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Identification of Peak Vibration Velocity From Passing Vehicles on Heritage Building

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Abstract: The vibrations from the traffic have become the main concern due to the increasing traffic volume. Hence, the vulnerability of heritage building may be affected by additional stresses from vibration wave from traffic. This study is conducted to analyse the highest velocity of vibration of the road traffic to heritage building in Muar and compare it to the limit set by department of Environment Malaysia (DOE): Malaysia Vibration guidelines. The case study took place at Old Telekom building, Muar with 23 m x 33 m x 7.5 m (length x width x height). Finite Element Modelling (FEM) was performed using BEAM4 and SHELL63 in ANSYS software and modal analysis was calculated using Block Lanczos in ANSYS software. Field vibration measurement was conducted to obtain the highest vibration velocity from traffic using smartphone with iDynamics application. The deformation of slab and beam was found to be critical at second floor due to timber beam characteristics. Velocity vibration response was found to be decreased with the increase in distance. Peak vibration velocity was found to be 0.6 mm/s lower than 3 mm/s which considered as safe. It is also found that the peak vibration velocity, 0.6 mm/s was lower than the recommended limit for traffic-induced vibration for heritage building, 1 mm/s. Therefore, potential damage to the building was insignificant and no effect to the building's safety. Nevertheless, same resolution sensor and proper instrument were required for more accurate reading.

Keywords: Heritage Building, Modal Analysis, ANSYS, Vibration Velocity, Idynamics, Vibration Measurement Application, Smartphone, Ground-Borne Vibration

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1. Introduction

Heritage building is any building of one or more premises which require conservation, preservation for historical, architectural, artisanry, aesthetic purposes, cultural, environmental, and ecological purposes and include of land within the heritage building area to preserve the building. In 60s era, traffic volume was not a concern as a factor in designing building. The increasing volume of traffic may result to the additional stresses acted on building foundation as the vibration from traffic propagates through soil. The vibrations from traffic have become the main concern due to the increasing of traffic volume, heavy vehicles and road irregularities [1]. However, due to vibration nature, sources of multiplicity and the difference in building response make the vibration effect difficult to be assessed. The effects of vibration to the heritage building may react verily to the quality of building materials and workmanship [2]. The peeling of the wall, cracks in the wall and ceiling may be caused by heavy traffic. Nevertheless, traffic vibrations were not high enough to cause such deterioration [1], [3], [4]. Ground-borne vibration becomes an important issue when the building requires protection and preservation such as heritage, historical, or cultural building [4]. Vibrations in built environment can be divided into three parts which consists of the external sources, the medium, and the receiver as shown in Figure 1.

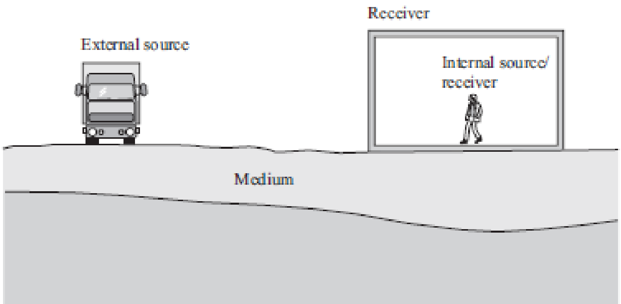


Figure 1: Example of vibration transmission [5]

Muar district is famed with the name “Bandar Maharani” and its heritage building as tourist and local attractions. As a result, the number of vehicles on the road increases. The vulnerability of heritage building may be affected by additional stresses from traffic vibration wave. Countries and cities where their building was built near a roadway system have encountered ground-borne vibration problems especially in dense-populated area. The environmental and economic aspects have been considered for the ground-borne vibration issue although it is very unlikely to cause major damage to the buildings and it required a thorough assessment of the problem especially in congested areas [4]. Besides, the usage of smartphone in assessing vibration was not well-recognized in Malaysia. The use of mobile application in collecting data is one step ahead over expensive technologies to measure vibration because it has the same function with other vibration measuring device. Therefore, this study was conducted to analyse the peak vibration velocity from field measurement using an application, iDynamics. This paper is written for the objective as to perform field vibration measurement, evaluate peak velocity and compare it to the limit set by Department of Environment, DOE: Vibration Limits, 2007 with only focusing on the ground-borne vibration from traffic.

