The Prediction Of Traffic Noise Disturbance Due To Noise Events

Dalianis S. and Cambourakis G.

Department of Electrical and Computer Engineering
Division of Communication, Electronic and Information Engineering
National Technical University of Athens
Heroon Polytechniou 9, 157 80, Athens, Greece
(E-mail:dalias@central.ntua.gr)

ABSTRACT

It is known from EEG studies that the occurrence of noise events, their amplitude and frequency determines the quality of sleep. In this paper a statistical method for the automatic detection of noise events in noise signals is presented and the basic elements for an index of sleep disturbance due to noise events are proposed. The method detects events and classifies according to the disturbance they may cause to someones normal sleep cycle. The developed method was used to study the sleep disturbance caused by the traffic noise of a major motorway in Athens.

INTRODUCTION

This paper describes a statistical method for assessing sleep disturbance due to noise according to a number of parameters. The basic parameters are: the amplitude difference between the sound pressure level of noise events in comparison to the background noise, the number and the frequency of occurrence of events and the short time spectral characteristics of the events. In addition to using the A-weighted equivalent continuous sound level L(A)eq), as an index of annoyance. Sleep disturbance caused by excessive noise levels includes increased sleep latency, shorter duration of sleep, increased number of awakenings and abnormal shifts in sleep stages resulting in symptoms such as tiredness and slow reaction for the person. Disturbing events arise from internal noise sources, such as machines and human activity and external noise sources, such as road traffic.

The system proposed on this paper was designed and implemented in order to detect events in noise signals that are likely to cause psychoacoustics disturbance. The aim of the system is to log noise events exceeding some thresholds and determine the significance of the event according to a metric. The metric used is the difference between the sound pressure level (SPL) and the background noise when the event occurs. This is the most important parameter in order to estimate sleep disturbance. Events are classified according to this difference. The values of L(A)10 and L(A)90 are calculated in order to extract event types using variable time intervals to take into account noise fluctuations within the duration of sleep.

Intensity and frequency of events are combined with frequency and duration of sleep cycles to provide an index for evaluation of the quality of sleep for a specific architectural environment. Events are identified according to their duration and their amplitude in the time frequency domain. In the time domain events are identified as short-term, mid-tem and long-term and in the frequency domain as harmonic, broadband and narrow band. In this time frequency manner, patterns of events with specific duration and frequency properties are analysed using auto and cross correlation methods.

The hardware requirements of the system were kept to minimum in order for the system to be mobile and easy to install and operate. The software can be used to detect different types of events in noise signals. Selecting properly the threshold SPL value, the duration and the spectral characteristics of the event different patterns of events can be found. Once the events are found they are presented together with their differences from the value of the background noise.

The validity of the system was checked using a known signal and testing the obtained results against the expected results. Furthermore, the developed method was used to detect the events in road traffic noise of a major motorway in Athens. Measurement, event detection and analysis of road traffic noise comprised the study. Several noise descriptors were either measured or calculated and used to evaluate events likely to cause disturbance. The characteristics and pattern of the calculated events were compared to the pattern of normal sleep cycle. Then the index of quality of sleep is evaluated.

1. NOISE MEASUREMENTS AND SLEEP DISTURBANCE

Traffic noise assessment is usually produced using (L(A)eq) levels for every hour which correspond to a continuous stationary noise source equivalent to the non-stationary sound pressure levels actually measured in an acoustic environment. It is obvious that this index is not taking in to account differences of the (L(A)eq) levels or noise events occurring in the time interval of one hour.

The day-night index (L day-night, LDN) is taking into account that high levels of noise are more disturbing during the sleep cycle. For the evaluation of this index 10dB are added to the SPL measurements for the night period from 23:00 to 07:00 hours. This index is also using a statistical average of SPL levels every hour. Again, in this case, differences of the (L(A)eq) levels or noise events in measurements are not represented from the index.

For traffic noise assessments other indexes have been proposed and used in order to include disturbances during the sleep cycle such as the Noise Pollution Level, Lnp [1] and the Traffic Noise Index, TNI [2]. Laboratory studies of the sleep cycle conclude that the most important parameters for sleep disturbance are the noise level and the number of noise events. For the estimation of sleep disturbance it has been proposed that these parameters can be used as independent variables instead of estimating one single index [3].

