Active Noise Control Using Waveform Synthesis with Improved Convergence and Tracking

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***Abstract* - Active noise control of periodic sounds, as commonly produced by rotating machinery, can be efficiently implemented using a synchronized waveform generator that produces a secondary signal necessary for noise cancellation. Synchronization of synthesized waveform is achieved by the use of reference tacho signal picked up by the magnetic or optical sensor. Waveform adaptation is performed in accordance with the residual noise signal after noise cancelation. Such approach for active noise control works well when a spectrum of offending noise is not changing much. However, during initial machine spool up, varying load and final spool down significant adaptability from waveform synthesizer is required to counteract changes in machine noise. In this paper, methods for improving convergence and tracking properties of waveform generator are presented and analyzed. An adaptive coefficient of waveform generator is modified in accordance to elapsed time during startup, varying frequency of the reference tacho signal and residual noise level. Results of simulations with different noise spectrum corresponding to various machinery rotational speeds are included.**

Keywords - active noise control; periodic noise; waveform synthesis; convergence; tracking

I. INTRODUCTION

When noise is dominated with low to mid frequency range where passive methods for noise attenuation lose its effectiveness, active noise control may be applied for its cancelation [1],[2]. Often, the offending noise is of periodic nature, e.g. noise produced by rotary machinery like motors and engines. This also includes humming noise generated by transformers and other devices and appliances that use electricity main. Such type of noise can be attenuated using active noise cancelation based on the synchronized waveform generator. Synchronization of the waveform synthesizer is achieved using reference tacho signal, [3]. There exist few methods for implementing synchronous waveform synthesizer. Here, coherent averaging, [4]-[6] of the residual noise waveform is used. Output waveform needs to be adapted to the change of the rotational speed and load conditions. This adaptation process uses adaptive coefficient, also called a convergence factor. To facilitate faster convergence and better tracking of changing acoustic noise spectrum and level it is beneficial to relate value of this factor to changes in rotational speed and residual noise level. This paper proposes methods for calculating variable adaptive coefficient. They are motivated by the behavior of rotating machinery during rotational speed change, RPM, and load change, influencing spectrum and noise level.

II. ACTIVE NOISE CONTROL USING WAVEFORM SYNTHESIS

A. General System Using Waveform Generator

Block diagram of the waveform generator applied to active noise control is illustrated in Fig. 1, [2]. It does not use a reference microphone and doesn't depend on measurement of the original noise. System is based on the synchronized waveform generator that uses synchro signal picked from non-contact inductive or optical tacho sensor. As there is no reference microphone, there is no possibility for unwanted acoustic feedback between secondary source and reference microphone.

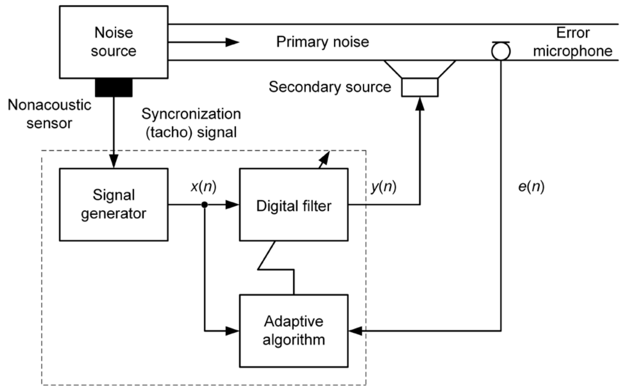

Figure 1. Block diagram of ANC using waveform synthesis

B. Secondary Path

Secondary path includes D/A converter, reconstruction low pass filter, amplifier, secondary source, acoustic path between the secondary source (sound propagation delay), an error microphone, it's preamplifier, antialiasing filter and A/D converter, [2]. The transfer function of the secondary path is not ideal and it has its frequency and phase characteristics. Most components in secondary path have reasonably linear frequency and constant phase characteristics. The cancelling speaker is generally the greatest contributor to frequency and phase deviations. The transfer function of the microphone has amplitude and phase characteristics that are in the frequency range of interest much closer to ideal one, so no additional consideration is given to their influence on the operation of the ANC system. There exists methods for addressing influences of the secondary path, inspired by Filtered-x LMS (Fx-LMS) algorithm, [1,2]. However, it requires off-line or on-line identification of the secondary path and together with filtered-*x* signal adds significantly to the complexity of ANC system.

