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Wavelet Transfer Function in the Analysis of the Influence of a Palm Grip on Actual Vibrations of an Upper Limb

Wojciech Batko
Robert Barański

Department of Mechanics and Vibroacoustics, AGH University of Science and Technology, Kraków, Poland

Algorithms used to determine the vibrations to which hand–tool operators are exposed take into account only vibrations measured on a tool. Thus, the significant influence of constraints joining the elements of the tool–operator system is neglected. This paper attempts to determine the influence of grip on vibrations recorded both on the tool and on the limb. The estimation was based on the use of the wavelet transfer function, in which the analysis was done by filtration with wavelet functions. Signals recorded with the specially designed system were utilised in investigations.

wavelet analysis hand vibration

1. INTRODUCTION

Vibrations are an annoying stimulus present in nearly every aspect of our life, both professional and private. Their influence on the human body has been relatively well known [1, 2]. Past investigations made it possible to select certain kinds of occupational work with an increased probability of the occurrence of vibration. Hand-tool operators belong to such a group. Tools are hand-operated by machining operators mainly at building sites and in workshops. Frequently vibrations that affect limbs have such high values that they cause health effects. The white finger disease is a common symptom caused by long exposure to vibrations [1, 2]. Despite various personal protection devices and legal requirements, which have to be met by those devices before they can be used, vibrations acting on the operator very often exceed permissible levels.

Questionnaires administered by the Central Institute for Labour Protection, Poland, in 2002 indicated that 44% of the examined employees complained that vibrations affected their hands [3]. However, according to 2001 data from Poland's Central Statistical Office (GUS), the vibration syndrome (which includes the white finger disease) constituted 3.4% of all occupational diseases in Poland, with nearly 40 000 people exposed to excessive levels of vibration [4].

Therefore periodic checks, based on measuring vibrations generated by devices in conditions of their actual use, are very important in employee protection. Current legal regulations determine both measurement methods and permissible levels of vibrations [5, 6]. They are based on an approach from the 1970s [7], i.e., mainly using weight filtration followed by the determination of its effective value.

However, for the past few years there has been a significant development in measurement as well as in calculation methods. Cheaper and more advanced computers have made signal analysis possible; until recently it could not be done

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Correspondence and requests for offprints should be sent to Wojciech Batko, Katedra Mechaniki i Wibroakustyki, Wydział Inżynierii Mechanicznej i Robotyki, Akademia Górniczo-Hutnicza im. St. Staszica w Krakowie, Al. Mickiewicza 30, Budynek D-1, 30-059 Kraków, Poland. E-mail: <batko@agh.edu.pl>.

due to strictly technological limitations of its complicated calculation algorithms. Those new possibilities have resulted in a search for new methods of measuring exposure to vibration. The new methods would consider additional factors in the influence of vibration on the human body. Several research centres investigate the development of new ways of identifying vibration, using unique measurement and calculation systems [4, 8, 9].

This paper presents an algorithm which could be an additional tool in assessing the vibration dose the operator's upper limbs are exposed to. It uses, among others, the wavelet transform. The main advantage of the algorithm is that it takes into account vibrations recorded not only on the tool but also on the operator's limb. That is why it supplements the gap in the presently used solutions focused entirely on the vibration of the tool. An application of wavelet transformations makes an analysis of nonstationary processes in the time domain possible. Thus, determination of the properties of a time-dependent signal is possible.

2. MEASURING SYSTEM

The measuring method described in Standard No. ISO 5349:2001 [5, 6] utilizes a vibration signal recorded with a sensor mounted on the tool. Not taking into account the remaining factors influencing vibration transmission from a tool to an operator's limb constitutes a weakness of the method.

The most important factors affecting the vibrations perceived by operators and, what is essential, operators have control of, are palm grip force on the tool handle and the force of pressing the tool to the object being machined, which significantly varies in time (it is nonstationary).

Since these authors assumed that the measuring system developed for research should be applicable in actual conditions of use, only the factor related to the grip of the palm on the tool handle was taken into account. This selection was caused by certain limitations of the measuring procedure of the pressing especially since the known solutions are based on utilising the platform on which

