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Mechanical Models in Structural Engineering

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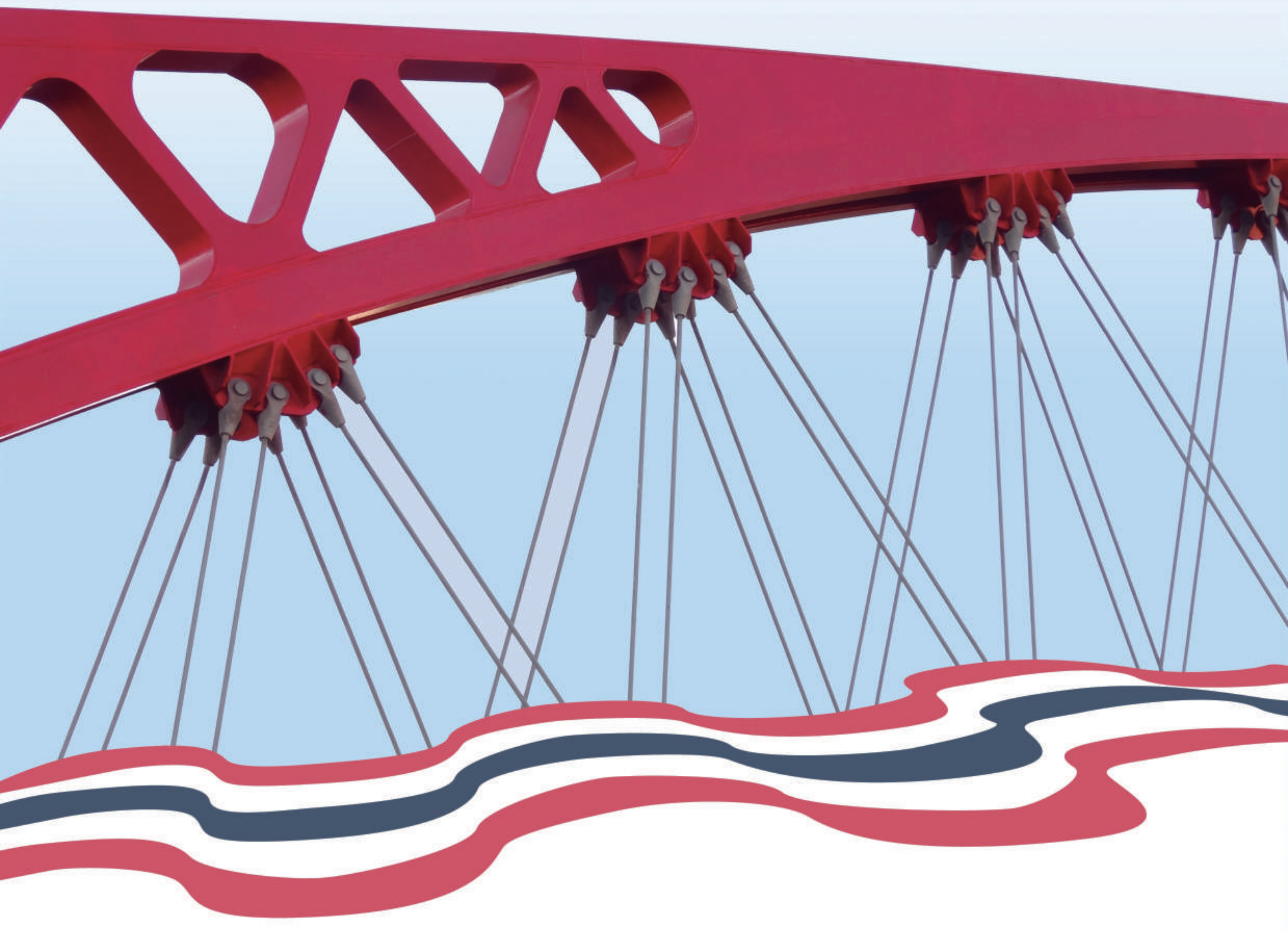

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UNIVERSIDAD DE GRANADA

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Edita: Editorial Club Universitario
C/ Decano, n.º 4 – 03690 San Vicente (Alicante)
www.ecu.fm
original@ecu.fm

ISBN: 978–84–17924–58–4
ISBN papel: 978–84–17924–22–5

Printed in Spain

Organizan:

Universitat d'Alacant
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MAPEI
ADHESIVES·SEALANTS·CHEMICAL PRODUCTS FOR BUILDING
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CONTENTS

