

Order Selection of the Hearing Aid Feedback Canceller Filter Based on its Impulse Response Energy

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Abstract— Numerous methods have been proposed to cancel the unpleasant effects of acoustic feedback between the loudspeaker and microphone in hearing aid systems. Adaptive Feedback Cancellation (AFC) methods are often used to estimate an FIR filter for cancelling the feedback path effect. In estimating the AFC FIR filter, it is important to select the order of the filter properly; especially when the feedback path changes from one environment to another and no knowledge about it is available. Choosing improper filter order causes deficient system performance or excessive computations and power usage in the system. We present tracking of the energy of AFC FIR filters and its convergence behavior as a new criterion for determining the proper order for AFC FIR filter. Experimental results show validity of the proposed criterion.

I. INTRODUCTION

Adaptive Feedback Cancellation is among the most widely used techniques to decrease the interfering effects of acoustic feedback path between loudspeaker and microphone in a hearing aid system. Because of having a closed loop system, due to the existence of feedback path, many AFC methods use some sort of de-correlating techniques to separate the original signal from that coming from the feedback path to the microphone. Inserting a processing delay in the forward path, inserting de-correlating pre-filters, and noise injection techniques are among the methods used to de-correlate the mentioned signals [1]. The feedback path characteristics change from one environment to another and adaptive estimation of the canceling filter is needed. In order to use AFC methods, as well as other methods, order of the canceling FIR filter is needed. Underestimate of the order of the canceling filter results in poor performance of the hearing aid system, i.e. inadequate cancellation of the feedback effect. Overestimate of the order requires excessive computations, more power usage, and unnecessary extra delays, while it does not alleviate the feedback path effect significantly. Thus, a good estimate of the order of the canceling filter will be quite beneficial in design of feedback path cancellation systems.

Performance of an AFC technique can be assessed using two criteria; the Perceptual Evaluation of Speech Quality (PESQ), and the Misalignment (MISA). However, in real situation, neither one of these criteria can be used for finding an appropriate order for the canceling filter since they both require a priori full knowledge of the true feedback path model or desired signal ($s[n]$ in Fig. 1).

Here, we propose a new criterion to find an appropriate AFC FIR filter of optimal/semi-optimal order without requiring a priori knowledge of the true feedback path model

or desired signal. To present the proposed method, we use a one-time short-duration (20 msec) White noise injection technique to estimate the feedback path model using least squared error method. We use three different true feedback path models measured in laboratory and implement numerous experiments to validate our results. We show that both PESQ and MISA criteria converge to some optimal values as the order of estimated AFC FIR filter increases. Based on the analysis of these criteria we show that the energy of the estimated AFC FIR filter also converges as a function of the filter order with results consistent with those for the PESQ and the MISA. However, unlike the PESQ and MISA, computation of the energy of AFC FIR filters is easily possible in practical scenarios since it does not require any information about the true feedback path model or desired signal. Therefore, our proposed method is based on computing and tracking the energy of the estimated AFC FIR filter as its order increases, and selecting an estimated filter whose order falls in the region of convergence of the energy function. Our experiments show that the proposed criterion results in selection of an AFC FIR filter with optimal/semi-optimal order giving the best compromise between performance and computational complexity.

Section II briefly describes the applied noise injection method and its evaluation based on PESQ and MISA. In Section III, the proposed criterion, i.e. the FIR filter energy as a function of filter order, is derived. Section VI presents the experimental results and Section V concludes the paper.

II. NOISE INJECTION METHOD

Fig. 1 represents the noise injection technique used in this paper. The selected technique is categorized in non-continuous noise injection group. Regardless of other methods in this group [2]-[5], White Gaussian noise is injected once and for a very short duration of time, i.e. 20 msec.