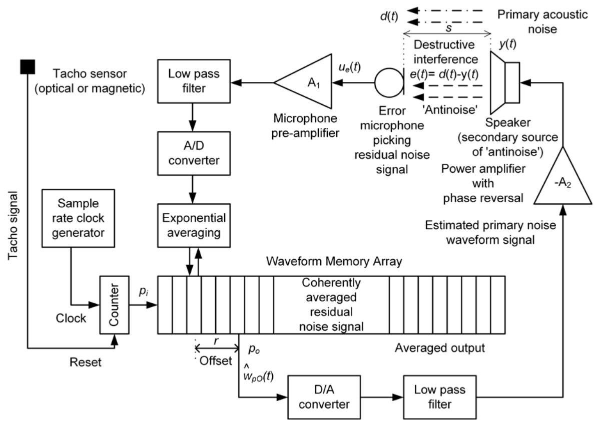

Figure 2. ANC using waveform synthesis by coherent averaging

C. Coherent Averaging of Residual Signal

Block diagram of the waveform generator applied to active noise control that uses coherent averaging of residual noise is shown in Fig. 2. Waveform generator uses a memory table, where waveform samples w_i are stored, N is max period, (1).

$$\boldsymbol{w} = [w_0, w_1, \dots, w_{N-1}] \tag{1}$$

For a signal of period L, samples w_0 to w_{L-1} are streamed out to D/A converter with appropriate sample rate f_s. After D/A converter, low pass filter is applied to smooth output signal. There is an offset of r samples between input and output address pointer, due to the time necessary for the propagation of sound the distance s from secondary source to the error microphone, v is the speed of sound, (2). Some variable delay is also present due to the frequency dependent phase shift in secondary source.

$$r = \frac{s f_s}{v} \tag{2}$$

It separates positions of input pointer p_i and output pointer p_O. If p_O is larger than L it wraps around, (3).

$$p_O = (p_i + r) \; mod \; L \tag{3}$$

In the coherent averaging process (also known as vector averaging), multiple sets of signal plus noise samples are collected and averaged over the successive periods, as illustrated in Fig. 3. After averaging process remains only periodic signal, while random signal components cancels out over the successive averagings. To perform this averaging very precise alignment of successive periods of the originating signal must be provided. For this purpose, tacho signal is used. Time synchronous averaging acts as a low pass filter.

Let the $x(t)$ represent periodic acoustic noise signal, (4). It is a sum of deterministic periodic component $s(t)$, (5) with the period T and nonperiodic or random noise component $n(t)$.

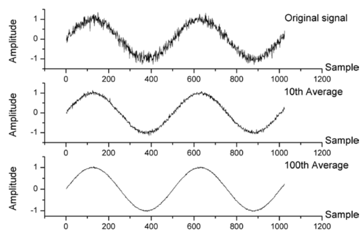

Figure 3. Coherent averaging of signal

$$x(t) = s(t) + n(t) \tag{4}$$

$$s(t + T) = s(t) \tag{5}$$

The idea behind coherent averaging performed over the period of the signal is that random noise $n(t)$ will cancel itself out and only deterministic periodic signal $s(t)$ will remain. Two types of averaging exist, arithmetic and exponential averaging. Arithmetic averaging of signal over N periods is described by (6), $\hat{x}_i$ is an averaged signal of the i-th sample in the waveform (one period), x is the input signal and L is the period length in samples:

$$\hat{x}_i(t) = \frac{1}{N} \sum_{k=0}^{N-1} x(t - kL) \tag{6}$$

In practice, not all summations are necessary for each period, just subtract oldest sample and add the newest sample to the sum that is already present. Exponential averaging uses for averaging just sample from the last period, giving more emphasis on new input signal sample. It is described by (7).

$$\hat{x}_i(t) = (1 - \alpha)\hat{x}_i(t - 1) + \alpha x(t) \tag{7}$$

The period it takes for the exponentially smoothed response of a unit step function to reach ≈ 63,2% of the original signal is called time constant, τ. If sampling interval ΔT is small compared to τ, it can be estimated from (8), giving info about relevant period for averaging.

