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A New Look at Adaptation in Active Noise Control Systems

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studia na Wydziale Automatyki, Elektroniki i Informatyki Politechniki Śląskiej w Gliwicach ukończył w roku 1986 na kierunku Elektronika, specjalności Automatyka Przemysłowa i Pomiary. W 1992 roku uzyskał stopień doktora nauk technicznych, a w 2000 roku stopień doktora habilitowanego nauk technicznych. Od ukończenia studiów jest pracownikiem Instytutu Automatyki Politechniki Śląskiej. Jego zainteresowania badawcze obejmują m.in. komputerowe systemy sterowania, identyfikację modeli matematycznych obiektów i sygnałów, sterowanie adaptacyjne oraz syntezę sygnałów o zadanych własnościach czasowych i widmowych.

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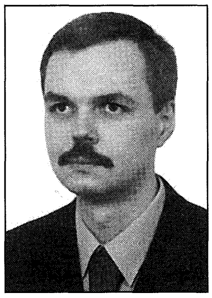

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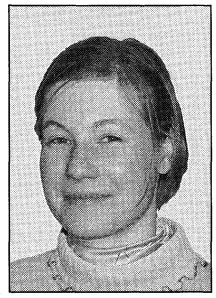

Streszczenie

W artykule przedstawiono nowe spojrzenie na adaptację w układach aktywnego tłumienia hałasu (ATH). Zwrócono uwagę na to, że adaptacja wprowadza do układu ATH nieliniowe sprzężenie zwrotne, którego konsekwencją jest pojawianie się złożonych okresowych lub chaotycznych odpowiedzi czasowych układów ATH. Zamieszczono przykłady takich odpowiedzi otrzymane w wyniku doświadczeń laboratoryjnych, w których układy ATH wykorzystywano do tworzenia lokalnych przestrzennych stref ciszy w pomieszczeniu zamkniętym.

Summary

In the paper a new look at adaptation in active noise control (ANC) systems is presented. The adaptation is interpreted as a nonlinear feedback. This nonlinearity could be manifested in behaviour of ANC systems with occurrence of complex periodic and chaotic time-domain responses. Results of real-world experiments with adaptive ANC systems used to create a local zone of quiet in a laboratory enclosure showing apparently this behaviour are included.

Key words: active noise control, chaotic dynamics, adaptive systems, nonlinear systems.

1. Introduction

In many real-world applications of adaptive active noise control (ANC) systems their unexpected behaviour implied by parameterisation of adaptation algorithms can be observed. The ANC systems may generate unwanted sound waves even though they are not present in the attenuated noise. For example the error signal may pulsate in regular time periods or additional frequency components may appear. It can be observed that the pulsation intensity or the number of additional frequency components is a function of adaptation algorithm parameter.

In the paper, the adaptation in ANC systems is interpreted as a nonlinear feedback. It is well known that such feedback is an essential prerequisite for chaos [5, 9, 10, 14]. Properties of adaptive ANC systems are discussed from the chaos theory point of view [13, 15] as a function of adaptation algorithm parameter. The unexpected behaviour of ANC systems is illustrated by results of real-word experiments with laboratory adaptive feedforward and internal model ANC systems. They are used to create a local zone of quiet in a reverberant enclosure [1, 4]. Examples of their apparently complex periodic and chaotic time-domain behaviour are included.

2. ANC systems

Real-world ANC system implementations are mainly done using digital adaptive feedforward or feedback systems [6, 8, 11].

The block diagram of a classical adaptive feedforward ANC system creating a local zone of quiet surrounding a single (error) microphone in a reverberant enclosure is shown in Fig. 1. It is assumed that the ANC system is working with the sampling interval T and i is the time instant. The enclosure is disturbed by a deterministic noise (generated by a primary source), which should be reduced using a secondary source (control loud-speaker). In this case the reference signal $x(i)$ is measured using non-acoustic sensor. The disturbance path represents an acoustic space between the reference and error microphones. The secondary path is composed of D/A converter, reconstruction filter, amplifier, control loudspeaker and an acoustic space between the loudspeaker and error microphone. When the reference signal is measured using a reference microphone placed near to the primary source, the acoustic wave generated by the control loudspeaker goes not only to the error microphone but also reaches the reference microphone. This interaction is called an acoustic feedback. The corresponding acoustic feedback path (Fig. 2) is composed of D/A converter, reconstruction filter, amplifier, control loud-speaker and the acoustic space between this loud-speaker and the reference microphone. In the feedforward ANC system the acoustic feedback may be compensated by an additional filtration of control signal $y(i)$ by a linear approximation of acoustic feedback path represented in Fig. 2 by the transfer function $\hat{F}(z^{-1})$.