DYNAPP: A MOBILE APPLICATION FOR VIBRATION SERVICEABILITY ASSESMENT

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

ABSTRACT

Human loading may induce significant vibrations in some types of structures such as long-span floor slabs or light-weight pedestrian bridges, affecting their vibration serviceability limit state. In many cases, this limit state is not taken into account properly within the structural design process or this is not fulfilled during its life span. Finding the source of the problem may be an awkward task and a monitoring campaign to check this behavior may be expensive. In this paper, a dynamic analysis mobile phone tool named DynApp has been developed in Android. This allows the user to make in one go the measurements and the identification of the resonant frequencies of the structure avoiding engineers to carry out dynamic analysis of structure with tedious setups (accelerometers, long cables, acquisition systems, power suppliers, etc.) and difficult-to-use specialized software.

DynApp guides practitioners/engineers easily through frequency and time domain tests and helps them to make a decision shortly about the serviceability Comfort Class. This tool is also used in master classes for teaching the background content.

Keywords: Vibration serviceability; dynamic testing; structural identification; vibration control; teaching innovation.

1. INTRODUCTION

Actually, the development of materials, the computational tools and the technological advances make more frequent to find lightweight structures where the users can feel the vibration. This may became an undesirable phenomenon depending on several factors as, the type of the structure, the activity developed, the time over the vibrating slab, the position of the user, etc. The vibration serviceability limit state stablishes some limits according to these issues in order to assure a proper serviceability Comfort Class. Depending on the used standard, different parameters are measured, and limits may vary, but the considered criteria are essentially the same and leads to similar results.

Vibration perceived by a user is an environmental parameter that acquires importance with the development of a society, as it had previously happened with pollution or noise. The industry has been adapted to a more demanding market over the time. A clear example is car manufacturers where the reduction of noise and vibration is associated with comfort, technology and leading industries. However, civil structures are not replaced every decade to fulfill our new requirements. Even more,

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many structures have suffered changes to be adapted for different demands that may infer vibration serviceability problems. Therefore, structures that were designed in the past may not meet the current required standards. This makes necessary to have tools to evaluate the actual comfort index of existing structures.

Nowadays, the structural design requires to accomplish with the Ultimate Limit States (ULS) where the collapse of the structure is evaluated, and the Service Limit States (SLS), where the structure is evaluated to meet technical requirements for use. One of the last added SLS is the Vibration Service Limit State (VSLS) as seen in [1-3], which define the standards that must be fulfilled over existing structures. VSLSs must be taking into account in the design of modern and complex projects. Uncertainties in civil engineering constructions may have a large importance in the final user perceived comfort. Actually, on-site measurements are required to assure that an in-service structure is meeting the VSLS. Therefore, a real structure, a measurement campaign, and the necessary knowledge is required to carry on with the process.

Usually, dynamic identification of an existing structure requires expensive campaigns with specialized technicians, the placement of expensive measurement equipment, with long cables, electric generators etc.

Besides, it should be taken into account that, if humans feel the vibration, the MEMS sensor inside of our actual mobile phones are also capable to record accelerations with sensitivity enough [4]. DynAPP is a mobile application [5] that, using this capability, easily allows to evaluate the VSLS. The use of this software is cheap and simple, and it only requires one cell phone and an experienced user to choose the hot locations for the structural feelings.

At the same time, younger engineers require a more advanced training to cope with these new situations. DynApp helps them to understand, in a practical way, complex concepts associated with the structural dynamic analysis and it is used as a teaching tool at master level. The process involved from the in-site measurement to get the comfort level requires a multidisciplinary knowledge that should be clearly understood by a master student to compete in a market connected to their future job opportunities [6-9].

Important concepts in the time and frequency domain, as well as the Fourier Analysis to transform among them are relevant. These include, signal acquisition, where frequency sampling, sensitivity are key values, signal processing, with the necessary filtering understanding, and finally the calculation of the required index to evaluate the comfort [10-12].

2. DynApp Description

DynApp is an application developed in Android to fulfill all the aforementioned requirements. In fact, some commercial applications can be used for part of the processes involved, but no one is able to complete all the steps. There is also a lack of information in the way that existing apps are doing some necessary intermediate steps. Most of them, present nice results, but from our programming experience the accelerometers in Android, require making some assumptions that they are not explained. These assumptions may become important to make a proper evaluation of the possible limitations and error estimators involved in the whole process.