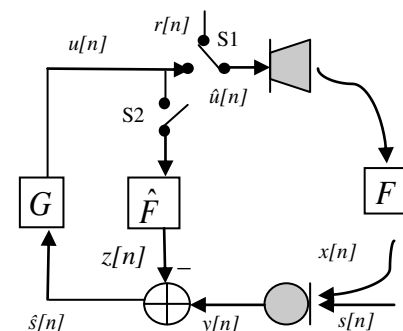


Fig. 1. Noise injection structure in hearing aid

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According to Fig. 1 the microphone signal is written as:

$$y[n] = s[n] + \hat{u}[n] * f[n] \quad (1)$$

where $f[n]$ is the impulse response of the feedback path; and during noise injection period $\hat{u}[n] = r[n]$. $r[n]$ is the injected zero-mean stationary White noise. Finding the cross correlation between the microphone signal and the injected noise leads to:

$$r_{y\hat{u}}[l] = r_{s\hat{u}}[l] + r_{\hat{u}\hat{u}}[l] * f[l] \quad (2)$$

In which, l is the correlation lag and “*” denotes linear convolution operation. $r_{s\hat{u}}[l]$ is negligible as the White noise is considered uncorrelated with the speech signal. Stacking the equations corresponding to different lags, a new equation can be written in the matrix form:

$$\mathbf{r}_{y\hat{u}} = \mathbf{R}_{\hat{u}\hat{u}} \cdot \hat{\mathbf{f}} \quad (3)$$

where

$$\mathbf{r}_{y\hat{u}} = [r_{y\hat{u}}[0] \ r_{y\hat{u}}[1] \ \dots \ r_{y\hat{u}}[L-1]]^T_{1 \times L} \quad (4)$$

$$\hat{\mathbf{f}} = [\hat{f}_0 \ \hat{f}_1 \ \dots \ \hat{f}_{M-1}]^T_{1 \times M} \quad (5)$$

$$\mathbf{R}_{\hat{u}\hat{u}} = \begin{bmatrix} r_{\hat{u}\hat{u}}[0] & r_{\hat{u}\hat{u}}[-1] & \dots & r_{\hat{u}\hat{u}}[-M+1] \\ r_{\hat{u}\hat{u}}[1] & r_{\hat{u}\hat{u}}[0] & \dots & r_{\hat{u}\hat{u}}[-M+2] \\ \vdots & \vdots & \ddots & \vdots \\ r_{\hat{u}\hat{u}}[L-1] & r_{\hat{u}\hat{u}}[L-2] & \dots & r_{\hat{u}\hat{u}}[-M+L] \end{bmatrix}_{L \times M} \quad (6)$$

M is the length of AFC filter $\hat{\mathbf{f}}$ (order = $M-1$) and L is the maximum lag. In common Cross Correlation method where the injected signal is considered perfect zero-mean White Gaussian noise, $\mathbf{R}_{\hat{u}\hat{u}}$ is a diagonal matrix and each filter coefficient \hat{f}_l can be easily derived by division of the corresponding $r_{y\hat{u}}[l]$ by a constant, i.e. $r_{\hat{u}\hat{u}}[0]$. Moreover, in case of having ideal zero-mean White Gaussian noise, the order of the feedback path can be easily found, since the cross correlation is zero for the lags higher than the order of the feedback path. However, using a short duration of injection, in other words, windowing the injected noise makes it not quite a White Gaussian process. Hence, [6] has used non diagonal $\mathbf{R}_{\hat{u}\hat{u}}$ represented in Eq. (6); and $\hat{\mathbf{f}}$ can be found by (least squared estimation):

$$\hat{\mathbf{f}} = (\mathbf{R}_{\hat{u}\hat{u}}^T \mathbf{R}_{\hat{u}\hat{u}})^{-1} \mathbf{R}_{\hat{u}\hat{u}}^T \mathbf{r}_{y\hat{u}} \quad (7)$$

In case of having $L=M$ which is more efficient and used in this paper, the coefficients can be derived by:

$$\hat{\mathbf{f}} = (\mathbf{R}_{\hat{u}\hat{u}})^{-1} \mathbf{r}_{y\hat{u}} \quad (8)$$

Once the estimated model is derived, it is put in parallel with the feedback path to cancel the feedback signal, i.e. the canceller path is connected to the other parts of the system by switch S2 (Fig. 1).

However, one important concern in AFC is how to select a proper order for filter $\hat{\mathbf{f}}$. A filter with an insufficiently small

order does not possess adequate efficiency in cancelling the feedback signal. Having a larger than required order increases the complexity of the system (hence, more power usage of the hearing aid) but does not considerably improve the system performance compared to what is provided by a proper order. Thus, optimum order is obtained as a result of good compromise between performance and computational complexity of the system.

