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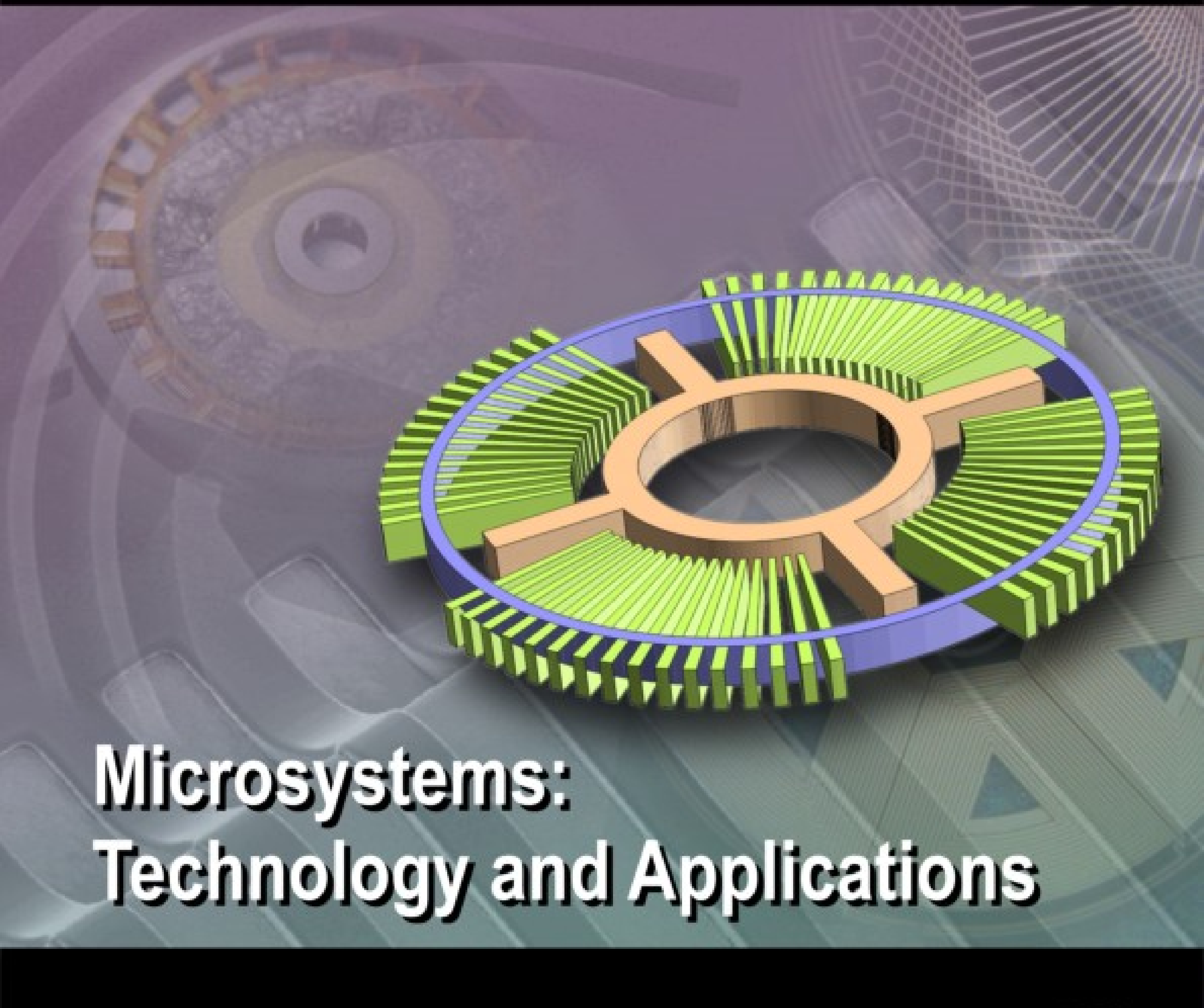

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Adaptive Subband Filtering Method for MEMS Accelerometer Noise Reduction

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Abstract: Silicon microaccelerometers can be considered as an alternative to high-priced piezoelectric sensors. Unfortunately, relatively high noise floor of commercially available MEMS (Micro-Electro-Mechanical Systems) sensors limits the possibility of their usage in condition monitoring systems of rotating machines. The solution of this problem is the method of signal filtering described in the paper. It is based on adaptive subband filtering employing Adaptive Line Enhancer. For filter weights adaptation, two novel algorithms have been developed. They are based on the *NLMS* algorithm. Both of them significantly simplify its software and hardware implementation and accelerate the adaptation process.

The paper also presents the software (Matlab) and hardware (FPGA) implementation of the proposed noise filter. In addition, the results of the performed tests are reported. They confirm high efficiency of the solution. *Copyright © 2008 IFSA.*

Keywords: MEMS accelerometer, Adaptive subband filtering, *NLMS* algorithm, Vibration measurement, Hardware filter

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1. Introduction

Basing on the observation and analysis of a vibration spectrum it is possible to detect broken parts of a machine, determine a type of the failure and predict its future development. In the currently used measurement systems, the information on vibration magnitude is provided by expensive piezoelectric accelerometers. An alternative to these sensors can be silicon microaccelerometers produced using micromachined technologies. These devices are relatively cheap and may be a component of a complex and comprehensive vibration measurement system built as a single IC. Unfortunately, commercially available micromachined accelerometers have some limitations. One of the most significant is a relatively high level of the self-noise observed in the output signal [1]. The noise limits measurement resolution, which makes it impossible to use these sensors for precise diagnostic measurements.