In this work a method is proposed for the estimation of sleep disturbance. The method is based on the evaluation of a number of parameters likely to cause disturbance as the number of events occurring in hourly measurements, the sound pressure level of the events the frequency of occurrence and also includes the spectral characteristics of each event. An algorithm for automatic event detection from traffic noise signals and the evaluation of the event's disturbance has been produced. The algorithm determines events according to the difference between the sound pressure level of the event and the background noise L(A)90 level. Spectral characteristic of the event are also taken into account. Analysis in time-frequency has been used for spectra studies The method also detects events that occur in frequency bands. This is implemented using time-frequency decomposition of the noise signal

in frequency bands [11] and then apply the detection algorithm in each band individually. For this purpose a recursive realisation of the Short Time Fourier Transform [12] is proposed.

2.   THE SLEEP FUNCTION AND DISTURBANCE

Sleep function disturbance is one of the most common reasons of annoyance because at this stage people have no resistance. As a result, the last 20 years researches found out the noise affects on sleep. Sleep as a phenomenon is very complicated. It may be concerned that sleep consists of sequences circles lasting 90 minutes and composed of the following stages. Stage 1is mediated between awaking and sleep. Stage 2 becomes after stage 1 and is the limit line of sleep. Sage 2 leads to sleep. Stages 3 and 4, known also as Delta sleep, are the deepest stages of sleep and the most revival. Stage 5 or REM (Rapidly Eye Movement) is the most active stage of sleep where dreams happen.

Different studies representations and methods cause difficulties to support that a specific noise level product a specific reaction about annoyance sleep. Important differences are mentioned between studies taking place in real acoustic environments and studies in a laboratory.

In spite of the problems about noise influence on sleep, investigations came to a conclusion. Abel describes a number of laboratory and home researches and reports that in almost every case increased level of noise caused disturbance in quality sleep, as a short time of sleeping, more times awaking, and slipping between different levels of sleep [4].

Studies about sleep disturbance report that the increase of level 1 has been affected by traffic noise major sound level 50-60 dB (A) and the number of events and the high level of noise are affected more by the equivalent level according to sleep disturbance [5], [6].

 The influence of noise is also depended on the time of sleep when the event happens. As time is passing it is easier for the sleep function to be disturbed. Ohrstrom studies report that between awaking and sleep the number of noise events are more important than the high level of noise, while the high level is relative on the possibility of awaking [7].

Except noise, many other elements affect quantity and quality of sleep. As the age, the family condition and how much deep or soft is someone's sleep. Fear is an other reason for sleep annoyance [8].

3.   EXTRACTING EVENTS OF TRAFFIC NOISE SIGNALS.

Noise events are extracted on the time domain using energy changes of noise signals and the time instances when the event happens are determined. Events are assigned to have more energy than the background noise, considering that the background noise level is non stationary, so that fluctuations of noise are intended.

The extracted events are characterized by the term of the time and relative intensity. The difference between the noise pressure level of the event and the background noise makes the relative intensity.

The disturbance caused by transportation noise is highly associated with the number, amplitude and frequency content of noise events [9]. Noise events are detected in the time domain using the fluctuations of the energy of the signal as an index to where an event occurs. Events are defined as having double energy of the background noise. The values of background noise are calculated using variable time intervals.

Event detection in transportation noise signals is usually employed to evaluate sleep disturbance. Sleep disturbance caused by transportation noise includes increased sleep latency, shorter duration of sleep, increased number of awakenings and abnormal shifts in sleep stages resulting in symptoms such as tiredness and slow reaction for the person. According to Horonjeff et al. it is probable the difference between the background noise level

and event noise levels rather than the absolute event level that is of importance for awakenings [10]. Following this approach the difference between the level of the detected events and the background noise level is calculated.

The decomposition of an event in time-frequency shows the allocated spectra ingredients and the relative of time term. So events can de distinguished in harmonics, wide and narrow spectra.

4. STUDIES OF KIFISIAS AVENUE ACOUSTIC ENVIRONMENT

The Olympic Stadium region has been chosen for noise traffic because of crossing Kifisias Avenue, which is a characteristic example of main road artery going across settlement areas. Olympic Stadium region is reconstructed area for Olympic Games 2004 coming, so it is interest to study the changes sequences of the acoustic environment.

Four counting acoustic microphones where placed in a distance of 10 meters on the nearest side of the road and in height 1.2 meters above the ground. The sound signal between the source and point were reported had no overshadowed objects. Research contains sound signal counting and the extract and analysis of noise events.