$$\tau \approx \frac{\Delta T}{\alpha} \tag{8}$$

Synchronized waveform generator used in experiment uses exponential coherent averaging to adapt tits waveform. Waveform synthesis is relatively simple and intuitive concept. Not to add complexity with the complex modeling of the secondary path using digital filter, simpler solution for the secondary path may be used, particularly if one can find a speaker whose phase characteristics doesn't deviate too much in a frequency range of interest for noise cancellation. Then main problem is to determine the time necessary for acoustic propagation of signal form secondary source to the error microphone, around which the zone of silence is to be formed. Hence, phase shift introduced by the secondary path, $S(z)$, must be within the interval (9) for all frequency components of the canceling signal. One solution for dealing with phase changes related to change of tacho signal is described in [7].

$$\theta \in [-60°, +60°] \tag{9}$$

D. Adaptation Using Residual Noise

One approach toward the adaptation of synchronized waveform generator makes use of coherent averaging of residual noise signal. At the beginning of the operation of the ANC system waveform is empty and a residual noise is present and signal $e(n)$ is picked by error microphone. This waveform is coherently averaged with the waveform of residual noise. After first averaging, there are now some nonzero sample values in the waveform and this waveform is used to cancel the offending noise. This time the residual noise should be a little weaker, because it is a little bit cancelled by the waveform from the waveform generator. The remaining noise waveform is again averaged with the stored waveform, whose samples are increasing. In next iteration residual noise signal is again lower, etc. until convergence is achieved and residual noise remains low. Residual noise signal $e(t)$ is determined as a difference between noise signal $d(t)$ and signal from the secondary source $y(t)$, in acoustical domain, (10).

$$e(t) = d(t) - y(t) \tag{10}$$

In detail, more parameters are considered: the gain of the error signal preamplifier, A_1, gain of output amplifier, A_2, the electroacoustic transfer factor of the secondary source B_S (Pa/V), microphone sensitivity S_M (V/Pa), distance s, so $e(t)$ is given by (11), $\widehat{w}_{pO}$ is averaged waveform output at pointer p_O, (3), Fig. 2. In the near field term $1/s^2$ can be neglected.

$$e(t) = d(t) - \frac{1}{s^2} A_2 B_S \widehat{w}_{pO} \tag{11}$$

Due to error signal preamplifier adaptation is given by (12).

$$\widehat{w}_i(t)(1-\alpha)\widehat{w}_i(t-1) + \alpha A_1 S_M e(t) \tag{12}$$

E. Adaptation to RPM Changes

For a system to be adaptive to changes in rotational speed, two approaches can be used. One is the use of variable sampling rate that is a multiple of the tacho signal (e.g. using a wheel with numerous markings to be detected by tacho signal). Another is to use fixed sampling rate and to add zero sample(s) to extend the waveform or skip sample(s) of the waveform to shrink the waveform. The remaining part of the waveform is not ideally suited for cancelation and must be adapted.

III. Periodic Noise of Machinery and Equipment

Periodic noise has a waveform of repetitive nature. Such noise has pronounced harmonic structure. Pure periodic noise is rare, it is often superimposed by broadband noise. Example of the periodic nose with superimposed broadband random noise is shown in Fig. 4.

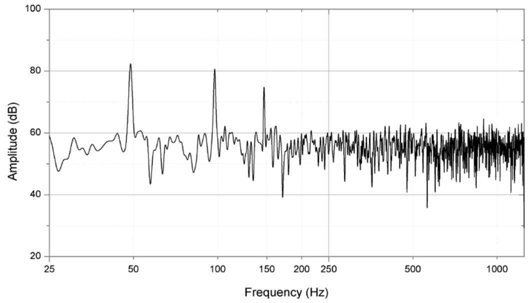

Figure 4. Periodic noise with superimposed broadband random noise

As already mentioned in the previous paragraph, ANC with synchronized waveform generator is suitable for reducing periodic noise. In an ideal case, all harmonic components should be cancelled and only the broadband noise remains.