A predominant noise component in the surface technology silicon microaccelerometers with low-noise acceleration detection circuits comes from Brownian motion of the proof mass. A study of the ADXL202 accelerometer produced by Analog Devices showed that amplitude-frequency characteristics of the observed noise signal from the sensor in standstill condition is constant in the frequency range up to about 2 kHz (Fig. 1). This was confirmed by the analysis of autocorrelation function of the noise [1].

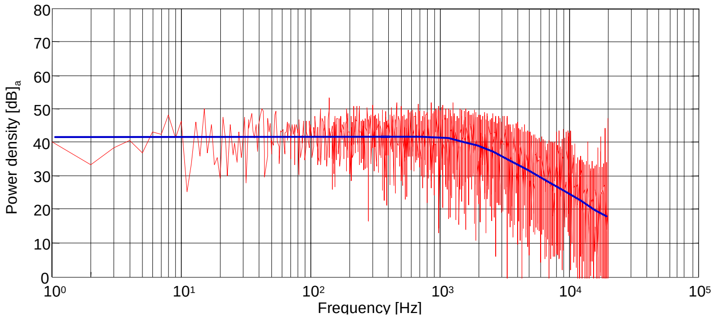


Fig. 1. Power density spectrum of the accelerometer noise.

Hence, in the given frequency range, the self-noise of the examined accelerometer can be treated as a white noise. The target application engages the use of MEMS accelerometers for turbogenerator vibration measurement. The most valuable sources of information for this type of machines are harmonics of vibration signal. The determination of their level and finding the correspondence with rotational frequency of the respective machine parts enables the identification of a failed part. The above observations indicate the possibility for the implementation of the Adaptive Line Enhancer (ALE) type circuit to reduce noise level.

2. Adaptive Line Enhancers

Adaptive Noise Canceller (ANC) circuits are based on the primary structure of an adaptive filter (Fig. 2) [2], [3].

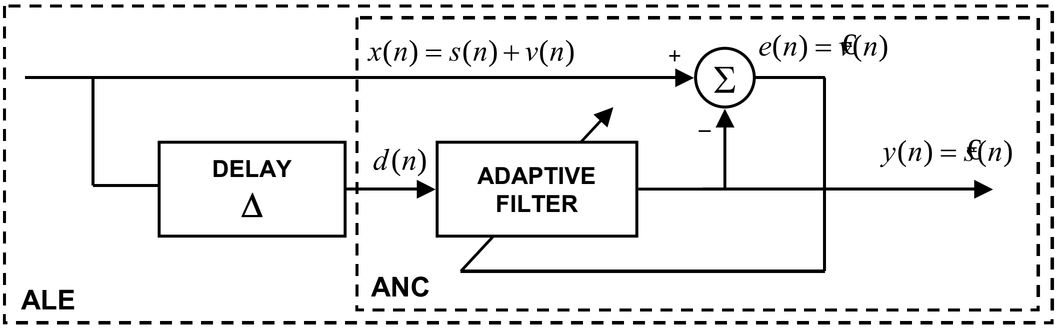


Fig. 2. Structure of the Adaptive Noise Canceller (ANC) and Adaptive Line Enhancer (ALE).

The input of ANC adder is fed with the signal *x(n)* to be filtered, which is a sum of the usable s*(n)* and interfering *v(n)* components, where $n \geq 0$ denotes subsequent time instants. It is assumed that the both components are uncorrelated with each other (they are independent).

The necessary condition on which the ANC circuit can work properly is that the *d(n)* signal, which is applied at the input of the adaptive filter, is correlated with the usable component *s(n)* and is not correlated with the interfering signal *v(n)*. However, in many real applications there is no possibility to separate the reference signal fulfilling this condition. Then the perfect solution is to apply the ALE filter. Here, the reference signal is the input signal *x(n)* delayed in time (by *d* samples). The introduction of the delay is aimed to decorrelate the interfering component *v(n)* between the input signal *x(n)* and the reference signal *d(n)*. Hence, the delay value needs to be selected [1] so that:

$$E\left[v(n)v(n-\Delta)\right] \approx 0 \tag{1}$$

Let us assume that a signal, which is a sum of stochastic and single sinusoidal waveforms, is applied to the filter input. As a result of adaptation, the filtering circuit steady–state transmittance becomes a transmittance of a band–pass filter with a very steep characteristic in transition band (large value of quality factor) and a center frequency tuned to a frequency of the input signal harmonic component *s(n)*. Consequently, the signal $y(n) = \hat{s}(n)$, which is an estimate of this component, will appear at the adaptive filter output. After subtraction of this estimate from the input signal, an error signal *e(n)*, which estimates the processed signal stochastic component *v(n)*, will be observed at the adder output. It means that the entire circuit will be a band–stop filter (*notch filter*) when the *ALE* filter output is the error signal *e(n)* output. This filter was used for the first time in such configuration by Widrow [2] for suppression of 60 Hz periodic signal (hum), which interfered with electrocardiograph output signal.