2. Liteature review

The usage of mobile device as a methodological equipment in data collection is developing and evolving around many researchers in various fields, such as engineering, business, transportation, structure and health monitoring, and in healthcare. Smartphones provide an opportunity to be used as preliminary assessment in estimating the effect of vibration to the building. Sensors embedded in smartphone can produce raw data on signal of motion, location and environment, and can be extracted using data mining techniques [6]. Researchers have conducted some measurement test for different smartphones. Sensing units in smartphone could help in structural health monitoring [7]. Researcher also found that the data measured by smartphone is affected by its test placing. Hence, the smartphone is located in z-axis with its back facing backwards to improve reading [8]. New smartphone provide more precise data than old smartphone with an error up to 0.96% and 4-5%, respectively [9]. Mobile developed application, iDynamics was able to detect low natural frequency at a sampling rate of 50 Hz. Furthermore, with high resolution smartphone, 1 mm/s^2, it can detect as low as 15 mm/s^2. For better precision of vibration amplitude, the gravitational acceleration, 9.81 m/s^2 must be subtracted from the measured total acceleration. During measurement process, the calibration is done, and the gravitational acceleration is used at initial measurement. Consequently, the usage of mobile device and application provide minimum effort in identifying simple vibration system, status check or structure health monitoring [10]. Vibration raw data can be averaged between smartphones to cancel the noise signal. However, cross reference between smartphone accelerometer and actual vibration measuring equipment need to be done [11], [12]. This is because, different mobile phone has different resolution and sensitivity and not synchronize with each other.

3. Methodology

The research was conducted at Old Telekom building, a two-storey building which is located at Jalan Majidi and was established in 1946 to provide a better telephone and telegraphic services for domestic and foreign purposes. This research studied the Old Telekom building's modal frequency and peak vibration velocity from passing vehicles. Modal analysis was performed using ANSYS. The vibration measurement was conducted at 2m and 8m from traffic source to obtain the vibration velocity generated by ground-borne vibration due to passing vehicles. The data was measured and recorded using iDynamics application. The peak velocity generated by passing vehicles was compared to the limit set by Department of Environment (DOE): Malaysia Vibration Guidelines.

3.1 Malaysia Vibration Guideline

The steady state vibration from traffic should not exceed the upper limit, 3 mm/s which is defined as "caution level" when under normal circumstances as shown in Table 1. Structural damage such as weakening of structure with large cracks may be likely to occur if the vibration level exceeding the limit 30 mm/s.

Table 1: Recommended limits for damage risk in buildings from steady state vibration [13]

Damage description	Vertical Vibration Peak Velocity, v_{max}, [mm/s] (0 to Peak) (10 to 100 Hz)
Safe	Less than 3
Caution level (Damage Not Necessary Inevitable)	3 to 5
Minor Damage	5 to 30
Major Damage	More than 30

Table 2 shows the acceptable road traffic induced vibrations limit in buildings with accordance to the type of buildings. Heritage building was considered as a building of cultural and historical value and the recommended vertical velocity limit is 1 mm/s.

Table 2: Acceptable road traffic induced vibrations in buildings [13]

Type of building foundation	Recommended Vertical Velocity Limit, v_{max}, [mm/s]
- Especially sensitive buildings, and buildings of cultural and historical value.	1
- Newly built buildings, and/or foundation of a foot plate (spread footings).	2
- Buildings on cohesion piles	3
- Buildings on bearing piles or friction piles.	5

3.2 Finite Element Modelling (FEM)

Finite element modelling is used in many engineering fields. It is important to predict and simulate the physical behaviour of complex engineering systems in order to provide data analysis, information and performance of the structural response when assigned by dynamic loads. The general procedure in simulating the vibration in finite element analysis involves certain steps such as pre-processing, numerical analysis and post-processing. ANSYS is a finite element software and is programmable friendly. The ANSYS command language The block Laanczos method is a default solver selected by ANSYS software to perform modal analysis. The building is estimated to be 23m x 33m x 7.5m (length x width x height). Beam and slab element is assigned as BEAM4 and SHELL63 respectively. Poisson ratio of concrete is 0.2. Meshing generation is made in meshing command where the commands allow in creating mesh on parts of the structures, using LMESH for beam and column, and AMESH for slab. All the slab and beam were set as fixed to the ground. The translation in X-direction (UX), Y-direction (UY), Z-direction, rotation about X-axis (ROTX), Y-axis (ROTY) and Z-axis (ROTZ) were all set as 0. The steps for modal analysis in ANSYS were as shown in Figure 2.