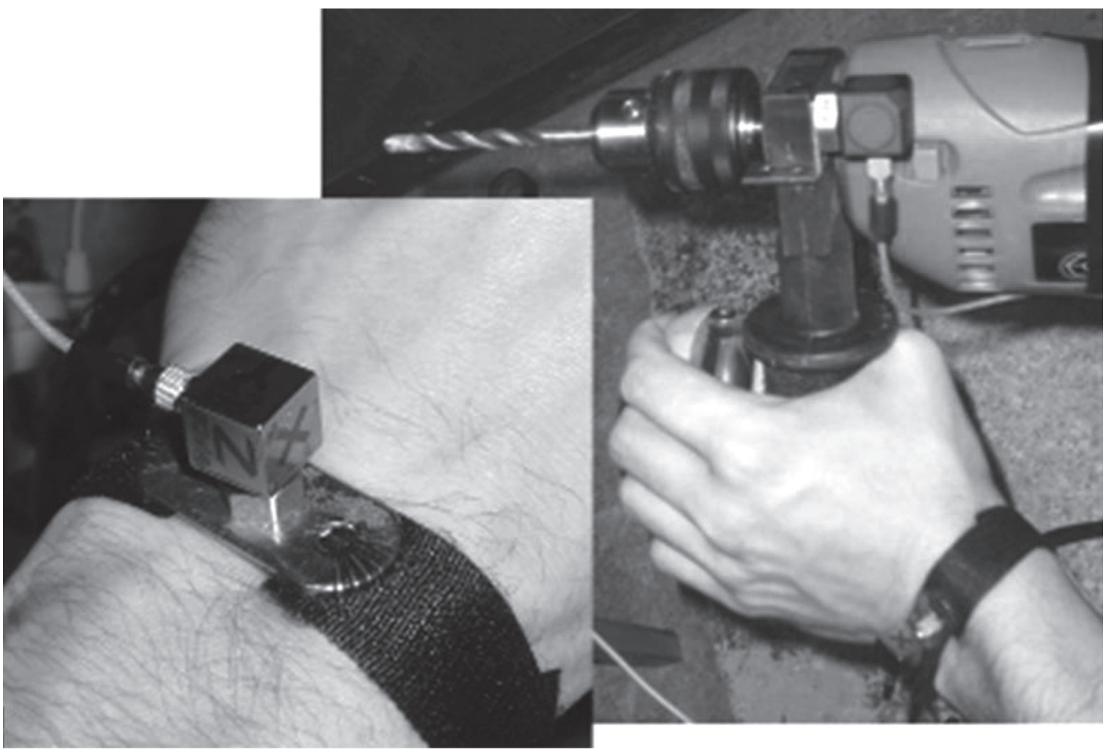

Figure 1. Sensor fittings.

the operator stands [4]; however, there are also solutions that use an element mounted on the tool (in the case of a driller) [10].

Measurements of vibrations both on the tool and on the limb were performed with two triaxial sensors of acceleration PCB 356 B08 and PCB 356A22 (PCB Piezotronics, USA). One was installed on the tool, the other one on the limb. Both sensors met the requirements of Standard No. ISO 5349-2:2001 [6] about the assumption that when the mass of the sensor does not exceed 5% of the mass of the tested object, it does not influence the results.

The way the sensor was placed on the limb and the way the grip on the tool handle was measured were innovatory. As the methods of measuring limb vibration used so far (i.e., with a laser [4, 8] and with an adapter [11]) have not been suitable for standard tool operation, a band was placed on the wrist.

Another proposal concerned measuring grip force with a pressure sensor. The system consisted of a container connected with a pressure sensor placed between two appropriately profiled covers (Figure 2). On the basis of Equation 1

$$pressure = \frac{force}{surface}, \qquad (1)$$

palm grip force on the tool handle was controlled with signal indicators recorded with the pressure sensor. It is important to mention at this point that further on in this paper, the notion of grip is used instead of grip force. This is so because to calculate correctly grip force from Equation 1, the change in the contact surface between the container and the covers as well as the compressibility of the gas (air) in the container should be taken into account. Because to carry out tests only quantitative control of force was necessary, using signal parameters recorded on the measuring card was justified.

In order to check whether the proposed measuring system could be effectively used in the experimental examinations the reproducibility of results was checked several times; the Liliefors test was used, among others [12].

The details of operations are given in Batko and Barański [13]. There was no reason to reject the hypothesis that the results corresponded to the predicted normal distribution at constant forced conditions.