To show the importance of order selection, the performance of the AFC FIR filter should be compared for different orders. To evaluate the performance, two criteria are used in this paper, i.e. the PESQ and MISA defined as follows.

A. Perceptual Evaluation of Speech Quality (PESQ)

PESQ is a test methodology for automated assessment of speech quality. The PESQ value is in the range of 0.5 (bad) to 4.5 (excellent) as described in [7].

B. Misalignment (MISA)

MISA is the normalized energy of the error between the original feedback model and the estimated one:

$$MISA = 10 \log_{10} \left(\frac{\int_0^\pi |F(e^{j\omega}) - \hat{F}(e^{j\omega})|^2 d\omega}{\int_0^\pi |F(e^{j\omega})|^2 d\omega} \right) \quad (9)$$

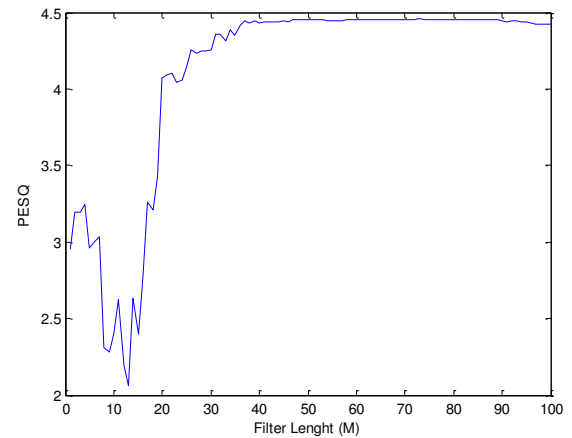


Fig. 2. PESQ values versus filter length

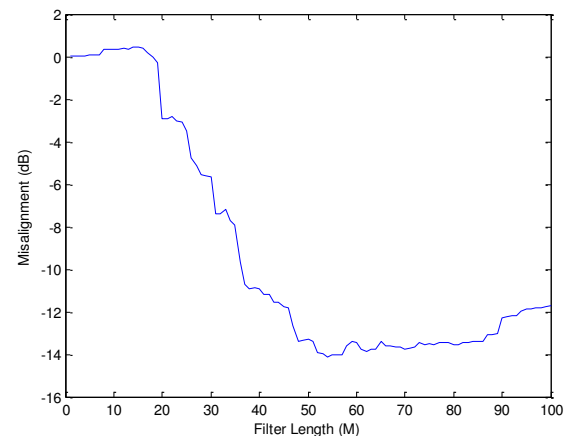


Fig. 3. Misalignment values versus filter length

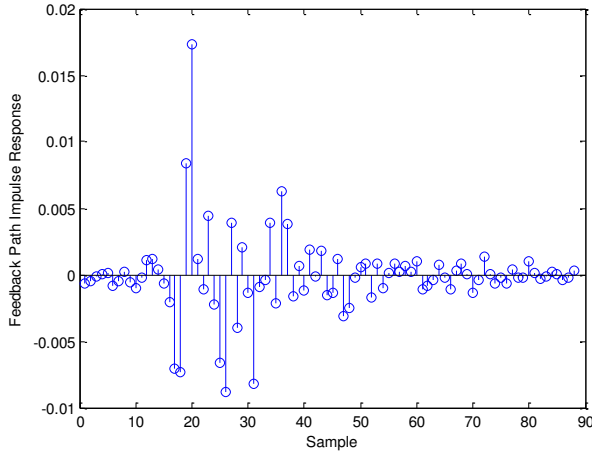


Fig. 4. Impulse Response of the measured/true feedback path

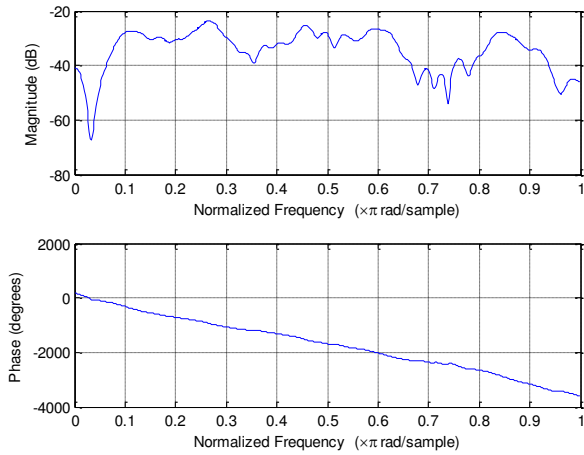


Fig. 5. Frequency Spectrum of the measured/true feedback path

Fig. 2 represents a typical curve for the PESQ values versus different orders of AFC filter. Higher values of the PESQ represent better performance of the system. Fig. 3 shows the same curve for the MISA. According to the description of the MISA, lower values correspond to higher performance.