A. Noise of Rotating Machinery and Tranformers

Motivation for modification of adaptation process stems from noise of rotating machines that are used in many engineering applications, [8]-[10]. Examples are pumps, compressors, motors and engines. Such machines have to operate over a range of speed and load conditions producing acoustic noise. Spectrogram of such noise has pronounced harmonic structure common in periodic noise.

Here are listed main causes that change the spectra of noise generated by rotating machinery.

1) Spool Up

Spool up is the process of increasing the rotational speed of an engine.

2) Spool Down

Spool down is the process of reduction of the rotational speed of an engine.

3) Other Speed Variations

Speed variations are not only limited to spool up and spool down, sometimes machine operates under various regimes with corresponding rotational speeds.

4) Load Variation

Noise of machinery is to an extent dependent on its load. Load variations can cause changes in rotation speed changing frequency spectrum and the overall noise level.

B. Transformer Noise

Transformer noise contains harmonics at odd multiples of twice the power grid frequency that is caused by core magnetostriction, [11,12]. However, noise level changes when the transformer is turned on and during load variations, [13]. Instead of tacho sensor, tacho signal is derived from zero crossings of power grid voltage.

IV. Adaptation Improvements

Proposed adaptation improvements are motivated by operation of machines that generate noise to be cancelled by ANC using waveform generator. Value of adaptive coefficient is changing according to regime of operation. Range of change R, (13) is bounded by use of min and max functions.

$$R = \frac{a_{max}}{a_0} \tag{13}$$

A. Basic System

In basic system, with no improvements, adaptive coefficient is held constant, (14), α_0=0.001.

$$\alpha_B(t) = a_0 \tag{14}$$

B. Initial Convergernce Period

A greater adaptive coefficient is used at the beginning of adaptation, and then gradually decreasing as adaptation progresses over the time t, (15). Essentially, after initial period of 10000 samples adaptive coefficient decays to α_0.

$$\alpha_I(t) = \alpha_0\, max[1, R(1-kt)]\ ,\ R=10, k=0.0001 \tag{15}$$

C. RPM Based

Value of adaptive coefficient depends on the rate of change of shaft rotational speed v_R. When speed changes, (16), producing noise of different spectrum, for the i-th signal period greater adaptation coefficient is used, (17).

$$\Delta v_R = |v_R(i) - v_R(i-1)| \tag{16}$$

$$\alpha_R(i) = \alpha_0(1 + \Delta v_R) \tag{17}$$

Not to complicate with calculation of v_R from the period between tacho impulses T_R that is already available, computationally simpler approach is used, (18) and (19).

$$\Delta T_R(i) = |T_R(i) - T_R(i-1)| \tag{18}$$

$$\alpha_R(i) = \alpha_0 max[1, min(R, M|\Delta T_R(i)|)],\ R=10, M=5 \tag{19}$$

D. RPM Based Plus Delay

This is an improvement of the previous RPM method. It acts same during RPM changes (18), (19), with the addition of end delay after the last RPM change (i.e. period T_R change as an inverse proxy) that keeps α higher for some time, e.g. K=2000 samples or several periods, (20).

$\alpha_D(t)=M\alpha_0$ for K samples after last RPM change, M=5 (20)

E. Residual Noise Level

If adaptive coefficient is small, the convergence is slow. Hence, when the residual noise level is large, greater adaptive coefficient is used. Once, when residual noise is significantly reduced, fine convergence could be achieved by smaller values of adaptive coefficient. Noise level L is determined by exponentially averaging absolute values of a residual noise signal $e(t)$, (21).

$$L(t) = (1-\alpha_L)L(t-1) + \alpha_L|e(t)| \text{ , } \alpha_L\text{=0.005} \quad (21)$$

Value of adaptive coefficient is given by (22), where L is the noise level and M constant of proportionality.

$$\alpha_{RNL} = \alpha_0 max\left(1, min\big(R, ML(t)\big)\right) \text{ , } R\text{=10, } M\text{=30} \quad (22)$$

V. Results of Simulated ANC System

For the purpose of running tests of convergence and tracking, test signals are generated and fed to ANC system.