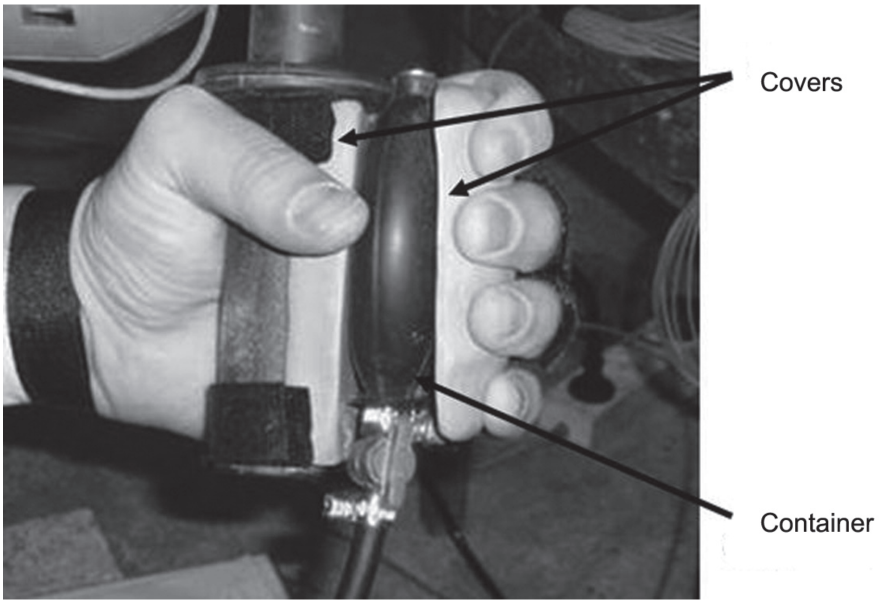

Figure 2. Measurement of the grip.

3. CALCULATION ALGORITHM

The currently applied method of estimating the vibration levels on the grounds of the recorded accelerations of vibrations is based on the algorithm described in Standard No. ISO 5349-1:2001 [5]. Thus, its first stage was signal filtration done by means of a filter of a given frequency response. Signals recorded in three mutually perpendicular directions were filtered. Then effective values of each axle were determined:

$$a_{w,śr} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(a_{w,zm})^2}. \qquad (2)$$

Finally, a reasonable value determining the degree of vibration exposure was found as a module of the vector:

$$a = \sqrt{(a_x)^2 + (a_y)^2 + (a_z)^2}. \qquad (3)$$

However, the standard concerns only the measurement methodology, signal treatment and estimation of the final value, i.e., the effective value. Information whether the measured value is within the values permissible for given work conditions must be found in legal regulations. Thus, the standard is based on a determination of a single-numbered value corresponding to the amount of energy which influences the operator's limbs during the whole time interval.

The standard does not take into account any influence of the contact between the operator and the tool. Variability of constraints between elements of the tool–hand system (during work) is completely disregarded. Of course, stiffness of the tool–hand connection influences tool vibrations; however, this phenomenon is so complex that on its basis only we are unable to assess changes in the constraints of the tool–hand system. In addition, when the mass of the tool is several times larger than the mass of the operator's limb, these changes are marginal and as such do not influence the results of the measurements performed on the tool.

Therefore the developed method took into account the influence of vibrations both on the tool and on the operator's limb. The grip on the tool was controlled during tests, too.

The main element of the algorithm, on which the method is based, utilises the wavelet transform [14] for signal analysis in scales from 1 to 1 024 with step 2^a (where a stands for scale). In calculations of wavelet coefficients, wavelet functions from the following families were used: Daubechies (db6 and db12), Coiflets (coif1, coif5), Symlets (sym2, sym6, sym8). A digital implementation of Meyers wavelet (dmey) was used, too[1].

Then the coefficient was calculated:

$$\tilde{G}_\psi(a,b) = \frac{\tilde{Y}_\psi(a,b)}{\tilde{U}_\psi(a,b)} = \frac{\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} y(t)\psi\left(\frac{t-b}{a}\right)dt}{\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} u(t)\psi\left(\frac{t-b}{a}\right)dt}. \qquad (4)$$

It should be emphasised that the quotient of both wavelet coefficients, $\tilde{Y}_\psi(a,b)$ and $\tilde{U}_\psi(a,b)$, was estimated for the coefficients calculated in the same scale a and shift b. The data vector of the length equal to the length of the input signals was to a certain degree the equivalent of the transfer function.

The data vector obtained in this way, apart from being a representation of a strong dependency between input and output signals, also carried certain disadvantages. When analysing the results, $\tilde{G}_\psi(a,b)$ we were quite often confronted with a situation in which the wavelet coefficient obtained from the signal on the hand was several times higher than the coefficient obtained from the signal recorded on the tool. Such values, called sticking out values, are presented as an example in the uppermost graph of Figure 3.

[1] All calculations were done with Matlab version R2007a, while the applied wavelet functions were implemented in the Wavelet Toolbox.

