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AN ATTEMPT OF THE APPLICATION OF MATCHING PURSUIT MP WITH GABOR DICTIONARY FOR EVALUATION OF RIDE COMFORT DISTURBANCE LEVEL

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Abstract

Ride comfort has always been considered to be essential for vehicle development. Nowadays it is one of aspects of vehicle industry that is getting more and more important. Disturbances in vehicle motion, for example drive across an obstacle or drive of a rail vehicle across the transition curve may be the reason for ride comfort disturbances. These excitation values may define the subjective negative comfort assessment by a passenger or a driver. Sudden changes of acceleration with low frequencies are particularly perceptible. That is why the attempts of evaluation of these disturbances are included in standards as PCT and PDE indexes for rail vehicles. In order to designate these indexes filtration of the recorded lateral acceleration runs is done. The values of changes of lateral acceleration, of lateral jerk and roll rate in time intervals are defined. This kind of analysis in which only the amplitudes of values measured were taken into account and in which 2 Hz filter was used may cause discrepancy between subjective assessment and evaluated level of vibration. Wavelet transform that is the tool of time-frequency analysis makes non-stationary signals such as acceleration signals in case of comfort disturbances possible. The problem of evaluation of vibration level that is based on wavelet transform analysis appears. In order to evaluate this vibration level algorithm of matching pursuit MP may be used to match the mother wavelet to the recorded signal in the best way possible. The article presents an attempt of matching pursuit algorithm with Gabor dictionary for evaluation of the discomfort level that was based on the run recorded in the tram.

Keywords: *comfort evaluation, comfort disturbances, matching pursuit, time-frequency dictionaries*

1. Comfort

Comfort is often defined as subjective well-being of a passenger that results from the absence of temporary comfort disturbances. This well-being can be reached or disturbed by various factors both physiological such as expectations, age, gender, posture, experience and mental activity or environmental factors such as vibration, air temperature, noise, characteristics of seat etc. These factors are reasons why the same vibration level is assessed in relation to given situation [1]. Physiological variables are important and can modify the severity of human responses. On the basis of the ENV 12299 [2] standards two types of comfort are defined, namely a mean comfort evaluation by measurements and taking into account the effects of vibration exposure on a long time basis (at least some minutes, 5 minutes according to ENV 12299) and continuous comfort evaluation by taking into account a level of accelerations over a short time interval [3]Human response to the mechanical vibration, perceived vibration exposure, depends on amplitudes, frequencies, directions, time of exposure and damping coefficients of vibrations [4].

Human body is characterized by different sensitivity to different frequencies of vibration. The same amplitudes do not cause the same level of discomfort to different frequencies of vibration. In order to match the measured physical vibration to the perceived vibration exposure it is necessary to apply ”weighting filters” to the measured data. These filters modify the frequencies response of the data, giving greater prominence to those frequencies where humans are more sensitive to vibration. The "weighting filters curves" are shown in Fig. 1 according to standards ISO 2631 [5] and BS 6841 [6]. W_b and W_k are the frequency weightings for vertical vibration, W_d for horizontal and W_e for angular vibrations. The W_k curve suggests higher sensitivity in frequency range from 0.5-4 [Hz].

