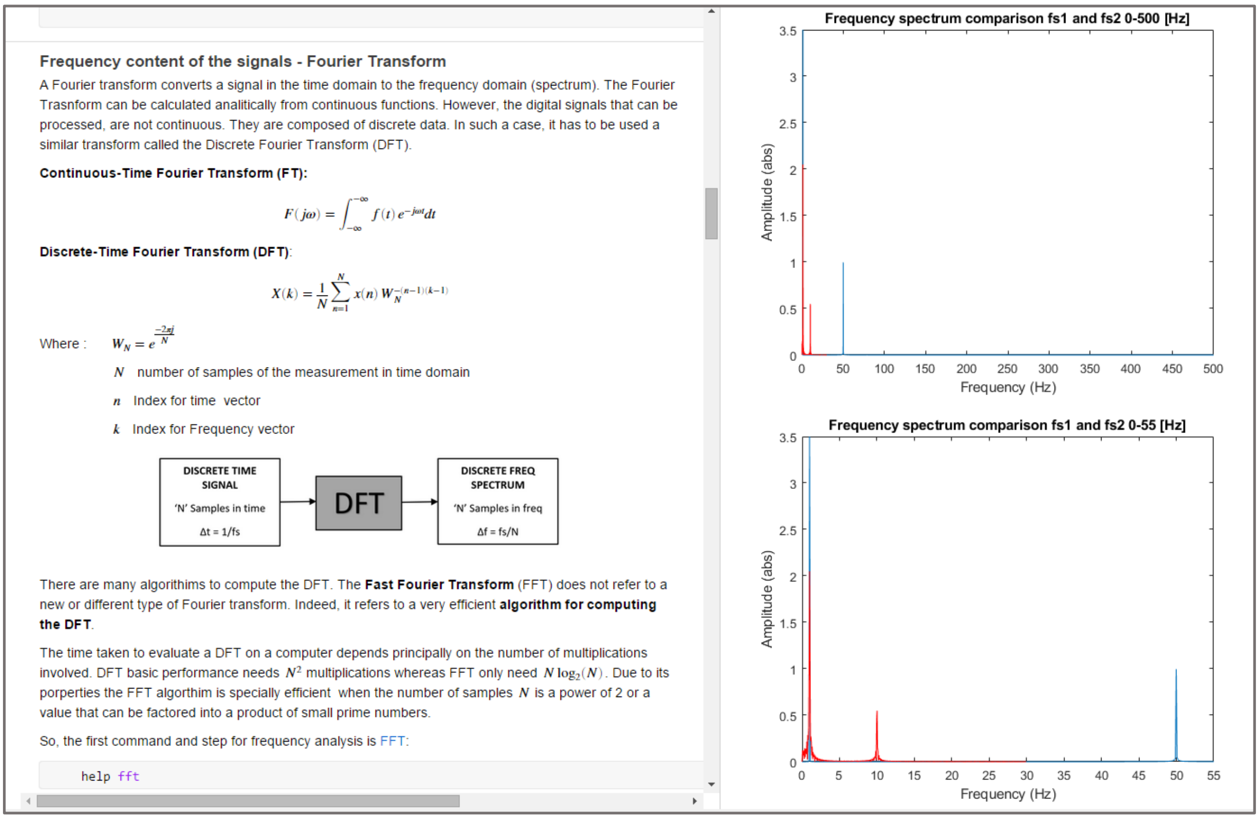


***Fig. 6:** MATLAB Live Editor environment. Explaining frequency domain analysis.*

4 STUDENT LEARNING PROCESS

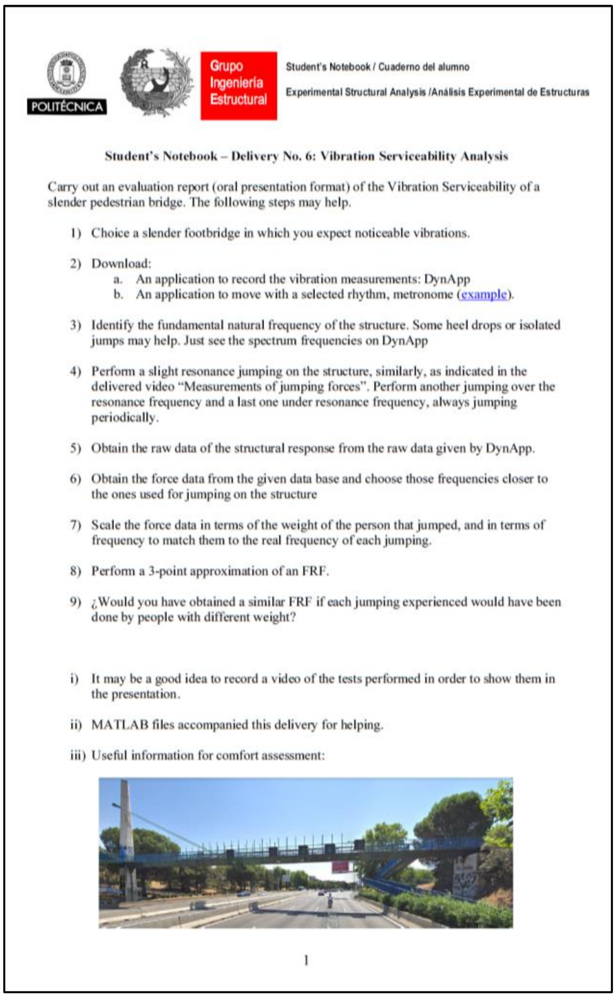
This teaching technique allows the student to develop his own perspective and understanding of the concepts presented in lectures, by experimenting by himself. This process has lots of advantages, since it really encourages the student to ask himself questions about his obtained results.