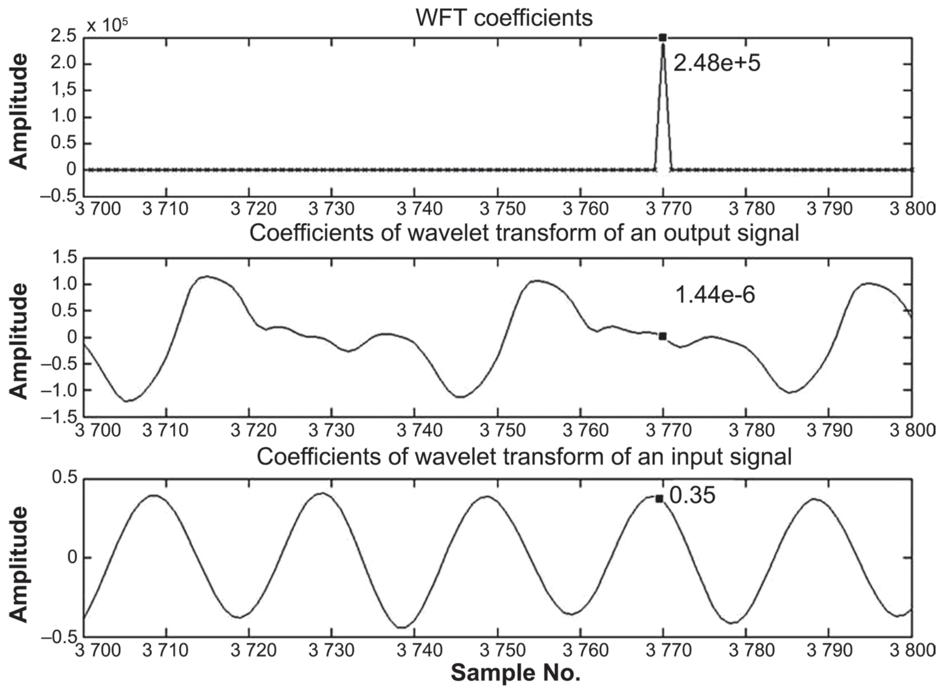

Figure 3. Unfavourable case: wavelet transfer function (WTF).

At the beginning it was assumed that the presence of sticking out values could be considered information on disturbances taking place during tool operation. However, it was found later that those values were solely a result of the lack of matching between the wavelet function and the fragment of the analysed signal (the value of the denominator in Equation 4 was close to zero, of the order 1^{-6}) (the centre and lower graphs in Figure 3). It should be emphasized that the values of the obtained wavelet coefficients can be considered a measure of similarity of the analysed signal and the wavelet function, which is close to zero when the similarity is negligible.

This phenomenon is so important that it was able to completely disturb the final pattern of the coefficient representing the analysed signal. Out of several procedures eliminating sticking out values, an algorithm was chosen. The algorithm is based on segmentation of the signal into 0.5-s intervals and 0.5% changes of the highest values in the segmentation under consideration.

The samples had values equal to an arithmetic mean of the neighbouring samples. The segmentation for time intervals was established for 0.5 s, since such segmentation ensures the occurrence of at least one frequency period from the analysed band. Values of the rejected samples were expressed as a percentage of signal length and were determined empirically.

The operation of the algorithm of sample exchange is presented in Figure 4. The signal selected as an example was obtained after application of the wavelet dmey, at the scale a = 64. A significant difference between both signals can be seen. Special attention should be focused on the amplitude values.