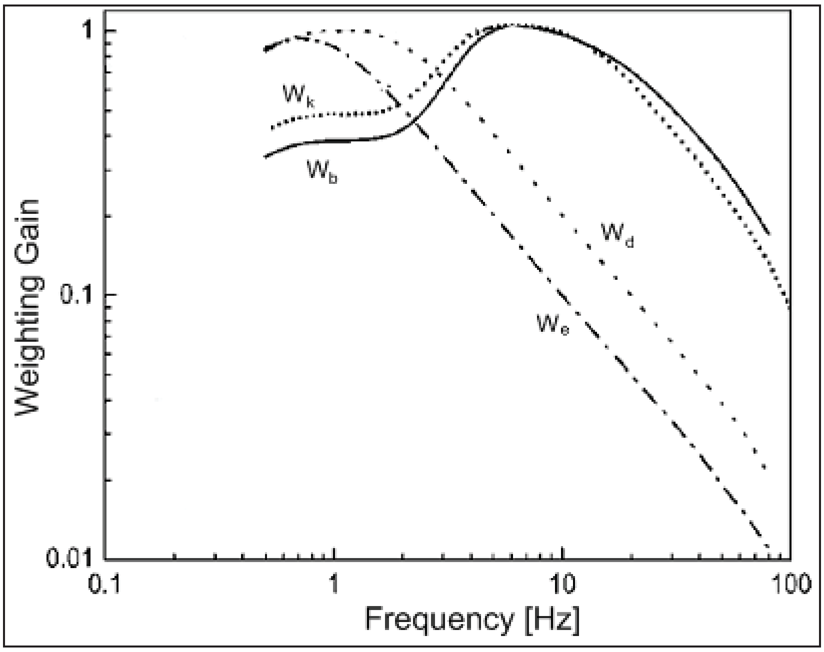

Fig. 1. Acceleration frequency weightings for whole body vibration as defined in BS 6841 and ISO 2631 [4]

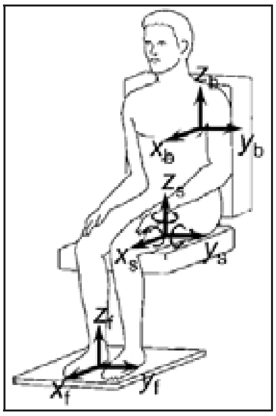

Fig. 2. Local reference systems for a person in a seated position [4]

Some frequencies weightings are used for more then one axes of vibration, with different "multiplying factor" allowing for overall differences in sensitivity between axes. The descriptions of these multiplying factors can be found in standards [5, 6]. The orientation and location of coordinate systems of axes of vibration are shown in Fig. 2. The measurement points are positioned in the same places. The indicator of discomfort level rise together with rise of vibration amplitude can be defined according to Steven's Power Law. Through series of experiments, Stevens found that a consistent relationship existed between the subjective magnitude of a signal (ψ) and physical magnitude of the same signal (φ) for a wide range of input stimuli. The relationship is known as Steven's Power Law and is given by: $\psi = k \cdot \varphi^n$ where: ψ is the perceived magnitude, k is scaling constant, φ is the physical magnitude and β is the stimulus dependent exponent. The results of Griffin experiment did show a significant variation of β with frequency for the lateral vibration but not for vertical vibration(range of vibration magnitude from

0.04 m/s^2 to 0.4 m/s^2). Griffin noted that, allowing for differences in experimental methodology and stimuli specification the results were broadly similar with β varying around unity.

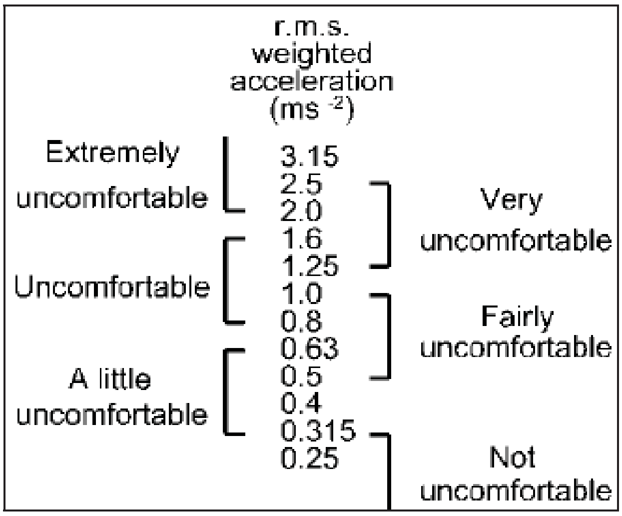

Fig. 3. Discomfort scale suggested by BS 6841:1987and ISO 2631:1985

The scale of vibration discomfort as a function of r.m.s. weighted acceleration is shown in Fig. 3. According to BS6841 and ISO 2631 the vibrations with r.m.s. weighted acceleration below 0.315 [m/s^2] do not cause discomfort feeling.

Human response to mechanical vibration depends, among others thing, on damping coefficient. The results of Ahn and Griffin [7] experiment show a significant influence of damping coefficient value, in the vertical vibration frequency range from 4-12 [Hz], on discomfort feeling. That means that the increase of damping coefficient causes decreasing of discomfort feeling.