Figure 1 shows the front end of the application on the left and contents of the data folder on the right.

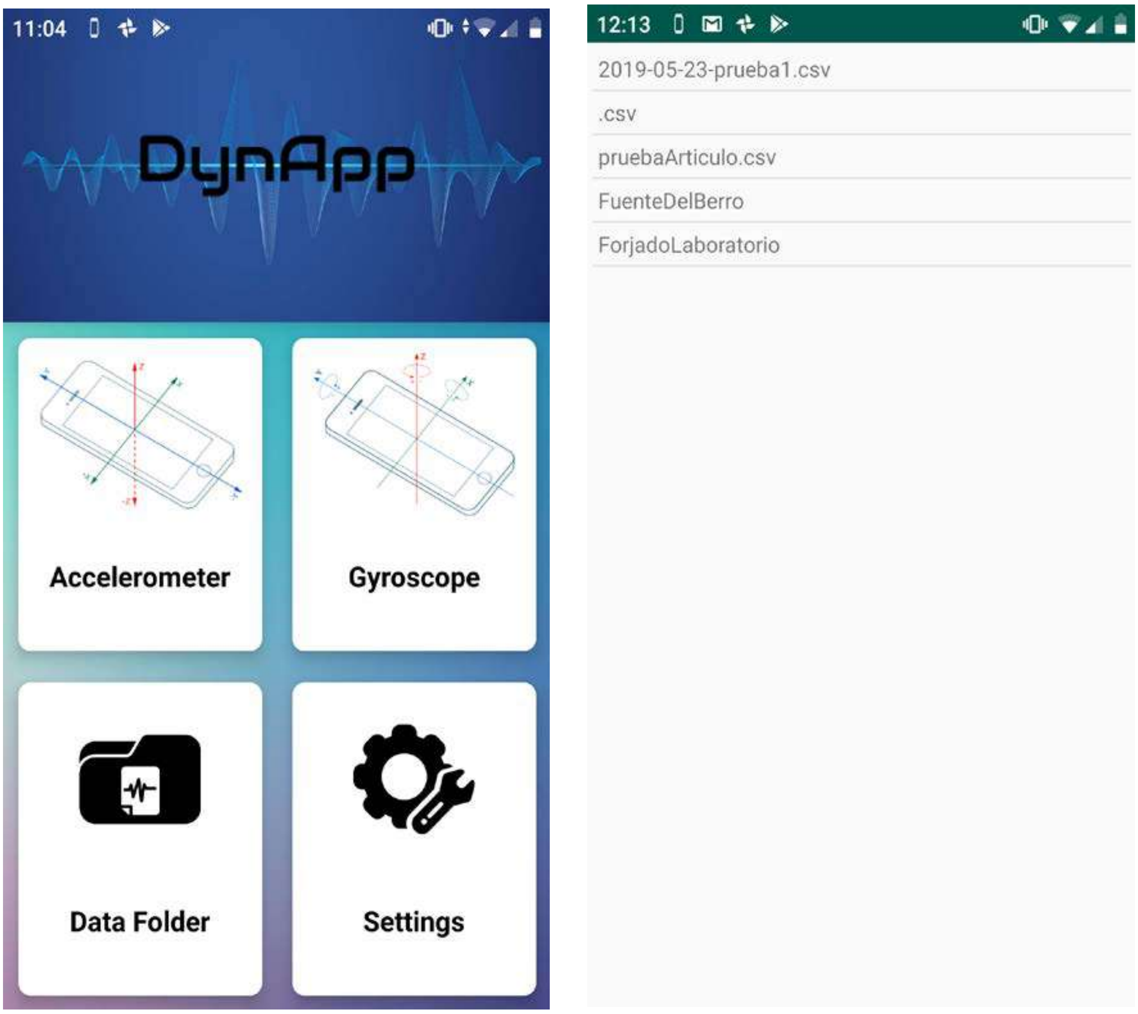


Figure 1. *Application front end (left) and Data Folder screen (right)*

The following list and figure 1 describe orderly the processes done with DynApp:

1. Establishing the settings for the actual Project, where the name of the project is defined, as well as the associated folders to store the records, pictures and another relevant information. In this case there are two folders available FuenteDelBerro and ForjadoLaboratorio.
2. Recording the acceleration for a prescribed time using the three-axis acceleration. This step has been optimized in order to reduce the number of processes involved to use the maximum capabilities of the phone. Figure 2 shows the recording of a signal on a structure where some hits have been applied. This is the case of the graphical recording. In the right menu is possible to change the vertical and horizontal scale as well as start the measurement recording. Finally, a button to access the analysis of a previous recorded signal is also included.
3. Analyzing the series to get the recording parameters, giving values as mean frequency, the maximum and minimum time differences between two consecutive records, the duration of the series, etc.

