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Vibration analysis using mobile devices (smartphones or tablets)

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Abstract

This paper investigates and describes the potential of mobile devices for vibration analysis, system identification and structural monitoring using a self-developed app, called “iDynamics”. It shows the differences between professional accelerometers and smartphone sensors, demonstrates the vibration measurement and evaluation capabilities using “iDynamics" and presents the application of the app using various practical examples. The application has been verified by results from vibration measurements with professional equipment and software. At the end, the application limits of the app and the requirements of the corresponding mobile devices are summarized.

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Keywords: vibration measurement app; vibration analysis; signal processing; system identification; structural monitoring

1. Introduction

In recent years, mobile devices (smartphones and tablets) found their way into our day-to-day life. They are used as multi-purpose devices for many professional (and non-professional) applications. They are always with us and we can use them simply and quickly. There are already several mobile apps, which can be used for simple structural analysis or design purposes. What is almost unknown in the engineering community, are the increased capabilities and possibilities of mobile devices to be used in the field of vibration analysis, system identification and structural monitoring. Beside advanced performance and increased storage capacity, different hardware components, like accelerometers and gyroscope improved considerably. To take advantage of these improvements, the “iDynamics” app has been developed at the University of Kaiserslautern. It uses the potential and sensitivity of build-in sensors of modern mobile devices for the purpose of simple vibration analysis, system identification and structural monitoring

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applications. The app was developed on the most widely distributed operating system "Android" and includes the acquisition of vibration amplitudes, determination of the rated "vibration strength" according to German DIN 4150 (Vibrations in buildings) [1] and the classification of comfort level based on VDI 2038 (Serviceability of structures under dynamic loads, Methods of analysis and evaluation) [2]. In addition to these time-domain parameters, the frequency content of the recording is evaluated by its FFT frequency spectrum. Furthermore, an assessment by means of the comfort or panic criterion according to ISO 10137 [3] is possible based on the calculation of the root mean square value of the acceleration, with is also integrated. A damping evaluation algorithm has also been implemented in the app. The application and analysis results were verified with results from vibration measurements using professional equipment and software.

2. Professional accelerometers and sensors of smartphones

Accelerometers are sensors which usually detect accelerations by utilizing the inertial force. The characteristics of accelerometers installed in smartphones differ from professional acceleration sensors used in vibration analysis. High-precision sensors have a resolution up to 10^{-9} g and a measuring range usually below ± 1 g. For smartphone technology miniaturization plays an important role as well as robustness, low energy consumption and low price. This comes with limitations of accuracy. In recent smartphones so called MEMS-Accelerometers (Microelectromechanical systems) with a resolution from 0.1 to 15 mg and a measuring range of ± 4 g (and more) are installed. Detailed information about the built-in sensor type and sensitivity can be determined with the "iDynamics" app.

3. Vibration measurement and evaluation with the "iDynamics" App

3.1. Installation and default settings

A fully functional free student/trial version of the "iDynamics" app can be downloaded from the website of the Institute of Structural Analysis and Dynamics at the University of Kaiserslautern [4].

The default settings are adjusted in a way that for the most widely used devices, the best and most precise results can be achieved, without sacrificing a smooth workflow. Depending on device type and the vibrations to be measured, an adjustment of the default settings can improve the results considerably. A sample rate of 50 Hz is preset for acceleration recording. An increase of the sample rate is indispensable for the assessment of signals containing high frequencies. However, the performance limits are quickly reached for older and cheaper smartphones. By decreasing the FFT-Resolution, which's default is 256, the computational load can be reduced and the additional gained computing power can be used in favor of a higher sampling rate.

At small vibration amplitudes, the recordings with smartphone sensors possess a small signal-to-noise ratio. To reduce the disturbing influence of the noise, different techniques (e.g. high-pass or low-pass filtering, smoothing algorithm) were investigated. To diminish abnormal peaks, a simple smoothing algorithm has been found to be more advantageously than complex methods. For this purpose, a 5-point smoothing algorithm was implemented, which calculates the mean value of the four closest values at each point [5]. The user can perform up to three iteration steps of the smoothing. However, caution is advised, because at low sampling rates high frequency signals are falsely "smoothed out". Fig. 1 shows the measured results with a professional sensitive Sensor and Smartphone on a low-frequency (1.8 Hz) and high-frequency (12.5 Hz) system. The effects of smoothing are also shown.