In the case of stationary acceleration signals r.m.s.(1) value of signal is the basic indicator in discomfort evaluation recommended by BS and ISO standards.

$$r.m.s.=\left[\frac{1}{T}\int_{t=0}^{t=T} a_w^2(t)dt\right]^{\frac{1}{2}}. \tag{1}$$

The results of experiment point that doubling of vibration magnitude requires, very approximately, a 16-fold duration reduction to maintain the same level of comfort. This leads to fourth-power relationships between the acceleration magnitude and duration. The root-mean-quad (2) gives greater relative weight to occasional higher vibration like shocks and peaks of acceleration. Both r.m.s. and r.m.q. values are averages because in these formulas the integral of frequency-weighted acceleration is divided by time period of exposure. They do not increase with the increase in duration of steady-state signals and they tend to decrease with increasing measurement duration if the signal is not stationary.

$$r.m.q.=\left[\frac{1}{T}\int_{t=0}^{t=T} a_w^4(t)dt\right]^{\frac{1}{4}}. \tag{2}$$

As the vibrations cause by vehicle motion are usually non- stationary it is difficult to define the moment to start and end of the calculation of the r.m.s. or r.m.q. of acceleration. It seems that the solution of this problem is the application of VDV (3). The VDV (vibration dose value) exploits the r.m.q. without dividing it by the exposure time. This indicator can be used to quantify vibration events of any type. According to Griffin[4] this indicator is very easy to use and sensitive to peaks in vibration. It seems more appropriate to vibration evaluation then r.m.s.

$$VDV=\left[\int_{t=0}^{t=T} a_w^4(t)dt\right]^{\frac{1}{4}}, \tag{3}$$

where:
$a_w(t)$ - the frequency weighted acceleration,
T - the period during which the person is exposed to vibration.

The indicator VDV is one of two indicators suggested by ISO standards as the additional indicator to evaluate the vibration in the case where the crest factor CF (4) is higher or equal 9.

$$CF = \frac{\max\,[a_w(t)]}{r.m.s.} \geq 9\,. \tag{4}$$

The second indicator is windowing r.m.s. for window τ=1[s]

$$r.m.s.(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w^2(t)dt\right]^{\frac{1}{2}}, \quad \tau = 1[s]\,. \tag{5}$$

A novel approach to temporary comfort disturbances is presented in CEN standard [2]. Two indexes are defined in this standard. These indexes are expressed in percentage of dissatisfied passengers. The scale of discomfort has five levels. The measured signals are filtered using the low-pass filter 2 [Hz].

Index P_{CT} is calculated for individual transition curve without evaluation of cumulative effect. The value of this index is calculated taking into account the following variables: maximum absolute value of lateral acceleration in vehicle body, maximum absolute value of lateral jerk on the transition curve and maximum absolute value of roll velocity. Index P_{DE} is a measure of passenger comfort for an individual discrete events, without evaluation of cumulative effects. The evaluation of comfort on discrete events is based on the relationship between the average percentage of dissatisfied passengers and the most relevant magnitudes of peak to peak lateral acceleration and mean lateral acceleration level. The indexes mentioned above can be used only for a defined situation and for defined track characteristics. Unfortunately, these indexes are useless for other means of transportation. ISO and BS standards are overall standards employing indexes and indicators for all kinds transportation means. According to Griffin [4], it can be stated that further direction of methods of comfort evaluation development will aim at standardization measurement and computation method.

2. Research

The tests were carried out in Cracow for two objects. The first of them is a 105 Na tram. The lateral acceleration and roll angle rate were measured. The measuring point was in middle part of tram and test was carried out without passengers [8]. Signal was recorded with 50[Hz] frequency. The second object was a small van Ford Transit.

