A mobile tool for teaching advanced dynamic analysis

Una aplicación móvil para el aprendizaje de análisis dinámico avanzado

Iván M. Díaz [1*], Jaime H. García-Palacios [2], José M. Soria [3], Carlos M.C. Renedo [4]

[1] *ETSI Caminos, Canales y Puertos. Universidad Politécnica de Madrid. Spain. ivan.munoz@upm.es*
[*] *Corresponding autor address: C/ Profesor Aranguren 3, 28040, Madrid. Spain.Tl.: +34910674153*
[2] *ETSI Caminos, Canales y Puertos. Universidad Politécnica de Madrid. Spain. jaime.garcia.palacios@upm.es*
[3] *ETSI Caminos, Canales y Puertos. Universidad Politécnica de Madrid. Spain. jm.soria@upm.es*
[4] *ETSI Caminos, Canales y Puertos. Universidad Politécnica de Madrid. Spain. carlos.martindelaconcha@upm.es*

Recibido: 11/02/2019 | Aceptado: 24/04/2019 | Fecha de publicación: 30/04/2017
DOI:10.20868/abe.2019.1.3885

HIGHLIGHTS

- A practical way for learning advanced dynamic analysis of structures.
- Using mobile phones to evaluate structural comfort.
- Tracking vibrations from classroom to structure itself.

TITULARES

- Una forma práctica de aprender análisis dinámico avanzado de estructuras.
- Uso de los teléfonos móviles para evaluar el grado de confort de las estructuras.
- Siguiendo la pista a las vibraciones desde el aula hasta la propia estructura

RESUMEN

El avance continuo de la tecnología en los teléfonos móviles ha facilitado el desarrollo de aplicaciones más complejas y especializadas. En la actualidad se pueden encontrar aplicaciones móviles sencillas para el cálculo de estructuras. En este trabajo, se da un paso más con una nueva aplicación para análisis dinámico. Más concretamente, se ha desarrollado una aplicación móvil que permite valorar el estado de servicio de vibraciones en estructuras y que puede ser utilizada tanto por profesionales como para la impartición de cursos de master en análisis dinámico. En este artículo se muestran los resultados obtenidos con la aplicación desarrollada, DynApp, en diversas pasarelas peatonales de la ciudad de Madrid. Estas campañas experimentales se han realizado por los alumnos de dos cursos de master de la Escuela de Caminos de la UPM: *Análisis Experimental de Estructuras* y *Análisis Dinámico y Sísmico de Estructuras.*

Palabras clave: *Tecnologías de aprendizaje activo; Educación multidisciplinar; Aprendizaje cooperativo; Tecnologías emergentes en la formación; Tecnologías móviles; Análisis dinámico de estructuras.*

ABSTRACT

The continuous advance of smartphone technologies has promoted the development of more complex and specialized mobile apps. Currently, it is possible to find several mobile apps that can be used for simple structural analysis. Here, a further step towards a newly specialized app for dynamic analysis is taken. More precisely, an app for the vibration serviceability assessment of structures has been developed, which is useful for professional practitioners and for imparting master courses on dynamic analysis. This paper presents experimental tests using the developed app, DynApp, on several in-service footbridges sited in Madrid. The tests have been done within two master courses imparted at ETSI Caminos of UPM: *Experimental Analysis of Structures* and *Dynamic and Seismic Analysis of Structures*.

Keywords: *Active learning technologies; Multidisciplinary education; Cooperative learning; Emerging Educational Technologies; Mobile technologies; Dynamic analysis of structures.*

1. INTRODUCTION

The actual development of knowledge and technologies opens new challenges in a more technological welfare society. User comfort related to bridges or footbridges is a new concept that is becoming increasingly important in the design process while maintaining the safety and reliability standards. At the same time, the beauty associated with structural design leads to more slender structures than in the pass, which may introduce annoying vibrations for the users (an example of a slender bridge constructive by innovated structural technologies is shown in Fig. 1). Nowadays, vibration allowed standards over the built structure [1, 2, 3] have become an essential requirement that engineers must manage when dealing with modern and complex projects. It should be taken into account that civil engineering construction uncertainties may have a large importance in the final user perceived comfort. Actually, the only way to assure that an in-service structure is meeting the vibration serviceability state is carrying out on-site measurements. This requires the real structure, a measurement campaign, and the necessary knowledge to carry on with the process.