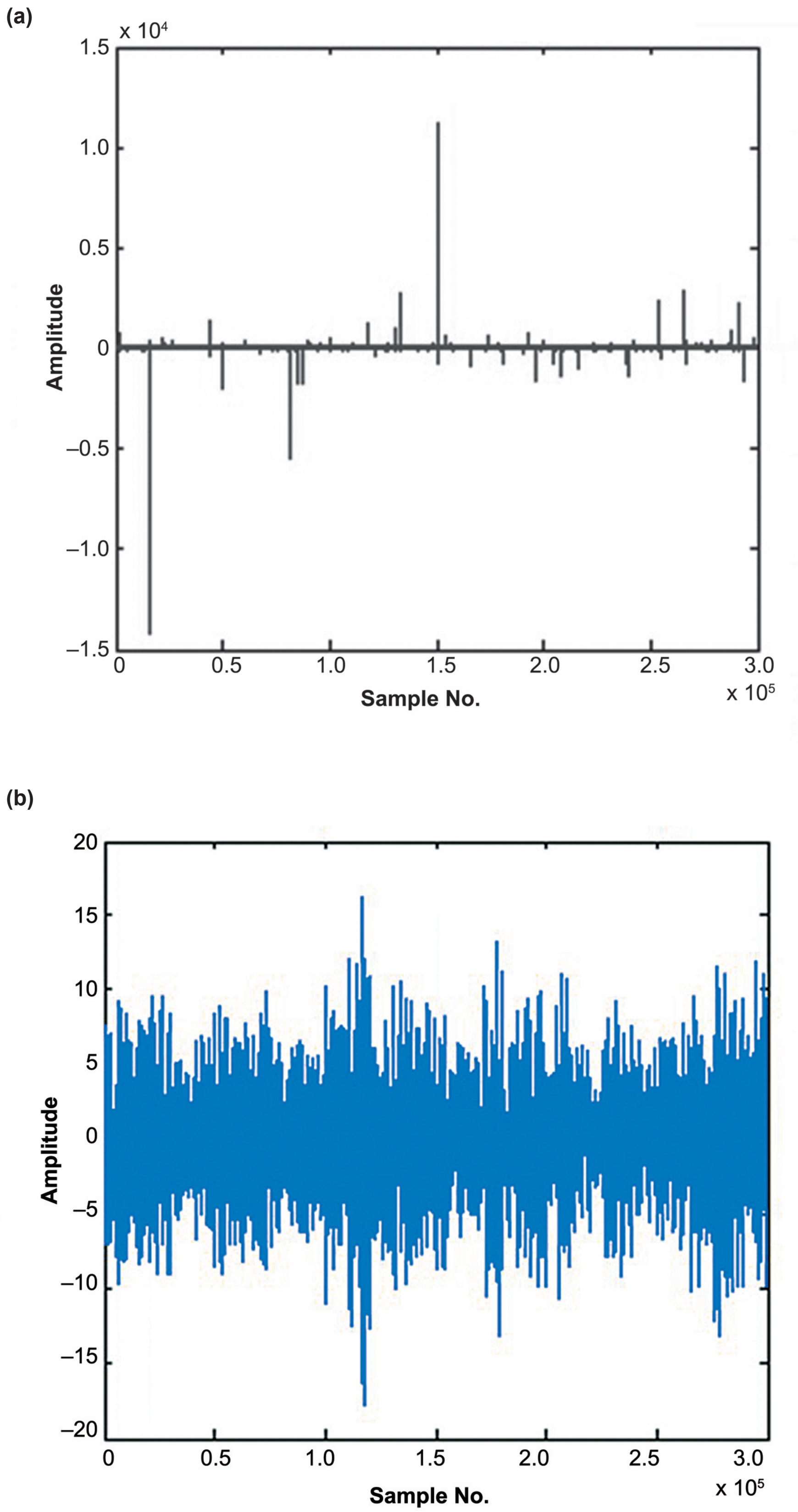

Figure 4. Operation of the function eliminating extreme values. (a) Result of a WTF operation without sample exchange, (b) result of a WTF operation after the algorithm of sample exchange was applied.
Notes. WTF—wavelet transfer function; scale *a* = 64.

4. EXAMPLE OF EXPERIMENT

Signals recorded during the work of three operators, in six series of 60 s each, were used in a verification of the proposed method of calculation. Frequency of sampling[2] was 10 kHz. Accelerations of vibrations both on the limb and on the tool as well as the grip were recorded with the system described in section 3. Recording was done when the tool was worked with, at a constant pressure on the machined element, while the grip on the tool handle changed.

The main purpose of investigations performed with the proposed algorithm was to verify its sensitivity to changes in the grip of the palm on the handle. The correlation coefficient was calculated for vectors representing rms values of 0.5-s periods determined for the measured variables. Therefore the average[3] correlation coefficient for proposed method–grip was estimated.

The results (Figure 5) indicated significant changes between individual series for the tested operators. The average correlation coefficients were very low for two operators (No. 1 and 3), while for operator No. 2 the coefficient was .67 for wavelet sym2. However, correlation between the tested signals was not strong.

Table 1 presents the average correlation coefficient from repeated measurements in a given measurement series for given wavelet functions. The best results were obtained when function sym2 was applied, which confirms the correctness of its application for this type of signals[4].