A. Test Signals

Generated test signals are composed of three sinusoidal harmonic components and superimposed broadband noise, (23), (24), (25) and (26). Signal is normalized to an interval [-1,1]. During the synthesis of signals, tacho signal is also generated marking the beginning of each signal period.

$$x(t) = a_1 sin(2\pi f_1 t + \theta_1) + a_2 sin(2\pi f_2 t + \theta_2) + a_3 sin(2\pi f_3 t + \theta_3) + n(t) \text{ ,}$$

$$a_1\text{=1.0, } a_2\text{=0.5, } a_3\text{=0.2} \quad (23)$$

$$f_2 = 2f_1 \quad (24)$$

$$f_3 = 3f_1 \quad (25)$$

$$n(t) = M(1 - 2 * rand(t)), \ M\text{=0.1} \quad (26)$$

Motivated by previous consideration regarding noise changes in rotating machinery and transformers, four test signals have been generated (electroacoustic loop gain is 30, involving A_1S_M = 10, and A_2B_S = 3).

B. Convergence Tests

Convergence tests were performed by applying a test signal at the start of ANC system operation. Continuous and spool up signal was used. Convergences, as mean squared error, MSE, are shown in Fig. 5, Fig. 6 and Table I.

1) Continuous Signal

Continuous signal of constant frequency and amplitude was applied, Fig. 5. Best convergence was achieved with an initial convergence, followed by noise level method, Fig. 6.

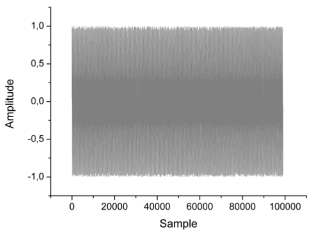

Figure 5. Continuous signal

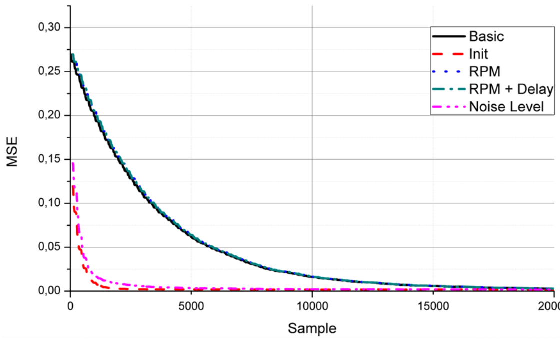

Figure 6. Convergence applied to continuous signal

2) Spool Up Signal

Signal with rising frequency (1:2 ratio) and amplitude was applied, Fig. 7. Significant advantage (faster convergence) was achieved with methods based on residual noise level and rotational speed with delay, Fig. 8.

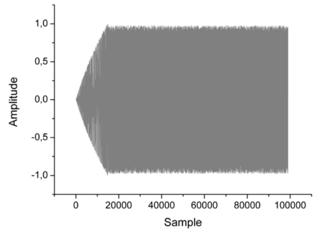

Figure 7. Spool up signal

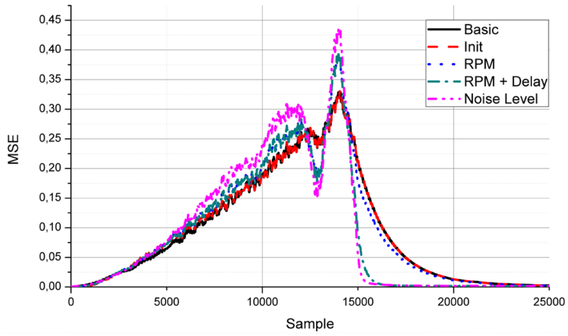

Figure 8. Convergence applied to spool up signal

TABLE I. Convergence Times

Method	Final MSE	90 % convergence (samples)
Continuous signal		
Basic	0.00196	7969
Initial period		782
RPM based[1)]		7969
RPM based + delay[1)]		7969
Residual noise level		1086
Spool up signal[2)]		
Basic	0.00193	18199
Initial period		18198
RPM based		17910
RPM based + delay		15273
Residual noise level		15041

[1)] RPM is fixed in continuous signal [2)]end of spool up at sample 15000

C. Tracking Tests

Tracking tests were performed by applying time-varying test signal to the ANC system that has already converged and operated in a steady state for some period. It shows the dynamic behavior of an ANC system when there is a change in the spectrum or noise level of the test signal (departure from the steady state). These tests verify adaptation after rotating machinery speed change and residual noise level change after load change. RPM change and load change test signals were used.