If the signal *y(n)* is used as the output signal, the circuit is an adaptive band–pass filter and it can be applied to isolate the input signal periodic component. The *ALE* filter operating in this configuration has been a subject of the studies on adaptive noise reduction methods intended for large rotary machines technical condition diagnostic systems.

The detailed analysis of properties of *ALE* filters used for filtering of signals whose useable component contains $M > 1$ harmonics [4] shows that the filter response in steady state can be interpreted as linear superposition of *M* independent ALE filters, each tuned to a given harmonic. The amplitude–frequency characteristic of the filter is similar to comb filter characteristic. The filter steady–state gain for a given harmonic with an angular frequency ω_m is equal to [4]:

$$a_m^* = \frac{L/2 \cdot SNR_{in\,m}}{1 + L/2 \cdot SNR_{in\,m}}, \quad \text{for } m = 0, 1, ..., M-1 \tag{2}$$

While

$$SNR_{in\,m} = \frac{\sigma_{S\,m}^2}{\sigma_V^2} = \frac{A_m^2}{2\sigma_V^2}, \quad \text{for } m = 0, 1, ..., M-1 \tag{3}$$

is a signal–to–noise ratio for *m*-th harmonic with an angular frequency ω_m, power σ_{Sm}^2 and amplitude A_m. Based on the relationship (2), one can conclude that a filter with insufficiently high order will attenuate highly noised components and it will distort diagnostic information carried by the processed vibration signal.

For the ALE filter using the LMS algorithm it was proved [4] that the theoretical SNR improvement is described by the relationship:

$$SNG = \frac{SNR_{out}}{SNR_{in}} = \frac{L}{2} \frac{\sum_{m=0}^{M-1} A_m^2 [1 + (4/L)(\sigma_v^2 / A_m^2)]^{-2}}{\sum_{m=0}^{M-1} A_m^2 \cdot \sum_{m=0}^{M-1} [1 + (4/L)(\sigma_v^2 / A_m^2)]^{-2}} \tag{4}$$

It is thus proportional to the number L of filter coefficients. Additionally, it depends on the amplitude A_m (of power) of the respective harmonics in the processed signal, their number M and the interfering signal power.

For sinusoids of equal power (amplitude), the relationship (4) can be simplified:

$$SNG_M = \frac{SNR_{out}}{SNR_{in}} = \frac{L}{2M} \tag{5}$$

As mentioned above, in the target application, the MEMS accelerometers measure turbogenerator vibrations. In the measured signal, for the frequency range of 10 Hz ÷ 6 kHz, one can observe over 100 harmonics. As a consequence, a significant SNR improvement requires the use of filters with large number of coefficients.

However, some limitations appear here. The first of them is the necessity for the application of the digital ICs with large computational power to implement the filter. Moreover, in [4], it has been proved that there exists some finite value $L = L_{lim}$, for which the ability of the ALE circuit to reduce noise is the highest. Thus the maximum SNR improvement for the signal containing M harmonics is limited to the value:

$$SNG_M = \frac{L_{\lim}}{4M} \tag{6}$$

This effect is a result of the adaptive filter transmittance noise, which is caused by an error in the filter coefficients adaptation. Due to the above property of the described circuit type, filtering may be insufficient even when a high order filter is applied. In order to determine a minimum filter order, one should take into account the following fact: A number of the ALE filter coefficients required to achieve a frequency resolution so that it is possible to distinguish harmonics having frequency difference Δf, present in a useable signal sampled with frequency f_p, is [4]:

$$L \geq \frac{f_P}{\Delta f} \tag{7}$$

In [1], it has been showed that for the signal containing M equidistant harmonics there is a necessity to apply the filter with the number of coefficients satisfying the inequality [2], [4]:

$$L > 2M \tag{8}$$

The above considerations indicate that it is possible to obtain high efficiency of the *ALE-NLMS* filter in terms of the SNR improvement for signals that are sampled with low frequency and whose useable component contains small number of harmonics. This conclusion was a basis for the development of the adaptive subband filtering method for the vibration signal of large rotating machines.

3. Adaptive Subband Filtering of Noise

Digital signal subband processing gains more and more popularity. The application range of these methods covers sound and video compression systems, voice signal processing systems, radar and sonar techniques. They are widely used in contemporary telecommunication systems.

The principle of operation of the circuit for adaptive signal processing in frequency subbands is illustrated in Fig. 3.

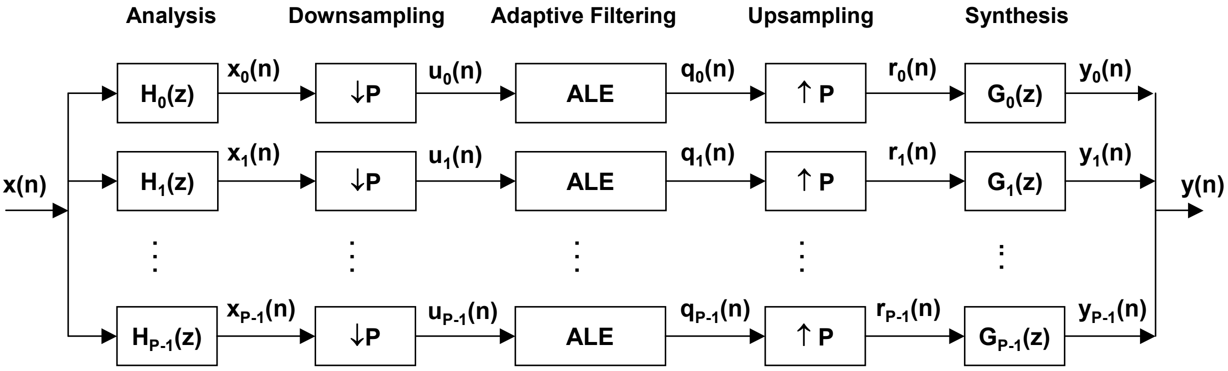


Fig. 3. Structure of the system for adaptive signal processing in frequency subband.

