AND9660/D

Ezairo® Preconfigured Suite Adaptive Feedback Canceller

ON Semiconductor®

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APPLICATION NOTE

Introduction

This information note describes the new Sub−Band Adaptive Feedback Canceller (Feedback Canceller) included in the Ezairo Preconfigured (Pre Suite) firmware bundles. The new Feedback Canceller is a completely re−designed algorithm that achieves significant performance improvements compared to previous products. A sub−band architecture, enhanced control parameters, active gain management feature, and live−display support combine to provide greatly improved feedback management for new hearing aid products.

The sections below provide an overview of the algorithm's operation, and a detailed description of available adjustments to the algorithm's behavior.

Algorithm Overview

As in previous products from ON Semiconductor, the new Feedback Canceller algorithm operates by subtracting an internal estimate of the true hearing aid feedback signal from the microphone signal. If the internal estimate is accurate, then the actual feedback is cancelled allowing higher acoustic gain without squealing or ringing artefacts. Maintaining an accurate estimate of the true hearing aid feedback signal is essential to proper operation of the algorithm.

In the Ezairo Pre Suite firmware bundle, the internal feedback estimate is based on a frequency domain representation of the external feedback path. This allows the algorithm to maintain improved matching of feedback paths that exhibit large fluctuations across different frequencies. The frequency domain architecture also allows separate algorithm control in each of 32 different frequency bands. The end result is better tuning of the algorithm performance and improved coordination between Feedback Canceller operation and that of the other algorithms in the device.

Since acoustic conditions change over time, the algorithm must also make continuous adjustments of the internal feedback estimate to ensure accurate matching of the external feedback. Fast internal adjustments eliminate feedback quickly but can sometimes lead to undesirable audio artifacts, particularly for tonal or music−like input signals. Slow adjustments reduce the potential for artefacts, but also permit feedback events to persist for longer periods of time.

The Ezairo Pre Suite Feedback Canceller solves this dilemma using an intelligent, feedback−detection mechanism. Feedback that results in device oscillation or howling is referred to as active feedback. During periods of active feedback, the algorithm makes rapid adjustments to the internal feedback estimate.

During idle periods, with no active feedback, the algorithm resorts to slower adjustments to preserve audio quality. This results in faster cancellation of acoustic feedback to better handle rapidly changing acoustic conditions, while preserving audio quality under static acoustic conditions.

In some situations, the internal feedback estimate may not be able to match the characteristics of the external feedback encountered in the hearing aid. This may occur under conditions of severe feedback that the algorithm is unable to adequately compensate for. Without other action in the signal processing, the end result can be a sustained period of squealing often combined with undesirable artefacts as the algorithm attempts to restore stability of the system. The gain−management feature of the Feedback Canceller is designed to eliminate this type of sustained howling. When enabled, this feature limits the forward gain of the device to a pre−programmed limit, relative to the current feedback estimate. Due to the frequency domain architecture, this gain limit is only imposed at frequencies where a risk of feedback has been identified. This has the benefit of eliminating sustained howling while allowing higher amplification at frequencies where there is little risk of feedback.

The data used in the gain−management feature is also made available to fitting software via the Live Display feature. This allows a real−time read out of the current feedback estimate as seen by the hearing aid. This is useful to establish gain limits during fitting, to help reduce the risk of feedback events during hearing aid use.

Finally, it is impossible to provide a single set of parameters that are suitable for all types of hearing instruments, under all conditions. Settings and optimizations for one type of instrument may lead to undesirable behavior for other instruments. Some users may require more aggressive feedback control than others. The new Feedback Canceller addresses this by providing a rich set of adjustments to control algorithm behavior. This includes start−up behavior, adaptation speed and gain management. The remaining sections in this information note describe these adjustments in more detail and provide examples of how adjustments affect device behavior for a sample hearing aid.