4.1. Subjective disturbance by traffic noise events

On form figure 1 traffic noise events are represented centralized (a) or detailed (b) during 03:00 on Thursday 15/02/2001. At hourly diagrams on vertical axis we can see the difference between events rate and the level of noise deepness and on the horizontal axis the time. Time appears as a sample.For each hour there are 360 samples, so every distance between 10 samples is corresponding in 8 minutes and 20 seconds.

On Thursday the time with the most noise events is 05:00 a.m. After 01:00 a.m. After 01:00 a.m. events were declining and become less at 04:00 a.m. (3 events) to increase vertically at 05:00 a.m. and following a decline line during 06:00 and 07:00 a.m. The inference is consistent on a working day. After 01:00 a.m. there is some traffic on the roads, while after 05:00 a.m. traffic increases. The most difference between events level and deepness noise are reported at 03:00 a.m., where deepness noise level is increased.

a)   b)
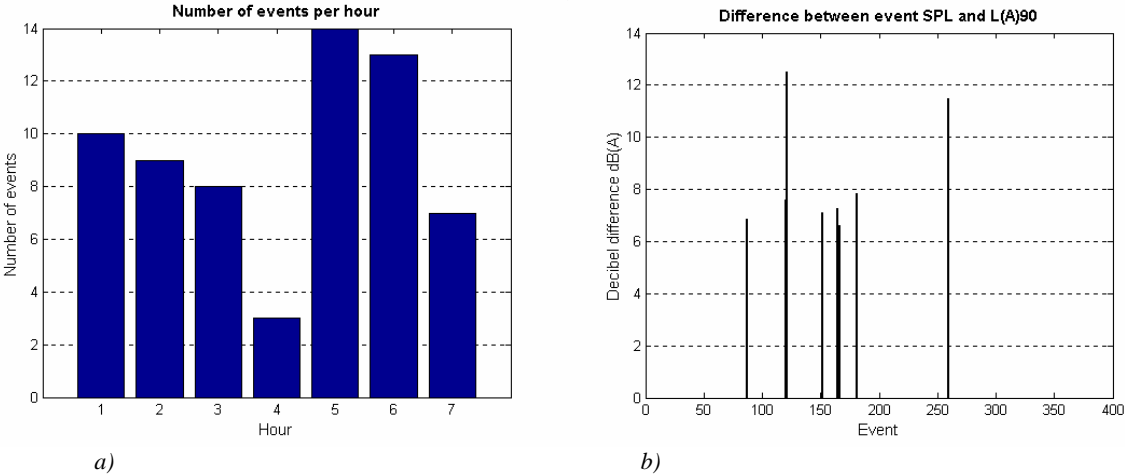
Figure 1. Number of detected events per hour for the hours 01:00 a.m. to 07:00 a.m. Thursday (a) and the difference between SPL and L(A)eq of detected events for the hour 03:00 a.m. (b)

On form figure 2 noise traffic events are represented centralized or detailed during 05:00 a.m. (c) and 07:00 a.m. on Friday 16/02/2001. Time with the more events is at 07:00 a.m. and 05:00 a.m. follows. Studying those two hours it clear that the events reported at 05:00 a.m. are independent, while at 07:00 a.m. there's a bunch of events caused by lanterns function.