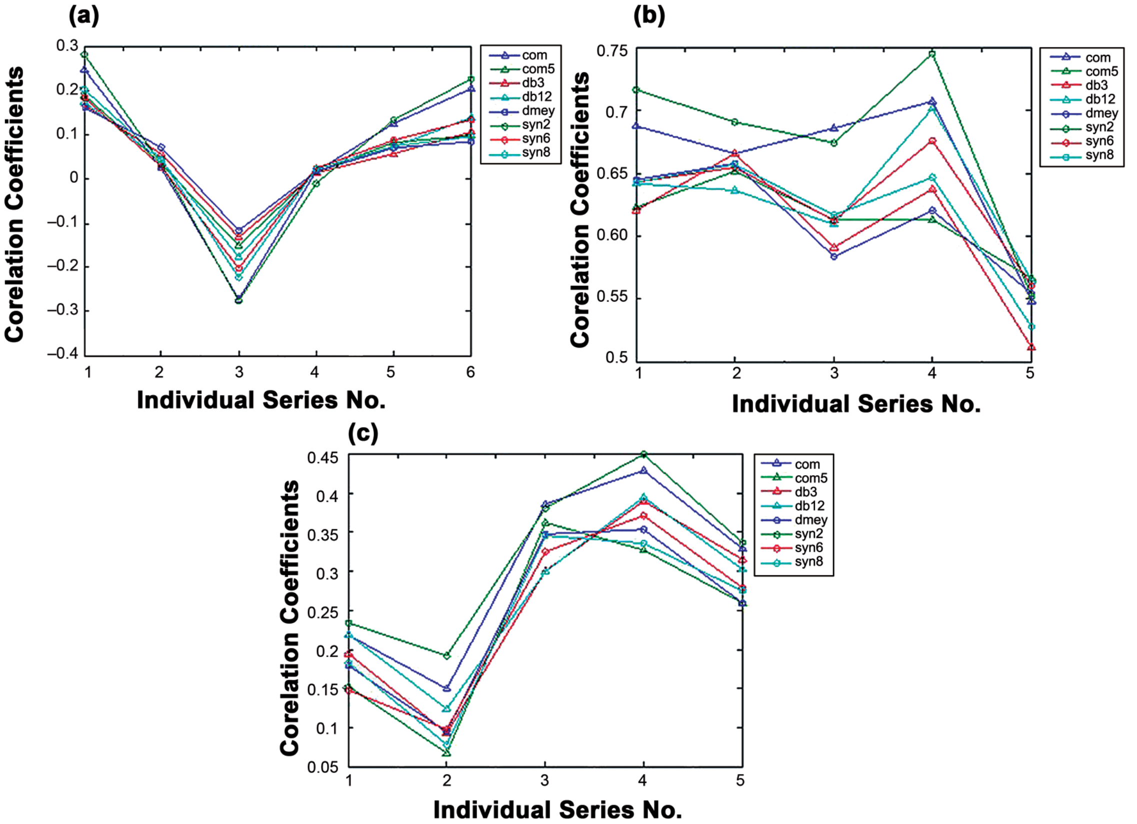

Figure 5. Average (for the measured case) value of the correlation coefficient for the WTF–grip pair. *Notes*. a—operator 1, b—operator 2, c—operator 3; WTF—wavelet transfer function.

[2] This is an essential value for frequency interpretations of results obtained for wavelet scales.
[3] Average values of the correlation coefficient for individual scales were determined and then the mean value from all results was calculated.
[4] The results of other investigations performed on signals recorded with the same device confirmed a higher effectiveness of algorithms when wavelet function sym2 was used.

