ISVR, Southampton, UK
ACTIVE 2002
2002 July 15-17

RESONATOR-BASED ACTIVE CONTROL OF TRANSFORMER NOISE

László Sujbert

Dept. of Measurement and Information Systems, Budapest University of Technology and Economics, Magyar Tudósok körútja 2., H-1521 Budapest, Hungary.
Email: sujbert@mit.bme.hu

1. INTRODUCTION

The resonator-based noise controller presented in Active '97 [7] is a dedicated controller for periodic noise cancellation. The controller is a real alternative of the conventional solutions based on the least mean square (LMS) algorithm: it shows faster convergence and needs less computation while the suppression is the same. That paper described the theoretical background and the design procedure of the controller for both single channel and multiple channel cases. Although the paper was mainly theoretical, it described a successful multiple channel experiment for propeller-driven airplane noise control. A meaningful noise suppression had been achieved in a small room designed like an airplane-cabin [8]. Generally, the application of the resonator-based controller is advantageous if the primary noise originates in a rotating machine.

This paper describes the application of the resonator-based controller for high-power transformers. The electric power of such transformers is in the range of 1 megawatt, their volume is in the range of 1 cubic meter. They are usually installed in electric stations, where the high voltage connection is also available. Their noise is mainly periodic and the fundamental frequency is twice as that of the mains. In some cases the electric stations are close to living spaces, and the transformer noise is a heavy environmental burden. Passive noise control cannot be installed: above the obvious disadvantages, the isolation should ensure the high-voltage connection and the ventilation. It is a straightforward application area of active noise control, one of the first solutions are designed for this problem [3]. However, the control system should work under different weather conditions (especially at different temperatures) and it should suppress the noise also in the far-field. The existing controllers utilize the well-known LMS-based methods [4].

Section 2. recalls the resonator-based noise controller, and section 3. describes its application for transformer noise control. Section 4. discusses the first experimental results, while section 5. concludes the paper and defines the further work.

2. RESONATOR-BASED NOISE CONTROL

The noise controller. The theoretical background of such a controller design is the adaptive Fourier analysis. The adaptive Fourier analyzer (AFA) is a structurally adaptive

This work was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences and the Hungarian Fund for Scientific Research under Grants OTKA F 035060

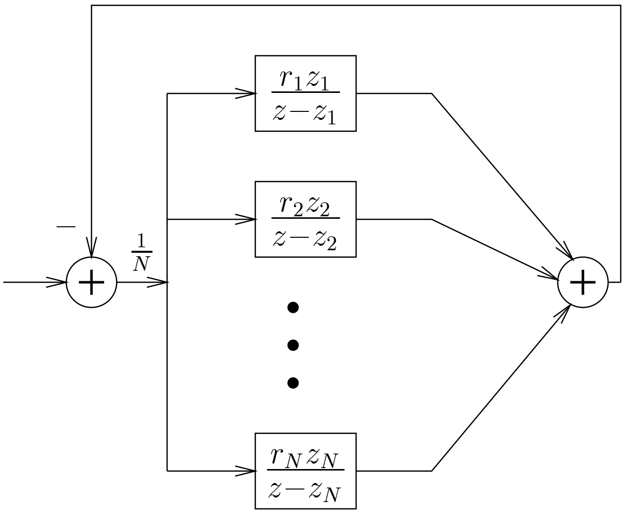
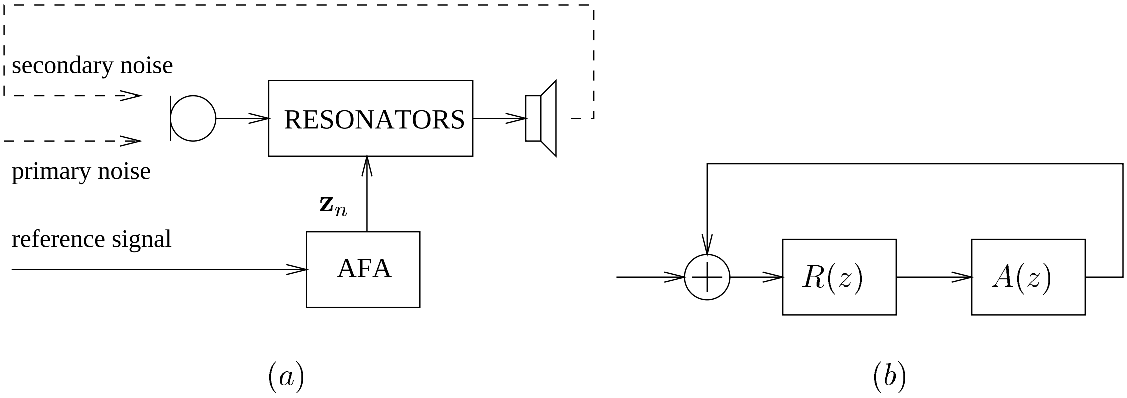