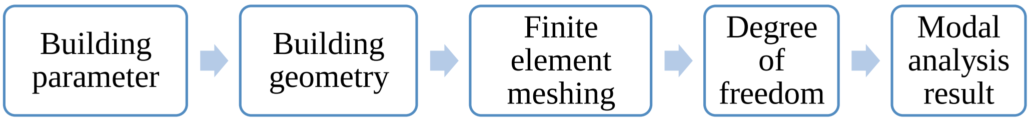


Figure 2: Modal analysis steps in ANSYS

3.3 Installations and setting

The iDynamics application is developed in a best way that can be used for a variety of smartphone models, which the default settings can be adjusted to improve the measurement of vibration. Sample rate of 50 Hz and resolution of 1024 was set. The resolution helps to reduce the computational load. Three smartphones were used in the field vibration measurement as shown in Figure 3 and its properties was listed as in Table 3.

Figure 3: Smartphones used were numbered accordingly

Table 3: Smartphone used in measurement

Smartphone	1	2	3
Smartphone model	YES 4G M631Y	Vivo Y20	SAMSUNG Galaxy Mega (GT-I9205)
Sensor type	BMA 2X2-Accelerometer	Accelerometer	Accelerometer
Vendor	Bosch	MTK	Invensense
Power	0.13 mA	0.001 mA	0.2 mA
Resolution	0.00957031 m/s^2	0.0012 m/s^2	0.15328126 m/s^2
Maximum range	±156.8 m/s^2	±78.4532 m/s^2	±39.24 m/s^2

3.4 Field vibration measurement

Measurement point was located at 2 m and 8 m from the traffic source. The smartphones were placed on a flat surface on the ground on measurement point. The vibration from traffic was recorded for 10s with a sample rate of 50 Hz. The data is recorded in the acceleration-time diagram. The frequency spectrum generated was also displayed. Table 4 shows the summary of field vibration measurement.

Table 4: Summary of field vibration measurement

Route	Jalan Majidi
Reason	Age of building Proximity of Old Telekom building to the traffic
Type of traffic	Road traffic
Test equipment	3 Android smartphones with iDynamics application
Sampling rate	50 Hz
Position	z-axis (back of the phone facing flat surface)
Measurement point	2m and 8m from traffic sources

4. Results and Discussion

Mode shape of Old Telekom building is generated through modal analysis in ANSYS Mechanical APDL software based on the building paramters. The measured vibration data from the nearest traffic at Jalan Majidi was recorded and analysed using iDynamics application.

4.1 Mode shape analyis

The dynamic properties of Old Telekom building were analysed through modal analysis when subjected to different frequency modes in terms of vibration. Old Telekom building was as shown in Figure 4. Modal analysis was carried out for the first 100 modes in ANSYS and the first tenth modes are discussed in this study. The mode shapes were a function of the mass and stiffness of the structure. Natural frequencies explained how the building going to vibrate without external forces. Mode 1 and Mode 2 showed a frequency 2.57 Hz and 3.20 Hz respectively. The fundamental mode of the building, Mode 1 (2.57 Hz) presented no noticeable deformation except in second floor where it can be seen light blue color with 0.005584 mm deformation. It is observed that all noticeable deformation occurred at second floor where there were timber secondary beam. Twisting mode also occurred in Mode 6 and Mode 8.