On Saturday 17/02/2001 the numbers of events are especially decreased relative to the two days before. It's remarkable that the number of events are less at 01:00 a.m., decreases dramatically at 02:00 and remains low (more than 10 events) during 03:00 and 04:00 a.m. The appearance of high number of events during the morning hours on Saturday is relative to transfer after entertainment activities, because Saturday is a day of. Centralized diagram of Saturday's events is shown in form figure 3.
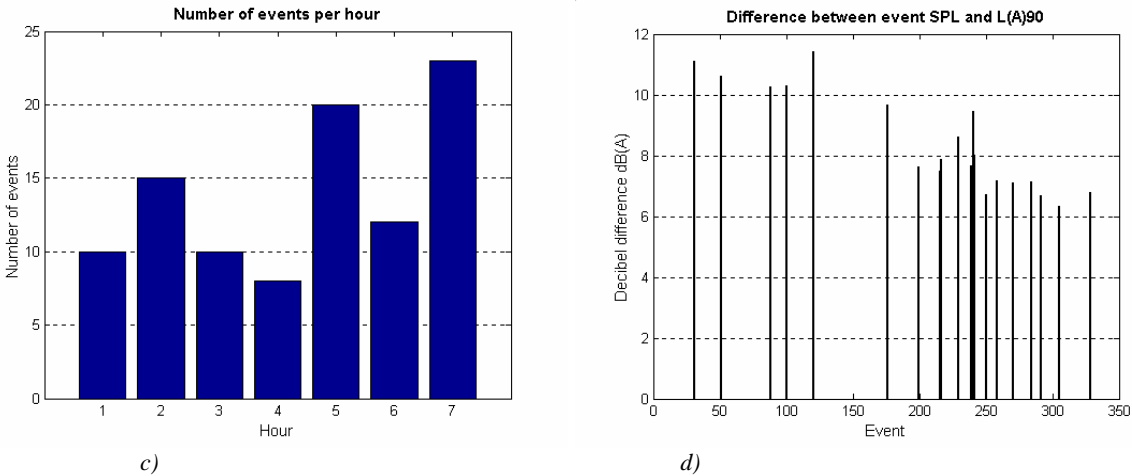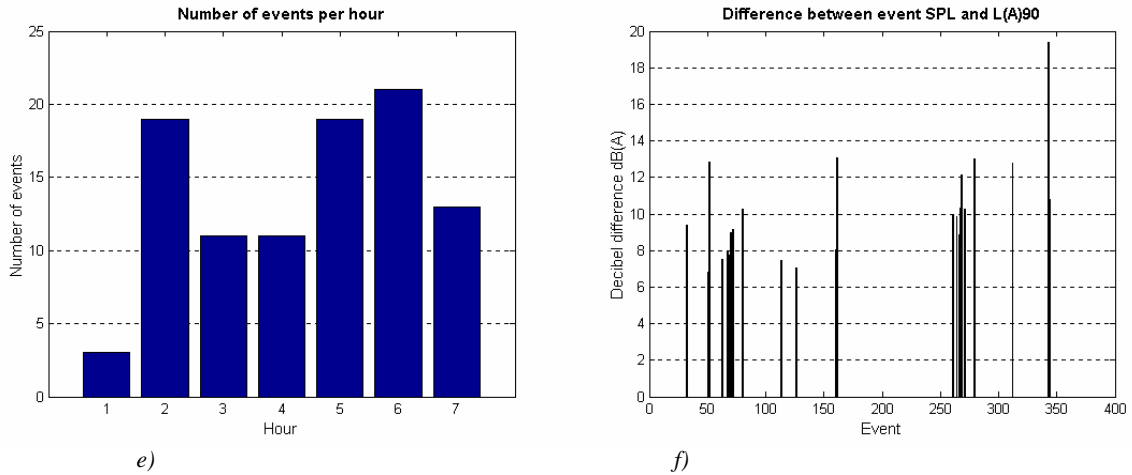

c)   d)

Figure 2. Number of detected events per hour for the hours 01:00 a.m. to 07:00 a.m. Friday (a) and the difference between SPL and L(A)eq of detected events for the hour 05:00 a.m. (b).

e)   f)

Figure 3. Number of detected events per hour for the hours 01:00 a.m. to 07:00 a.m. Saturday (a) and the difference between SPL and L(A)eq of detected events for the hour 07:00 a.m. (b).

4.2. Spectral analysis of noise traffic events

Fourier analysis provides the classical tool for decomposing signals in the frequency domain. However, many real world signals demonstrate non-stationarity and the use of the time or frequency domain individually has limitations. Time frequency methods analyse the two domains jointly and thus give the ability to describe time variable and frequency dependent characteristics of non-stationary signals. In this work time frequency methods are discussed for the detection of events in traffic noise signals and condition monitoring of marine diesel engines.

Detection of events is of vital importance for the detection of faults and the condition monitoring of rotating machinery. In the literature many methods have been proposed for this purpose. Traditional methods make use of cepstrum and waveform analysis [13-14]. Vibration signals however demonstrate non-stationarity and hence more elegant techniques based on time-frequency analysis have been developed. These techniques are based on the assumption that a non-stationary signal can be treated as the sum of consecutive quasi-stationary segments, where stationary classical Fourier transform based methods can be applied.

Staszewski and Tomlinson used a moving window procedure to identify series of impulses in vibration signals and detect a broken tooth in a spur gear [15]. They also demonstrated how different window function parameters affect the results. Wavelet analysis has been employed by Wang to detect transients in mechanical systems [16]. McFadden et al. used a variant of the wavelet transform, the generalised S transform, which allows calculation of the instantaneous phase of a signal and they applied this transform in mechanical systems for the early detection of failure [17].