Figure 1: *Observer for periodic signals*



(a) (b)

Figure 2: *Periodic noise control: (a) Physical arrangement (b) Block diagram of the control loop*

system for exact measurement of band-limited periodic signals of arbitrary fundamental frequency [1]. It is an extension of the resonator based observers developed earlier to perform the recursive discrete Fourier transform (RDFT) [2]. In these observers the resonators work in a common feedback loop providing zero steady-state feedback error at the resonator frequencies. The AFA adapts the resonator frequencies to coincide with those in the input signal. The noise controller can be considered as an extension of the AFA.

In the resonator based observer (Fig.1) in steady-state the input of the resonators (i.e. the feedback error) equals zero. This means that the feedback signal (the sum of the resonator outputs) *cancels* the input signal. If acoustic noise should be canceled, the output of the resonators should be connected to a loudspeaker and fed back using a microphone. (A multiplication by -1 is necessary in the controller.) The arrangement can be seen in Fig. 2.a. The frequency is estimated by an independent AFA and it passes the actual resonator positions ($\mathbf{z}_n$) to the controller. Reference signal can be any periodic signal with the same fundamental frequency as the primary noise. Fig. 2.b shows the block diagram of the control loop, where $R(z)$ and $A(z)$ denote the resonator based controller and the transfer function of the secondary path, respectively. The controller design is accomplished by the appropriate choice of the parameters r_k. They can be chosen as follows:

$$r_k = \alpha w_k;\ w_k = \frac{1}{A(z_k)};\ k = 1..N \tag{1}$$

where α is a convergence parameter. The actual set w_k depends on the fundamental frequency of the primary noise. $A(z)$ is in general not analytically known and (1) cannot be calculated on-line, therefore the transfer function should be measured at a finite number of points and the inverses ($f_i;\ i = 1..M$) should be calculated off-line. Thus the actual set w_k should be a result of a mapping $\{f_i\} \rightarrow \{w_k\}$ (e.g. the nearest available one).

In the multiple channel system to each loudspeaker belongs a resonator set, the input of which is the weighted sum of the microphone signals. The weighting of the microphone signals corresponds to the parameters w_k. Indeed, instead of a simple parameter set, here a matrix set should be applied. Extending the idea described above they can be chosen as follows:

$$\mathbf{W}_k = \mathbf{A}^{\#}(z_k) \tag{2}$$

where $\mathbf{A}(z)$ is the transfer matrix between the loudspeakers and the microphones, $\mathbf{W}_k$ is the weighting matrix and # denotes the pseudo- (or Moore-Penrose) inverse. This set of parameters $\mathbf{W}_k$ offers similar convergence properties as (1) in the single channel system. Single channel systems provide zero steady-state error. The multiple channel resonator based system minimizes the power of the remaining noise if the matrices $\mathbf{W}_k$ are chosen as (2) shows.

Advantages of the resonator-based controller. There is a strong relation between the resonator based controller and the usual filtered-X LMS or multiple error LMS (XLMS or MLMS) based solution (see e.g. [5] and [6]). The XLMS based system can be transformed to a resonator based system, but the corresponding parameters w_k (or $\mathbf{W}_k$) are not the inverses of the secondary transfer function (matrix), but its complex (transpose) conjugates. The phase shifts caused by the filter in the XLMS algorithm and the parameters w_k in the resonator based observer are obviously the same, thus from stability point of view the systems are identical. However, the adaptive filter does not aspire to approximate the inverse filter, therefore its convergence could be very slow. A heuristic explanation can be given: while in the resonator based observer the gain between the system output and the resonator input is unity, that of the adaptive filter is $|A|^2$. If the secondary path suppresses the signal, in the loop the square of this suppression occurs, so the system will be considerable slow. This idea can also be extended for broadband noise control resulting in a new filtered LMS algorithm [9].