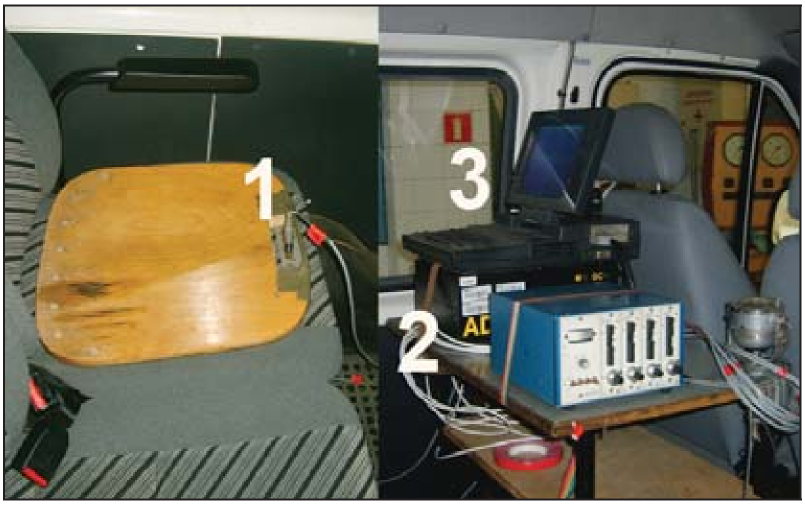

Fig. 4. Measuring apparatus: 1. Seat pan with acceleration sensor,2. Analog-digital converter, 3. Computer

Figure 4 shows the measuring apparatus installed in a vehicle. The vertical acceleration was measured using the HBM B12/200 (1) acceleration sensor, which then was converted in AD 12 analog-digital device (2) and afterwards recorded. SPECTR software installed in measuring computer (3) made further signal conversion possible. Acceleration sensor was fixed to seat pan measuring device over the rear vehicle axle. Test track contained the typical bumps and the velocity was 15 [km/h].

3. Research results

For further analysis two signals were selected. The first measured signal on the tram floor is shown in Fig. 5. The signal filtered with low pass filter 2 [Hz] is plotted on non-weighted lateral acceleration signal as a background. Moreover, the run of windowing r.m.s. is also shown. Arrowhead points the maximum value of r.m.s. The maximum value of r.m.s. appears on the curve of tramway at the velocity about 20 [km/h]. The maximum value of r.m.s. is 1.1207 [m/s^2]. In lower part of Fig. 5 the FFT of this signal is shown. The great value of amplitudes are noticed for frequency below 1[Hz] and peaks of amplitude for frequency about 11.5 [Hz]. This is the self frequency of one part of suspension.

The second signal is the vertical acceleration recorded on seat pan over the vehicle rear axle. This signal containing the non-weighted vertical acceleration is shown in Fig. 6. It can be noted that two peaks of vertical acceleration caused by the passage of the vehicle front and rear axle over the bump appeared. The period of vibration damping lasting about 2 [s] is also noticed.

The maximum value of r.m.s. is 3.8378 [m/s^2] for rear axle and 2.1635 [m/s^2] for front axle. The run of FFT points that big values of acceleration appear in ranges of frequencies from 1 to 6 [Hz]. This range of frequency comprises the range of high human sensitivity for vibration (Fig. 1). It is necessary to notice that both of these signals are non-stationary.