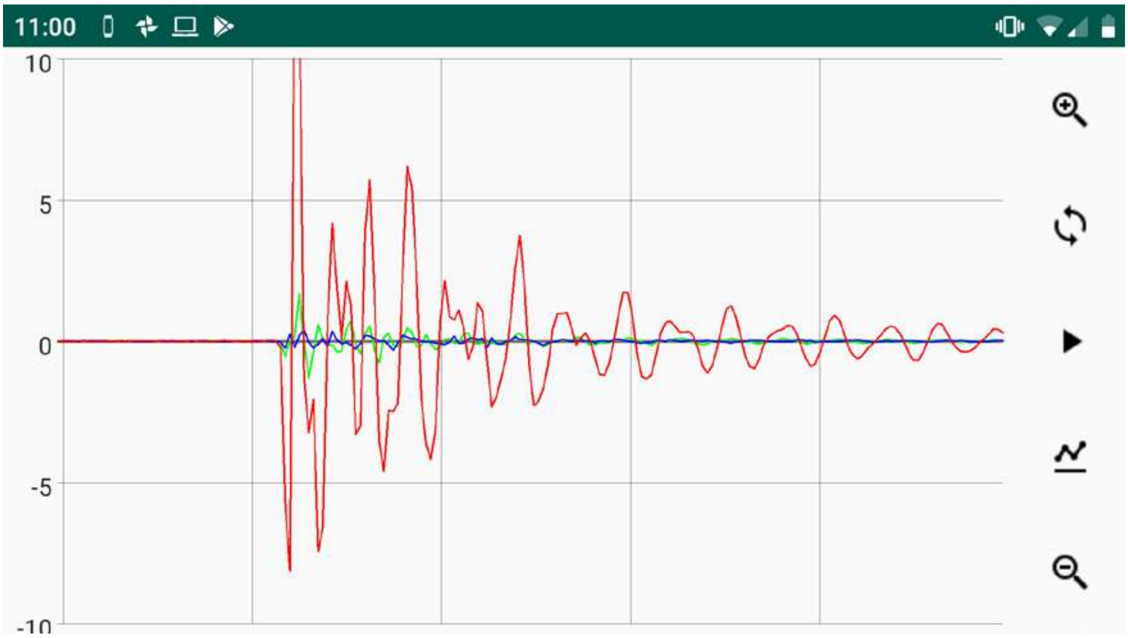


Figure 2.*Time history series recording*

4. Interpolating a constant series with the records with a given fixed frequency. The fixed frequency is recommended according the capabilities of the phone used.
5. Generating a report of the new series characteristics.
6. Generating interactive graphs with the time history series for each axis and all them together. It is possible to make zoom at any recorded time to check for specific values.
7. Extracting a properly proceeded frequency spectrum of the signal and identifying the main resonances of the structure.
8. Recording some tests (loading cases) to check the structure serviceability (such as heel-drops, a pedestrian or group of pedestrian walking or running with the help of a metronome, also installed in the used mobile phone) are recorded.
9. The acceleration recording is frequency weighted according to [1] in order to take into account the effects of how humans feel vibration.
10. From the weighted acceleration, the main predictors defined in current codes or guidelines are derived [1-[3]. These are the acceleration peak, the root-mean-square (RMS) acceleration of the whole test, the crest factor, the 1s-running RMS and its maximum value (usually known as Maximum Transient Vibration Value, MTVV) and the vibration dose value, among others. From these parameters, and the traffic class assigned to each loading case, the Comfort Class is obtained.
11. From heel drop tests and band-pass filtered signals around each resonance, modal free decaying analysis and modal damping ratios are extracted. This valuable information allows carrying out numerical dynamic analysis, in particular, using the Finite Element Method.

After the recording the application shows the screen in Figure 3 (left) with a menu to expand the information associated to the different steps followed. Some of these data is shown in the right part of the same figure.