Two main factors are critical in order to guarantee a minimum degree of dynamism at class, which can be translated into a successful learning experience:

- First, students need to get used to MATLAB programming language, if not, the testing experience becomes complex and messy, as the professor needs to attend too many doubts at the same time.
- Secondly, professor's role results to be fundamental in order to create an open and inspiring environment which encourage students to answer quick questions, to express their opinion and to collaborate for solving simple tasks proposed by the teacher.

To Sum up, dynamism in class is essential in order to achieve a successful learning process. Because of this, the professor must avoid long, boring and sleepyhead mathematical explanations. Indeed, qualitative descriptions of equations remarking their key parameters and their influence are enough. Similarly, difficult questions or tasks should be avoided, instead of that, the professor must propose easy, short and clarifying exercises, no longer than a few minutes. In other words, to teach making use of small pills of knowledge. This helps a lot on keeping the student's attention [12]. In fact, it is widely accepted that microtasks-finishing and objectives-updating result strongly stimulating for the brain's reward system, mainly responsible of most human pleasures [13].

Apart from the class activities and as an assessing activity, at the end of each lecture, the professor proposes a simple assignment, that must be delivered weekly, in order to assure that the student is interiorizing correctly all the explained ideas. The key point is that this exercise requires the student's fully comprehension of the explained concepts in order to apply them in a practical way to a real case, always related to structural engineering.


Student's Notebook / Cuaderno del alumno

Experimental Structural Analysis /Análisis Experimental de Estructuras

Student's Notebook – Delivery No. 6: Vibration Serviceability Analysis

Carry out an evaluation report (oral presentation format) of the Vibration Serviceability of a slender pedestrian bridge. The following steps may help.

1) Choice a slender footbridge in which you expect noticeable vibrations.
2) Download:
   a. An application to record the vibration measurements: DynApp
   b. An application to move with a selected rhythm, metronome (example).
3) Identify the fundamental natural frequency of the structure. Some heel drops or isolated jumps may help. Just see the spectrum frequencies on DynApp
4) Perform a slight resonance jumping on the structure, similarly, as indicated in the delivered video "Measurements of jumping forces". Perform another jumping over the resonance frequency and a last one under resonance frequency, always jumping periodically.
5) Obtain the raw data of the structural response from the raw data given by DynApp.
6) Obtain the force data from the given data base and choose those frequencies closer to the ones used for jumping on the structure
7) Scale the force data in terms of the weight of the person that jumped, and in terms of frequency to match them to the real frequency of each jumping.
8) Perform a 3-point approximation of an FRF.
9) ¿Would you have obtained a similar FRF if each jumping experienced would have been done by people with different weight?

i) It may be a good idea to record a video of the tests performed in order to show them in the presentation.
ii) MATLAB files accompanied this delivery for helping.
iii) Useful information for comfort assessment:

1

Fig. 7: *Delivery Assignment of frequency domain analysis of structures.*

In this case, the evaluation assignment presented in Fig. 7 consists of performing the frequency response at 3 test points in an in-service footbridge by means of using their mobile phones as measurement devices. For this objective, the students should also employ DynApp [14] (a new mobile App recently developed by the authors) in order to perform the vibration measurements. This enables them to obtain vibration signals that can be analyzed lately at the discrete frequency domain, making use of most of the concepts taught at class [15].

After having been applied, students were asked about their opinion of this new interactive way of teaching. Most of them declared to be satisfied with the learning experience. Furthermore, some of them remarked that the efficient software distribution provided by MathWorks and that the professor's positive and close attitude, were key aspects for the experience success.

5 CONCLUSIONS

An innovative way of explaining complex mathematical and physical background-concepts required for master courses of structural engineering has been developed. This methodology is based on two main points: 1) new technologies and state-of-the-art learning tools, as for example the "MATLAB Live editor", can be really interesting for the student learning process; and 2) set new way of understanding tricky ideas based on numerical experimentation.

The "Structural Engineering Group" from ETSI Caminos Canales y Puertos of UPM has implemented this new teaching philosophy in two master courses for explaining frequency domain analysis of vibration signals. For those lectures the professor developed a set of interactive lecture notes for the students. Through using these interactive notes, the class dynamism was substantially increased. In this sense, brief theoretical explanations followed by a set of short and clarifying numerical experiments proposed by the professor, were fundamental key for the teaching success.

As a result, the student's feedback has been quite more positive in comparison with the one obtained for other lectures with a more classical approach.

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