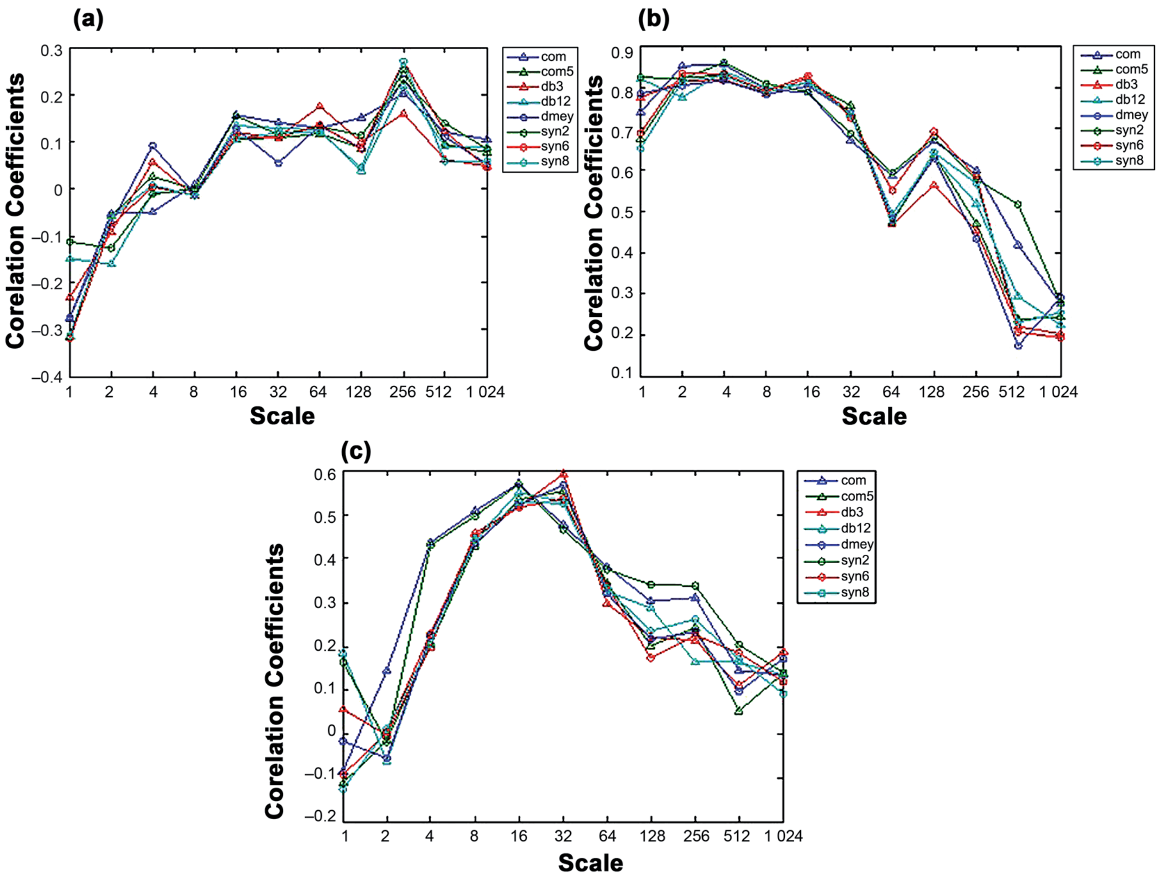

Figure 6. Average (for the scale) value of the correlation coefficient for the WTF–grip pair. *Notes.* a—operator 1, b—operator 2, c—operator 3; WTF—wavelet transfer function.

TABLE 1. Average Global Correlation Coefficients WTF–Grip Calculated for All Repetitions of Measurements

	No. of Measuring Series		
Wavelet	**Operator 1**	**Operator 2**	**Operator 3**
coif1	.0581	.6591	.3024
coif5	.0449	.6134	.2338
db12	.0452	.6053	.2586
db6	.0452	.6307	.2680
dmey	.0486	.6121	.2469
sym2	.0656	.6757	.3186
sym6	.0429	.6295	.2440
sym8	.0367	.6184	.2434

Notes. WTF—wavelet transfer function.

Because the results just presented indicate either no or weak dependency between the grip and the calculated value of the wavelet transfer function (WTF), a more detailed signal analysis was performed: in scales, i.e., in bands of narrower frequency intervals.

Figure 6 illustrates the correlation coefficient between the rms value calculated from the WTF and from the grip on the tool handle, for each tested scale.

The highest correlations (.65–.85) were obtained for operator No. 2, too, for scales from 1 to 32, which in our case corresponded to the frequency range from Nyquist's frequency (5 000 Hz) to 150 Hz.

Regardless of the relatively low correlation coefficients between the WTF and the grip, the distribution of the rms values of the WTF and of the grip calculated for 0.5-s intervals was determined. Visual analysis of the distributions confirmed the assumption of a direct proportionality of the tested variables. Therefore the distributions were described with 1st- to 9th-order multinomials. Tests indicated that

- the difference between rms errors introduced by the multinomials used was within 5%,