To carry out successful experimental campaigns, it is needed to possess a strong multidisciplinary knowledge and be able to carry out cooperative activities. From the theoretical point of view, it is necessary to cope with difficult-to-understand background knowledge that involves Fourier analysis (Fig. 2) in discrete and continuous domain and dealing with digital signals with the well-known problems associated to the use chopped signals [4]. This point becomes a nightmare for professors and an esoteric discipline for students. From the practical point of view, on the one hand, previous thoroughgoing planning should be carried, on the other hand, the campaigns are expensive and difficult to carry out since they involve the use of awkward and heavy equipment, such as electrical generators, acquisition systems and long cables that are difficult to deploy. Fig 3 shows an example of experimental testing of a floor, shakers, cables, accelerometers, reels, etc. can be observed.

Fig. 1: *Stress-ribbon footbridge with a single span of 85 m providing minimal impact to the surroundings, Valladolid*.

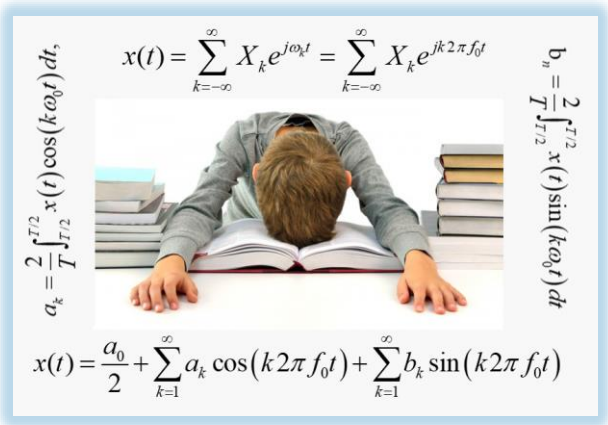


***Fig. 2**: Fourier analysis becomes a nightmare for professors and an esoteric discipline for students*.

In order to find easier ways to cope with the above-mentioned problems, a unique worldwide mobile app for advanced vibration analysis has been developed. Mobile phones are computers equipped by sensors to fulfil certain capabilities that make their use friendlier. However, these sensors can be used for other purposes such as the assessment of comfort level associated with vibration serviceability limit state through the measured accelerations. Current smartphones have triaxial MEMS accelerometers with enough sensitivity and sampling frequency to measure the expected acceleration of slender structures [5]. Thus, the authors have decided to develop a mobile app, DynApp, in order to allow: 1) practitioners to quickly assess the serviceability in one go and in both, frequency and time domain, and 2) students to be familiar with Fourier analysis and the implications related to the use of digital signals. This practical approach joints the instrumentation of structures with the serviceability analysis. Thus, DynApp is shown as a simple, rigorous and understandable app for teaching advanced structural dynamics.