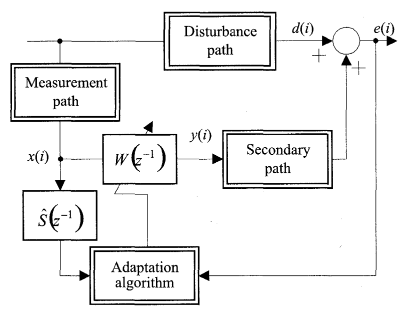

Fig.1. Block diagram of a feedforward ANC system with non-acoustic sensor.

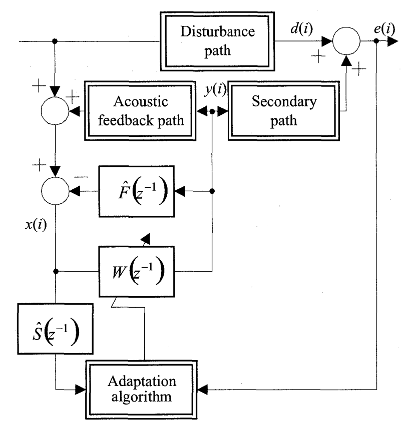

Fig. 2. Block diagram of a feedforward ANC system with acoustic feedback neutralization.

When there is no possibility to measure the reference signal, internal model ANC system may be applied. In this system a linear model of secondary path represented in Fig. 2 by the transfer function $\hat{S}(z^{-1})$ is used to estimate an unavailable reference signal (Fig. 3).

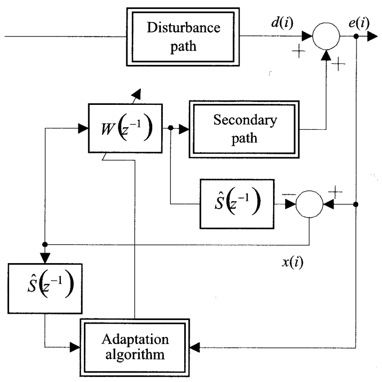

Fig. 3. Block diagram of an internal model ANC system.

To design ANC system there is a necessity to identify linear approximations $\hat{S}(z^{-1})$ and $\hat{F}(z^{-1})$ of secondary and acoustic feedback paths. It is done off-line before activation of the ANC system.

3. Adaptation as a nonlinear feedback

In the above ANC systems a linear filter is used as the adaptive controller $W(z^{-1})$. Its coefficients are tuned on the basis of error signal $e(i)$ and reference signal $x(i)$ (or its estimate) filtered through the secondary path model $\hat{S}(z^{-1})$. The goal of adaptation algorithm is to calculate the coefficients of digital filter $W(z^{-1})$ that minimise the mean square value of error signal $e(i)$.

The coefficients of digital filter $W(z^{-1})$ may be adapted using various versions of recursive Least-Mean-Squares (LMS) or weighted Recursive-Least-Squares (RLS) estimation algorithms. The heart of recursive parameter estimation algorithms is the following nonlinear recursion [7, 12]: *{new parameter estimate} = {old parameter estimate} + {function of an adaptation parameter, reference and error signals} * {function of prediction error}*, where the adaptation parameter is the step size μ for LMS type algorithms or forgetting factor λ for RLS algorithm. This recursion implies that output of the ANC system (error signal) affects input of the ANC system (noise) in a nonlinear way thus influencing ANC system operation. It implies that adaptation is a kind of nonlinear feedback. It is a prerequisite for chaos in adaptive ANC systems. The nonlinear feedback implied by adaptation algorithms could be manifested in behaviour of ANC systems with occurrence of complex periodic time-domain responses leading to chaos.

In the sequel, properties of the adaptive ANC systems are discussed as a function of adaptation parameter with a focus on time- and frequency- domain behaviour of the signal $e(i)$ from error microphone. The feedforward and internal model ANC systems are seen from the chaos theory point of view as the following nonlinear iterated map f:

$$e(i)=f(e(i-1),\ x(i), \text{adaptation parameter}) \qquad (1)$$

where $e(i-1)$ is a vector of previous values of the error signal and $x(i)$ is the corresponding vector of previous values of reference signal.

4. Examples

Feedforward and internal model ANC systems were used to create a local zone of quiet in a small laboratory enclosure (Fig. 4) of about 23 m^3 cubature. The enclosure was disturbed by pure tones of frequencies 70 and 80 Hz. Primary noise source was driven from a signal generator.

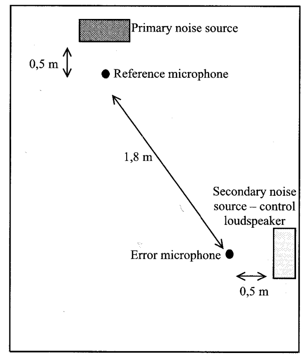

Fig. 4. Active noise control laboratory.