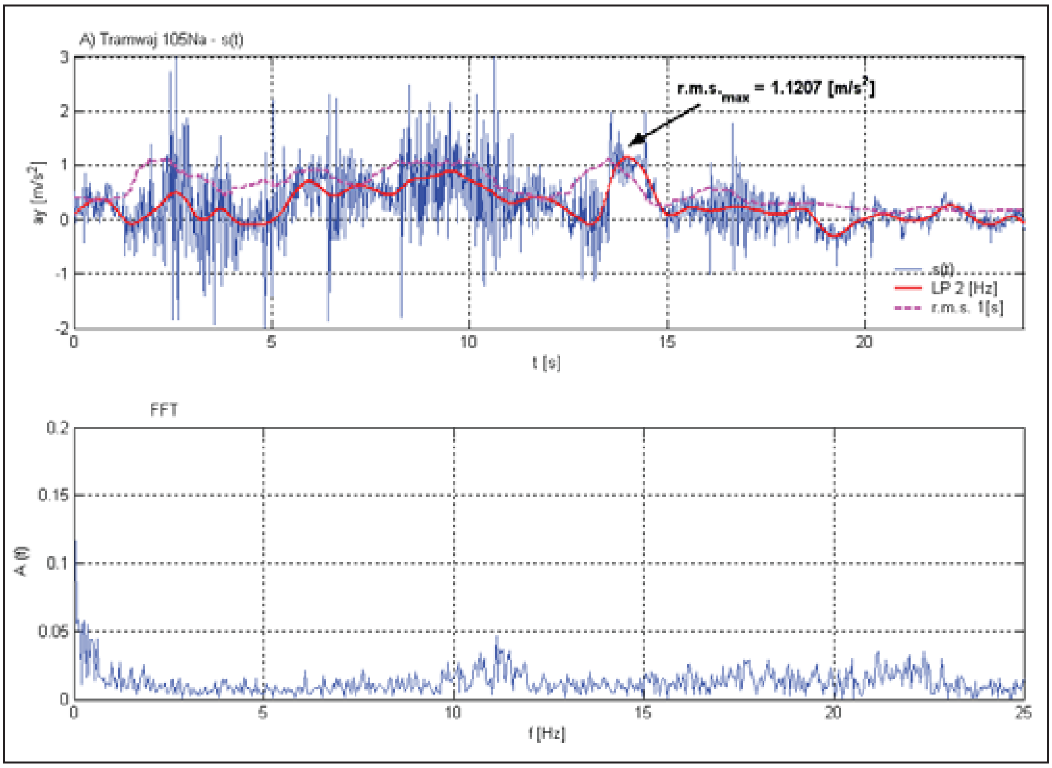

Fig. 5. Run of lateral acceleration recorded in 105Na tram (upper part) and FFT of this signal (lower part)(Description in text)

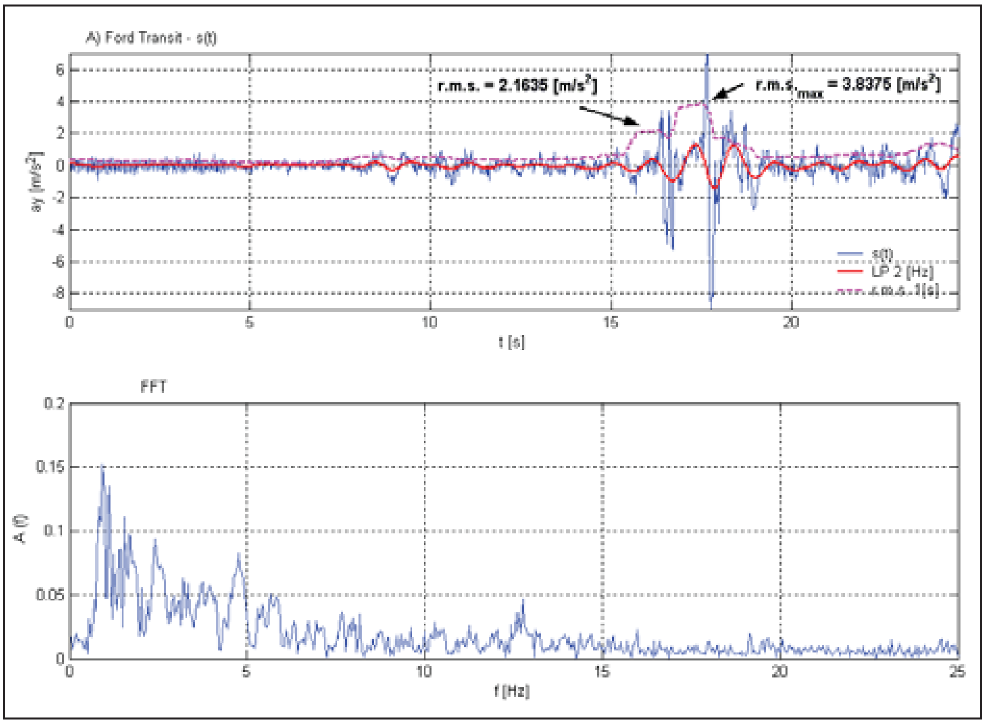

Fig. 6. Run of vertical acceleration recorded in Ford Transit (upper part), and FFT of this signal (lower part) (Description in text)

Applying the Fourier transformation for further evaluation seems to be improper. According to the Authors time frequency transformation, for example wavelet transformation is a better tool for evaluation of comfort disturbances.