As it was mentioned in the above subsection, the controller needs the off-line identification of the secondary path. However, the actual set of w_k is only a subset of f_i. It is a great advantage, since $M \gg N$, i.e. the required number of measurement points (the length of the reference filter in the XLMS algorithm) is much greater than the number of the controlled harmonics. This reduces the computational demand of the algorithm. On the other hand, the rest of the controller has the same computational complexity as the standard LMS algorithm.

The resonator-based controller is designed specially for periodic noise suppression providing simpler structure and better control results than the conventional adaptive controllers.

3. TRANSFORMER NOISE CONTROLLER

Noise controller design was preceded by recording transformer noise samples. The samples were derived by measurements of a 100 MVA transformer. The periodic noise has a fundamental frequency of 100 Hz. It is not a pure sine wave, its harmonic content is significant up to 1 kHz.

Reference signal source could be the mains itself. Using a small transformer and a rectifier circuit a nice reference signal can be derived. In the first experiments the recorded noise signal was the reference, as well (see later).

Since noise suppression has to be achieved also in the far-field, some simulations were carried out to specify the microphone and loudspeaker arrangement. These simulations were not too complicated, the only goal was the determination of the main tendencies. The simulations pointed out that the secondary sources should be placed near to the transformer and the error microphones on the contrary: they should be placed as far as possible from the transformer. The latter is an ambivalent requirement, since it makes the control problem more difficult.

The control problem requires a multiple channel system. However, simulations have shown that one direction can be well shielded also by a single channel system, so the first experiments were carried out by such a system. The simulation results coincide with those of [4].

Noise controller design is almost straightforward. Since active noise control is efficient up to about 1 kHz, 10 resonators were placed in the controller. The sampling frequency was designed to be 8 kHz. The calculation of the parameters w_k (see (1)) is very simple. Since the fundamental frequency can be treated as constant (the frequency deviation is usually in the range of 10 mHz), the secondary transfer function has to be identified only at the controlled frequencies. It means only 10 measurements using sine wave excitation at 100 Hz, 200 Hz, ... , 1 kHz. This fact clearly shows the advantage of the resonator-based controller: the identification is a simple measurement and the sine wave excitation allows synchronized averaged measurements. The latter is important if outdoor measurements have to be carried out. These measurements can be done by another resonator-based structure [10].

4. RESULTS

An Analog Devices EZ-KIT LITE development board was used for control purposes. It contains one ADSP-21061 floating point digital signal processor and a stereo codec. The control program was written in assembly in order to minimize the computational burden.

The experimental set-up is depicted in Fig 3. P and S denote the primary and the secondary sources, respectively. M indicates the error microphone, and the crosses O1...O4 denote the places of observer microphones. In this experiment the transformer was substituted by a 100 W-loudspeaker. The primary source was also a loudspeaker, the excitation of which was the noise record mentioned above. It is a real drawback of the experimental set-up, since the original noise source had a much bigger surface. However, at such wavelength our sound sources produce ball-shaped wavefronts. The latter proves our arrangement. The reference signal was the low-pass filtered noise record itself. The used loudspeakers and microphones were quite common. The microphone signals were evaluated by a digital storage oscilloscope, containing an FFT module. The experiments