User Controls

User controls for the Feedback Canceller are collected together in a single tab on the Sound Designer Control Panel screen. All Feedback Canceller parameters are specific to each program memory providing customizable behavior for different situations. For example, when starting the Ezairo Sound Designer Software Application for the first time using the Ezairo 7150 SL Demo Library, the Feedback Canceller tab appears as shown in Figure 1.

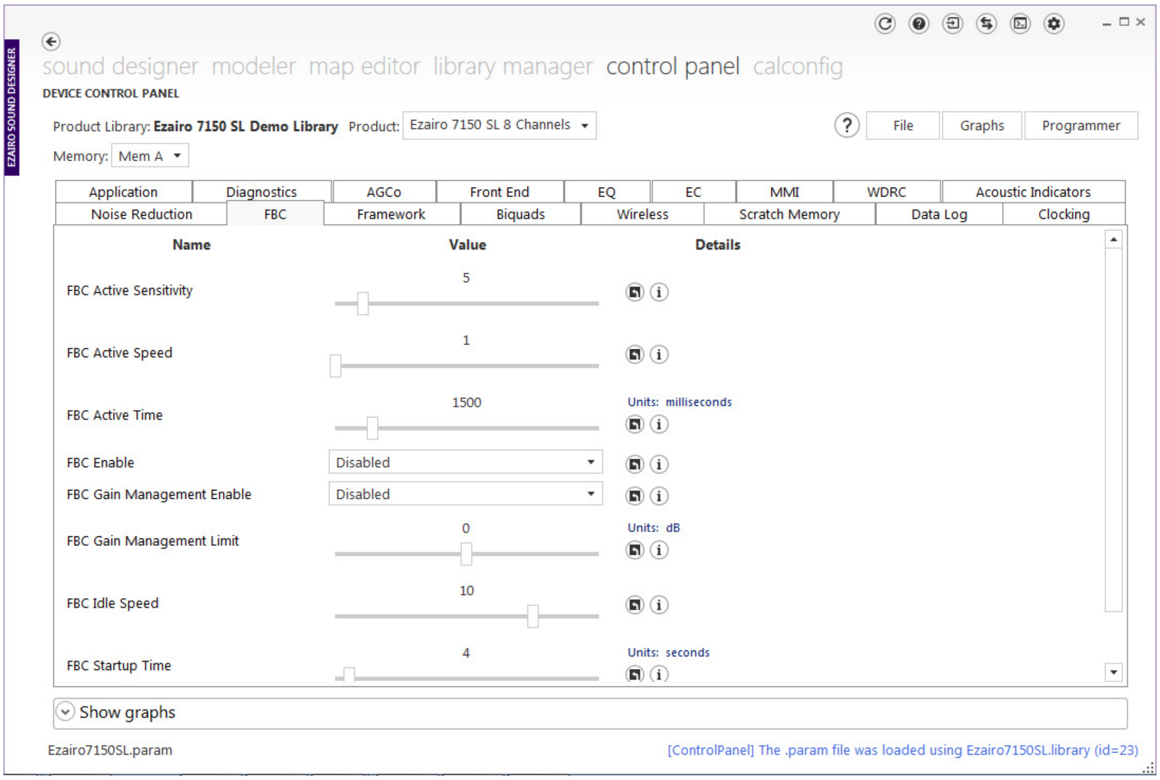

Figure 1. Control Panel Tab for the Ezairo 7150 SL Feedback Canceller

The Feedback Canceller Enable control turns the Feedback Canceller on and off, as desired. The Startup Time parameter controls the initialization behavior of the Feedback Canceller. Adaptation speed is controlled by the Active Speed, Idle Speed, Active Time and Active Sensitivity parameters. Gain Management is controlled through a separate enable parameter as well as the Gain Management Limit. Each of these controls are described in detail below.

Start Up

When applying power to the device for the first time, the Feedback Canceller starts in an uninitialized state. In order for the algorithm to initialize itself, the algorithm enters a rapid adjustment mode immediately upon power up. This rapid adjustment persists for a preset amount of time before the algorithm reverts to its normal operating mode. This allows the Feedback Canceller to obtain a rapid initial estimate of the feedback path.