4. Matching Pursuit

In the case of complex signal with transient element that are characterized by wide scope of the patterns, linear expansion in a single basis (for example windowing Fourier, wavelet) is not flexible enough to be good representation of the analyzed signal. The dictionaries can help, as on the basis of the assumed criteria the most suitable signal structure elements can be selected. Optimal signal representation can be obtained by the selection of such subset dictionary elements, whose linear combination explains the biggest percent signal energy from all subset with the same number [9]. The algorithm , called matching pursuit, worked out by Mallat and Zhang [10], decomposes any signal into linear expansion of waveforms that are selected from a redundant dictionary of function. Dictionary G={$g_1(t)$,$g_2(t)$,….,$g_n(t)$} is a set of functions called time-frequency atoms. The general family of atoms created from single window function g(t) by a dilations, b translation and ξ frequency modulation in opposition to wavelet transformation.

$$g_I(t)=\frac{1}{\sqrt{a}}\cdot g\left(\frac{t-b}{a}\right)\cdot e^{i\xi t}\,. \tag{14}$$

Factor $\frac{1}{\sqrt{a}}$ is used for energy normalization. Index $I = (a,\ b,\ \xi)$ defines the atom parameters set such as: dilation, translation and frequency modulation.

MP algorithm analyzes *s(t)* signal and selects from dictionary G the atom g_{I0} which is the best match to the signal structure. The *s* signal can be presented as a sum of orthogonal projection on g_{I0} and a residuum first order R^1s.

$$s=\left\langle s,g_{I0}\right\rangle g_{I0}+R^1s\,. \tag{15}$$

The best atom match to the signal structure can be obtained when the value of a scalar product will be the highest. In each step of iteration the approximation of residuum n order is made by selection and matching g_{In} atom and calculation the residuum n+1 order *($R^{n+1}s$)*.

$$R^n s = \left\langle R^n s, g_{In} \right\rangle g_{In} + R^{n+1} s \; . \tag{16}$$

After m-iterations of MP algorithm s signal can be written in the following form:

$$s = \sum_{n=0}^{m-1} \left\langle R^n s, g_{In} \right\rangle g_{In} + R^m s \; . \tag{17}$$

The result of MP algorithm is the signal representation which is the sum of expansion components in respect to dictionary elements selected to the best match of the signal [11].

In most cases the *s* signal is a real function in digital form. The analyze of the real discrete signals, are carried out on the basis of discrete dictionary of real time-frequency Gabor atoms $g_{(\gamma,\varphi)}(n)$ where *n* means discrete time axis:

$$g_{(\gamma,\varphi)}(n) = K_{(\gamma,\varphi)} g_j (n-p) \cos\left(2\pi \frac{k}{N} n + \varphi \right) \; . \tag{18}$$

The constant $K_{(\gamma,\varphi)}$ is adjusted so that $\|g_{(\gamma,\varphi)}\|=1$. Index $\gamma=(j, p, k)$ is a discrete counterpart of $I=(a ,b, \xi)$ continuous index. It is assume, that an analyzed signal consists of $N=2L$ samples, where *L* is an integer. When the *a* scale changes with power of 2, $a=2j$ a new parameter called octave *j*, $0< j< \log_2 N$ that defines the width of atom in time is obtained; *j* is an integer. For parameters *p* and *k*, $0<p <N$ and $0<k<N$ the same period of sampling is adopted $2j$. When the chosen parameters change in this way the dictionary is very limited but on the other hand the calculation is simplified. The *p* parameter means the localization of a centre of an envelope of a atom; *k* frequency of atom modulation. The phases φ, $\varphi \; \varepsilon \; [0, 2\pi)$ are usually treated separately to optimize for each adjusted function. Signal structures are fully defined by the parameters set such as: amplitude (atom energy), frequency, localization, octave and phase. Illustrations of these parameters based of Gabor atom are presented in Fig. 7. As it was discussed by Mallat and Zhang in their work [10] the presented dictionary digitizing with Gabor atoms applied allows for effective implementation of MP algorithm.