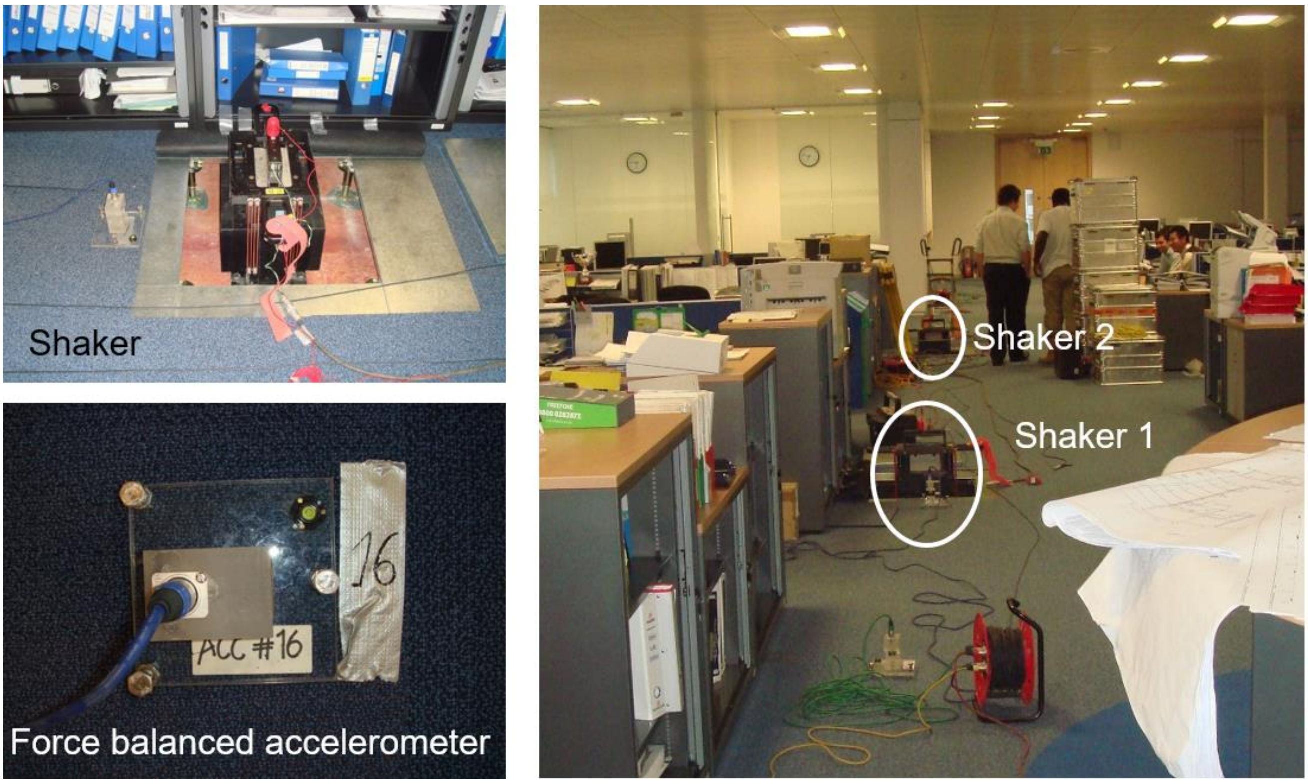


***Fig. 3**: Experimental campaign on an in-service floor*.

This paper focuses on the capabilities of this mobile tool to impart structural dynamics to master students. The use of mobile apps for teaching is an emerging educational technology that allows to apply active and cooperative learning strategies simultaneously. The app enables students to understand, from the practical point of view, the awkward mathematical background involved in the process of extracting useful information from real measurements. This fact matches perfectly the current demand of the master-level student of easy, interactive and applicable discipline which are directly connected to their future job [6, 7, 8].

2 APP DESCRIPTION

The two main objectives for the development of this app are: to have a full capability of measuring vibration serviceability limit states, and to guide students and professionals in all the necessary steps of this process. The first one could have been met with just pushing a button, while the second one requires information of all the sequential processes involved to reach the solution. This extra information is also necessary to evaluate the uncertainty of the final result and to write a complete engineering report as it will be required to the students. Active and cooperative learning tools are used at this point [9, 10].

DynApp is being developed within an educational innovation project financially supported by the Technical University of Madrid (see Fig. 4). The project started with a revision of the existing similar apps in the market, assessing their capabilities and limitations to reach the objectives [11, 12, 13]. Some free apps are able to acquire data and store them in a file. They also have a nice interface that usually allows showing the signal while it is acquired. Non-free applications usually add more sophisticated tools like Fast Fourier Transform (FFT) computing of signal, trimming the series etc.