The duration of the initialization phase is controlled by the Startup Time parameter. It can be adjusted in one−second increments from 1 up to 59 seconds. This allows the initialization phase to persist while the device is being placed onto the user’s ear, for instance, and can result in minimization of feedback events during that period. Once the device is in a stable position on the ear, the algorithm will quickly learn the new feedback path and will revert back to normal operation without user intervention.

Adaptation Speed

Adaptation speed is the rate at which the internal feedback estimate is updated. Fast adaptation causes large, rapid changes to the internal feedback estimate and will eliminate feedback very quickly. During periods with no feedback, however, the rapid internal adjustments are unnecessary and may lead to audible disturbances. Slow adaptation, on the other hand, causes small, slow changes to the internal estimate. When adapting slowly, feedback may persist for longer periods of time but there is a much smaller chance of undesired audible disturbances.

To provide rapid elimination of feedback while maintaining audio quality, the Feedback Canceller uses a new mechanism to control adaptation speed. This mechanism automatically switches between two different adaptation speeds depending on whether active feedback is detected or not. Both adaptation speeds are user−selectable allowing specific customization of Feedback Canceller behavior, as described below.

If active feedback is detected, the device switches to the Active Speed setting. The Active Speed setting is a number between 1 and 5 with smaller numbers resulting in faster adaptation. Typically, it is set to a small number to provide fast adaptation and quick elimination of feedback. The Active Speed setting is maintained inside the device for a time period determined by the by setting of the Active Time parameter. For rapidly changing conditions, or where a user is intolerant of feedback, a longer Active Time can result in fewer feedback events. A shorter Active Time can result in fewer audible disturbances, particularly when listening to music.

If active feedback is not detected, the device switches to the Idle Speed setting. The Idle Speed setting is a number between 1 and 10 with smaller numbers resulting in faster adaptation. The Idle Speed setting is maintained inside the device at all times when there is no active feedback. It is typically set to a larger number than the Active Speed to provide improved audio quality when the risk of feedback is very low.

Determination of active feedback is a complex process that depends on many variables internal to the algorithm. It is possible, however, to adjust the sensitivity of the algorithm to detecting external feedback using the Active Sensitivity parameter. A small value for Active Sensitivity lowers the detection threshold for external feedback and will result in more frequent triggering of the Active Adaptation speed setting. Conversely, a larger value will raise the detection threshold and will result in less−frequent triggering of Active Speed. With fewer active feedback events, the algorithm will spend more time in Idle Mode.

The default value for Active Sensitivity is 5. This provides good behavior under a wide variety of conditions and is suitable in high−gain program memories where feedback events may be more likely. Conversely, a higher value for Active Sensitivity can be used in program memories with lower gain or where music signals are expected. The reduced sensitivity to feedback will result in fewer Active Speed adjustments.

Gain Manager

The Feedback Canceller has the potential to provide rapid elimination of feedback under a wide range of conditions. However, there may still be brief periods of audible feedback while the algorithm is adapting or there may be situations where the external feedback is so severe that the algorithm is unable to adequately compensate. The Gain Management feature is designed to handle feedback under such conditions.

Gain Management is an optional feature of the Feedback Canceller that automatically limits the device gain to a pre−set level relative to the current feedback estimate. It is implemented independently in each frequency band so that gain is limited only at frequencies where a risk of feedback exists. The algorithm is fast−acting and incorporates knowledge of all algorithms affecting the audio path. The amount of gain management can be controlled directly through the Gain Management Limit parameter.

The Gain Management Limit is an adjustable parameter that can be set to a value from −16 dB to +16 dB. This parameter determines the maximum gain allowed, relative to the current feedback−path estimate. Negative values result in a gain limit that is below the estimated feedback path. This results in very few audible feedback events since the gain is maintained at a level below the expected feedback limit. Positive gain−limit values allow the gain to exceed the current feedback estimate and, therefore, require the adaptive part of the algorithm to maintain device stability. This provides more gain but may result in occasional, audible feedback events.