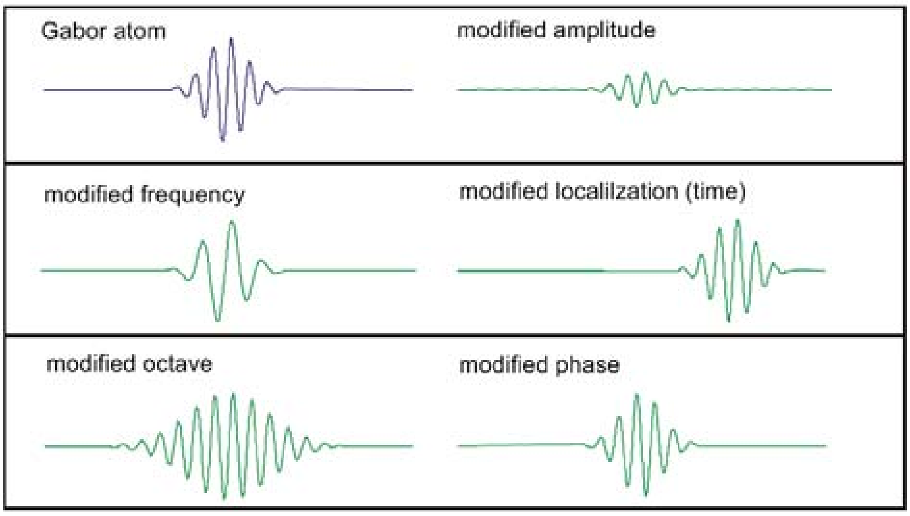

Fig. 7. Gabor atom parameters [9]

4.1. Analysis of signals

As MP algorithm classifies the atoms starting from the most important, that forms the highest part of energy in a signal. Due to this fact it is very important, as it can find temporary acceleration impulses and temporary comfort disturbances with considerable energy. These features are the ones that the authors want to focus in later part of the article. Signal decomposition is done in a Guimauwe [12] program that is license-free. The program is set in such a way that the algorithm describes the function by a single atom, and that is why the part of the signal in which the highest energy occurs will be selected and describes by the atom parameters. In this way temporary potential comfort disturbance can be found. Octave value is the next limit contained in the program. The range of 2-8 octave corresponding to the width of atom from 0.08 to 5.12 [s] is defined. This range corresponds to the length of temporary disturbances suggested by Harris [3].

The results of decomposition of a tram signal were converted to text file and it was used in Matlab program. Fig. 8 shows the results of decomposition of the first atom (broken line) plotted against the analyzed lateral acceleration signal.