During laboratory experiments the ANC systems were working with the sampling interval $T = 0.002$ s. The compensator $W(z^{-1})$ was a FIR filter of order 2. Its coefficients were adapted using LMS algorithm. Secondary and acoustic feedback paths were modelled using FIR filters with 250 coefficients each. Their parameters were identified without acoustic disturbance before activation of the ANC system.

Results of laboratory experiments are presented below as diagrams. The error signal $e(i)$ for ANC system off (0-8s) and for ANC system on (after 8s) are in each plot shown in the left column. In the right column the corresponding power spectrum density (PSD) diagrams of the error signal $e(i)$ with ANC system off (dotted line) and with ANC system on (solid line) are presented, respectively. In Figs. 5, 6 and 7 the successive plots (from top to down) are shown for increasing value of adaptation algorithm parameter μ. To calculate power spectral densities the 8192-sample error signal sequences were taken from the end of experiments. For each sequence using 1024-point finite Fourier transforms 8 periodograms were calculated and the corresponding averaged values were plotted.

In Fig. 5 results obtained for feedforward ANC system with the nonacoustic sensor are shown. The enclosure was disturbed by a pure tone of frequency 80 Hz. For the smallest value of μ (plots in the first row) the disturbance was thoroughly attenuated (26 dB) but it can be seen that a frequency component of frequency 92 Hz was generated. For higher value of μ also next frequency component of frequency 68 Hz appeared. The disturbance attenuation was 7 dB. For the highest value of μ the disturbance frequency was still attenuated (2 dB), however the frequency components (68 Hz and 92 Hz) were present in the error signal. It is important to note that these frequencies were not present in disturbance signal. They were generated by the ANC system.

In Fig. 6 results obtained for the feedforward ANC system with acoustic reference sensor are shown. In such ANC system the generated additional frequency components may be added to reference signal when acoustic feedback is not compensated fully. The enclosure was disturbed by a pure tone with frequency 70 Hz. In this case the disturbance tone was slightly attenuated, however after some time a new tone of 106 Hz frequency was generated. This additional frequency, not present in the disturbance signal, was not generated continuously, unlike in the feedforward ANC system with nonacoustic sensor. This frequency component pulsated - arose and disappeared with the frequency dependent on the value of μ. The greater the value of μ was, the more frequently the frequency component pulsated. Increase of the value of μ caused that more additional frequency components were generated. It implied that the small attenuation was observed for two first experiments shown, for the next two the disturbance was amplified. It should be emphasised that described phenomenon may be dangerous, because once the control signal reaches its limit, the system works no more properly. This phenomenon was analysed in [3] from the point of view of linear control theory taking into account nonstationarity of the ANC system.

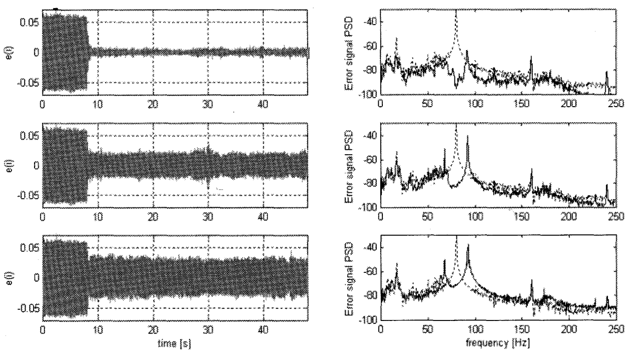

Fig. 5. Error signal *e(i)* and the corresponding power spectral densities for different values of μ - feedforward ANC system with nonacoustic reference sensor.

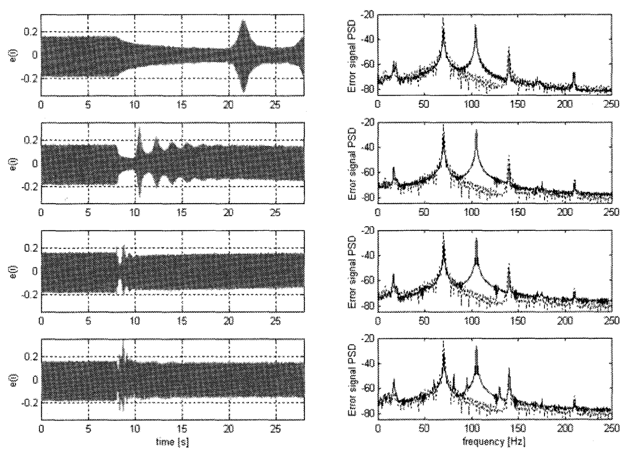

Fig. 6. Error signal *e(i)* and the corresponding power spectral densities for different values of μ -feedforward ANC system with acoustic reference sensor.