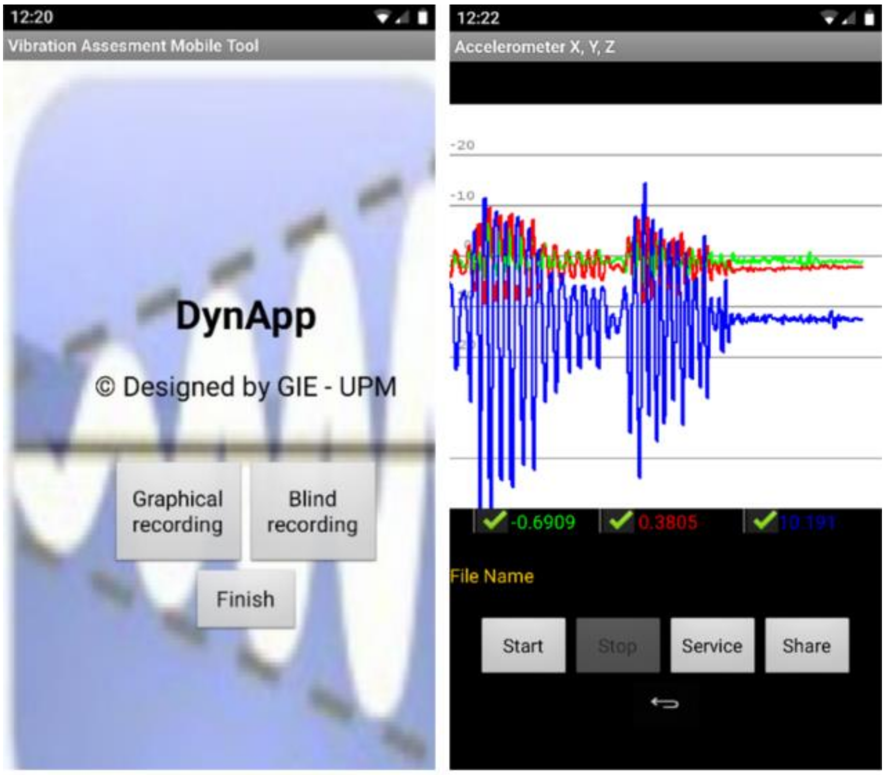


Fig. 4: *DynApp, front-page and an example of measuring*.

Nowadays, there is not any available app able to: acquire, undertake frequency analysis and obtain serviceability parameters (all in one go). In fact, there is a lack of information in all of them of the processes followed. Additionally, in all the apps found by the authors, the records are not carried out under constant time intervals, which is an issue to undergo any frequency domain analysis. This is an important drawback of current apps. To solve this problem, DynaApp carries out an ad hoc signal interpolation post processing. Interestingly, DynApp save data in files that are automatically sent to a server for a more complete analysis and backup copy. The DynApp capabilities are summarized in Fig. 5.

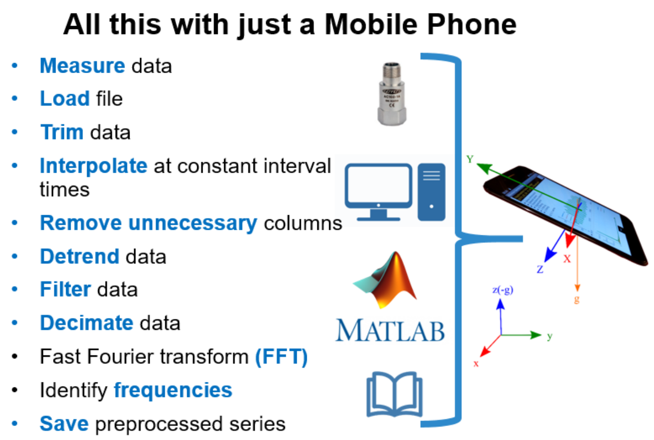


***Fig. 5**: DynApp capabilities.*

The sequential of using DynApp are the following:

- Start the application
- Select between graphical or non-graphical, but more efficient, recording interface.
- In the recording interface, select the starting of the measurement. In this step, a file name is automatically assigned with the date and time of the measurement. The measure will finish after pressing stop button.
- Once the recording is finished, the file will be closed and can be send it to the server for backup with just the press of a button. This task is not automated to avoid storing the unnecessary or failed tests that are not interesting for the measurement campaign. In any case, these files are still kept safe in the phone until they are explicitly removed by the user.
- Another option, independent from the previous one, is to analyze the results.

For theoretical teaching purposes, this becomes the main task. The steps followed in this process are sequential, and the practical implementation shows to students the importance of every step. In fact, for each one of the steps of the application, a tool based on the state-of-art live MATLAB editor that combine theoretical and practical implementation [4] is provided to the students. In this way, they can complete individual tasks with the measurements they have record in groups in order to have individual marks to evaluate their individual performance. This is also important as remarked by [10].

These processes, made automatically by DynApp, but explained in class in a more critical way, are following described:

The first one, is to get the duration of signal, the number of records, the mean and dispersion values of the sampling frequency, as well as the maximum gap between two consecutive records. The app shows the problem of acquiring at a constant time as well as the reduction in the mean value of the sampling frequency when more processes are added during the recording as the graphical interface. Finally, a reliable acquisition is programed. In this step, students will realize about the importance of knowing the tools they are using to be able to reach successful results.