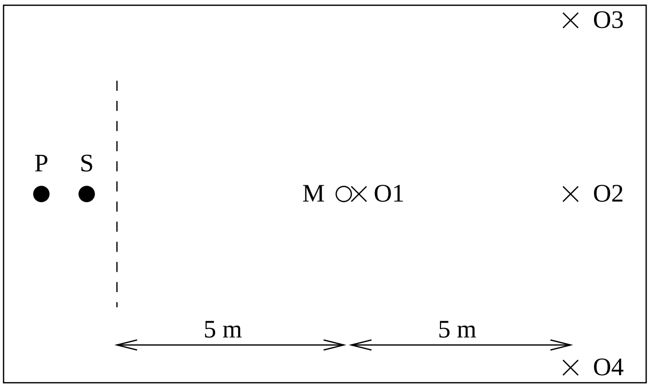


Figure 3: *Experimental set-up*

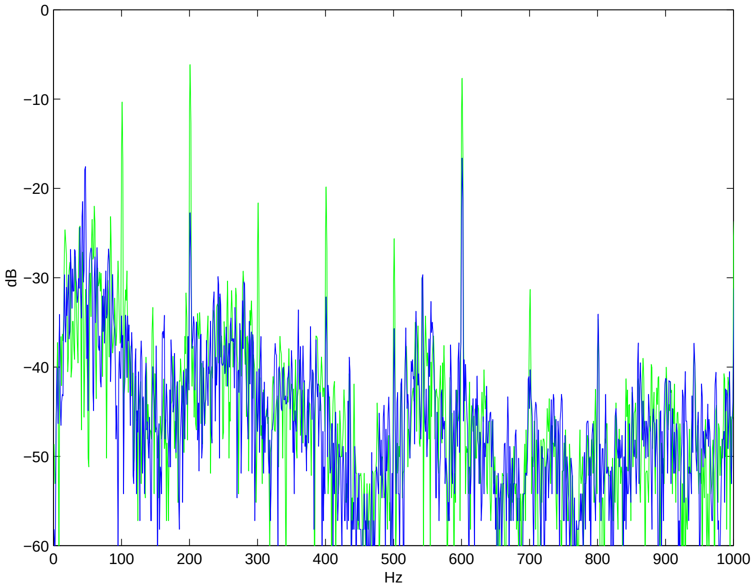


Figure 4: *Spectra of the error microphone signal. Black/blue: control on; grey/green: control off*

were performed in the garden of the university.

Fig. 4 shows the spectra of the error microphone signal. The black one is the spectrum of the residual noise (control on) , while the grey one is the spectrum of the original noise (control off). (In color printing the original spectrum is green, and the residual one is blue.) The dB scale on the spectrum is relative. The algorithm works well (almost 30 dB reduction for the first harmonic). The reduction of the 600 Hz component is very poor, less than 10 dB. It is probably because of the jitter of the reference signal.

Fig. 5 shows the spectra of the O1 observer microphone signal. O1 was situated directly behind the error microphone. The spectra are very similar to the previous ones. The only role of this measurement is to strengthen the first result.

Fig. 6 shows the spectra of the O2 observer microphone signal. O2 was situated at a distance of 5 m from the error microphone and at a distance of 10 m from the secondary source. The main components are well suppressed (10..20 dB reduction), the only weakly damped component is at 600 Hz. Note that its suppression is poor in the error signal, as well. This measurement shows that the system can suppress the noise also in the far-field.

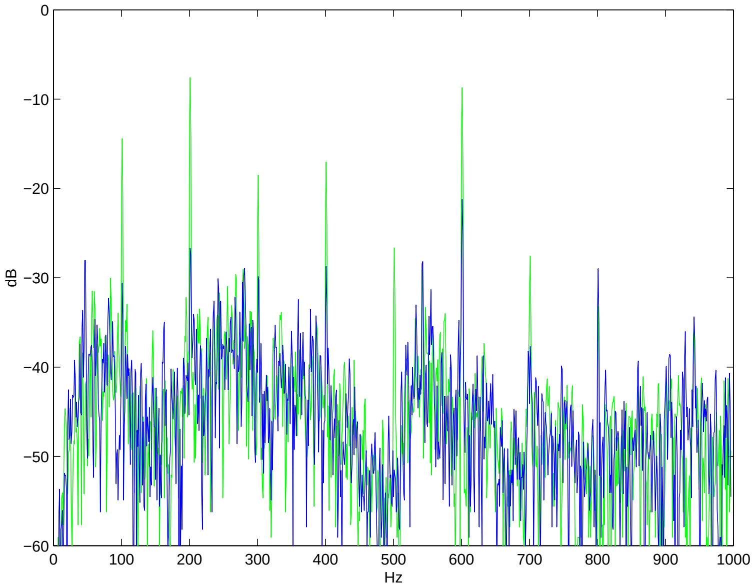


Figure 5: *Spectra of the observer microphone signal at position 1. Black/blue: control on; grey/green: control off*