Figure 4: Old Telekom building in Muar

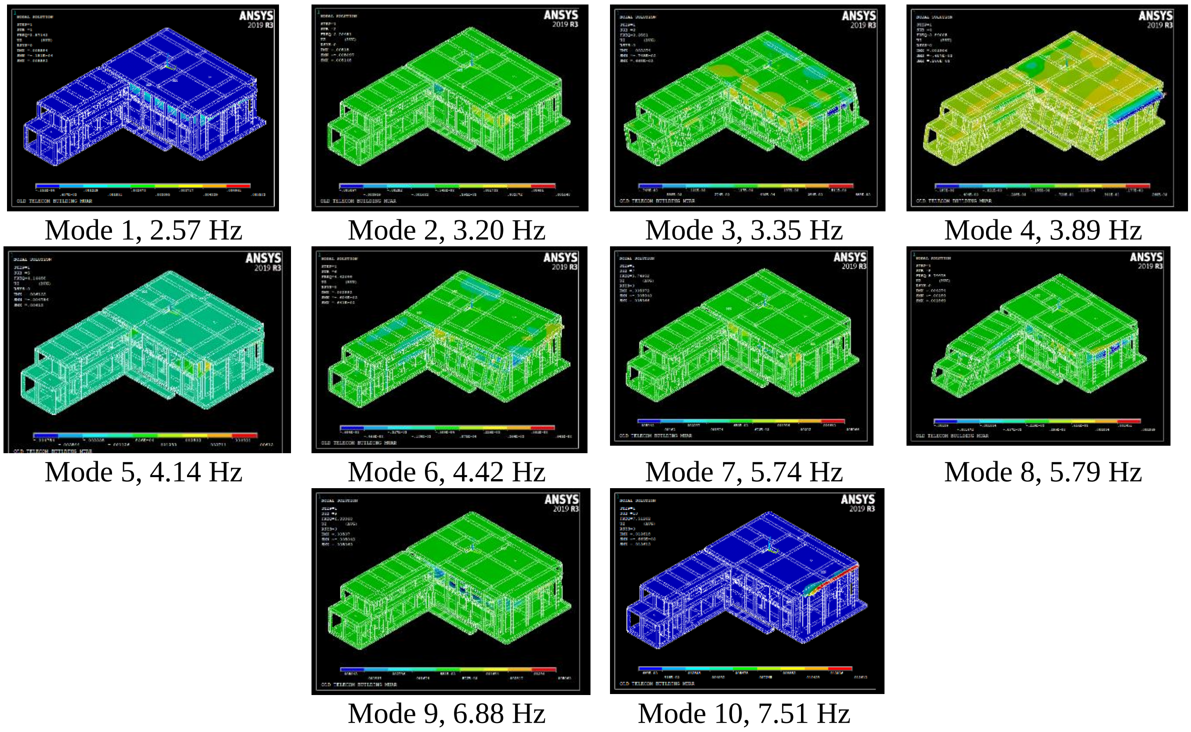


Figure 5: First ten mode shape of Old Telekom building

4.2 Peak velocity

Measured vibration is recorded in acceleration-time histories. The raw data is then evaluated using iDynamics application. Band-pass filter is performed with 10 to 100 Hz which means, peak velocity will be evaluated within frequency 10 until 100 Hz as shown in Figure 6. Analysis of graph showed the vibration velocity from each point at 2 m and 8 m. In most cases, the measured vertical velocity of vibrations in ground are smaller than 3 mm/s which was in safe level. From the graph, it is noticeable that the peak velocity is highest at 2 m with value of 0.006 m/s and peak velocity decreased with increased in distance, at 8 m with velocity value 0.002 m/s. The unit is converted to mm/s in accordance the guideline from Malaysia Vibration guideline. The results were presented in graphical data below with two axes, velocity (m/s) versus time (s) as measured vibration in z-axis and peak velocity was tabulated as in Table 5.