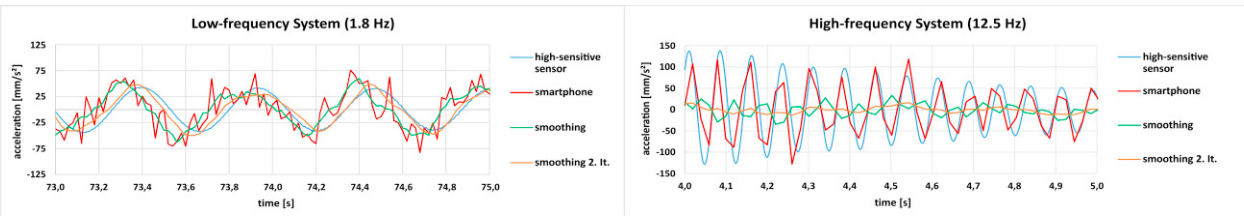

Fig. 1. Vibration results with professional high-sensitive sensor and smartphone with and without smoothing (sampling rate: 50 Hz).

3.2. Measurement

Starting the measurement, the data of the sensor is recorded and displayed in the acceleration-time diagram. The frequency spectrum generated by the fast Fourier transform (FFT) is also displayed parallel to the time signal. FFT is an algorithm for the fast calculation of the discrete Fourier transformation (DFT). It is used to split the calculation of the DFT into smaller computations, thereby speeding up the process. A frequency spectrum from 0 Hz to the half of the selected sampling rate (in Hz) is the result. A parallel implementation of split-radix and mixed-radix algorithms [6], optimized for symmetrical multiprocessor systems has been used in the FFT algorithm. The method is very efficient and allows a simultaneous visualization of the time signal along with the corresponding frequency spectra.

3.3. Evaluation

After the measurement, different evaluation options are available. The natural frequency or measured main frequency, the maximum acceleration and velocity amplitude as well as the maximum frequency weighted “vibration strength” KB_{Fmax} can be obtained. In addition, a classification of the vibrations according to the German standards DIN 4150-2 [1], DIN 4150-3 [7] and VDI 2038 [2] is implemented.

3.3.1. Vibration amplitudes and natural frequencies

Vibration amplitudes as well as the natural frequencies can be displayed during the measurement for all three coordinate axes directions (see Fig. 2).

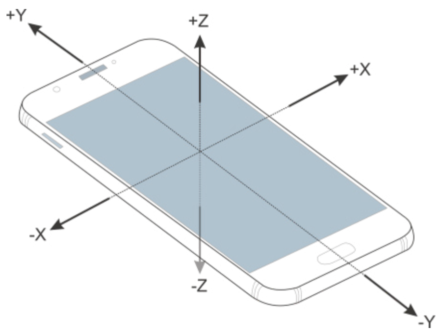

Fig. 2. Coordinate axes direction

If the vibration amplitudes are too small, so that a correct determination of the maximum amplitude is too inaccurate or the estimation of the main frequency is unclear, a warning message will appear. The time history and the frequency response can be saved in a text file (e.g. for an import into a professional vibration processing system).

For precise detection of the vibration signal, the gravitational acceleration must be subtracted from the measured total acceleration. This calibration is carried out during the measurement process. In a simplified approach a gravitational acceleration of $g = 9.81\ m/s^2$ is used at the beginning of the measurement. After determination of the exact gravitation, the recorded data is automatically corrected.

Since built-in sensors of smartphones show poor results in the frequency range below 0.5 Hz, a high-pass filter of first order is used to reduce those false frequency components.