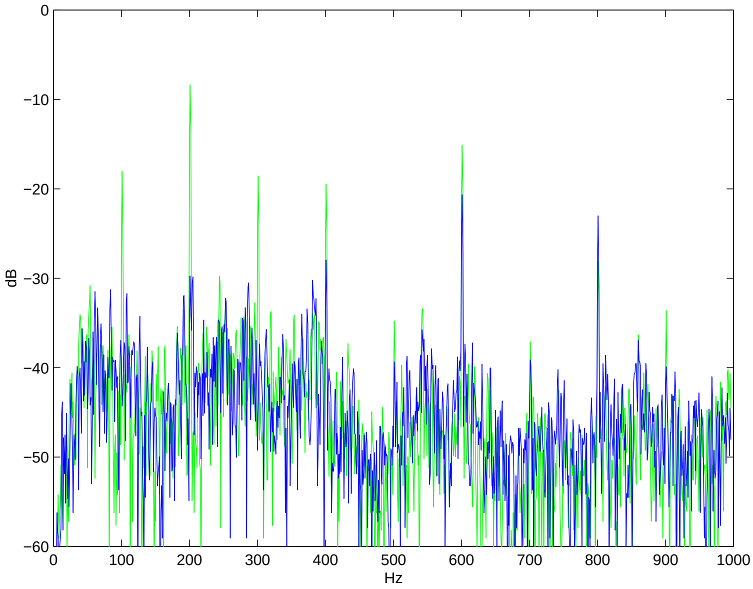


Figure 6: *Spectra of the observer microphone signal at position 2. Black/blue: control on; grey/green: control off*

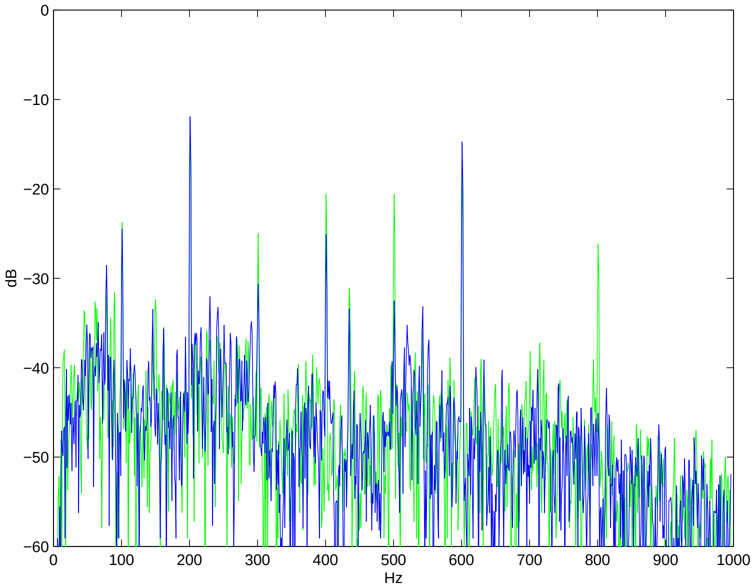


Figure 7: *Spectra of the observer microphone signal at position 3. Black/blue: control on; grey/green: control off*

Fig. 7 and Fig. 8 show the spectra of the O3 and O4 observer microphone signals, respectively. O3 and O4 were situated at a distance of 10 m from the secondary source, but they were not on the line defined by the secondary source and the error microphone. In these positions the single channel systems cannot reduce the noise. (There are weakly suppressed and simultaneously weakly gained components). The microphone positions O3 and O4 specify the area where single channel system can reduce the noise.