In the applied method, the input signal *x(n)* is divided into *P* frequency subbands with the use of the suitably designed [1] bank of bandpass analysis filters. After the filtering, each subband signal occupies *P* times narrower band as compared to the input signal. As a result, all these signals are 16 times up-sampled. The sampling frequency for each signal is reduced by the factor of *P* with the use of reducers, which leave one sample out of *P* consecutive samples in the signal (down-sampling). As a result, the subband signal spectrum is widened *P* times. The signals processed in this way are filtered with ALE filters. Upon appropriate processing, the frequency of each subband signal is increased with the use of expanders, which insert zero–value samples between two successive samples (up-sampling). After *P*-times oversampling, the processed signal spectrum is narrowed *P* times and its pattern repeats every π radians. The resultant signals are merged together in the bank of bandpass synthesis filters forming output signal of the filter.

The presented method for the signal processing in the frequency subbands enables the use of the ALE filter for the signals containing many harmonics, including a complex signal typical of rotating machine vibrations. The increase in the filter operation efficiency arises from the reduction in the width of the frequency band of the processed signal and from the decrease in its sampling frequency. The band limitation reduces the number of harmonics present in each subband. The decrease in sampling frequency results in higher frequency resolution of the filter.

The described digital signal processing method is a very good solution also from hardware implementation point of view. An effective adaptive filtering of wideband polyharmonic signals requires the use of high order filters. When the signal is divided into subbands, similar effects can be achieved by using many, easier to implement, lower order filters. The analysis of the presented DSP system operation indicates that it can be implemented in a reprogrammable IC (for example FPGA) or ASIC (Application Specific Integrated Circuit) by employing single transversal filter structure with programmable weights. Due to the possibility of weight values reprogramming, it can serve as input and output passband filters or as a filter used for adaptive filtering process. As a result, the hardware resources required for circuit implementation are significantly reduced.

4. Algorithms of Filter Weight Adaptation

After the preliminary analyses, it was decided to apply the *NLMS* (Normalized Least Mean Squares) algorithm [3]. This choice is the trade-off between algorithm and hardware implementation simplicity, on the one hand and weight adaptation precision and speed of convergence to the optimal solution, on the other hand. In the considered algorithm the update of the filter coefficients vector ***w*** is performed in accordance with the equation:

$$\mathbf{w}(n+1) = \mathbf{w}(n) + 2\mu_0 \gamma \mathbf{x}(n) e(n) \tag{9}$$

where $\mathbf{w}(n) = [w_0, w_1, ..., w_{L-1}]$ is the vector of coefficients (weights) for the filter of order L, $\mathbf{x}(n) = [x(n), x(n-1), ..., x(n-L-1)]$ is the vector of the subsequent input signal samples, applied to the respective filter weights, μ_0 is the adaptation coefficient, γ is the normalizing coefficient. Normalizing coefficient value is determined from the relationship [3]:

$$\gamma = \frac{1}{\chi + \left\| \mathbf{x}(n) \right\|^2} , \tag{10}$$

where $\|\mathbf{x}(n)\|^2$ is the squared norm of the vector of L samples of a signal fed into the filter weights, χ is the small constant (it is often assumed that $\chi = 0.01$).

In practice, the value of the squared signal norm is calculated basing on the relationship [3]:

$$\left\| \mathbf{x}(n) \right\|^2 = \mathbf{x}(n) \mathbf{x}^T(n) \tag{11}$$

Unfortunately, this method is time-consuming and requires the use of many resources when applied in hardware. Considerable hardware resources are also required to perform the division operation that appears in the equation (10).

In order to simplify the selected method for updating the filter coefficients, two modifications of the *NLMS* algorithm were proposed. The first of them - *RP-NLMS* takes into account the fact that in theoretical considerations it is often assumed that:

$$\left\| \mathbf{x}(n) \right\|^2 \cong L\sigma_x^2 \tag{12}$$

The signal variation σ_X^2 at time instant n can be replaced by its estimate determined recursively [1]:

$$\hat{\sigma}_x^2(n) = \alpha \hat{\sigma}_x^2(n-1) + (1-\alpha) x^2(n) \tag{13}$$

Which for the signal with zero mean value is equivalent to:

$$\tilde{P}(n) = \alpha \tilde{P}(n-1) + (1-\alpha) x^2(n) . \tag{14}$$

It was suggested that the filtration coefficient α can be determined from the equation which relates its value to the filter order and the scaling factor g accelerating filter response rate for temporary signal amplitude changes [1]:

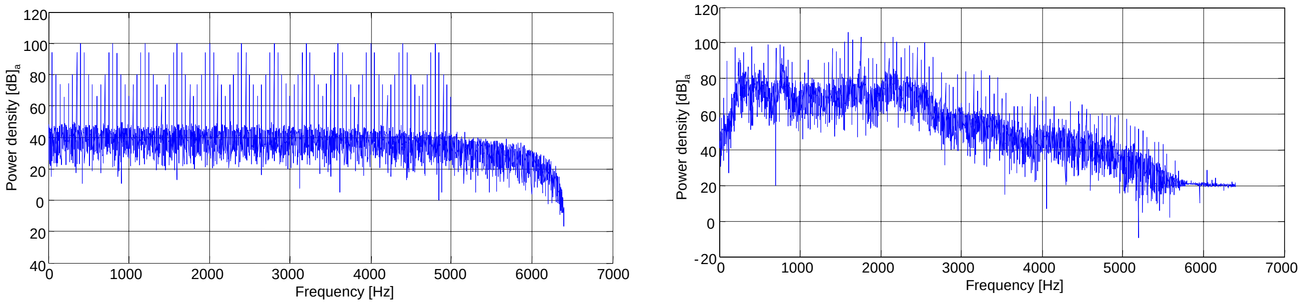
$$\alpha = \exp\left(-g / L\right), \quad g = 0, 1, 2, ... \tag{15}$$

The use of the presented method considerably simplifies the procedure for finding the value of $\|\mathbf{x}(n)\|^2$, since it requires only 4 multiplication operations and one addition (instead of L multiplications and $L-1$ additions required previously).

In the search for further simplification of the algorithm, it was noticed that the decrease in the precision of γ factor value determination does not cause significant deterioration in adaptive filter properties. As a result, it is possible to introduce the modification in the algorithm which consists in quantizing the values of this factor. In order to do it, the subsequent values of γ were determined for certain values of $\|\mathbf{x}(n)\|^2$ (in the range from 2^{-7} to 2^{12}) basing on the equation (10) and they were stored in the table. The χ constant could be neglected, thanks to assuming that $\gamma \leq \gamma_{max}$. The choice of the table element used in a given algorithm iteration is made basing on the current value $\tilde{P}(n)$. Here, it is worth to mention that for a given value of μ_0 it is possible to store the whole expression $2\mu_0 / \|\mathbf{x}(n)\|^2$ in the table. In the case, when the values of μ_0 and γ are powers of 2, the multiplication by these factors can be replaced in hardware implementation by a bitwise shift operation. This algorithm has been called *T-NLMS*.

5. Application of Subband Adaptive Filter for Noise Reduction in Turbogenerator Vibration Signal

Initially, the subband adaptive filter was implemented in software, with the use of Matlab scientific computing environment. The studies on properties of the filter and algorithms were conducted at first using a modeled signal, which was generated in Matlab (Fig. 4a). The purpose of these studies was to verify the correctness of the filter operation as well as to determine its properties and the behavior in the stationary environment. The stationarity of the test signal made it possible to determine the maximum amplification error and the time of MSE (Mean Squared Error) minimization. Next, the simulations were repeated for a real vibration signal of 200 MW turbogenerator (Fig. 4b).



(a) (b)

Fig. 4. Test signals for subband adaptive filter: modeled signal (a) and real signal (b).

The efficiency of the filter in field of noise level reduction was verified on the basis of the SNR (Signal–to– Noise Ratio) improvement coefficient, defined as:

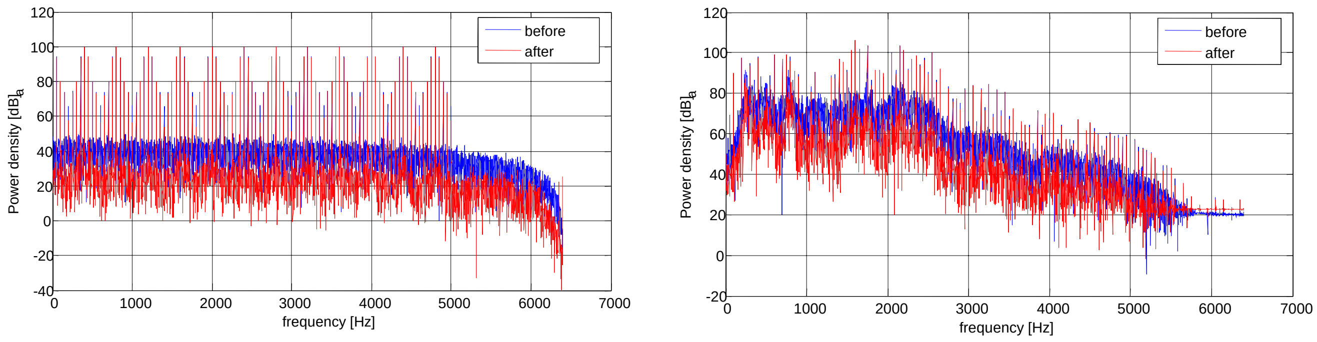
$$SNG = \frac{SNR_{out}}{SNR_{in}} = 10\log\frac{P_{V\,in}}{P_{V\,out}}[dB] = 10\log\frac{\sigma^2_{V\,in}}{\sigma^2_{V\,out}}[dB], \tag{16}$$

where $P_{V\,in}$ is the power of noise at the filter input, $P_{V\,out}$ is the power of noise at the filter output, $\sigma^2_{V\,in}$ is the variance of noise at the filter input, $\sigma^2_{V\,out}$ is the variance of noise at the filter output. Moreover, the maximum filter amplification error for harmonic signals and the time of MSE minimization were also evaluated.