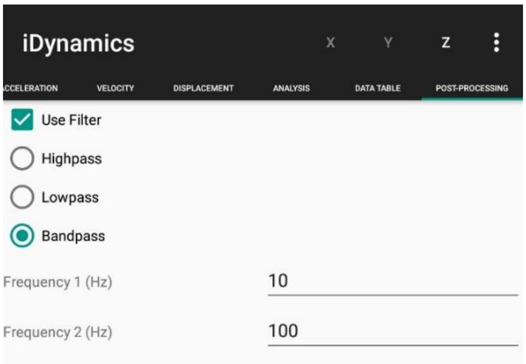
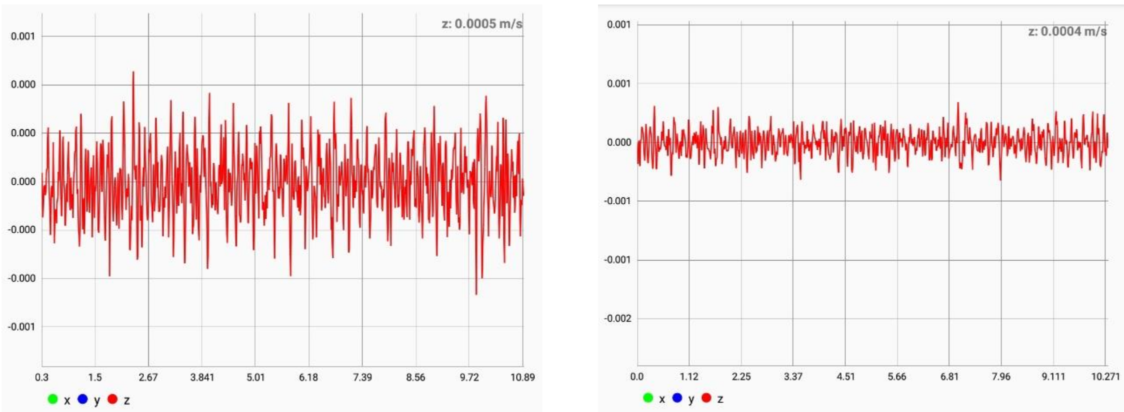
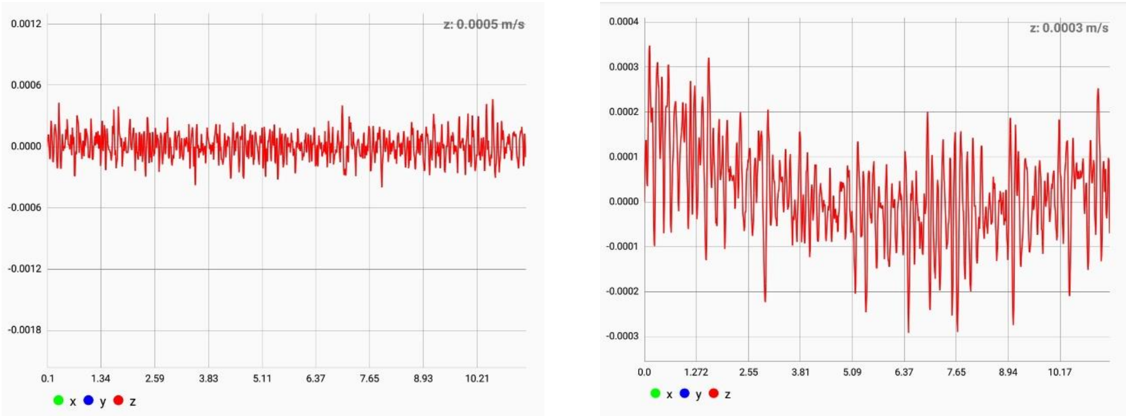


Figure 6: Band-pass filter option in iDynamics



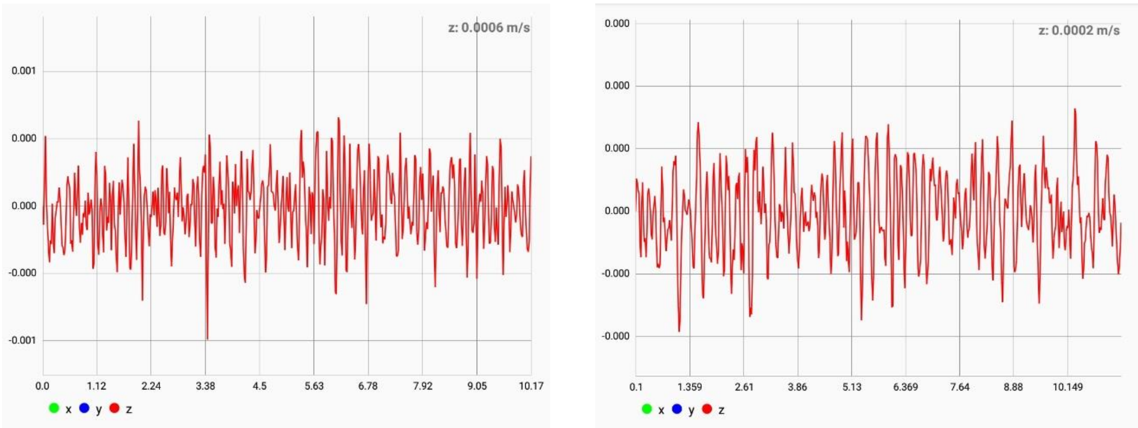
(a) (b)

