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Smart wearable devices for human exposure vibration measurements on two-wheel vehicles

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ABSTRACT
The comfort experienced while driving a motorcycle is becoming a subject of great importance; indeed, the driver is exposed to vibrations that are typically caused by irregular profiles or wear of the road surface as well as by the aerodynamic influence and high-frequency rotation of the motorcycle engine. This paper discloses an original solution that allows the driver to monitor their exposure to vibration during a ride using a low-cost wearable device (smartwatch). A suitable measurement system has been designed and tested using a real motorcycle. The system captures acceleration signals in real time through Bluetooth communication and interfaces with a wearable device with a microcontroller unit that calculates vibrations transmitted through the driver's hands. Different indexes proposed in the literature are adopted for the comfort analysis in both time and frequency domains. The hand transmitted vibrations are also experimentally compared with those measured through a fixed accelerometer according to the prescription included in the standard ISO 5349 to show the feasibility of the proposed approach in typical application conditions.

Section: RESEARCH PAPER

Keywords: vibrations; wearable device; accelerometer; ISO- 5349; suspension system

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1. INTRODUCTION

Body vibration is a term used when vibrations (mechanical oscillations) of any frequency are transferred to the human body. People are exposed to many different types of vibrations in their daily lives; for example, consider the time spent in a vehicle (car, train, plane, motorcycle, etc.) or the use of power tools. Vibration experienced as part of a particular type of work can become a potential form of professional risk, particularly after years of exposure [1].

Humans are exposed to vibration through a contact surface that is in a mechanical vibrating state. In recent years, human exposure to vibrations has increased progressively with the development of agricultural, industrial mechanisation and the use of vehicles.

Due to this increased use of vehicles in recent decades, many people spend at least an hour a day in a vehicle, so it has become crucial to analyse the phenomenon of vibration and the types of stress it might place on the human body. Mechanical vibrations are produced by the oscillatory movement of a body around a position of equilibrium; they are characterised by frequency (Hz), amplitude (m/s^2) and the length of time that the body is exposed to the vibration.

In most cases, vibrations are unwanted effects that can dissipate energy and create noise. The study of the impact of vibrations is very complex [2]-[4]; there are many researchers focused on the effects of vibrations on certain parts of the human body [5], [6]. These studies consist of the analysis and control of all possible ways the vibrations might interfere with the human body to cause discomfort or negatively affect the activities and well-being of a person, including consideration of the effects due to a prolonged exposure over years. There are different effects if the human body is exposed to short-term or long-term vibrations. In the first case, the vibrations cause small physiological effects, such as an increase in heart rate or an increase in muscle tension. In the second case, they produce effects such as alteration of the vertebral column, degenerative processes of the lumbar segments, arthrosis, problems of the digestive system and problems with the genital and urinary system [7], [8].

Some international regulations supervise the exposure of human beings to different sources of vibration. ISO 2631-1 [9] and ISO 5349 [10] are the reference standards for the analysis of human exposure to vibrations. The standards define methods and quantify the vibrations transmitted to the body with regard to human health and well-being. The standards do not indicate limits of vibration exposure, but they do describe vibration assessment methods for exposure risk that can be used as a basis for determining these limits. ISO 2631-1 and ISO 5349 each address different types of vibration and different affected body parts:

1) ISO 2631-1 assesses exposure to whole-body vibration (WBV) [11], [12].
2) ISO 5349 evaluates exposure to vibration transmitted to the upper limbs, known as hand–arm vibration or hand-transmitted vibration (HTV).

Vibrations transmitted to the whole body can create feelings of discomfort and unease, influencing the standard capacity for human performance or exposing the human body to health risks, such as pathological damage or psychological changes. Stress can occur in different directions, contain many frequencies and vary over time. The standards establish the criteria for measuring the vibrations transmitted to the body, considering the following types: random, periodic and transient vibrations. When the vibrations have frequencies close to the resonance frequencies of the human body, then the harmful effects increase. Consider that the resonance frequency of the spine, which is about 5 Hz, is similar to that produced by many earth-moving machines [13]. Within the subset of vehicles, motorcycles represent a vehicle of great interest for the analysis of vibrations due to their increased sensitivity to the roughness of the road when compared to other vehicles [14], [15].