A number of simulations were performed to determine the influence of filtering circuit parameters and the algorithm itself on the filter operation efficiency. Results of these simulations and their interpretation are presented in [1]. Because of problem extensiveness, it has been decided to discuss in this paper only the results obtained for a 128–order filter which divides signal into 16 frequency subbands. The adaptation coefficient μ_0 equal to 0.125 was selected. This value is theoretically optimal for the 128–order filter, when signal is divided into 16 subbands. It also trades off filter operation efficiency against amplification error value and *MSE* minimization time.

For the *RP-NLMS* algorithm, the effect of *g* factor value, which determines the filtering coefficient value (equation (15)) in the recursive method of signal power calculation (equation (14)), was studied. It turned out that taking the *g* factor value to be larger than 1 improves operation efficiency of the examined filters. It can be also noticed that for a given filter order and adaptation coefficient value μ_0 there exists a limit value $g_{\lim}$ at which further increase of the g factor does not bring any improvement. For instance, $g_{\lim} = 2^3$ for the 128–order filter and at $\mu_0 = 2^{-3}$. Furthermore, it can be noticed that the higher is the adaptation coefficient value, the larger the influence of the scaling factor *g* on SNR improvement. For small enough μ_0 values, application of the scaling factor *g* does not bring an expected improvement. For values larger than 1, introduction of the *g* factor does not result in any significant changes in the properties of examined filters as far as amplification error and convergence time are concerned. In fact, introducing the g factor accelerates the reaction of *NLMS* algorithm for changes of input signal power.

Comparative simulations performed during the studies showed that also for the *T-NLMS* algorithm the use of *g* factor leads to the improvement of filter operation efficiency. For instance, at *g* = 16, 128–order filter, 16 subbands and 70 dB attenuation, SNR improvement increased from 11.2 dB to 14.3 dB, while the amplification error remained unchanged and adaptation time became slightly longer.
The result of operation of the selected subband adaptive filter is shown in Fig. 5 and Fig. 6.



(a)

(b)

Fig. 5. Exemplary operation result for the 128–order filter, which divides signal into 16 subbands and uses the *RP-NLMS* algorithm: modeled signal (a), real signal (b).

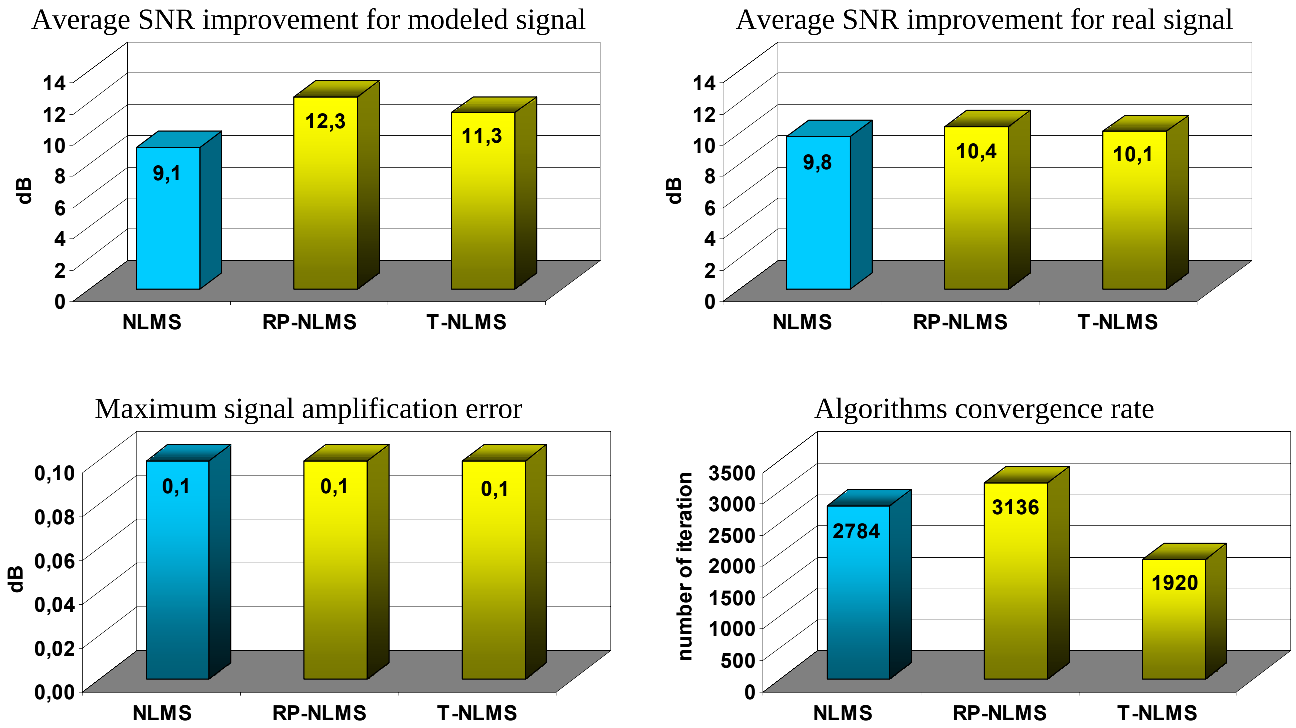


Fig. 6. Comparison of parameters of the 128–order filter, which divides signal into 16 subbands and uses the *NLMS*, *RP-NLMS*, *T-NLMS* algorithms.