Quadratic time frequency distributions have also been used. The first to be introduced and the most widely used in practice is the Wigner-Ville distribution (WVD). Improvements of the WVD include the smoothed-WVD [18] and the weighted-WVD [19]. Staszewski et al. proposed the application of statistical and neural pattern recognition to the WVD for condition monitoring of gearboxes [20]. Williams and Zalubas proposed an improved and generalized version of the exponential distribution of Choi and Williams and they showed that it overcomes several drawbacks of the spectrogram and the Wigner-Ville distribution [21]. Other approaches to condition monitoring and fault detection include the use of higher order statistics [22-23] and non-linear diagnostic methods [24-25].

In this work linear time frequency analysis is used because it is simple to implement and provides means of synthesis and simulation of non-stationary systems. In particular we employ a recursive algorithm for the evaluation of the short time Fourier transform, which is faster compared to non-recursive realisations. The method proposed in this paper is implemented recursively using filter banks. This recursive approach provides the potential of real time implementation in hardware. Use of the developed system is demonstrated in the context of two applications.

On form 4 reports the analysis of time-frequency noise event produced by a passing police car with its siren on.. It is obvious that the siren produce noise containing intermittent changing frequencies between 500 Hz and 1200 Hz. This noise is predominated of the produced by cars motion, remains for long time and is more annoyance.
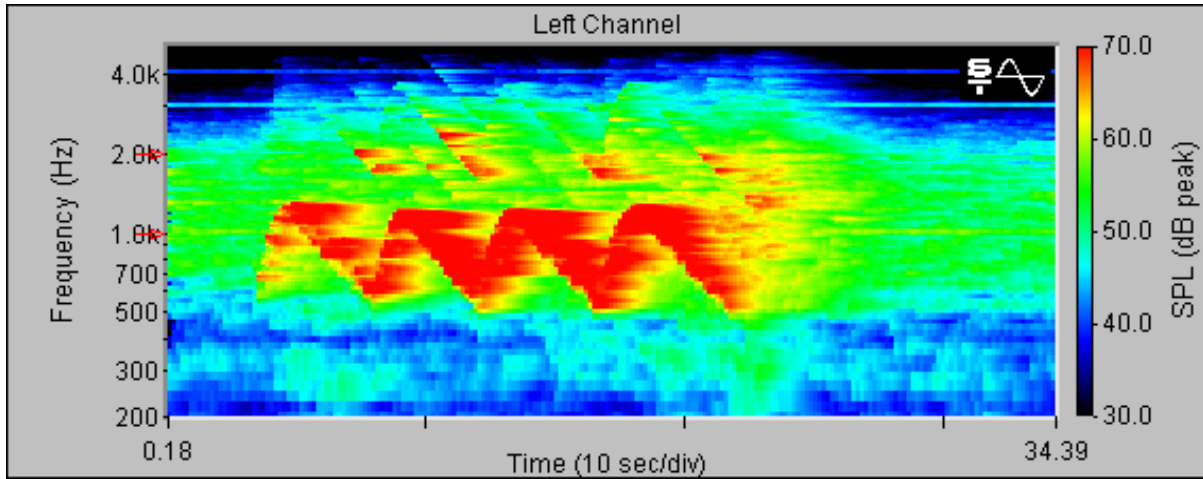
Figure 4. Time-Frequency analysis of a traffic noise event caused from a pass by ambulance.

5. TIME FREQUENCY ANALYSIS AND EVENT DETECTION

5.1. Short time Fourier transform

The short time Fourier transform (STFT) of signal x(t) is defined as

$$X(t,f) = \int_{-\infty}^{+\infty} x(t')w(t'-t)e^{-j2\pi ft'}dt'$$ (1)

where w(t) is a window function.

Thus the short time Fourier transform is the Fourier transform of the windowed signal and is a function of frequency f and the window position t. The spectrogram is defined as the square of the magnitude of the short time Fourier transform.

Short time Fourier transform demonstrates shift invariance in time and frequency. Thus for a signal $x(t)$ with short time Fourier transform $X(t,f)$ it is

$$x(t-t_0) \leftrightarrow X(t-t_0, f)$$ (2)

(3)

$$x(t)e^{j2\pi f_0 t} \leftrightarrow X(t, f-f_0)$$

Short time Fourier transform also possesses the properties of reality and positivity and is free of interference terms in case of multi-component signals [18].