The vibration analysis band for a motorcycle varies from 0.25 Hz to 20 Hz [16], [17]. Excitations at very low frequencies (below 0.25 Hz) are caused by natural variations in the slope of the road and are not transmitted to the human body. Frequencies above 20 Hz can be considered noise, which does create different sensations in the body while driving, but these are not caused by the movement of the motorcycle. The remaining frequency range, between 0.25 Hz and 20 Hz, could also be divided into two other bands: frequencies below 1.5 Hz, which can be set aside due to their low contribution in terms of vibrations, and frequencies from 1.5 Hz to 20 Hz, which include all the primary vibrations foreseen by the dynamics of a motorcycle [18], [19]. The most significant component affecting the human body's exposure to vibrations during a motorcycle ride is vertical acceleration. Indeed, the inertia forces to which the internal organs of the passenger's body are subjected are proportional to the vertical acceleration, while their relative displacements are influenced by the frequency of excitation [20]. This paper presents an experiment with the use of a wearable device, an object that today is commonly used in everyday life, to evaluate the vibrations transmitted to a human body during a motorcycle ride. Furthermore, the results will be compared those derived from a more typically used fixed accelerometer through the calculation from both of several comfort indexes in the time and frequency domains.

The paper is organised as follows: Section 2 describes the measurement system used for the experiment, Section 3 reports the experimental tests, showing the calculation of several comfort indexes for different types of road, and, finally, sections 4 and 5 present a discussion of the results followed by the conclusion.

2. THE MEASUREMENT SETUP

A typical urban motorcycle was used for the evaluation of human body exposure to vibrations during the ride. A suitable data acquisition system was set up, including a wearable device worn by the driver and a data acquisition system able to sample the acceleration data measured on the arm of the driver. A fixed accelerometer mounted across the contact point between the driver's hand and the motorcycle steering was used as a reference for the vibration measurement according to [21]. For more details, see Figure 1.

The measurement system is composed of:

1) Wearable device ST STEVAL-WESU1 (equipped with a 3D accelerometer and a 3D gyroscope LSM6DS3) mounted on the wrist of the driver.
2) STM32F401RE Nucleo board equipped with a Bluetooth module.
3) Fixed accelerometer (LSM6DS3) mounted on the motorcycle's steering.
4) Data logger MDLog (Spring Off).

The wearable device STEVAL-WESU1 [22] includes a MEMS accelerometric sensor for the measurement of accelerations with different ranges: ± 2 g / ± 4 g / ± 8 g / ± 16 g. The sensor is characterised by an accuracy equal to ± 90 mg at full scale. The acceleration measurements used to evaluate the vibrations transmitted by the motorcycle to the driver would normally be carried out directly on the points of contact between the motorcycle and the driver, but in this experiment, we decided to put the sensible device directly on the driver's arm, as is typical of a wearable device.

The axis reference system of the accelerometer sensor according to the wearable device arrangement (located on the left wrist) is shown in Figure 2. The fixed accelerometer has been mounted at the end of the handlebar.

The STM32F401RE Nucleo board [23] was responsible for the data recording, carried out at the sampling frequency of 400 Hz, which was accomplished through the adoption of several methods of data compression in order to reduce the

a) b) c)

Figure 1. The measurement setup: a) The wearable device, b) The Nucleo board equipped with the Bluetooth module c) The data logger.

Figure 2. The reference system for the wearable device.

power consumption and the computational burden [24]-[26]. The communication channels used for data transfer were a Bluetooth bridge with the wearable device and the SPI with the fixed accelerometer. As for data logging, a suitable data acquisition system was designed to store the data collected by the STM32F401RE Nucleo board. The data acquired at a frequency of 400 Hz are:

1) Acceleration value on the x-axis a_x
2) Acceleration value on the y-axis a_y
3) Acceleration value on the z-axis a_z.

Several tests were carried out on a mixed urban-suburban road, specifically chosen to obtain data on different road surfaces. Data was collected for about 30 km, classifiable by road typology as follows (see Figure 3):

1) 10 km of urban road with an irregular road surface
2) 10 km of cobblestone road
3) 10 km of highway.

3. EXPERIMENTAL TEST

As previously explained, considering the massive growth of wearable devices in recent years, the experiment aimed to analyse the use of such a device in the field of human exposure to vibration and compare the results with those obtained from a fixed accelerometer such as would typically be used in the field. Specifically, attention was paid to the vertical accelerations transmitted to the motorcycle driver's body. With this aim, several indexes were evaluated for both accelerometers (i.e. the reference accelerometer and the one included in the wearable device) in order to highlight the annoying frequency components and the daily vibration dose to which the human body is exposed on different road surfaces. In particular, the following indexes were calculated:

- Calculation of HTV in the time domain, which is the RMS acceleration weighted in frequency for the evaluation of comfort concerning an observation window of 8 hours as reported in [10].
- Evaluation of vibration dose value (VDV), useful for the evaluation of vibration transmitted as a result of shock events caused by concentrated obstacles.
- Analysis in the frequency domain of the mean combined auto-spectrum on a range of frequencies of interest.