There are also some steps that can be done with a series to improve the results. Figure 4 summarizes the main possible steps to process the signal

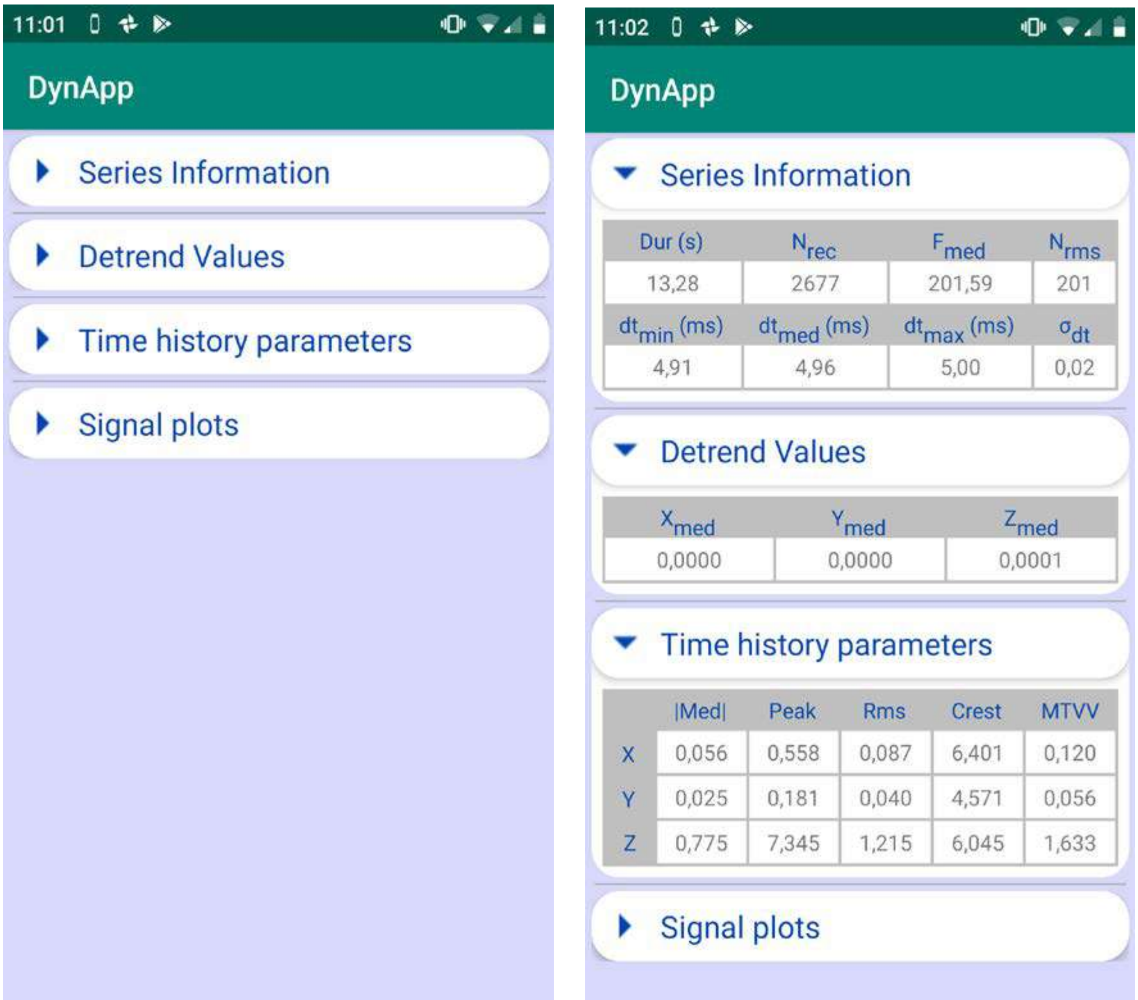


Figure 3. *Service screen analysis. Main screen (left) & some options results shown (right)*