The following section illustrates the effect of these parameters through measurements on a typical hearing aid.

Feedback Canceller Tuning

Adjustment of the various parameters can be demonstrated using recordings and measurements of a typical hearing aid. In this article, measurements were performed using a Receiver−in−the−Canal (RIC) hearing aid fitted with a closed, tulip−style ear tip. The hearing aid was mounted on an acoustic mannequin that permitted recording of the hearing aid output signal using an ear−canal microphone. This setup is used to explore the additional gain provided by the Feedback Canceller, adaptation speed of the algorithm and considerations for maximizing audio quality.

Additional Gain Provided by the Feedback Canceller

The primary goal of the Feedback Canceller algorithm is to cancel active feedback and allow the gain of the instrument to be increased. The amount of additional gain provided by the Feedback Canceller can be measured using a very simple procedure.

1. With the Feedback Canceller disabled, start at a low gain level and increase the gain of the hearing aid in small steps (2 dB in this example) until feedback is observed. The highest gain recorded before the onset of feedback is referred to as the Maximum Stable Gain (MSG) of the hearing aid. Set the hearing−aid gain to this level.
2. Enable the Feedback Canceller then continue to increase the gain of the hearing aid in small steps (2 dB in this example) until feedback is observed again. The highest gain recorded above MSG before the onset of feedback is referred to as the Added Stable Gain (ASG) provided by the Feedback Canceller.

This process is illustrated in Figure 2, which shows the recorded output of the hearing aid as the gain is increased. The recorded waveform consists of a number of ambient−noise segments followed by short periods of white noise that are played from a loudspeaker in front of the hearing aid. The white−noise segments can be identified in the waveform by the sudden amplitude changes. The white−noise data are used in the subsequent analysis to determine the spectrum of the hearing aid output (as shown, for example, in Figure 3). The increasing amplitude of the noise segments from left to right indicates the gain changes. The gain at each segment is indicated by the numbers directly above the waveform in the diagram. As shown, the gain increases in 2 dB steps from MSG up to MSG + 24 dB. The very large−amplitude signal starting at time 275 s represents the onset of feedback with the Feedback Canceller enabled. The highest gain recorded before feedback is 22 dB, so the ASG is 22 dB for this configuration.