3.3.2. Damping

After the measurement, the damping in an adjustable range can be determined by selecting two points in the acceleration-time curve history. The method chosen is known as the free-vibration decay method [8] and can be used if the modes are well separated. It determines the damping ratio ξ (fraction of critical damping) from the ratio of two peaks a_n and a_{n+m} over m consecutive cycles in the selected area with equation (1).

$$\xi = \frac{\ln\left(\frac{a_n}{a_{n+m}}\right)}{2\pi m} \qquad (1)$$

3.3.3. Vibration limits in guides and standards

DIN 4150-2 [1] deals with the effect of vibrations on persons in buildings. The app calculates the maximum frequency weighted “vibration strength” $KB_{F\max}$ directly from the vibration velocity history, according to the simplified method in DIN 4150-2 (paragraph 7) [1], by means of natural frequency and maximum velocity amplitude:

$$KB = \frac{1}{\sqrt{2}} \frac{v_{\max}}{\sqrt{(1+\left(\frac{f_0}{f}\right)^2}} \qquad (2)$$

$$KB_{F\max} = KB \cdot c_F$$

f Frequency in Hz
f_0 5.6 Hz (high-pass filter cutoff frequency)
v_{max} maximum vibration velocity
c_F constant in the range of 0.6-0.9 according to Table 3 from DIN 4150-2 (default 0.8)

The vibration velocity is obtained by integrating the acceleration-time history and baseline correction afterwards [9]. DIN 4150-3 [7] provides guidance on the assessment of the effects caused by vibrations on building structures. According to the standard, vibration velocities below given limiting values do not lead to damage in buildings. These limiting values has also been implemented in the app.

Furthermore, the app evaluates the comfort level (high comfort, medium comfort, low comfort/discomfort/panic) for various structures by means of maximum acceleration or “vibration strength”, according to VDI 2038 Part 2 [2].

For the assessment of vibrations, acting on floors of assembly rooms or vibrations in stadiums, the effective value of acceleration (RMS) is used in ISO 10137 [3]. The effective value of acceleration (RMS) is the root mean square value of the acceleration a over a selected period of time t:

$$RMS = \frac{1}{n}\sum_{i=1}^{n} a(t_i)^2 \qquad (3)$$

ISO 10137 [3] defines two vibration criteria. The first criterion is the comfort of the passive part of the audience and the second is the safety of the audience. For the comfort criterion a measurement duration of 10 s (t_n-t_1 = 10 s) and for the panic criterion 1 s is recommended. The limit vibration levels are given by the base curves in ISO 10137 Figure C.1-C.3 [3] and a multiplying factor, depending on the criterion (200 for comfort, 400 for panic). In the App, the maximum RMS value can be determined over an arbitrary selected period of time.

4. Verification with professional vibration measurements

On the basis of several practical applications, the capabilities of the “iDynamics” App were explored and the results compared with those from professional measuring devices. Therefore, vibration measurements were carried out in parallel with smartphones from different manufactures and with professional software using highly sensitive sensors

(ACF24, ZINSZIEGLER Instruments GmbH). The results of an older smartphone with a resolution of about 10 mm/s² and a newer device with 1 mm/s² are discussed in this paper.

4.1. Benchmark tests

For verification purposes, benchmark tests were carried out under laboratory conditions by means of two beams of different stiffnesses (1.8 Hz and 12.5 Hz), representing a low- and high-frequency system (see Fig. 1). The beams were excited by tapping and the acceleration was recorded until complete decay of the vibration. By analyzing different measurement sections amplitudes in the range of 1000 mm/s² and 5 mm/s² were investigated and the quality of the measurement is evaluated. The amplitudes required for a proper vibration analysis are specified in section 5.1.

4.2. Practical applications

The versatile utilization as well as the limitations of vibration analysis using mobile devices have been explored by practical applications. The vibrations of a pedestrian bridge at the University of Kaiserslautern were measured under ambient conditions and under excitement as a result of two pedestrians crossing the bridge (see Fig. 3). Even the natural frequency could be measured with newer devices under ambient conditions by a sampling rate of 100 Hz. The amplitudes occurring in this case were around 35 mm/s². Crossing pedestrians caused amplitudes up to 800 mm/s², allowing to determine even several natural frequencies with new and old devices. In addition, a road and a railway bridge were investigated. In the case of traffic, natural frequencies could also be determined here. Measurements on the railway platform and highway road were useless. On the top floor of a 12-storey administrative building of the University of Kaiserslautern, the possibility of ambient vibration investigations of buildings was tested. During the measurement, amplitudes of just 4.5 mm/s² occurred in the horizontal direction, which are far too small for being measured properly by the smartphone.