3.1. HTV index

For the measurement of the vibrations generated by the motorcycle and transmitted through the handlebar, we adopted the techniques described in ISO 5349, which estimate the vibrations conducted to the hand-arm system (i.e. the HTV).

The vibration assessment described by the standards is calculated according to the following equation:

$$a_w = \sqrt{k_x^2 a_{w,x}^2 + k_y^2 a_{w,y}^2 + k_z^2 a_{w,z}^2} \quad (1)$$

where $a_{w,x}$, $a_{w,y}$, $a_{w,z}$ are the RMS acceleration components on the three axes weighted in frequency, and k_x, k_y, k_z represent a multiplicative factor defined by ISO 5349 that depends upon the position of the subject and the contact point between the vibrating surface and the body. In our case, those multiplicative factors were considered equal to 1, as we disregarded the influence of the subject on the contact point [27] and instead considered that all the vibrations generated to the handlebar were transmitted to the driver.

The values of the RMS accelerations $a_{w,x}$, $a_{w,y}$, $a_{w,z}$ are calculated for each axis (x, y and z) applying a weighting factor according to (2)-(4):

$$a_{w,x} = \sqrt{\sum_i \left(W_{hi}\, a_{hi,x}\right)^2} \quad (2)$$

$$a_{w,z} = \sqrt{\sum_i \left(W_{hi}\, a_{hi,z}\right)^2} \quad (3)$$

$$a_{w,x} = \sqrt{\sum_i \left(W_{hi}\, a_{hi,x}\right)^2} \quad (4)$$

where $a_{hi,x}$, $a_{hi,y}$, $a_{hi,z}$ are the accelerations in m/s^2 measured along the x, y and z axes at the i^{th} frequency; W_{hi} represents the weighting factors.

Table 1 presents the frequency weighting in terms of the evaluation of HTV laid out in ISO 5349.

a) b) c)

Figure 3. The road experimented: a) Urban road with irregular profile, b) Cobblestones, c) Highway.

Table 1. Weighting factors for the HTV index.

Frequencies in Hz	Weighting factor W_{hi}
1	0.0235
2	0.1000
4	0.3981
5	0.5450
6.3	0.7270
8	0.8730
10	0.9510
12.5	0.9580
16	0.8760
20	0.7820
25	0.6470
31.5	0.5190
40	0.4110
50	0.324

The weighting aims to highlight specific, particularly troublesome frequencies for the human body. In the present case, the weighting was carried out as shown in Table 1, which was extracted from the weighting curve reported in ISO 5349. The application of the table consisted of filtering the acceleration signal with an appropriate set of filters centred in the next i^{th} frequency defined in Table 1.

The acceleration signal was filtered for each i^{th} band to calculate the value $a_{\text{hix,hiy,hiz}}$. Finally, the acceleration was multiplied for the i^{th} frequency with the appropriate weighting value W_{hi} according to Table 1.

From this operation, it was possible to calculate $a_{\text{wx,wy,wz}}$, which represents the frequency-weighted RMS acceleration along the three x, y, z axes.

The index, calculated for the three orthogonal directions x, y, z, was combined into a single index that defined the effective value of the frequency-weighted acceleration expressed as a combination of the accelerations measured in each direction using (1).

The HTV index was calculated for each road profile by considering consecutive time windows of 30 s in order to achieve a set of 30 values, the mean value and corresponding standard deviation of which are summarised in Table 2. Moreover, the percentage coefficient of variation (CoV, i.e. the standard deviation normalised to the mean value) for each result is reported.

3.2. VDV index

The VDV index was evaluated when the motorcycle crossed a concentrated obstacle, which was a generic bump such as is often encountered in an urban scenario (see Figure 4).

To analyse the data of interest, a 3-second time window centred from the peak of the oscillation was taken, and 20 tests were considered. The VDV is a parameter used for the assessment of comfort in case of vibrations due to shock events caused by a concentrated obstacle such as a bump. The mathematical equation used to calculate the VDV index is the following:

Table 2. HTV indexes calculated on different types of roads with the proposed measurement setup.