5.2. Recursive realisation

The method for the evaluation of the short time Fourier transform used in this work follows Papoulis [14], who proposed a recursive digital implementation of a rectangular window short time Fourier transform. The running Fourier transform of a signal has been defined as the integral

$$F_x(t,\omega) = \int_{-c}^{+c} x(t+\tau)e^{-j\omega\tau}d\tau \tag{4}$$

with the inversion formula

$$x(t) = \frac{1}{2c}\sum_{m=-\infty}^{\infty} F_x(t,m\omega_0), \quad \omega_0 = \frac{\pi}{c} \tag{5}$$

where c is a given constant describing the limits of the segment of analysis for a fixed t.

$F(t,\omega)$ are the Fourier transformation coefficients, with respect to τ, of the segment $x(t+\tau)$, of $x(t)$, where $-c \leq t \leq c$. The above definition has been chosen because it leads to a recursive formulation. The evaluation of the spectrogram directly from this expression requires computation of the Fourier transform at any time instant t. It can be proved that $F(t,m\omega_0)$ satisfies the first order differential equation:

$$\frac{dF_x(t,m\omega_0)}{dt} - jm\omega_0 F_x(t,m\omega_0) = (-1)^m[x(t+c) - x(t-c)] \tag{6}$$

In order to reduce the computation time, *Fx* can be evaluated recursively. Implementing in discrete time, the running z-transform is defined as the short time z-transform of a delayed signal. For a sequence x(n), the running z-transform is:

$$\Phi(n,z) = \sum_{k=0}^{N-1} x(n-k)z^{-k} \tag{7}$$

For fixed n, $\Phi(n,z)$ is the z-transform in the variable k of the segment x(n-k) of x(n). The inversion formula, considering evaluation on the unit circle, is

$$x(n) = \frac{1}{N}\sum_{m=0}^{N-1} \Phi(n,w^{-m}) \tag{8}$$

where $w = e^{j\frac{2\pi}{N}}$.

Hence, the running *z*-transform is the sampled version of the Fourier transform of a delayed sequence x(n-k). For simplicity the above formulation assumes a rectangular window function applied to the signal:

$$g(n) = \begin{cases} 1 & for \quad 0 \le n \le N-1 \\ 0 & elsewhere \end{cases}$$

Substituting k+1=p in (7), results in

$$\Phi(n-1, z) = z \sum_{p=1}^{N} x(n-p) z^{-p} \qquad (9)$$

It follows that function $\Phi(n, z)$ satisfies the first order recursion equation

$$\Phi(n, z) - z^{-1}\Phi(n-1, z) = x(n) - z^{-N} x(n-N) , \qquad (10)$$

and with $z = w^{-m}$, function $\Phi(n, w^{-m})$ follows the simple recursion:

$$\Phi(n, w^{-m}) - w^{m}\Phi(n-1, w^{-m}) = x(n) - x(n-N) , \qquad (11)$$

Equation (11) defines a discrete recursive system with input x(n), output $\Phi(n, w^{-m})$ and system function

$$S(m, z) = \frac{1 - z^{-N}}{1 - w^{m} z^{-1}} , \qquad (12)$$

The system consists of one shift register with output x(n-N), one delay element and one multiplier (Fig. 1). Connecting N such systems together in parallel, results in a running Discrete Fourier Series (DFS) spectrum analyser which can be realised using filter bank structure (Fig. 2).
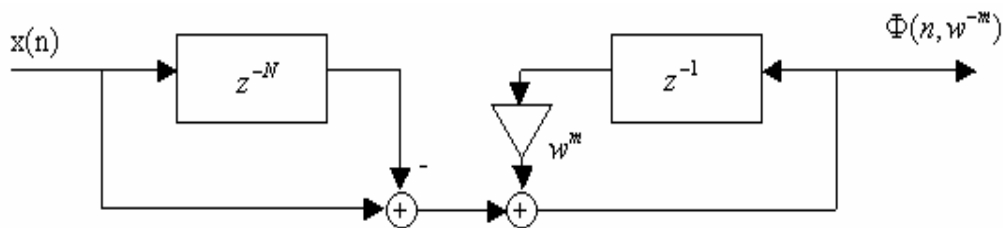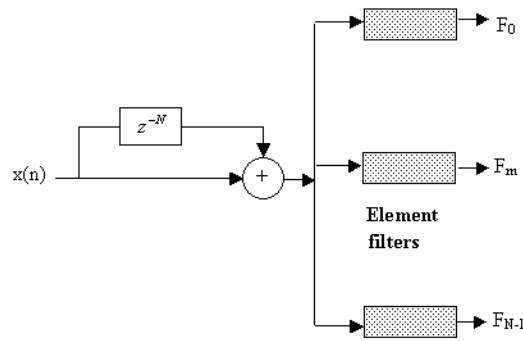

Figure 5: Elementary filter structure.