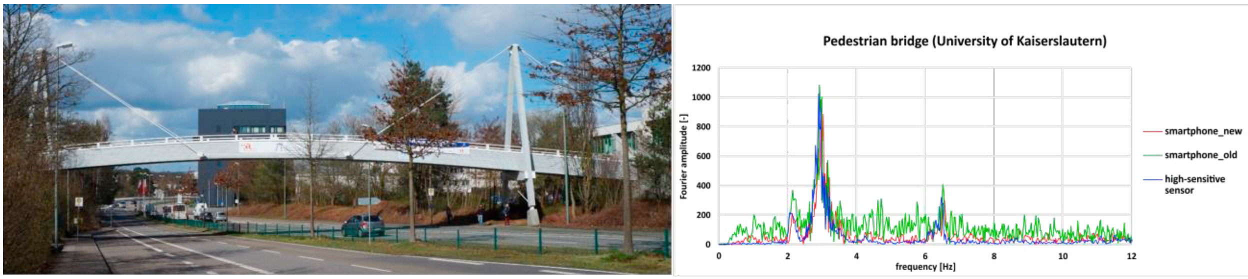

Fig. 3. Pedestrian bridge (University of Kaiserslautern) and Fourier spectrum of vibrations caused by crossing pedestrians

5. Current limitations of measurements with smartphones

5.1. Required amplitudes

The resolution of the acceleration sensors installed in smartphones is a crucial factor for the applicability of smartphones as vibration measuring devices. The higher the resolution, the less disturbing is the inherent noise and the better is the accuracy of the recorded signal. Also the sampling rate is an important parameter. An increase to 100 Hz is especially recommended for high-frequency vibrations. But even for low-frequency signals this could improve the recording quality considerably. Devices with a resolution of 10 mm/s² were able to detect natural frequency at low frequencies with amplitudes of 25 mm/s² at a sampling rate of 50 Hz. Smartphones with a resolution of 1 mm/s² were able to determine natural frequencies even at 15 mm/s².

For low-resolution devices (10 mm/s²) the inherent noise is in the range of 100 mm/s². For smartphones with higher resolution (1 mm/s²) the noise is only half the size. For a correct amplitude determination, larger amplitudes are required, which have to lie clearly above the noise level. For older and cheaper models deviations of 20% in amplitude occur even at amplitudes of 500 mm/s². In case of newer devices, similar deviations appear at 250 mm/s².

For high-frequency vibrations, such as vibrations of massive structures, measurements with sampling rates of 50 Hz do not allow a reliable amplitude determination. A natural frequency detection is possible by devices with low resolution at 150 mm/s² and with high resolution at 100 mm/s².

5.2. Ambient vibration measurement

Using devices with a resolution of 1 mm/s² natural frequencies of flexible systems, e.g. bridges or towers can be measured at sampling rates of 100 Hz, even under ambient conditions (without external excitation).

For stiff systems, ambient vibration amplitudes are too small to be measured based on the current development level of smartphone sensors. These systems must be excited for vibration analysis. Often, existing loads can be used as excitation, so that no additional exciting devices/systems are necessary. For the investigation of a bridge, traffic or larger wind loads can be useful. In general, a longer measuring time can improve the determination of the natural frequency considerably.

6. Conclusions

The “iDynamics” app allows semi-professional vibration measurements. For this, no expensive and extensive measuring devices and software are required. Smartphones or tablets are always available and at hand, so spontaneous field measurements are possible at any time. Vibration amplitudes, natural frequencies and damping values can be determined. The user can thus identify resonance problems, vibration limit violations and initiate measures for reduction or elimination. Simple system identification, status check or structural health monitoring is possible with minimum effort. The measuring results can be stored and if necessary processed by professional software for further evaluation.

Decisive for the usability of the results are the vibration amplitudes. In principle, more accurate results can be achieved with larger amplitudes. For relatively flexible structures such as pedestrian bridges, tall towers or generally long-spanned constructions, a system identification is even possible under ambient conditions (without excitation). With the progressive development of the devices, the detection of building vibrations at small amplitudes will hopefully soon be feasible.

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