The original feedback path model considered in the above simulation is an FIR filter with order 88 measured in the laboratory and sketched in Figs. 4 and 5. Tracking PESQ and MISA curves show inadequate performance for small orders (orders less than 40). However, for orders approximately higher than 40 both criteria fluctuate around an average value. In other words, they converge for filter orders even less than the order of original feedback path model, i.e. 88. Based on Fig. 2 and 3, increasing the order of the filter beyond certain value does not improve the PESQ and the MISA notably but will increase computational complexity and processing delay. Hence, an AFC FIR filter of order smaller than 88, like 50, should be good enough based on the PESQ and the MISA criteria.

III. NEW CRITERION FOR AFC FIR FILTER AND ITS ORDER SELECTION

In light of the discussion of Section II, a question which should be answered is how to find an AFC FIR filter of proper order compromising performance and computational complexity of the system. The method in [8] tracks the PESQ and the MISA criteria and finds a filter of optimum order based on the convergence of these two performance criteria. Although simulation lets us calculate the PESQ and the MISA, in a real scenario it is almost impossible to compute these two criteria. The MISA calculation requires the true transfer function of feedback path, i.e. $F(e^{j\omega})$ in Eq (9) which is not available. Also, to compute the PESQ the desired signal, i.e. $s[n]$ in Fig. 1, is required which is again unavailable in real situation. Hence, a practical criterion is needed which is developed and presented here.

As shown in Fig. 2 and 3 both the PESQ and the MISA converge after some order, $N_0 \cong 50$. Similar converging behavior was observed for the PESQ and the MISA when we used 3 different measured/true models of the feedback path.

It can be easily seen that the convergence of MISA in Eq. (9) to small positive value for AFC FIR filters of order $N = N_0 + k$ where $k = 1, 2, 3, \dots$, implies the convergence of average power of the error function to small positive value of δ as shown in Eq. (10).

$$\left(\frac{1}{2\pi}\right) \int_{-\pi}^{\pi} |F(e^{j\omega}) - \hat{F}_N(e^{j\omega})|^2 d\omega = \delta = \mathbf{y}^T \mathbf{y} \quad (10)$$

Where $\mathbf{y}^T = [\mathbf{f} - \hat{\mathbf{f}}_N]^T$, \mathbf{f} and $\hat{\mathbf{f}}_N$ are column vectors containing the finite impulse response samples of the true and estimated feedback path (FIR) impulse responses, respectively. Subscript N denotes the order of the estimated filter. We note that \mathbf{f} and $\hat{\mathbf{f}}_N$ are taken to be of the same length by zero padding of the shorter vector as N varies.

Thus, the convergence of the MISA to small positive values produces biased estimates of the feedback path \mathbf{f} given by $\hat{\mathbf{f}}_N$, due to using 20 msec of data. Furthermore, it implies that the energy of the estimated FIR filters also converges as the order of the filter increases. The convergence can be tracked better by tracking the energy of AFC FIR filters $\hat{\mathbf{f}}_N$ as the order is increased. Moreover, calculating the square of the coefficients for the energy generates a smoother curve; and convergence is more easily observed. Fig. 6 shows the convergent behavior of the energy of the estimated filter as its order increases. We note that the convergence occurs for $N = N_0 + k$ where $k = 1, 2, 3, \dots$ just as it did for the MISA and the PESQ. Therefore, tracking of the energy of the estimated AFC FIR filter as a function of the filter order provides a criterion to obtain appropriate order for AFC filter.

Unlike the MISA and the PESQ criteria, computation of the energy of the AFC filters can easily be done without requiring spectrum of the measured/true feedback path transfer function or desired signal. Thus, we propose the energy curve to be used as viable criterion to find the AFC FIR filter of appropriate order in a real scenario. Next section evaluates the proposed criterion.