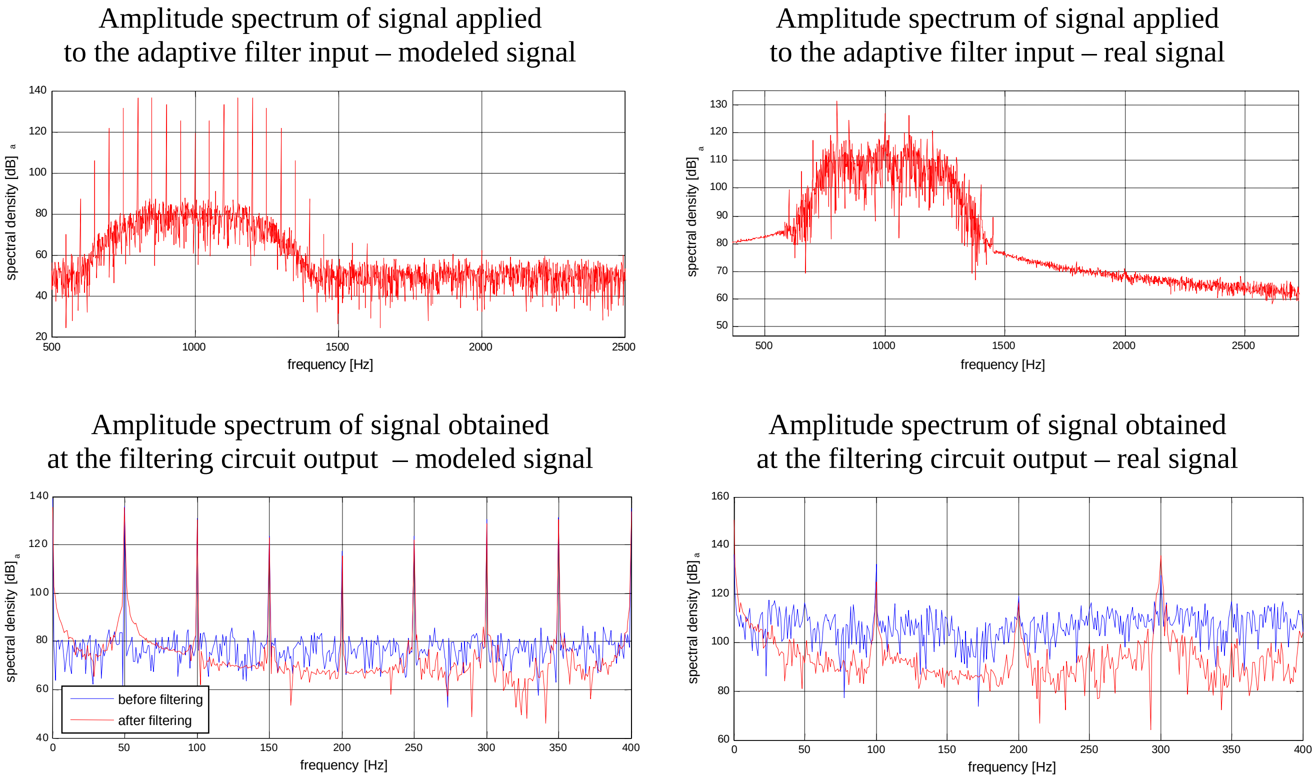
Based on the obtained results, one may state that for both *RP-NLMS* and *T-NLMS* algorithms, the studied filters have similar properties. In the case of filters using the *T-NLMS* algorithm, a small decrease in SNR improvement is observed (for 128–order filters) with respect to the filters applying the *RP-NLMS* algorithm. The results of additional studies indicate that maximum amplification error slightly increases for the *T-NLMS* algorithm when the filter order is decreased (from 128 to 64) and when frequency subbands number is reduced (from 16 to 8). This algorithm, however, has shorter adaptation time. The comparison of parameters of filters which use the proposed, simplified algorithms, with a filter based on the original version of the *NLMS* algorithm shows that the modified algorithms bring better SNR improvement without any change in the amplification error value. Moreover, the *T-NLMS* algorithm is also faster than the *NLMS* one.

The next step of the conducted studies was to implement the denoising filter part, which is responsible for the adaptive noise level reduction in one of the subbands, in an FPGA (*Field Programmable Array*) device. The basis for the hardware implementation of this filter was the *T-NLMS* algorithm. Samples of the test signals, after preprocessing in the Matlab environment (passband filtering and decimation), were fed to the circuit input (see Fig. 7).

Fig. 7. Block diagram of ALE adaptive filter application circuit.

After the appropriate processing of signal by the adaptive filter, signal samples were stored and again subjected to software processing (signal frequency up–conversion, passband filtering).

The result of the circuit operation is presented in the Fig. 8. They confirm the possibility for hardware implementation of a fully functional adaptive subband filter that reduces the level of noise in periodic vibration signal.


