ACOUSTIC FEEDBACK CANCELLATION IN HEARING AIDS

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ABSTRACT

We describe a maximum phase cancellation scheme for hearing aids that prevents acoustic oscillations. In this scheme, the open-loop phase delay in the primary audio frequency region is canceled to the largest extent possible. At the same time, the magnitude response of the new open-loop transfer function outside the primary audio frequency region is suppressed by using negative feedback. The use of both these techniques increase the stability and the maximum usable gain of the overall hearing aid system. Computer simulations, using real measured data, are used to confirm our results.

1. INTRODUCTION

Hearing aid research has made tremendous strides both in miniaturization and in limiting power consumption in the last few years. However, a fundamental problem that places severe limitations on the maximum usable gain is acoustic feedback. The hearing aid can be modeled as a positive feedback system where acoustic oscillations are initiated when the open-loop gain of this feedback system is unity and the open-loop phase is a multiple of 2π radian. A number of techniques have been tried to alleviate the acoustic feedback problem by either altering the gain response or the phase response of the overall loop; these include time-delay, inverse filtering and feedback cancellation.

Figure 1 shows a signal flow graph of the hearing aid modeled as a feedback system. In this figure TM represents the transfer function of the microphone. THA represents the transfer function of the hearing aid including the preamplifier and filters. TR represents the transfer function for the receiver and the output power amplifier, and TF represents the transfer function of the mechanical and acoustic feedback that initiates acoustic oscillations. In figure 1, the filled in blocks represent electrical signals while the clear blocks represent acoustic signals.

The transfer function of the overall hearing aid including acoustic feedback is given by

\[ T_{system} = \frac{T_M T_{HA} T_R}{1 - T_M T_{HA} T_R T_F} \] (1)

By defining the open-loop transfer function as

\[ T_{open} = T_M T_{HA} T_R T_F \] (2)

Figure 1: Control system model of a hearing-aid system

it is possible to see that when the magnitude of the open-loop transfer function is equal to unity and the phase is a multiple of 2π then the system transfer function is undefined and the hearing aid becomes unstable. The effects of acoustic feedback can be reduced by altering the gain or the phase relationships of the feedback-loop of the hearing aid. Phase altering approaches include frequency shift [1], [2] where the input spectrum entering at the microphone is shifted by a few Hertz prior to being fed it to the receiver. Though successful with public address systems for years this approach has not had much success in hearing aids due to the large percentage variation of the feedback path. The phase information can also be altered by providing a time-varying delay in the signal path. This approach provides a maximum of 1-2dB of extra gain and also suffers from a audible warbling sound [3]. Other phase altering techniques [4] have not enjoyed much success either. In gain altering approaches the primary aim is to reduce the gain of the system at the frequencies where oscillations are likely to occur. The usual method that is employed to accomplish this is the use of a narrowband notch filter [5], [6] or a number of narrowband notch filters [6]. Unfortunately, even adaptive notch filtering techniques [3], [6] have provided only 3-5dB of additional usable gain and is not sufficient for high gain hearing aids. In feedback cancellation an attempt is made to cancel the entire effect of the feedback signal by providing an additional feedback path that is equal to but 180 degrees out of phase from the normal problematic feedback path. Adaptive versions of the feedback cancellation scheme has provided the maximum increase in usable gain ([7], [3], [8], [9]). Though feedback cancellation has enjoyed greater success it too is limited by some inherent problems. During normal use the acoustic feedback path changes quite dramatically and if the internal feedback path does not adapt to this change then the overall hearing aid system is
likely to become unstable primarily due to the effects of the internal feedback path itself.

The idea of a phase cancellation scheme is inherently more immune to both gain and phase variations. Theoretically it is capable of providing 180 degrees of phase margin and is totally immune to gain variations if both poles and zeros of the open-loop transfer function lie in the left-half-plane. But, unfortunately, the open-loop transfer functions of real hearing aids do contain right-half-plane zeros. Because of these right-half-plane zeros complete phase cancellation is not possible. We introduce maximum phase cancellation where the phase delay of the original open-loop is canceled in the primary audio frequency region (100Hz-5kHz) to the largest extent possible. At the same time the zero-phase frequencies in the resulting open-loop transfer function are moved to a region outside the primary audio frequency range. The magnitude outside the primary audio frequency range is further suppressed to be less than unity by using negative feedback. As mentioned earlier the feedback path transfer function changes during normal operation. However, for this paper, we we shall assume it to be fixed at a value close to the maximum seen in normal use. Any reduction in the value only makes the system more stable. In the future, we plan to publish techniques that are capable adapting to variations in the feedback path.

In section 2, we describe the method of maximum phase cancellation in the primary audio frequency range for a hearing aid system. In section 3, we illustrate the use of negative feedback in suppressing the magnitude response of hearing aid outside the primary audio frequency range. And finally, we provide a summary of the results discussed in this paper.