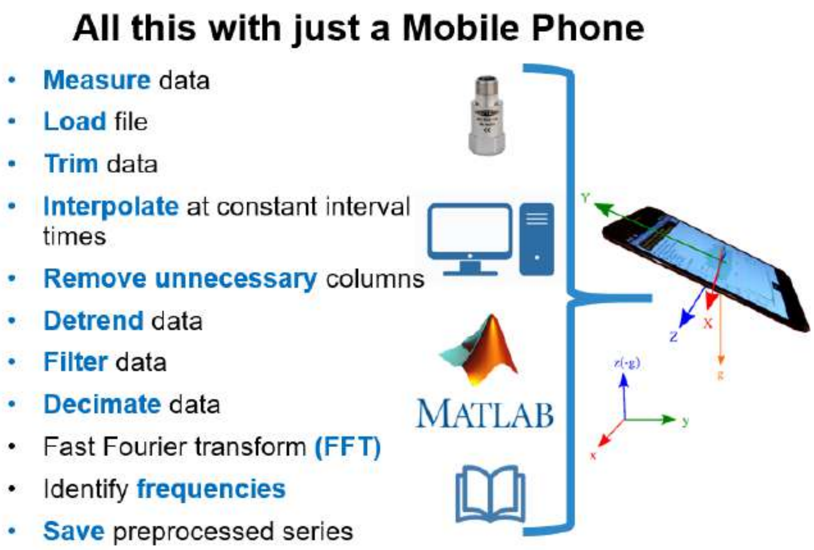


Figure 4. *Possible processes to improve the acquired signal before analyzing the service*