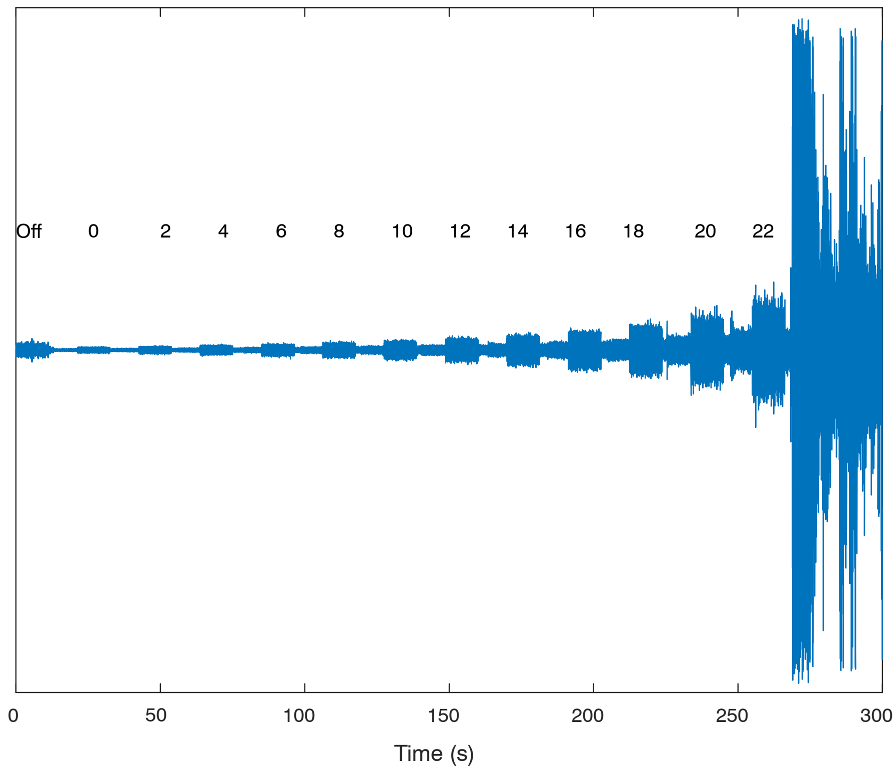

Figure 2. Hearing Aid Output Signal as the Gain is Increased in 2 dB Steps from MSG up to MSG + 24 dB. The Off Label indicates Feedback Canceller is Disabled. Numerical Labels indicate the Gain in Decibels above MSG.

Note that the level of the noise burst for a gain of MSG is higher when the Feedback Canceller is disabled than when it is enabled. This is due to ringing artefacts in the output signal that occur as the device approaches instability. The ringing artefacts are manifested as sharps peaks in the output signal as illustrated by the blue curve in Figure 3. The peaks occur at frequencies where there is strong feedback, which is from 3 to 4 kHz in this example. Once the Feedback Canceller is enabled, however, this strong feedback is eliminated and the spectral peaks, and their audible disturbance, are greatly reduced. This is illustrated by the red curve in Figure 3.

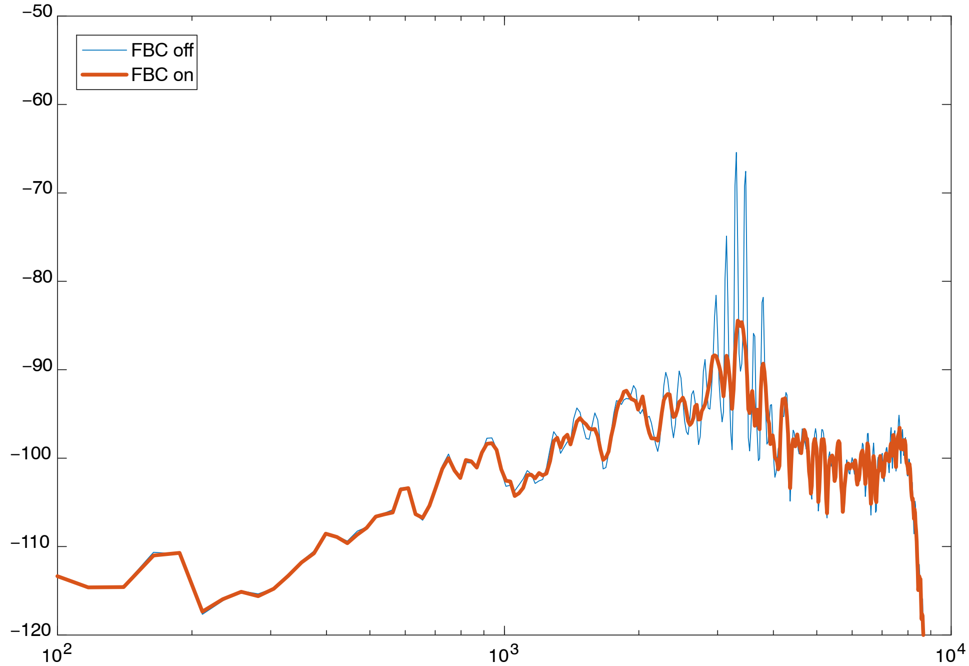

Figure 3. Hearing−Aid Output Spectra at Maximum Stable Gain (MSG) Point Comparing Feedback Canceller On and Off

Figure 4 shows the output−signal spectra for gains of MSG, MSG + 10 dB and MSG + 20 dB. As seen, the hearing aid is stable and spectral ripples are reduced to less than observed when the Feedback Canceller is off, although still visible at MSG + 20 dB.