IV. EXPERIMENTAL RESULTS

In this section the proposed criterion is used to find the optimum order for the AFC FIR filter. We used 3 different measured/True models of the feedback path. Similar results were obtained for all the different models as the one presented here. The feedback path model discussed here is an FIR filter of order 88 measured in the laboratory. As depicted in Fig. 1, 20 msec of zero-mean White Gaussian noise signal is sent to the loudspeaker. The estimated coefficients are calculated by Eq. (8) for different orders. Since the injected noise is random, in order to have more reliable comparison, the results are the average of 30 executions of the algorithm. The PESQ and the MISA curves are the same as what depicted in Figs. 2 and 3. Energy of the impulse response of the AFC FIR filter is plotted in Fig. 6. Comparing this curve with the curves for the PESQ and the MISA reveals the same convergence behavior in all three criteria. The convergence of the energy can be seen better by smoothing its curve by averaging or using Median filter. Fig. 7 is one smoothed curve using average of 9 consecutive orders. According to Fig. 6 or 7, an order between 50 and 55 satisfies the required performance of the system. That is, by choosing an order not outside the 50 to 55 range we can obtain satisfactory PESQ and MISA while avoiding higher order filter and additional computations.

It should be mentioned that between the PESQ and the MISA, the PESQ determines the quality of the sound signal heard by the patients and is more important than the MISA. Our optimum order between 50 and 55 provides the PESQ of 4.4520 which is only 0.0020 less than the PESQ of 4.4540 for the filter of order 88. This amount is not sensible by the hearing aid user but the computations and delays for an order between 50 and 55 are much less than that for a filter of order 88. Direct calculation of Eq. (8) requires $O(M^3)$ operations. Hence, the required operations are reduced from $O(88^3)$ to $O(50^3)$ in case of using the order of 50 instead of 88.

V. CONCLUSION

Feedback cancellers are usually used in order to decrease the interfering and annoying effects of the feedback path in hearing aid system. However, finding an appropriate order for the AFC FIR filter is needed in system design. This issue becomes more important when the feedback path characteristics vary from one environment to another requiring an updated AFC filter. In this paper a new criterion is proposed that enables finding an appropriate AFC FIR filter of semi-optimal order without requiring any knowledge of the true transfer function and the order of the feedback path. Comparing the results of the experiments with respective PESQ and MISA criteria show the validity of selecting the AFC FIR filter based on the proposed new criterion.

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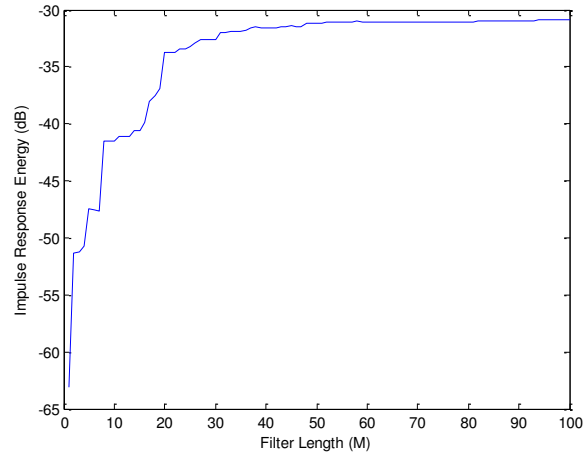


Fig. 6. Energy of AFC filter

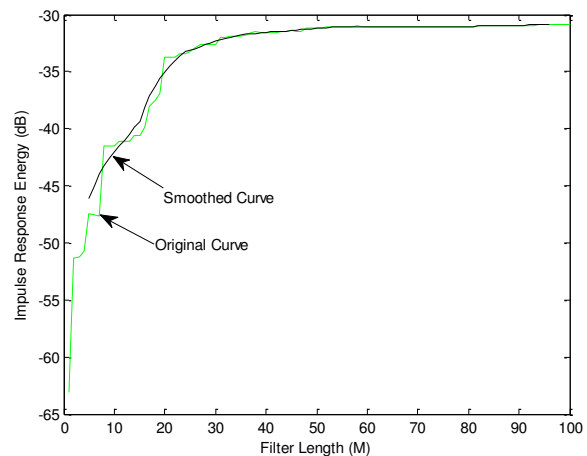


Fig. 7. Energy of AFC filter, original curve and smoothed curve