Typology	Fixed accelerometer			Wearable device		
	Mean in m/s²	Std in m/s²	CoV in %	Mean in m/s²	Std in m/s²	CoV in %
Cobblestone	2.58	0.15	6	3.07	0.11	4
Highway	2.64	0.10	4	1.69	0.05	3
Urban	4.48	0.18	4	1.55	0.07	4

Figure 4. The bump used for the calculation of the VDV index.

$$VDV = \sqrt[4]{\frac{1}{T}\int_0^{T_s} a_{\text{w}}^4(t)dt} \tag{5}$$

where T_{s} is the duration of the observation window expressed in seconds and $a_{\text{w}}(t)$ is the measured acceleration. Specifically, the calculation uses the fourth power of acceleration, which, compared to the RMS value, is more sensitive to the peaks generated by these shock events. Passing over the concentrated obstacle will generate a spike on the acquired dataset of accelerations, which can be seen from the graph reported in Figure 5. For example, it is possible to recognise the peak of accelerations at around 35.3 s on the acquisition record. The mean VDV index calculated with both of the accelerometers is reported in Table 3 along with the corresponding standard deviation and percentage CoV.

3.3. Frequency Domain Analysis

The index analysed is the combined medium spectrum, calculated from the signals measured by the accelerometers during 15 minutes of data acquisition. In detail, the auto-spectrum was calculated by applying the discrete Fourier transform (DFT) to the signal samples and multiplying the value obtained by its conjugated complex, as reported in (6):

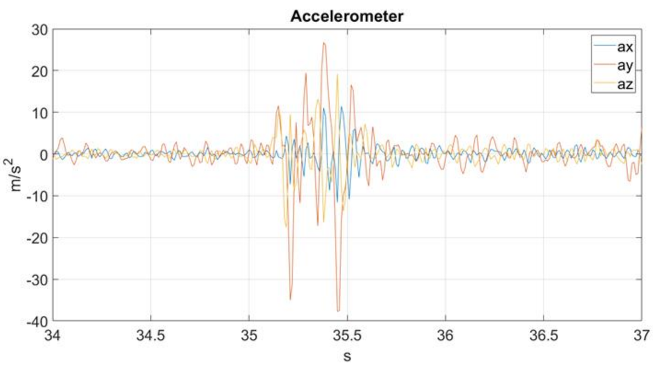

Figure 5. Spike in the acceleration signal due to a bump.

Table 3. VDV indexes calculated by the devices under test.

Fixed accelerometer			Wearable device		
Mean in $m/s^{1.75}$	Std in $m/s^{1.75}$	CoV in %	Mean in $m/s^{1.75}$	Std in $m/s^{1.75}$	CoV in %
2.25	0.08	4	4.39	0.64	14

$$S_{xx} = A(f) \cdot A^{*}(f) \tag{6}$$

where $A(f)$ is the Fourier transform of the signal, and $A^{*}(f)$ is the complex conjugate of $A(f)$.

The auto-spectrums were calculated for each axis of the accelerometers x, y, z (the data pre-processing was performed through the application of a suitable high pass filter aiming to suppress the continuous component). Subsequently, the individual auto-spectrums were combined using the following formula:

$$S_{\text{comb}} = \sqrt{S_{\text{xx}}^2 + S_{\text{yy}}^2 + S_{zz}^2} \tag{7}$$

where S_{xx} is the auto-spectrum in the direction x, S_{yy} is the auto-spectrum in the direction y and, finally, S_{zz} is the auto-spectrum in the direction z.

Finally, the quantitative evaluation was performed, considering as an objective index the integral of the auto-spectrum calculated in the frequency range 0 Hz to 50 Hz:

$$I = \int_0^{50} S_{\text{comb}} \, \text{d}f \tag{8}$$

The frequency range was selected to highlight through the combined spectrum the expected vibration peaks associated with:

- Frequency of suspended masses
- Frequency of unsuspended masses
- Frame frequencies

As an example, the combined spectrum of the signals measured by the fixed accelerometer is reported in Figure 6.

The frequency analysis was performed in such a way as to calculate the integral I (8) of the combined average spectra for each type of road. The results are reported in Table 4 in terms of the mean value, standard deviation and percentage CoV derived from 30 samples of the integral I (8).

4. DISCUSSION OF RESULTS

The experimental results summarised in Table 2–Table 4 show the satisfying data quality of the measurement campaign, as highlighted by the limited coefficient of variation exhibited by the proposed indexes, particularly when computed on the signal outputs from the wearable device (CoV < 15 %). Moreover, as determined by a mean test with a confidence level not lower than 95% for the varying road typology, the corresponding values for each index type are statistically significant since they result from different distribution (i.e. the null hypothesis H_0, according to which two indexes may result from the same population, is refused regardless of which combination of device and/or road typology is considered).