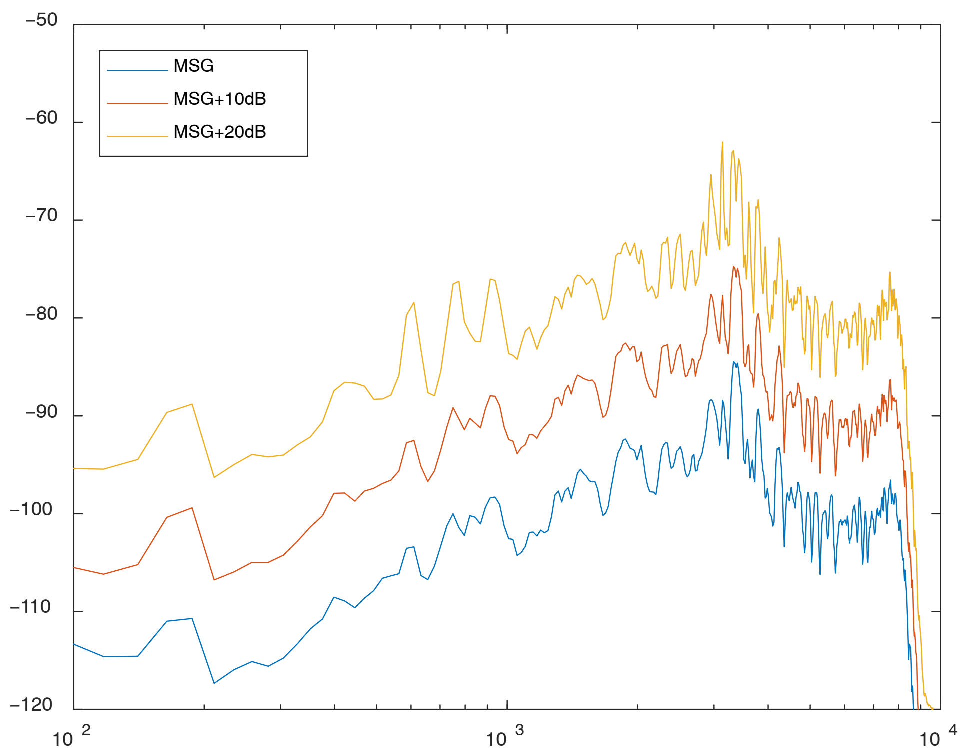

Figure 4. Hearing−Aid Output Signal Spectra for Different Gain Level. Feedback Management is Disabled.

The Gain Management feature can be used to further suppress ringing artefacts or feedback bursts that may occur for higher gain settings. For instance, if the Feedback Canceller is required to provide as much gain as possible while minimizing ringing artefacts, a large, positive Gain Limit can be chosen. A Gain Limit of 10 dB will limit the gain at feedback frequencies to 10 dB above MSG or less.

To illustrate this, the recording described in Figure 2 was repeated but with a Gain Limit set to 10 dB. The output−signal spectra for gains of MSG, MSG + 10 dB and MSG + 20 dB are shown in Figure 5. As shown in the figure, the output spectra for gains of MSG and MSG + 10 are very similar to those without the Gain Management feature enabled. For a gain of MSG + 20 dB, however, the output signal has been limited in the vicinity of the feedback frequencies to the level observed for MSG + 10 dB. With this setting, feedback is controlled but further feedback events are still possible since the allowable gain exceeds the maximum stable gain for the hearing aid.