The second step is to remove the signal trend. This value, is also given by the program, and the civil engineering students, that are not usually familiar with these signal concepts can, however, understand the physical meaning of the signal mean of every channel. From these values, they can extract the phone position relatively to a horizontal plane perpendicular to the gravity axes (see Fig. 6).

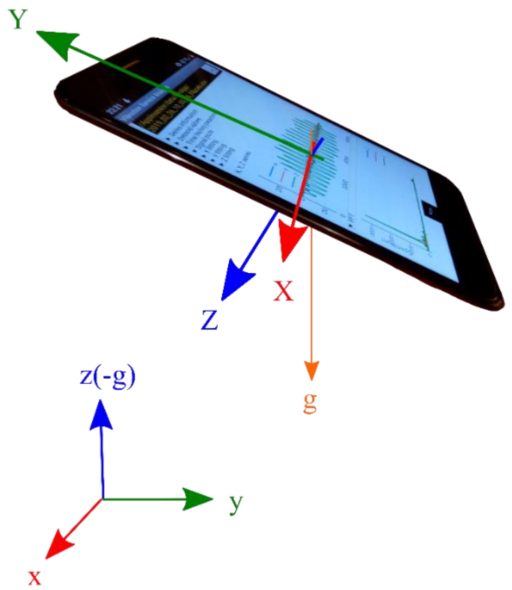


***Fig. 6**: Global and local axes.*

The third step is to obtain some time history parameters of the original series that provide information about the maximum acceleration registered in each axis as well as mean, running mean values, etc. These parameters are given by the app and can be compared with current codes. Students learn the theoretical background of these values and its practical application within the codes. Fig. 7 depicts the above-mentioned three steps. This figure corresponds to one of the test carried out master students in an in-service footbridge.

Following, and before undertaking a frequency analysis, it is important to have a time series with a regular time interval. Therefore, a spline interpolation is carried out trying to keep unaltered the original signal information. The program provides graphical information on this calibration and the students may try different solutions to see the influence of this critical process over the precedence results. Fig. 8 shows the time history series of z-axis, and Fig. 9 is a zoom where it can be seen the original and interpolated series at a constant time interval of 100 Hz.

▼ Series information

Dur (s)	N_{rec}	Fs_{med}	dt_{med}	dt_{max}	σ_{dt}	N_{rms}
25.07	3223	128.6	7.779	14.00	7.853	128.0

▼ Detrend values

X_{med}	Y_{med}	Z_{med}
0.5359	-0.7173	10.07

▼ Time history parameters

	|Med|	Max	Rms	Crest	MTVV
x	0.04777	0.2576	0.06135	4.198	0.1043
y	0.02500	-0.1519	0.03515	-4.322	0.06104
z	2.226	8.271	2.934	2.819	4.890

***Fig. 7.** Example of post processing carried out in an in-service footbridge.*

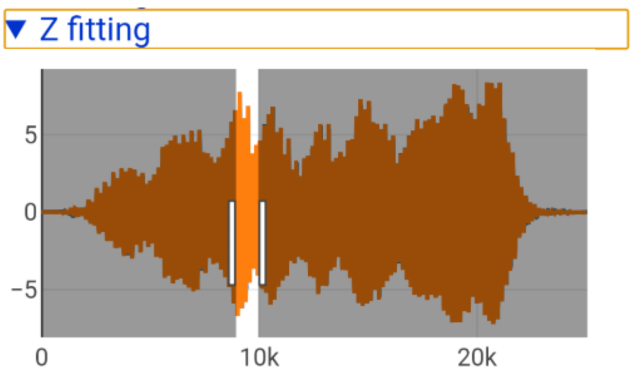


***Fig. 8.** Time history recording after bouncing on a footbridge.*

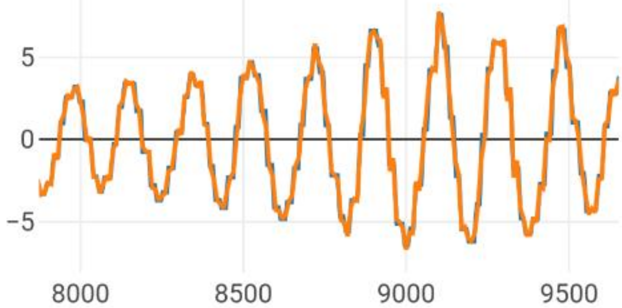


***Fig. 9.** Original (blue) and interpolated signal (orange), with perfectly constant time interval.*

Fig. 10 shows the acceleration responses at regularized time step intervals. These measures have been done in a footbridge under bouncing excitation. It can be seen that the z-axes response hides the other two responses since the excitation is vertically.