5. CONCLUSION, FUTURE WORK

The paper described the application of the resonator-based controller for high-power transformer noise cancellation. LMS based solutions are well-known for noise controller designers, but the resonator-based controller needs a quite different approach, therefore the theory was briefly recalled. In the second half of the paper the first experimental results were reviewed. The resonator-based controller has proven its ability to solve the noise control problem. Now the preparation of real-life experiments is in progress. The hopefully successful investigations can be continued with multiple channel experiments.

All noise control systems need the identification of the secondary path. This is valid also for the resonator-based controller. Now the identification is done off-line. However, outdoor noise controllers' secondary path model should adapted on-line, mainly because of the temperature changing. There are already some initial results that the resonator-based noise controller can be easily completed by on-line secondary path model adaptation.

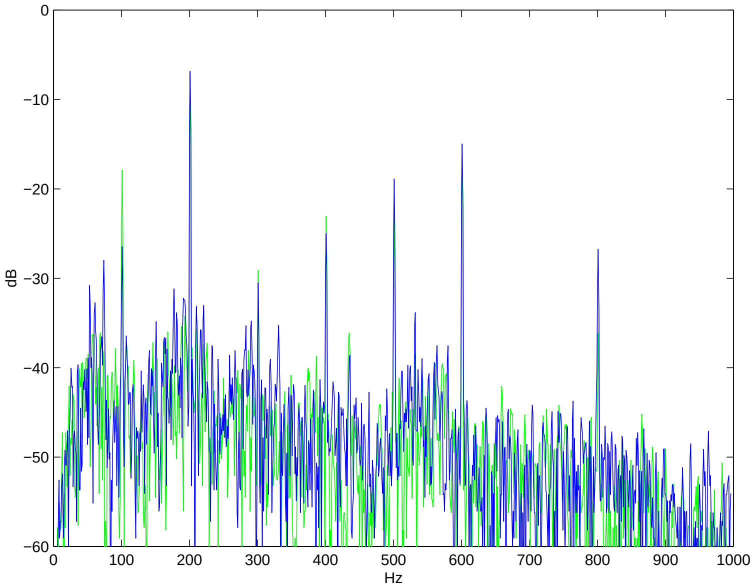


Figure 8: *Spectra of the observer microphone signal at position 4. Black/blue: control on; grey/green: control off*

REFERENCES

[1] F. Nagy. Measurement of signal parameters using nonlinear observers. *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-41 No. 1. pp. 152-155, Feb. 1992.

[2] G. Péceli. A common structure for recursive discrete transforms. *IEEE Transactions on Circuits and Systems*, Vol. CAS-33 No. 10. pp. 1035-36, Oct. 1986.

[3] S. J. Elliot, P. A. Nelson. Active noise control. *IEEE Signal Processing Magazine*, Vol. 10, No. 4. October, 1993, pp. 12-35.

[4] S. M. Kuo and D. R. Morgan. Active noise control: a tutorial review. *Proceedings of the IEEE*, vol. 87. No. 6., pp. 943–973, June. 1999.

[5] B. Widrow, E. Walach. *Adaptive Inverse Control.* Prentice-Hall, Inc., 1996.

[6] S. J. Elliot, I. M. Stothers, and P. A. Nelson. A multiple error LMS algorithm and its application to the active control of sound and vibration. *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-35. No. 10., pp. 1423–1434, Oct. 1987.

[7] L. Sujbert, G. Péceli. Periodic noise cancelation using resonator based controller. In *1997 Int. Symp. on Active Control of Sound and Vibration, ACTIVE '97*, pages 905–916, Budapest, Hungary, Aug. 1997.

[8] L. Sujbert, R. Dunay. *Resonator Based Periodic Noise Cancelation.* Technical Report (TPD-HAG-95-RPT-0044), TPD-TNO, 1995, Delft, the Netherlands.

[9] L. Sujbert. A New Filtered LMS Algorithm for Active Noise Control. In *1999 Int. Symp. on Active Control of Sound and Vibration, ACTIVE '99*, pages 1101–1110, , Dec. 1999.

[10] L. Sujbert, G. Péceli and Gy. Simon. Resonator Based Non-parametric Identification of Linear Systems. In *IEEE Instrumentation and Measurement Technology Conference*, Budapest, Hungary, pages 166–169, May. 2001.