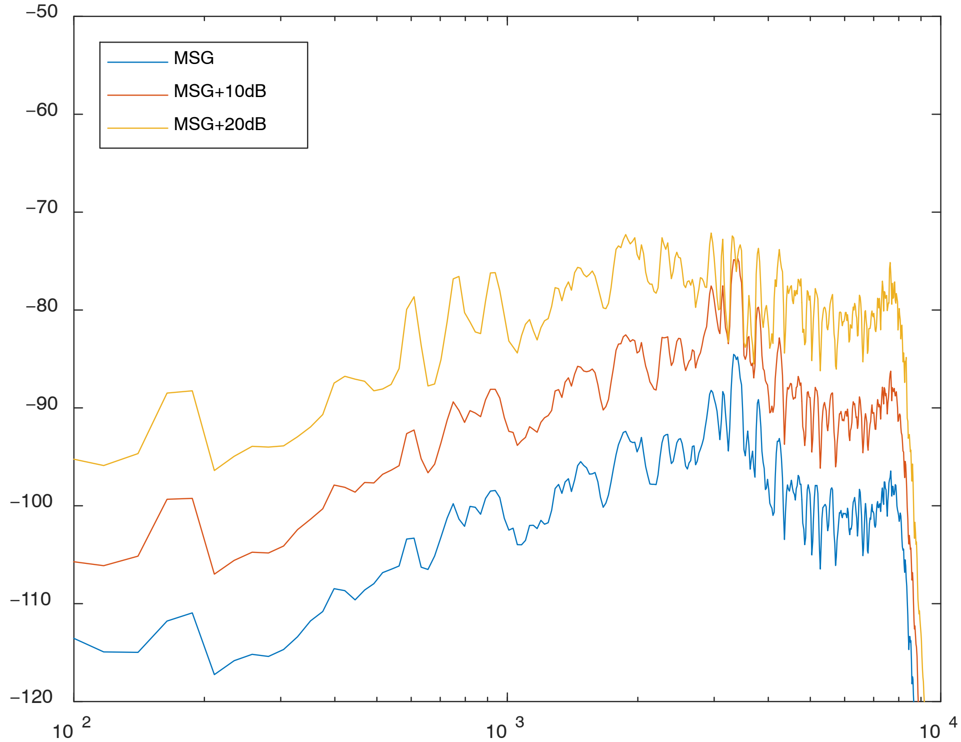

Figure 5. Hearing−Aid Output Signal Spectra for Different Gain Level showing the Effect of the Gain Management Feature. The Gain Limit was set to 10 dB.

For situations where feedback elimination is a priority, a more restrictive Gain Limit can be chosen. Figure 6 and Figure 7 show similar results for gain limits of 0 and −10 dB, respectively. These settings limit the gain to the MSG level and 10 dB below the MSG level, respectively. Since the gain is restricted to a level at or below the maximum stable gain, feedback events are eliminated.