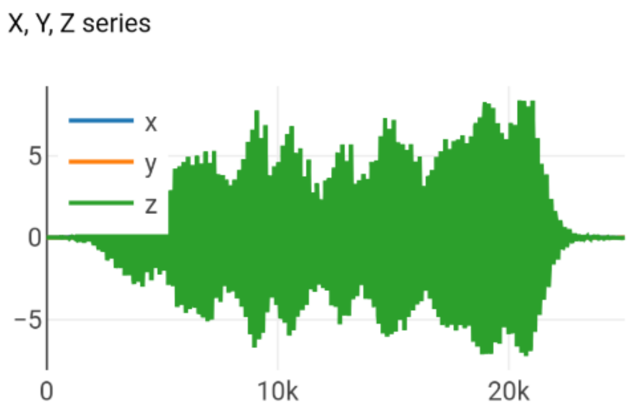


***Fig. 10.** Accelerations recording the three spatial directions.*

Thus, the complete process of the serviceability evaluation can be carried out in situ. Controlled tests, such as walking, running bouncing (individually, groups or stream) or heel drops can be planned and carried out in the same test [14, 15]. The students have to design the tests and make measurements. They should make decisions on the tests in a short time!

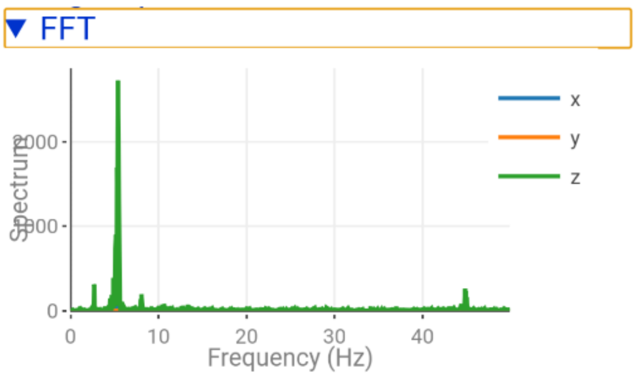


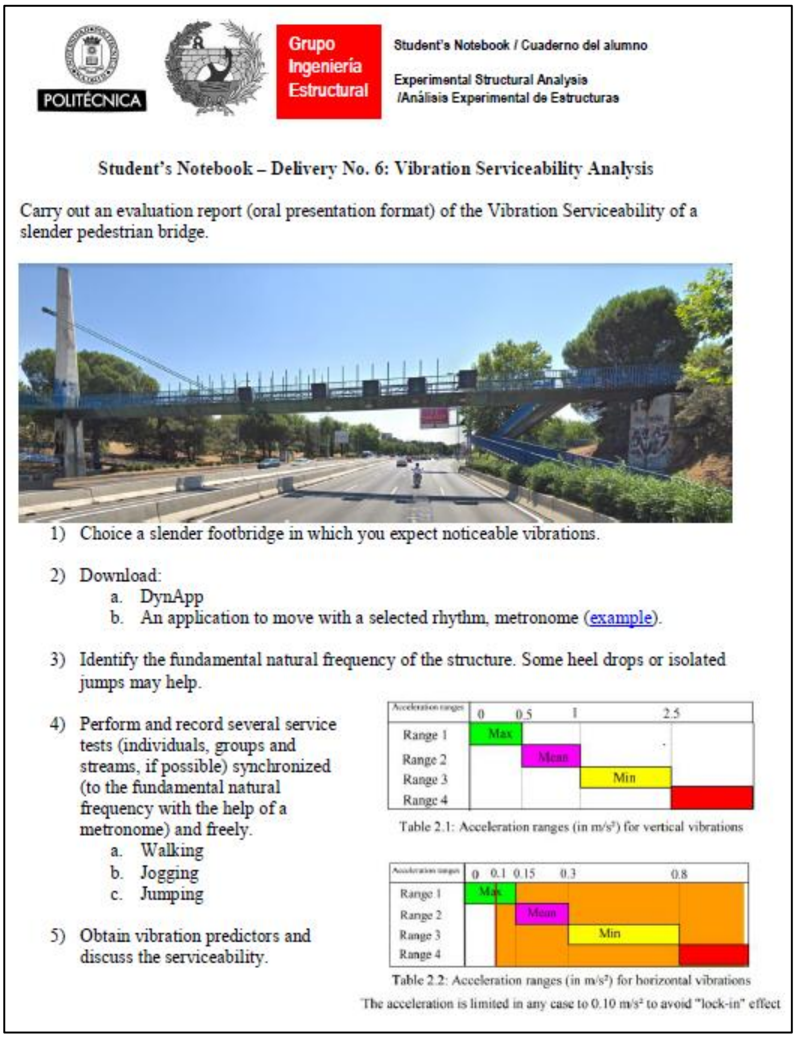
***Fig. 11** Frequency domain analysis of accelerations.*