2. MAXIMUM PHASE CANCELLATION (MPC)

In general, we can express the open-loop transfer function of an ordinary hearing aid system as

\[ T_{open} = A(s - z_1)(s - z_2)...(s - z_m)(s + z_{m+1})...(s + z_n) \frac{(s + p_1)...(s + p_n)}{(s + p_1)...(s + p_n)} \]  

(3)

where A is a constant, m is the number of left-half-plane zeros, n - m is the number of right-half-plane zeros, and p is the number of left-half-plane poles. These zeros and poles can either be real or complex (complex ones appear in pairs). The value for the poles and zeros are extracted from curve fitting measured values [10]. Our studies show that there always exists some right-half-plane zeros in the transfer functions of the receiver and the acoustic feedback path. As a result, it is impossible to provide complete phase cancellation while maintaining the stability of the entire system. Nevertheless, the open-loop phase delay can still be canceled to a large extent. Theoretically, the maximum phase cancellation, under the constraint of system stability, can be reached by implementing an equalization block \( T_{EQ} \) inserted between the amplifier and the receiver as shown in figure 2. The transfer function of \( T_{EQ} \) is equal to the inverse of the fractional part of equation (2), i.e.

\[ T_{EQ} = \frac{(s + p_1)...(s + p_n)}{(s + z_{m+1})...(s + z_n)} \]  

(4)

Figure 2: Control system model of a hearing-aid system with a maximum phase equalization block

As an example, in figure 3, the response curves of the original open-loop and the open-loop with \( T_{EQ} \) inserted in between the amplifier and the receiver are plotted in dashed and solid lines respectively. From this figure, we see that the phase delay of the new
open-loop with \( T_{EQ} \) inserted is much smaller than the original one.

In fact, in the original open-loop phase response curve there are three zero-phase frequencies (i.e. 0.6kHz, 2.2kHz, 4.2kHz). However the magnitude of the open-loop transfer function exceeds unity at 2.2kHz. As a result of this, oscillations occur, and is shown in figure 6. The dashed curve in figure 6 shows the closed-loop magnitude response of the original system, where the peak located at 2.2kHz represents acoustic oscillations. Since in normal use of the hearing aid the transfer function of acoustic feedback path is fixed or varies unpredictably, the only way to avoid acoustic oscillations is to reduce the gain of the forward-path. Therefore the usable gain is limited by onset of acoustic oscillations. If the forward gain is reduced sufficiently, then no oscillations occur. An example of such a closed-loop magnitude response is plotted as a dotted curve in figure 6.

The advantage of inserting \( T_{EQ} \) into the loop is that the phase is maximally canceled, and the zero-phase frequencies become zero and infinity. No zero-phase point appears in the primary audio frequency region. Unfortunately, the magnitude of the open-loop including \( T_{EQ} \) increases rapidly with increased frequencies. Additionally, it is also desirable to reduce the gain at lower frequencies to increase intelligibility [11]. But this problem can be solved if we consider the following: first, we notice that, there are some zeros in equation (2) located at the origin. Second, there are a number of poles in the receiver transfer function that lie beyond 10kHz. A simple explanation for this is that the impedance of receivers increases rapidly with increased frequencies. These poles do not contribute much phase delay in the primary audio frequency region. Therefore, \( T_{EQ} \) can be chosen as the inverse of the partial original open-loop transfer function in which only the left-half-plane poles and zeros located in the primary frequency region are included. We call this approach as the primary audio frequency maximum phase cancellation scheme (PAFMPC). In this scheme, the magnitude response decreases at lower frequencies and does not increase as rapidly as shown in figure 2 in the high frequency region.

3. NEGATIVE FEEDBACK

Further magnitude reduction in the high frequency region can be achieved by implementing a negative feedback-loop using blocks \( T_{C1} \) and \( T_{C2} \) as shown in figure 4.

If we set the transfer function \( T_{C2} \) to be equal to \( 1/T_{EQ} \), the transfer function of the inner-loop can then be simplified as

\[
T_{inner} = \frac{T_{EQ}}{1 + T_{C1}}
\]

Obviously, in order to maintain the stability of the system and suppress any acoustic oscillation, \( T_{C1} \) should be chosen to meet the following conditions:

- \( T_{C1} \) must be a polynomial in \( s \) of order \( m \), i.e. the number of right-half-plane zeros.

![Figure 4: Control system model of a hearing-aid system with a maximum phase cancellation block and a negative feedback loop](image)

- The coefficients of this polynomial should be chosen such that the transfer function of the resulting inner-loop \( T_{EQ}/(1 + T_{C1}) \) will have only left-half-plane poles.
- The zero-phase crossing points introduced by additional phase delay of \( 1/(1 + T_{C1}) \) should lie outside the primary audio frequency region.

In our example, \( m \) is equal to 4, where one pair of right-half-plane zeros \( z_{1,2} = (3.5026 \pm i.5156)10^3 \) come from the receiver transfer function, and another pair \( z_{3,4} = (3.4009 \pm i.0998)10^3 \) comes from the acoustic feedback path. It is easy to show that the following simple choice of \( T_{C1} \)

\[
T_{C1} = \frac{s/3500 + 1}{s^4}
\]

will satisfy the above three conditions if the gain of forward-path is adjusted appropriately. Computer simulation results of the new open-loop transfer function with \( T_{EQ} \) and the negative feedback-loop discussed above is plotted in figure 5. From the curves in this figure, we see that the zero-phase points of the new-open loop are located below 800Hz or above 5kHz. However, the magnitude of the open-loop response at these zero-phase frequencies is less than unity. Therefore acoustic oscillations will not occur.

Computer simulation results of the closed-loop transfer function for the PAFMPC scheme is plotted in solid in figure 6. In comparison to the original closed-loop response curves which are plotted in dashed and dotted lines, we see that the new closed-loop transfer function not only prevents acoustic oscillations but also improves the maximum usable gain.

4. SUMMARY

In summary, we have presented a maximum phase cancellation scheme (MPC) for a hearing aid system which can prevent acoustic oscillations and increase the usable gain. Two techniques have been introduced, one, the phase equalization block \( T_{EQ} \) which cancels the phase delay in the primary audio frequency range; and two, the blocks \( T_{C1} \) and \( T_{C2} \) that are used to reduce the magnitude of the open-loop outside the primary audio frequency region. A number of additional techniques exist to increase the maximum usable gain and are to appear in another paper in the near future [12].
Figure 5: New open-loop frequency response

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References


Figure 6: Closed-loop magnitude response