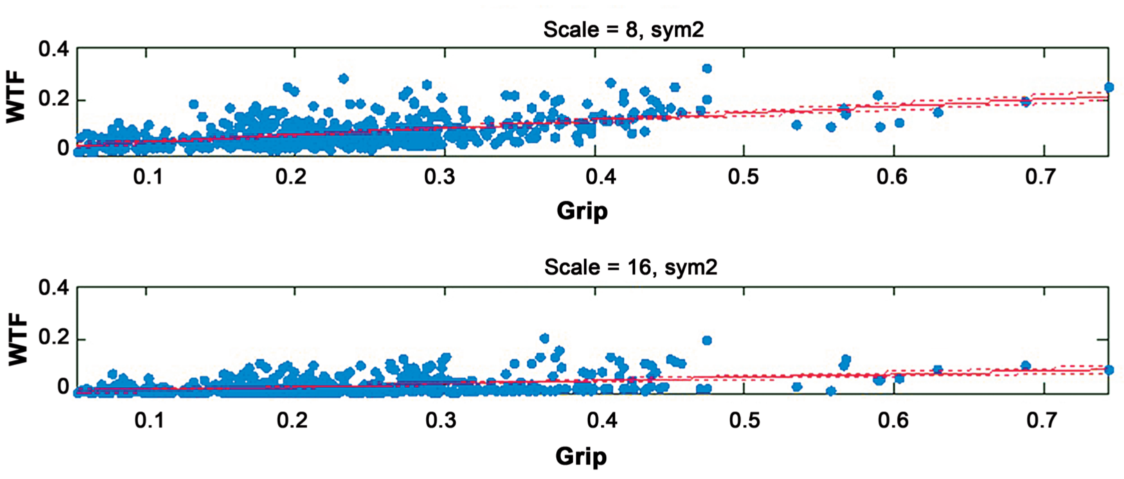

Figure 7. Distribution of points: WTF–grip. *Notes.* WTF—wavelet transfer function.

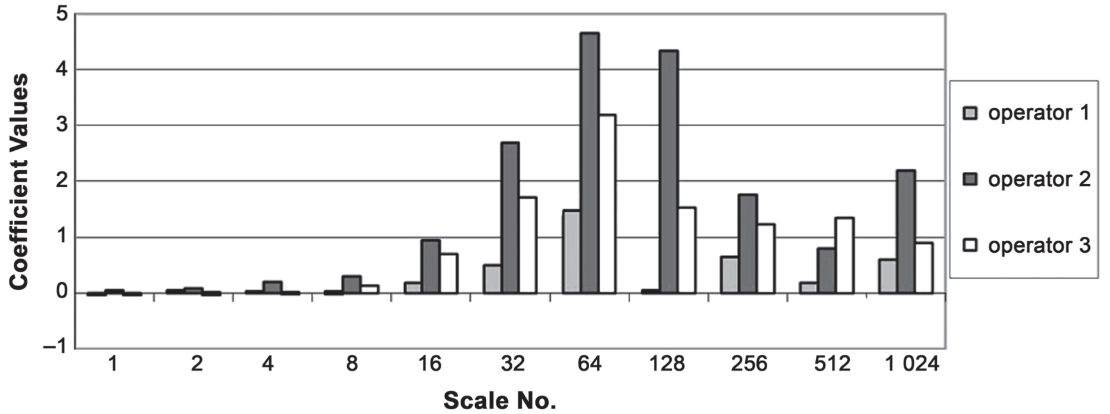

Figure 8. Directional coefficient values of the 1st-order multinomial.

which means that the application of a 1st-order multinomial would not significantly lower the representation of the WTF–grip behaviour;

- the obtained directional coefficients of the multinomial were above zero, which could be interpreted as a proportionality of the tested variables. Figure 7 illustrates sample distribution points.

Figure 8 presents sample multinomial coefficients determined for the three operators. The domination of coefficients determined for operator No. 2 is clear. In addition, their highest values are for scales 32, 62 and 128, which indicates that the frequencies of those scales are the most sensitive to changes caused by the grip on the tool handle.

Moreover, very small values of coefficients for low scales[5] (1–8) indicate a very strong attenuation of frequencies represented by those scales (which is consistent with the theoretical considerations and with the properties of soft tissues that are one of the building materials of a human hand).

[5] Low scales correspond to high frequencies, which means that when the scale increases, the frequency represented by it decreases.

5. CONCLUSIONS

This research aimed to present a different approach to measurement and calculation methods related to exposure to vibration. The developed measuring system makes measuring vibration on the limb as well as on the tool possible.

The results indicated that the application of the mutual correlation coefficient for the estimation of constraints in the WTF–grip pair does not correspond to the actual dependencies between these variables. The points representing changes of the WTF and the grip were significantly scattered due to the complicated character of the phenomenon.

The suitability of the algorithm in the analysis of the influence of the palm grip on the actual vibrations of the upper limb is reflected by the distribution of the instantaneous rms WTF values as a function of the grip. In addition, because it was possible to analyse the signal in wavelet scales, information on frequencies most significantly transferred by the investigated system was captured.

The calculation algorithm based on the application of the wavelet transform makes analysing the signal in the time domain possible. Therefore, investigations on ways to improve the algorithm, with the application of time segmentation of wavelet transformations, will continue.

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