Figure 7: Vibration velocity on 28th November 2020 at 2pm (a) 2 m (b) 8 m



(a) (b)

Figure 8: Vibration velocity on 29th November 2020 at 9 am (a) 2 m (b) 8 m



(a) (b)

Figure 9: Vibration velocity on 29th November 2020 at 2 pm (a) 2 m (b) 8 m

Table 5 shows peak vertical velocity at each point. The results showed that the ground-borne vibration from passing vehicles is considered as safe to the building. Vertical vibration at point 2 m on 28th November 2020 is 0.5 mm/s. This value is then compared with the limit for damage risk due to steady state vibration, which is from passing vehicles, 3 mm/s. The comparison shows that the measured vibration is lower than the 3 mm/s, hence the measured vibration is considered as safe, as well as at point 8 m. Besides, at 2m on 29th November 2020, the highest vibration velocity measured was 0.5 mm/s same as the measured vibration on 28th November 2020 at point 2 m. As it can be seen in the table, all the measured vibration is below the limit damage risk, 3 mm/s. Although the highest measured vibration is 0.6 mm/s at 2 m, the measured vibration is considered as safe as it is lower than the limit damage risk of 3 mm/s. The standard also has stipulated acceptable road traffic-induced vibrations which the limit for sensitive building is 1 mm/s. The peak vibration velocity measured at 2 m on 28th November 2020 at 2 pm and 29th November 2020 at 9 am and 2 pm is 0.5 mm/s, 0.5 mm/s and 0.6 mm/s respectively, while at 8 m, the peak velocity measured is 0.4 mm/s, 0.3 mm/s and 0.2 mm/s respectively. Moreover, the peak vibration velocity is lower than 1 mm/s. Hence, measured peak vertical vibration showed no indication for any types of damage of Old Telekom building structure.

Table 5: Peak vertical velocity at each point

Date	Time	Distance (m)	Measured peak velocity from traffic (mm/s)(10 -100 Hz)	Limit damage risk (mm/s) [13]	Criteria	Acceptable road traffic-induced vibrations [13]
28/11/2020	2 pm	2 m	0.5 mm/s	< 3 mm/s	Safe	< 1 mm/s
		8 m	0.4 mm/s	< 3 mm/s	Safe	< 1 mm/s
29/11/2020	9 am	2 m	0.5 mm/s	< 3 mm/s	Safe	< 1 mm/s
		8 m	0.3 mm/s	< 3 mm/s	Safe	< 1 mm/s
	2 pm	2 m	0.6 mm/s	< 3 mm/s	Safe	< 1 mm/s
		8 m	0.2 mm/s	< 3 mm/s	Safe	< 1mm/s

5. Conclusion

The fundamental frequency of the building as indicated as in Mode 1 which the frequency was 2.57 Hz. Modal frequency increases as the mode shape increases. It can be concluded that the mode shape shape and frequency obtained in modal analysis were influenced by the stiffness of material and height from ground. The velocity analysis was analysed primarily according to the vertical response of the vibrations. This study found that the highest velocity, 0.6 mm/s was at 2 m from traffic sources. The velocity response decreased with an increase in distance from the traffic vibration source. Therefore, it can be concluded that the direct potential damage to the building was insignificant. Hence, there was no effect for the measured vibration velocity to the building's structural safety. However, some recommendations can be suggested to improve data reliability such as:

i. To ensure data is measured correctly in z-axis, the gravitational acceleration, 9.81 m/s^2 need to be set as initial reading as the gravity may have influence on data reading.
ii. Geophone can be used as reference accelerometer since it does not require external power source.
iii. Use smartphone with same sensor resolution to ensure that the data is measured in equally space time interval.
iv. Superposition technique can be used to produce more reliable data. The data can be analysed in three axis; x-axis, y-axis and z-axis.

Nevertheless, the results of this study shows that smartphones can be used as a preliminary measure for vibration measurement with a low-cost consumption, economical and low maintenance equipment. The results ontained can be evaluated in the application itself and assess the vibration according to the limit. Moreover, the data can be accessed through the file in iDynamics application and easily transferred to Microsoft Excel for further evaluation.

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