Amplitude spectrum of signal applied to the adaptive filter input – modeled signal

Amplitude spectrum of signal applied to the adaptive filter input – real signal

Amplitude spectrum of signal obtained at the filtering circuit output – modeled signal

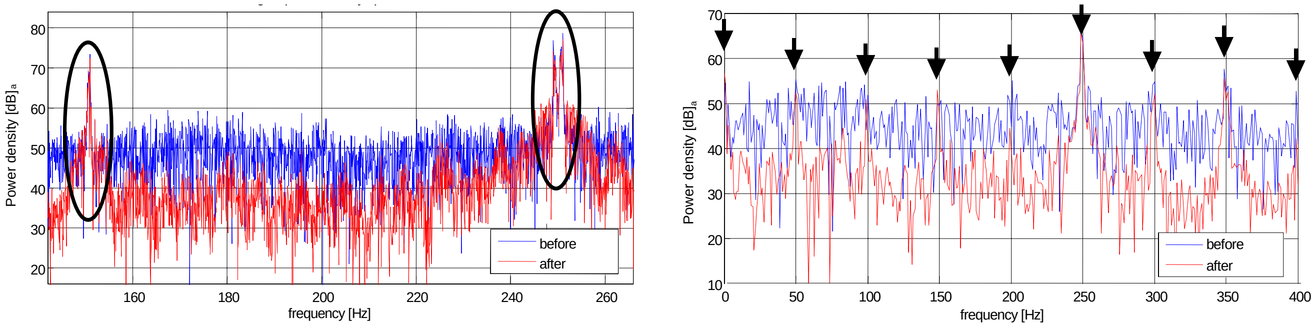
Amplitude spectrum of signal obtained at the filtering circuit output – real signal

Fig. 8. Result of operation of the hardware-implemented adaptive noise filter applying the *T-NLMS* algorithm.

The additional benefits from the application of the proposed filter are shown in Fig. 9. The first figure presents the circuit usefulness for filtration of complex signals containing periodic components which are not harmonics of the fundamental frequency (advantage over comb filters). The second figure shows the capability of the filter (with large number of coefficients) to detect harmonic components masked by a high level noise.

6. Conclusions

The paper describes adaptive method for the reduction of the level of stochastic interference present in the turbogenerator vibration signal that is recorded with the use of micromachined accelerometers. The method applies the Subband Adaptive Line Enhancer circuit. The conducted research indicates the high effectiveness, parametrizability and the possibility for a relatively simple hardware implementation of the method. The proposed method can be employed in rotating machine diagnostic systems that apply harmonic analysis of the vibration signal. The implementation of the method enables the use of MEMS sensors in these systems.



(a) (b)

Fig. 9. Result of complex signal denoising with 128-order subband adaptive filter (a) and the effect of applying 1024-order filter for detection of low SNR components (b).

Acknowledgements

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Guide for Contributors

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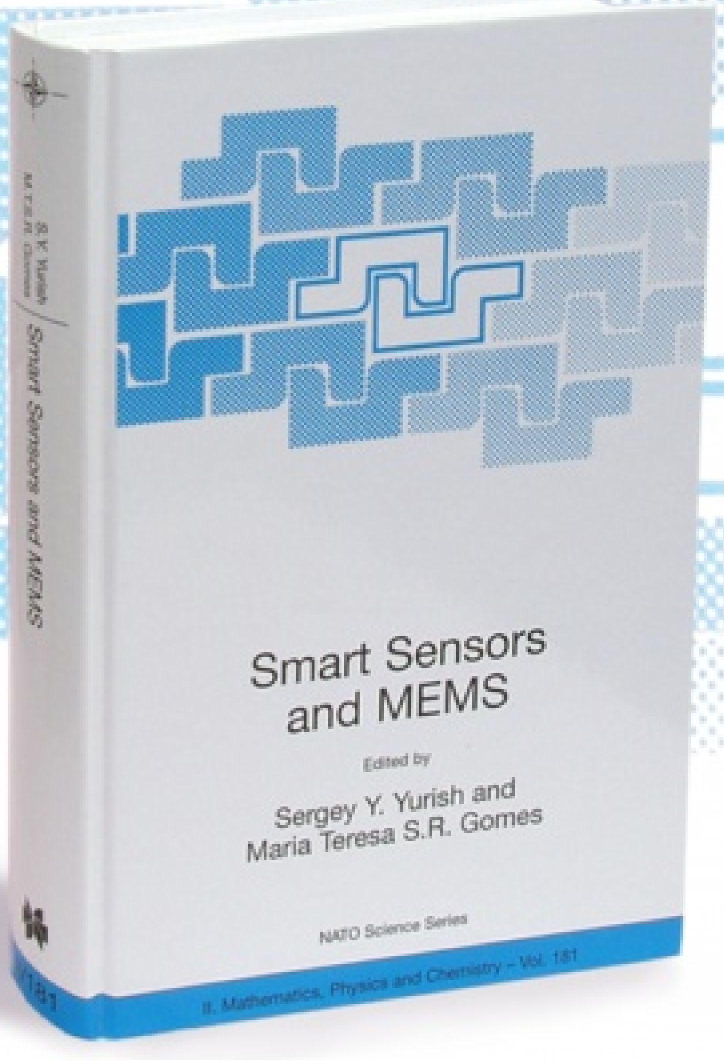
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