The FFT of the recorded signals is carried out. In frequency domain, the natural frequencies of the structure in each direction can be identified. For the vibration serviceability assessment, the natural frequencies should be firstly identified in order to evaluate the probability to be excited a particular vibration mode during operation. The concept and power of the FFT is here understand by students in a practical application. Furthermore, new concepts such as human loading or human-structure interaction are introduced and how they are dealt with by codes is exposed. Figure 11 shows the one-side spectrum of the three-axes acceleration. Clearly, z vibration dominates the structural response.

All the described steps are carried out by DynApp installed in a phone, without the need to send and process the data in a remote server.

3 STUDENT SELF LEARNING PROCESS

DynApp is being used within two master courses imparted at ETSI Caminos of UPM: *Experimental Analysis of Structures and Dynamic and Seismic Analysis of Structures*. Figure 12 shows one of the Deliveries carried out by students. A methodology using the experiences drawn in [16] has been used for teaching. Therefore, students have to make the practical work [9] in small groups. Every group of 3 students analyze the serviceability of one footbridge sited in Madrid. Figure 13 shows master students carrying out experimental tests on in-service footbridges, and figure 14 shows the corresponding assessment of the vibration serviceability. That is, the evaluation of the comfort level.



POLITÉCNICA

Grupo Ingeniería Estructural

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.

1) Choice a slender footbridge in which you expect noticeable vibrations.
2) Download:
   a. 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.
4) Perform and record several service tests (individuals, groups and streams, if possible) synchronized (to the fundamental natural frequency with the help of a metronome) and freely.
   a. Walking
   b. Jogging
   c. Jumping
5) Obtain vibration predictors and discuss the serviceability.

Acceleration ranges	0	0.5	1	2.5
Range 1	Max			
Range 2		Mean		
Range 3			Min	
Range 4				

Table 2.1: Acceleration ranges (in m/s^2) for vertical vibrations

Acceleration ranges	0	0.1	0.15	0.3	0.8
Range 1	Max				
Range 2			Mean		
Range 3				Min	
Range 4					

Table 2.2: Acceleration ranges (in m/s^2) for horizontal vibrations

The acceleration is limited in any case to 0.10 m/s^2 to avoid "lock-in" effect

Fig. 12. *Example of delivery for master students.*

Fig. 13*: Pictures illustrating tests carried out by students.*

	Pedestrian walking		
	1	2	4
a	Max.	Med.	Min.
a_w	Max.	Max.	Med.
$a_{RMS} \cdot \sqrt{2}$	Max.	Max.	Max.
$MTVV \cdot \sqrt{2}$	Max	Max.	Max.

	Pedestrians jumping		
	1	2	4
a	Min.	Int.	Int.
a_w	Med.	Min.	Min.
$a_{RMS} \cdot \sqrt{2}$	Med.	Med.	Min.
$MTVV \cdot \sqrt{2}$	Med.	Min.	Min.

Fig. 14. *Vibration serviceability assessment*

4 CONCLUSIONS

An interesting mobile app, DynApp have been developed for advanced dynamic testing and vibration serviceability of civil structures. DynApp guides practitioners/engineers easily through frequency and time domain tests and helps them to make a decision shortly about the vibration serviceability comfort level. The complete analysis depends on the structural type, length, number of measuring points, number of tests, etc., but for the main vibrating location, the whole evaluation can be carried out in minutes.