Figure 6: Recursive DFS analyser.

5.3. Transportation noise event detection

Detected events are decomposed in the time frequency domain and narrow band components of the signal are calculated in order to extract event types. In Fig. 5 the time frequency analysis of a train horn noise event is shown. The event was detected in a traffic noise signal. The sampling frequency is 11025 Hz and the signal is analysed using a rectangular window of 512 points length. The harmonic structure of the signal is clearly shown.

The described methodology does not depend on the use of A-weighted equivalent continuous sound level (L(A)eq) as a single index for the evaluation of transportation noise disturbance. Instead it proposes the use of the number of events and the difference between the event noise level and the background noise level as independent variables. Moreover, the type of event, identified by time frequency analysis as harmonic, broadband or narrow band, is taken into account.
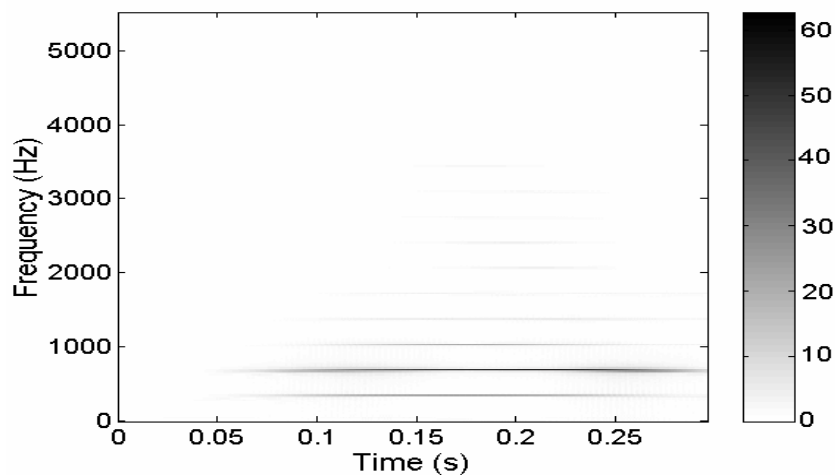

Figure 7: Time frequency analysis of train horn using the recursive DFS analyzer.

CONCLUSIONS

This work proposes the estimate of noise events and the difference between events level and deepness of noise. Changing of energy of the reported signal is been used for recognizing noise events. Time-frequency analyses methods are been used for events spectral characteristics classifying as harmonic, wide and narrow spectra.   Relation among different event types and disturbance is a further research.

In this work the short time Fourier transform is used for condition monitoring of marine diesel engines and for the event detection and disturbance assessment of transportation noise. The short time Fourier transform is evaluated recursively, using a methodology, which is faster when compared to non-recursive realisations, and provides the potential of real time implementation in hardware. The recursive realisation is performed using filter banks.

For the assessment of transportation noise disturbance we propose the use of the number of events and the difference between the event noise level and the background noise level as independent variables. Detection of events is based on the fluctuations of the energy of the signal. Detected events are analysed using time frequency methods and events are identified as harmonic, broadband or narrow band. The relation between different types of noise events and the caused disturbance should be further investigated.