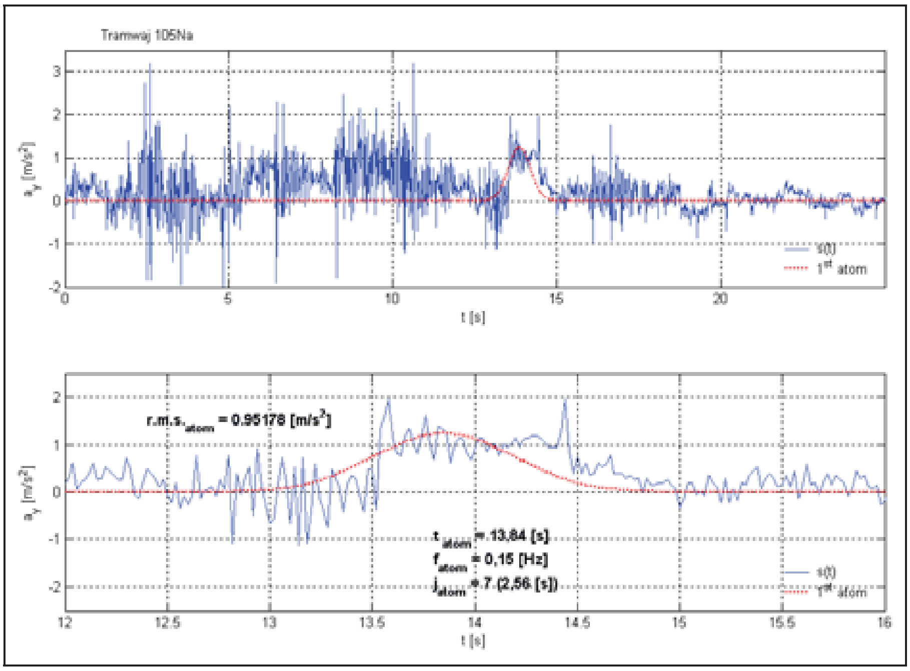

Fig. 8. First atom of decomposition and its parameters. Lateral acceleration

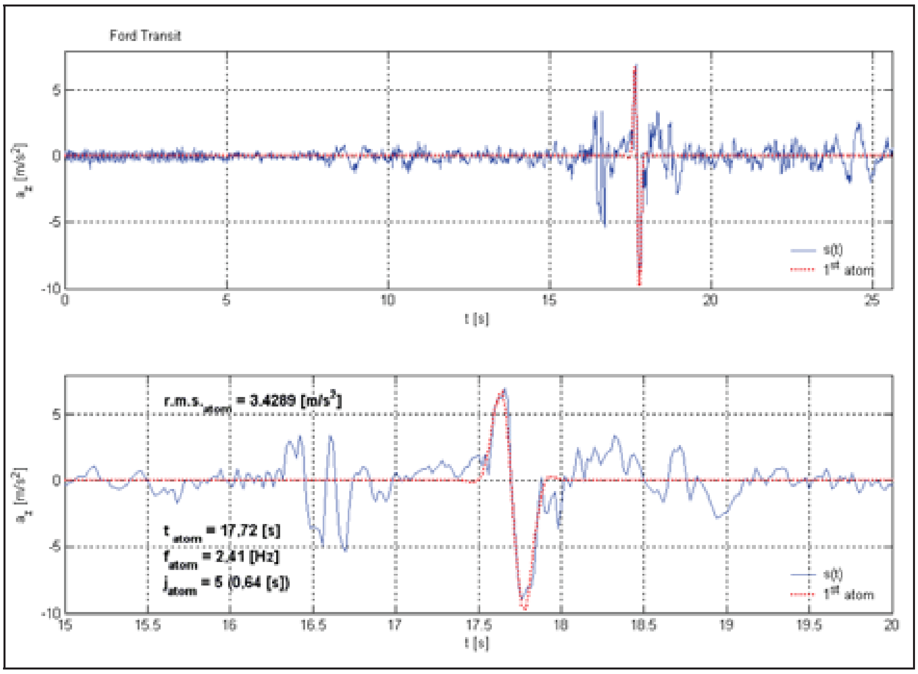

Fig. 9. First atom of decomposition and its parameters. Vertical acceleration

The lower part of the figure shows the magnified part of the signal with indicated atom and its parameters such as: time- localization, frequency and octave number describing the width of the atom. r.m.s. value for window 1[s] is also presented. MP algorithm localizes the point in the signal for which the r.m.s windowing is of maximum value (Fig. 5). Atom localization (its center) on time axis is only 0.3 [s] different in relation to the localization of the maximum value of windowing r.m.s. The difference between the values of a windowing r.m.s for the signal and the atom is 0.1689 [m/s^2] (relative error is 15%). Duration time of the atom 2.56 [s] is close to real time of disturbance that means from 13.5 to 15 [s].

The result of the decomposition of vertical acceleration is shown in Fig. 9. The first atom is localized for the file of vertical acceleration caused by passing of rear axle over the bump. The atom localization is delayed by about 0,1 [s] when compared with maximum values of windowing r.m.s. signal (Fig. 6). The differences of windowing r.m.s are 0.4086 [m/s^2] that results in relative error of 10%. Algorithm MP describes this disturbance by 2.41 [Hz] frequency and duration of 0.46 [s].

5. Conclusion

The work present an attempt of the application of matching pursuits for the time and frequency acceleration signals analysis. The MP algorithm decomposing the signal into the time-frequency atoms classifies them according to the function of the defined signal energy; from the atom with the highest energy to the atom with the lowest energy. This feature is used for finding the temporary comfort disturbances, that are caused by high energy excitations. The analysis results confirmed proper time localization as well as frequency of temporary comfort disturbances. Moreover, the duration of the disturbances that was described by the octave defined real disturbances in a satisfactory way. Owing to the fact that the limits of the discomfort level suggested by standard ISO 2631 are not precisely defined differences of 0.1689 [m/s^2] and 0.4086 [m/s^2] between the windowing values for r.m.s and atom are acceptable. These levels are the same in the range from 0.13[m/s^2] to 0.5[m/s^2]. On the basis of windowing r.m.s the level of perceived discomfort may be defined. For the recorded case in a tram when r.m.s. is 1.1207 [m/s^2] (for atom 0.9517[m/s^2]) it will be the fourth level of discomfort (uncomfortable, Fig. 3). For a vehicle it is level six both (extremely uncomfortable) when the windowing r.m.s. or atom are taken into account. The authors suggest that MP algorithm is useful for searching and describing the temporary comfort disturbances.

6. References

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