This tool is used in master classes for teaching content related to dynamic analysis of structures and vibration serviceability limit state. The use of this tool requires the understanding of many concatenated processes, from planning of the measurement campaign, to final report. This makes the perfect excuse to introduce the necessary theoretical knowledge with the practical work. Furthermore, the extra tools developed in MATLAB to make the same processes with a bigger feasibility and direct access to the code allows students to test the importance of the involved parameters in the final process, as well as, to the teachers of proposing individual tasks. The final mark is composed of the individual student work, the work of the group plus a final exam.

It is worthwhile to comment that DynApp is continuously improved by adding new capabilities, more efficient ways of processing data and better user-friendly layout. The students have shown excellent feedback regarding the use of DynApp.

5 ACKNOWLEDGEMENTS

The authors acknowledge the Educational Innovation Project Técnicas Experimentales de análisis dinámico: caracterización dinámica y cancelación de vibraciones (IE1819.0407). They also want to acknowledge the master students for using and check DynApp. Finally, Carlos M. Renedo would like to thank Universidad Politécnica de Madrid for the financial support through a PhD research grant.

REFERENCES

[1] ISO 10137 (2007). Bases for Design of Structures. Serviceability of buildings and walkways against vibrations. Geneva: International Organization for Standardization.

[2] EN 1990:2002/A1:2005 (2005). Eurocode – Basis of structural design. Application for bridges.

[3] SÉTRA (2006). Assessment of vibrational behaviour of footbridges under pedestrian loading. Technical guide. Paris: Technical Department for Transport, Roads and Bridges Engineering and Road Safety.

[4] Renedo, C.M.C., et al. (2019). Understanding frequency domain analysis through numerical experiments. International Conference of Educational Innovation in Building, Madrid.

[5] García-Palacios, J.H., Díaz, I.M., et al. (2018). Learning dynamic analysis of structures using handy and affordable equipment. On the way of smart structures. IV International Conference on Structural Engineering Education, Madrid.

[6] Sáez-Pérez, M.P. (2018). Innovación docente y profesión. Competencias y metodologías activas en áreas técnicas. Advances in Building Education, vol. 2(3), pp. 45-64.

[7] Gutierrez, A.B., et al. (2018). Incorporación de las TIC en la enseñanza y el aprendizaje en la toma de medidas de confort y transmisión de calor. Advances in Building Education, vol. 2(2), pp. 90-104.

[8] Gutierrez, A.B., et al. (2017). Implementación TIC en la docencia universitaria: estudio de los esfuerzos en vigas. Advances in Building Education, vol. 1(1), pp. 37-46.

[9] Freeman, S., Eddy, S. L., et al. (2014). Active learning increases student performance in science, engineering, and mathematics. PNAS June 10, vol. 111 (23), pp. 8410-8415.

[10] Ahn, B, Nelson, M. (2018). Assessment of the effect of using the cooperative learning pedagogy in a hybrid mechanics of materials course. International Journal of Mechanical Engineering Education, online.

[11] Felbusch, A., et al. (2017). Vibration analysis using mobile devices (smartphones or tables). X International Conference on Structural Dynamics, EURODYN 2017. Procedia Engineering, vol. 199, pp. 2790-2795.

[12] Chen, D., et al. (2019). A novel smartphone-based evaluation system of pedestrian-induced footbridge vibration comfort. Advances in Structural Engineering, vol. 22(7), pp. 1-13.

[13] Matarazzo, T.J., et al. (2018). Crowdsensing framework for monitoring bridge vibrations using moving smartphones. Proceedings of the IEEE, vol. 106(4), pp. 577-593.

[14] Muhammad, A., Reynols, P., et al. (2019). Review of Pedestrian Load Models for Vibration Serviceability Assessment of Floor Structures. Vibration, vol. 2(1), pp. 1-24.

[15] Piccardo, G., Tubino, F. (2012). Equivalent spectral model and maximum dynamic response for the serviceability analysis of footbridges. Engineering Structures, vol 40, pp. 445-45.

[16] Seaman, J., at al. (2017). The Evolution of Experiential Learning Theory: Tracing Lines of Research in the JEE. Journal of Experiential Education, vol. 40(4), pp. 1-21.