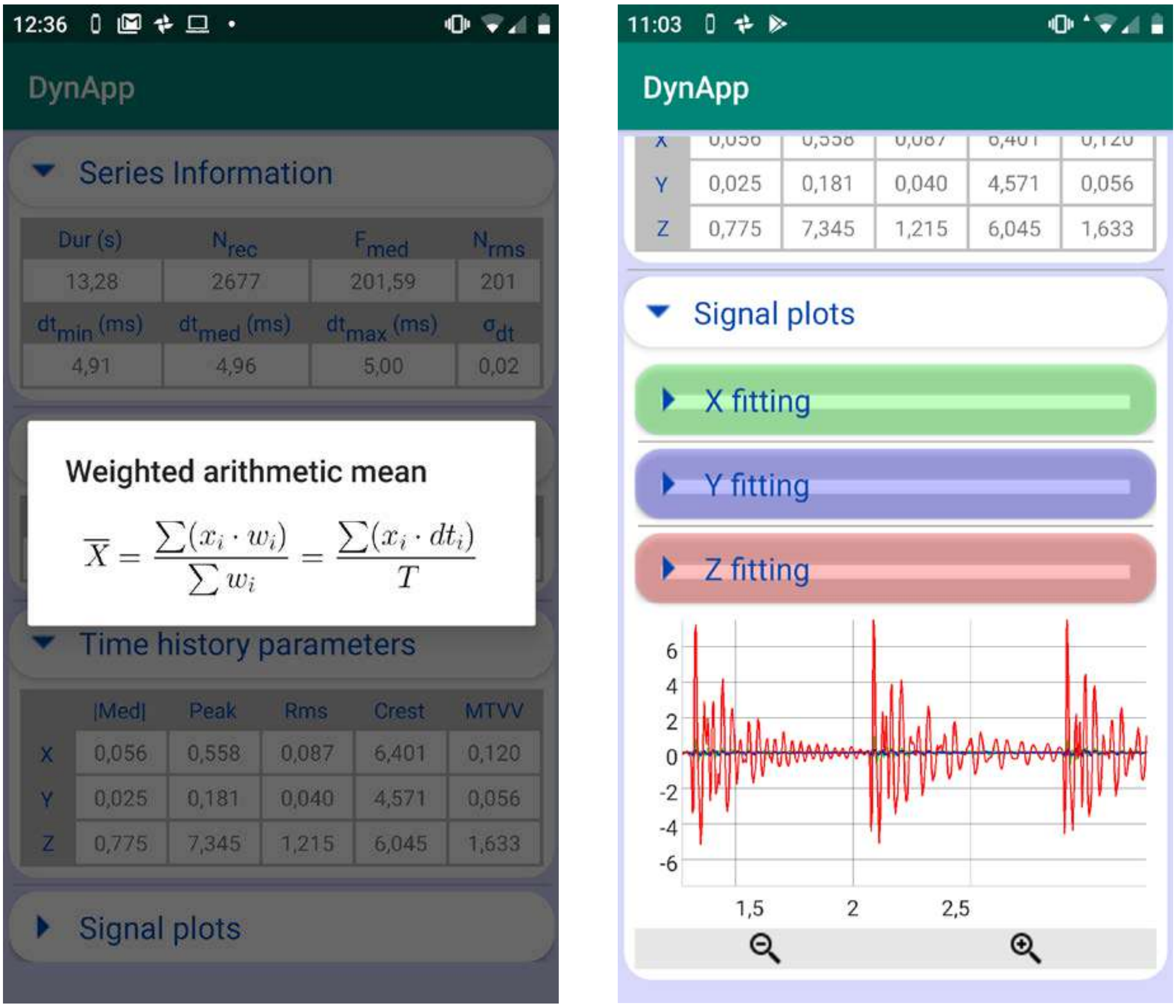
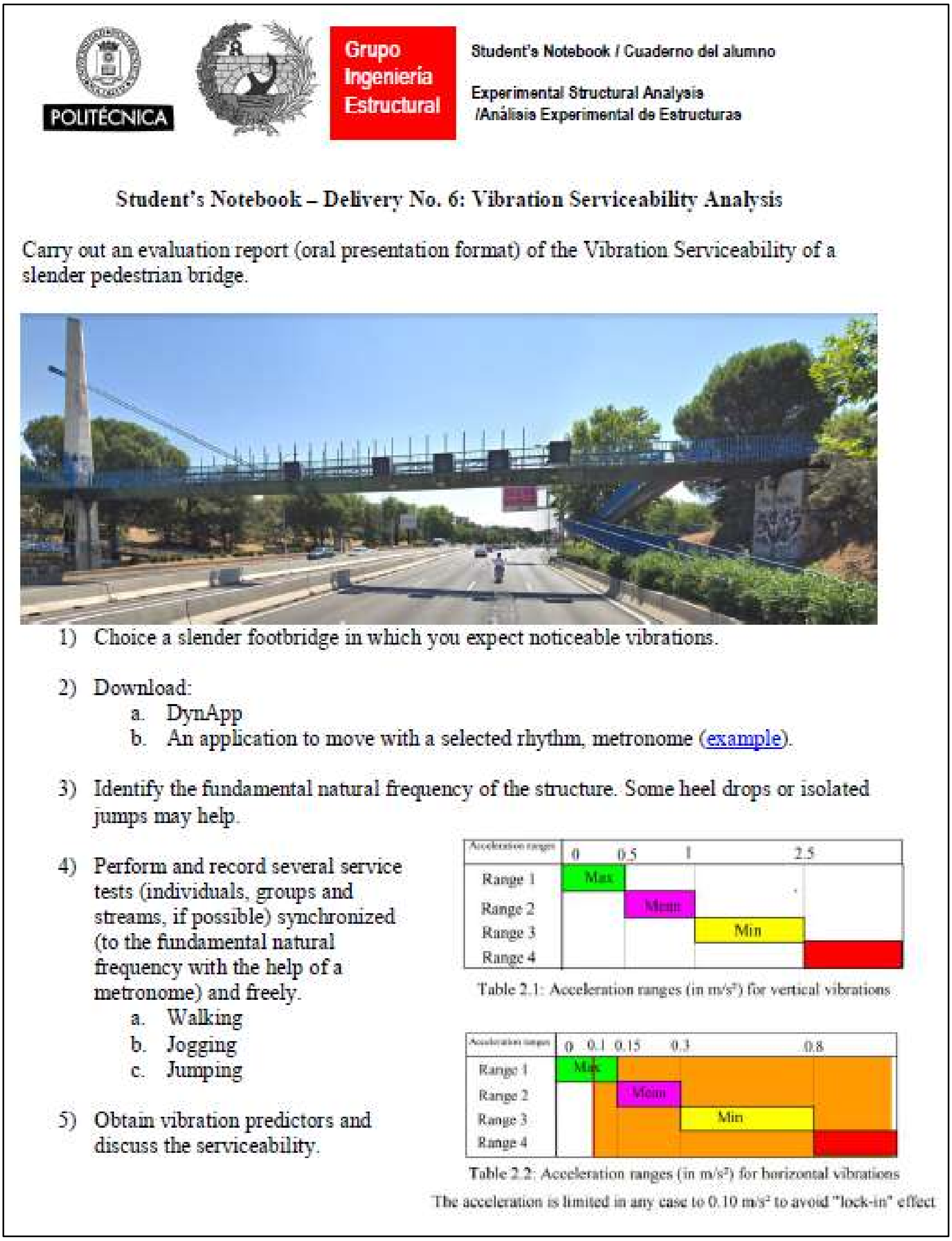


Figure 5. *Detail on the available help (left) and expanded option to see the signal series (right)*

In figure 5 (left), the help associated to the parameter Xmed is shown when the user pushes on the corresponding variable in the table head of the Detrend Values section. In this case, the original series is used and the obtained mean of the series takes into account that the recording does not have a regular time interval. The analysis of this fact was shown in figure 3 (right) where it can be seen that mean frequency during recording was 201.59 Hz with a minimum and a maximum time difference between two consecutive samples of 4.91 and 5.00 milliseconds respectively. The mean sampling interval and variance of the series in milliseconds is also given. This fact justifies the development of this app because is important to know the quality of the recorder signal at the measurement location. From the author knowledge, there is no any current app able to cope with this analysis. Finally, figure 5 (right) shows the graphical representation of the series. The graph is interactive and allows to make zoom into any area easily in order to be comfortably used in a smartphone screen.