Table 4. Auto-spectrum indexes calculated on different types of roads with the proposed measurement setup.

Typology	Fixed accelerometer			Wearable device		
	Mean in m^2/s^5	Std in m^2/s^5	CoV in %	Mean in m^2/s^5	Std in m^2/s^5	CoV % in %
Cobblestone	0.97	0.18	19	1.09	0.04	4
Highway	1.03	0.33	32	0.36	0.05	14
Urban	1.55	0.54	35	0.38	0.03	9

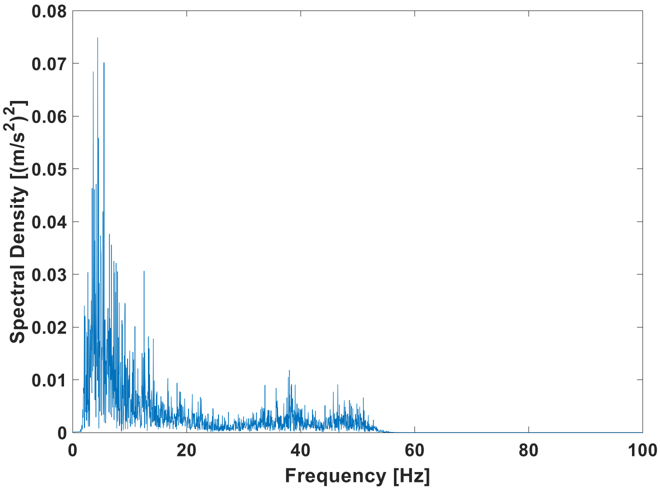

Figure 6. The spectrum of the acceleration signal.

As already highlighted in [21], the HTV index was shown to be the most reliable and significant, since:

- similar results in terms of small CoV (< 10 %) are exhibited with both the devices under test;
- the greatest span is exhibited for each device when different road typologies are considered, making it easier to identify the corresponding discomfort levels.

Moreover, all three indexes confirm that the comfort level as interpreted by the device on the driver's wrist is strongly influenced by the roughness of the road, which may be assumed to be the primary source of vibration at the lowest frequencies and motorcycle speeds. Indeed, with regard to the wearable device, all three indexes assume the most significant value in evaluation of the ride on cobblestone (here we assume as similar the behaviour exhibited in correspondence with the bump). Furthermore, for the first road type, both the HTV and the (combined spectrum integral) I index are characterised by greater value when both devices under test are compared, whereas the opposite behaviour is exhibited when riding on urban and highway roads is considered. In other words, both the time domain and frequency domain analysis highlight that the vibrations transmitted to the hand (as measured by the fixed accelerometer) while riding a motorcycle at high speed increase with the influence of the aerodynamics and the contribution of the frame vibration; these components are more significant than the vertical dynamics introduced by the road roughness. At the same time, the former vibration contribution is muffled by the driver mass, which reduces the corresponding index values computed on the signals outputted from the wearable device.

5. CONCLUSIONS

The evaluation of the vibration transfer to the human body during a motorcycle ride is of considerable interest in order to give relevant information to the rider about the stress accumulated during a ride. Considering the technological progress regarding the development of new tiny and wearable technologies, the paper focuses on the feasibility of the use of a typical wearable device (smartwatch) for the calculation of HTV indexes for different road profiles. From the time and frequency domain analysis represented by the most commonly adopted indexes, it is clear that the highest value of vibration is relative to the cobblestone; thus, a long ride on a road surface of this type will create more significant discomfort. Conversely, driving the motorcycle on a suburban road will involve less discomfort. Considering all the results described, the method is also useful for the evaluation of the quality of the road surface that a driver is obliged to use for daily commuting in order to give feedback and choose the best road for reduced exposure to vibrations (for example a suburban road instead of a highway). The measurement system described could also be used for the evaluation of the vertical vibration reduction introduced by a semi-active suspension system [28] instead of the classical suspension system in a motorcycle or for the detection of faults in a suspension system [29]-[32]. Indeed, the use of wearable devices (as opposed to the installation of expensive fixed sensors) offers the possibility of calculating the HTV index in real time (the most reliable method) for different kinds of vehicles, just by wearing a smartwatch. On the other hand, the main hypothesis of the proposal is the fixed position of the wearable device on the left wrist. Different installation positions should be investigated in order to give the end-user a multiplicative coefficient for the correction of the index.

Future research will also concern the analysis WBV according to ISO 2631-1: it will be investigated by introducing other wearable devices (i.e. foot pods) as well as an accelerometric sensor between the driver's body and the motor vehicle seat and combining the results with the analysis proposed in this work.

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