REFERENCES

1. Robinson D.W., 1969, «The concept of noise pollution level», National Physics Laboratory Aero Report Ac.38
2. Griffiths, I.D., Langdon, F.J., 1968, «Subjective Response to Road Traffic», Journal of Sound and Vibration, 16-32, 8 (1)
3. Bjorkman M., 1991, «Community noise annoyance: Importance of noise levels and the number of noise events», Journal of Sound and Vibration, 497-503, 151(3)
4. Abel S.M., 1990, «The extra-auditory effects of noise and annoyance: an overview of research», The Journal of Otolaryngology, 1-13, 19(1)
5. Ohrstrom E., Rylander R., 1990, «Sleep disturbance by road traffic noise - A laboratory study on number of noise events», Journal of Sound and Vibration, 93-101, 143(1)
6. Eberhardt J.L., Strahle L.-O., Berlin M.H., 1987, «The influence of continuous and intermittent traffic noise on sleep», Journal of Sound and Vibration, 445-464, 116
7. Ohrstrom E., 1995, «Effects of low levels of road traffic noise during the night: a laboratory study on number of events, maximum, noise levels and noise sensitivity», Journal of Sound and Vibration, 603-615, 179(4)
8. Reijneveld S.A., 1994, «The impact of the Amsterdam aircraft disaster on reported annoyance by aircraft noise and on psychiatric disorders», International Journal of Epidemiology, 333-340, 23
9. M. Bjorkman, *Community noise annoyance: Importance of noise levels and the number of noise events*, Journal of Sound and Vibration, Vol. 151, Academic Press (1991), pp. 497-503.
10. R. Horonjeff, S. Fidell, S. Teffeteller, D. Green, *Behavioral awakening as functions of duration and detectability of noise intrusions in the home*, Journal of Sound and Vibration, Vol. 84, Academic Press (1982), pp. 327-336.
11. Pappoulis A., 1977, «Signal Analysis», McGraw Hill
12. Sarris J.C., Dalianis S.A., Cambourakis G.E., Hammond J.K., 2002, «Time frequency analysis and event detection in noise signals», ISMA 2002, International Conference on Noise and Vibration Engineering, Leuven, Belgium

13. R. Randal, *Cepstrum analysis and gearbox fault detection*, Technical Report, Bruel & Kjaer Application Note, Nrum, Denmark, (1981), pp. 13-150.

14. P. McFadden, J. Smith, *A signal processing technique for detecting local defects in a gear from the signal averaging of the vibration*, Proceedings of the Institute of Mechanical Engineers 199, (1985)

15. W. Staszewski, G. Tomlinson, *Local tooth fault detection in gearboxes using a moving window procedure*, Mechanical Systems and Signal Processing, Vol. 11, No. 3, Academic Press (1997), pp. 331-350.

16. W. Wang, *Wavelets for detecting mechanical faults with high sensitivity*, Mechanical Systems and Signal Processing, Vol. 15, No. 4, Academic Press (2001), pp. 685-696.

17. P. McFadden, J. Cook, L. Forster, *Decomposition of gear vibration signals by the generalised S transform*, Mechanical Systems and Signal Processing, Vol. 13, No. 5, Academic Press (1999), pp. 691-707.

18. L. Cohen, *Time-frequency distributions-a review*, Proceedings of the IEEE, Vol. 77, (1989), pp. 941-981.

19. P. McFadden, W. Wang, *Analysis of gear vibration signatures by the weighted Wigner-Ville distribution*, *Proceedings of the Fifth International Conference on Vibrations in Rotating Machinery*, University of Bath, Institution of Mechanical Engineers, (1992), pp. 393-397.

20. W. Staszewski, K. Worden, G. Tomlinson, *Time–frequency analysis in gearbox fault detection using the Wigner–Ville distribution and pattern recognition*, Mechanical Systems and Signal Processing, Vol. 11, No. 5, Academic Press (1997), pp. 673-692.

21. W. Williams, E. Zalubas, *Helicopter transmission fault detection via time-frequency, scale and spectral methods*, Mechanical Systems and Signal Processing, Vol. 14, No. 4, Academic Press (2000), pp. 545-559.

22. B. Parker, H. Ware, D. Wipf, W. Tompkins, B. Clark, E. Larson, H. Poor, *Fault diagnostics using statistical change detection in the bispectral domain*, Mechanical Systems and Signal Processing, Vol. 14, No. 4, Academic Press (2000), pp. 561-570.

23. S. Lee, P. White, *Higher-order time–frequency analysis and its application to fault detection in rotating machinery*, Mechanical Systems and Signal Processing, Vol. 11, No. 4, Academic Press (1997), pp. 637-650.

24. W. Wang, J. Chen, X. Wu, Z. Wu, *The application of some non-linear methods in rotating machinery fault diagnosis*, Mechanical Systems and Signal Processing, Vol. 15, No. 4, Academic Press (2001), pp. 697-705.

25. J. Hammond, P. White, *The analysis of non-stationary signals using time-frequency methods*, Journal of Sound and Vibration, Vol. 190, No. 3, Academic Press (1996), pp. 419-447.