Therefore, DynApp guides practitioners/engineers easily through frequency and time domain tests and helps them to make a decision shortly about the serviceability Comfort Class. All this work should be undergone by experienced users, with this DynApp installed in their mobile phones. The help of some non-experienced users could be required to apply the loading cases. 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.



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.

Table 2.1: Acceleration ranges (in m/s²) for vertical vibrations

Table 2.2: Acceleration ranges (in m/s²) for horizontal vibrations

The acceleration is limited in any case to 0.10 m/s² to avoid "lock-in" effect

Figure 6. *Example of delivery for master students*

This tool is also used in master classes for teaching content related to dynamic analysis of structures and vibration serviceability limit state. It is worthwhile to comment that DynApp is continuously improved by adding new capabilities, more efficient ways of processing and better user-friendly layout.

Figure 7. Pictures illustrating tests carried out by students

Actually, a full series of test have been carried out and results compared with high sensitivity equipment (PCB-B31 accelerometers) connected to a National Instruments commercial acquisition equipment (a compactRio platform). The comparisons have done into Matlab software. The results are quite good for structures where vibration can be felt by humans. In these situations, the capabilities of the integrated mems accelerometers into current smartphones have shown to have enough sensitivity. However, they might not be used for stiffer structures less prone to vibrate.

Finally, within the application is possible to send the data to our server in order to have an automated backup copy of any measurement. Within the application, a link to an extended help is provided. There are also some recommendations to carry out the experimental tests. In this way, the help files are in our server and can be easily improved with the feedback of the app users.

3. Student deliveries

There are two courses where master students are using this application “Experimental Analysis of Structures”, and “Dynamic and Seismic Analysis of Structures”. Both of them combine theoretical knowledge with practical implementation with measurements in laboratory and over existing structures. In this way, the student understand the purpose of carrying out a measurement and the importance of the different aspects of the measurements process in the results. The location used to make the measurement, the difference between using one phone or another, the importance of the signal preprocessing or the time measuring spam become crucial. All these aspects are related to the underneath theory in order to make them better understand the whole process. In fact, some of them get very curious about the possibilities of the application to be used in structural dynamics.

Figure 6 shows one example of the deliveries that a student have to do during the course. In figure 7 some students, working in groups, are measuring a footbridge jumping at the resonant frequency with the help of a metronome at the maximum modal displacement location. The frequency was obtained in a previous measure few minutes before.

4. Conclusions

An interesting mobile app, DynApp have been developed for advanced dynamic testing and vibration serviceability of civil structures. This tool allows evaluating any kind of structure where vibration is felt by human users. A single experienced user can determine within minutes and the only help of his mobile phone if the vibration serviceability comfort level is fulfilled. In cases of reasonable doubt, he can carry out extra measurements with the help of untrained people according to the recommendations in the standards. The complete analysis depends on the structural type, length, number of measuring points, number of tests, etc., but once the main vibrating location is found, the necessary tests can be easily done. This makes the decision on the necessity or not of further studies very cheap, without the need to move heavy and expensive monitoring equipment.

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.

The ability of sending the data to our own server allows to use extra Matlab processes that are automated for a final detailed report. These tools are also used with the students to test the importance of the involved parameters in the final process, as well as, to the teachers of proposing individual tasks. This learn by doing applied to the complex theoretical background is greatly acknowledged by the students involved in the learning process.

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.

ACNOWLEDGEMENTS

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. The authors would like to acknowledge the financial support provided by the Spanish Ministry of Science, Innovation and Universities through the project SEED-SD (RTI2018-099639-B-I00). 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] 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.

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

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] Díaz, I M. et al. (2019). A mobile tool for teaching advanced dynamic analysis. Advances in Building Education, vol 3(1), pp. 72-82, doi:https://dx.doi.org/10.20868/abe.2019.1.3885 http://polired.upm.es/index.php/abe/article/view/3885.