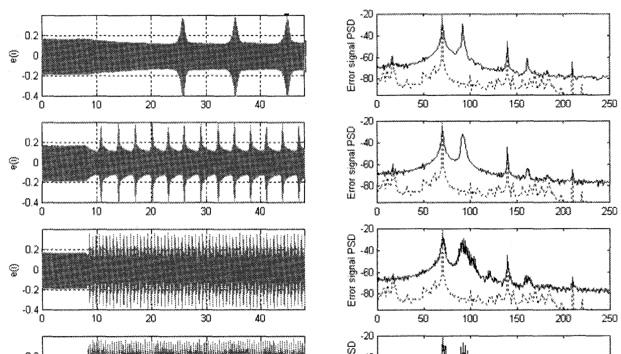

Fig. 7. Error signal *e(i)* and the corresponding power spectral densities for different values of μ - internal model ANC system.

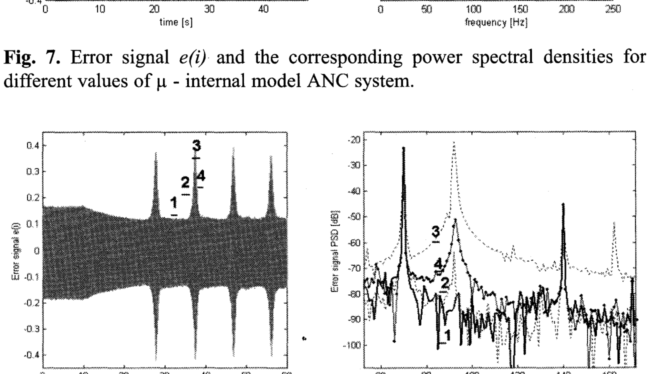

Fig. 8. Pulsation of additional frequency component

In the internal model ANC system [2] similar behaviour may be observed (Fig. 7). In this case the complex periodic behaviour of error signal quickly expands into the chaos. Initially one additional frequency component (92 Hz) was generated in the internal model ANC system. Along with the increase of the value of μ the error signal power spectral density broadened and the more pulsating frequency components were appearing. Finally, the disturbance that was to be attenuated was amplified.

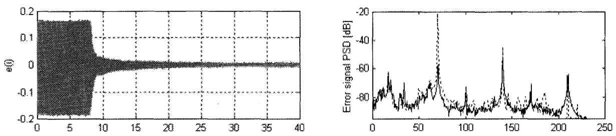

Fig. 9. Error signal *e(i)* and the corresponding power spectral density - internal model ANC system in a case of proper system performance.

Fig. 8 shows how the additional frequency component pulsated. The instantaneous error signal power spectral densities are calculated in consecutive time intervals marked on the error signal time plot. This figure presents the explosion of additional frequency seen as the growth of error signal amplitude and the growth of this frequency amplitude on the corresponding power spectral density plot. After the frequency component arose it is noticed by the controller like another disturbance frequency. The controller adapts to this change - starts to attenuate this additional frequency component while the disturbance frequency is let unattenuated, because the controller is simple (of order 2). After a time interval the additional frequency component is attenuated and then the disturbance frequency component dominates. Thus the controller adapts to attenuate the disturbance frequency and everything repeats. The higher the value of μ is, the faster is the adaptation and the pulsation frequency is higher. In some cases the balance may be reached - the both frequencies are continuously present in the error signal.

In Fig. 9 the error signal *e(i)* is plotted for the properly working internal model ANC system - with an appropriate acoustic feedback neutralisation. The noise attenuation was 29 dB.

The same complex periodic and chaotic time-domain responses may be observed in ANC systems with adaptation using normalised LMS algorithm and weighted RLS algorithm.

5. Conclusions

In the paper adaptive active noise control systems are analysed from chaos theory point of view with a focus on parameterisation of adaptation algorithms. The adaptation algorithm is interpreted as a source of nonlinear feedback. It is shown that on his way to chaos ANC systems may generate unwanted sound waves that are not present in attenuated noise. The presented analysis is illustrated by results of real-word experiments with laboratory adaptive ANC systems (feedforward and internal model control system) used to create local zone of quiet in a reverberant enclosure. Complex periodic and chaotic time-domain responses of the laboratory ANC systems are included.

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Tytuł: Nowe spojrzenie na adaptację w układach aktywnego tłumienia hałasu

Artykuł recenzowany

INFORMACJE

NAGRODY ZA OSIĄGNIĘCIA W DZIEDZINIE BADAŃ NIENISZCZĄCYCH w 2003 r.

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Nagrody zostaną wręczone w czasie seminarium na temat **„Nieniszczące badania materiałów“, które odbędzie się w dniach 16-19 marca 2004 r. w Zakopanem.**

Za kapitułę nagrody
- prof. dr hab. Julian Deputat
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