1) RPM Change

Signal of constant amplitude with the change in RPM (1:3 ratio) between the samples 40000 and 50000, Fig. 9 was applied. Best result was achieved with noise level method, very closely followed by RPM combined with delay, Fig. 10.

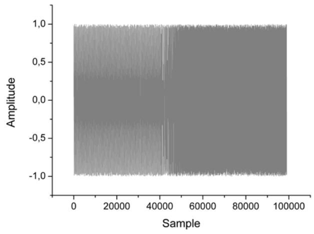

Figure 9. Signal with RPM change after steady section

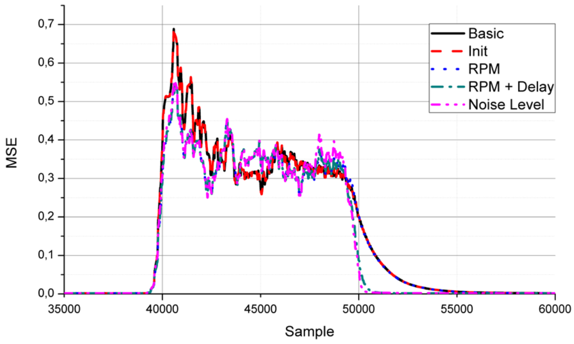

Figure 10. Tracking of RPM change after convergence

2) Level Change Signal

Signal with constant RPM but with the abrupt level change was applied. Drop in level of 50% was inserted between the samples 40000 and 60000, Fig. 11. Best result was achieved with noise level method, Fig. 12.

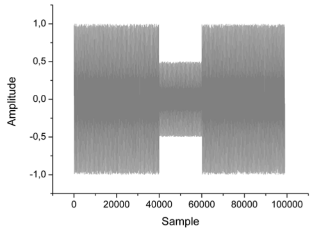

Figure 11. Level change signal

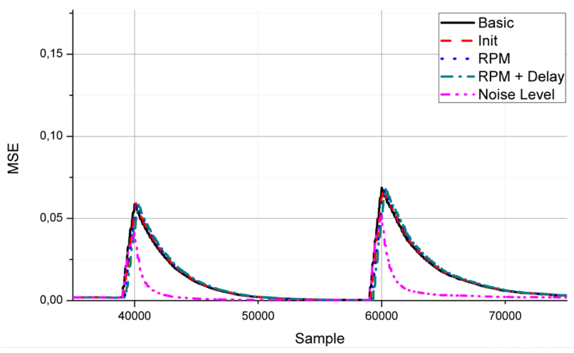

Figure 12. Tracking of level change after convergence

VI. Discussion

Results depend to an extent on the parameters used for defining adaptive step of each method: α, α_L, M, R, initial convergence period, the rate of change of RPM and the noise level in test signal. Simple, basic and initial period methods yield acceptable results, with initial period providing support for spool up. RPM based method with delay and noise level method have close results on spool up and RPM change tests. Keeping adaptive coefficient at a higher level for some time after the last RPM change is a significant improvement to the raw RPM method. Due to the mild rate of change of RPM in test signals, there is no great difference between results of noise level and RPM method. The noise level method is slightly more complex.

VII. Conclusion

ANC by the synchronized waveform generator is a viable solution for attenuation of periodic noise present in rotating machinery and transformers. Convergence and tracking properties can be improved by introduction of variable adaptive coefficient. Motivated by operation of rotating machinery (spool up, spool down, change of rotational speed and load change) and transformers (load change), the variable adaptive coefficient that depends on elapsed time (initial period), RPM with variant (delay) and the residual noise level has been investigated. Greatest improvements have been achieved with adaptive coefficient related to noise level and RPM with delay. For rotating machinery best approach are methods based on the residual noise level and RPM with delay or a combination (maximum of both). For transformers (fixed frequency), the best approach is a method based on a residual noise level.

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