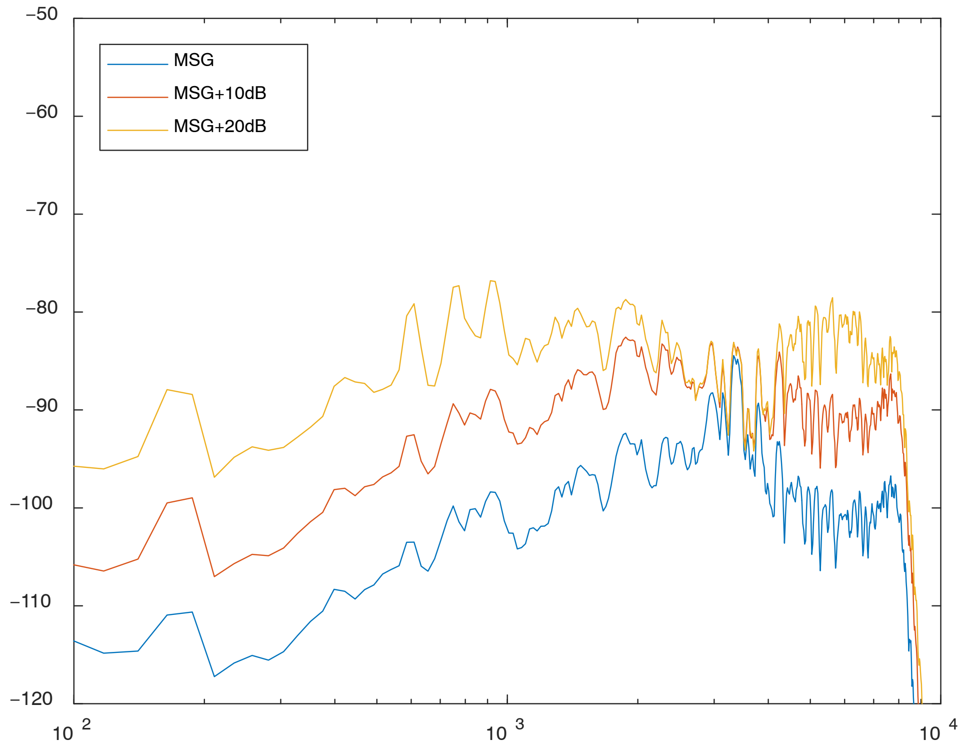

Figure 6. Hearing−Aid Output Signal Spectra for Different Gain Level showing the Effect of the Gain Management Feature. The Gain Limit was set to 0 dB.

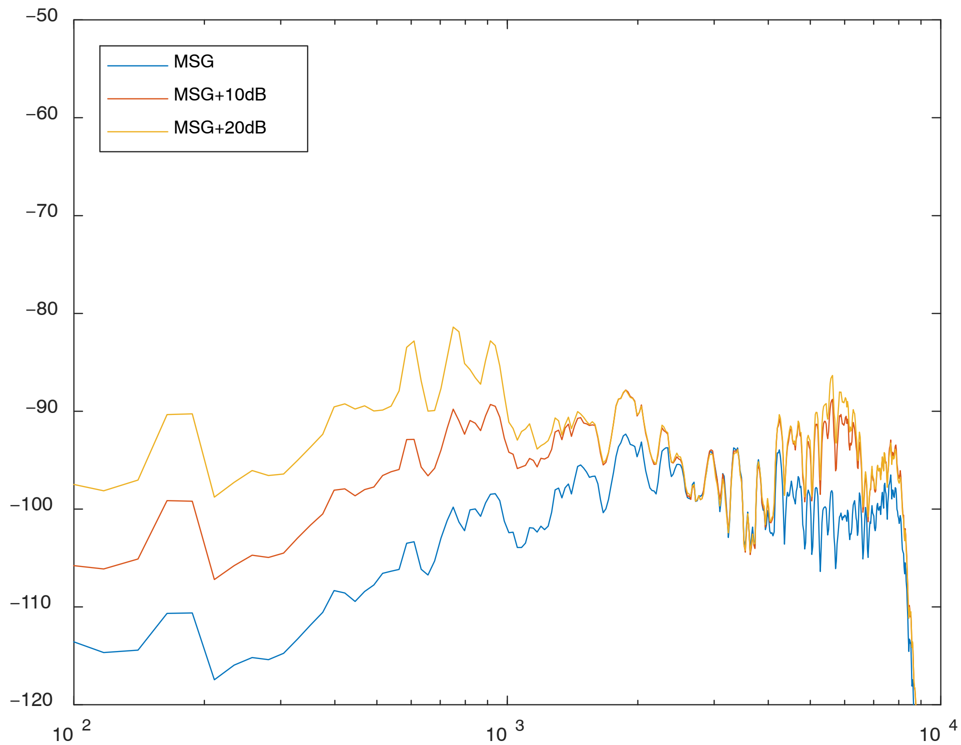

Figure 7. Hearing−Aid Output Signal Spectra for Different Gain Level showing the Effect of the Gain Management Feature. The Gain Limit was set to −10 dB.

Live Display

Since knowledge of the current state of the Feedback Canceller is useful during fitting, some of the internal states of the algorithm are made available to fitting software via the Live Display feature. The algorithm exposes the current feedback−path estimate, the instantaneous gain level and an indication of the current risk of feedback. An example Live Display plot is shown in Figure 8.

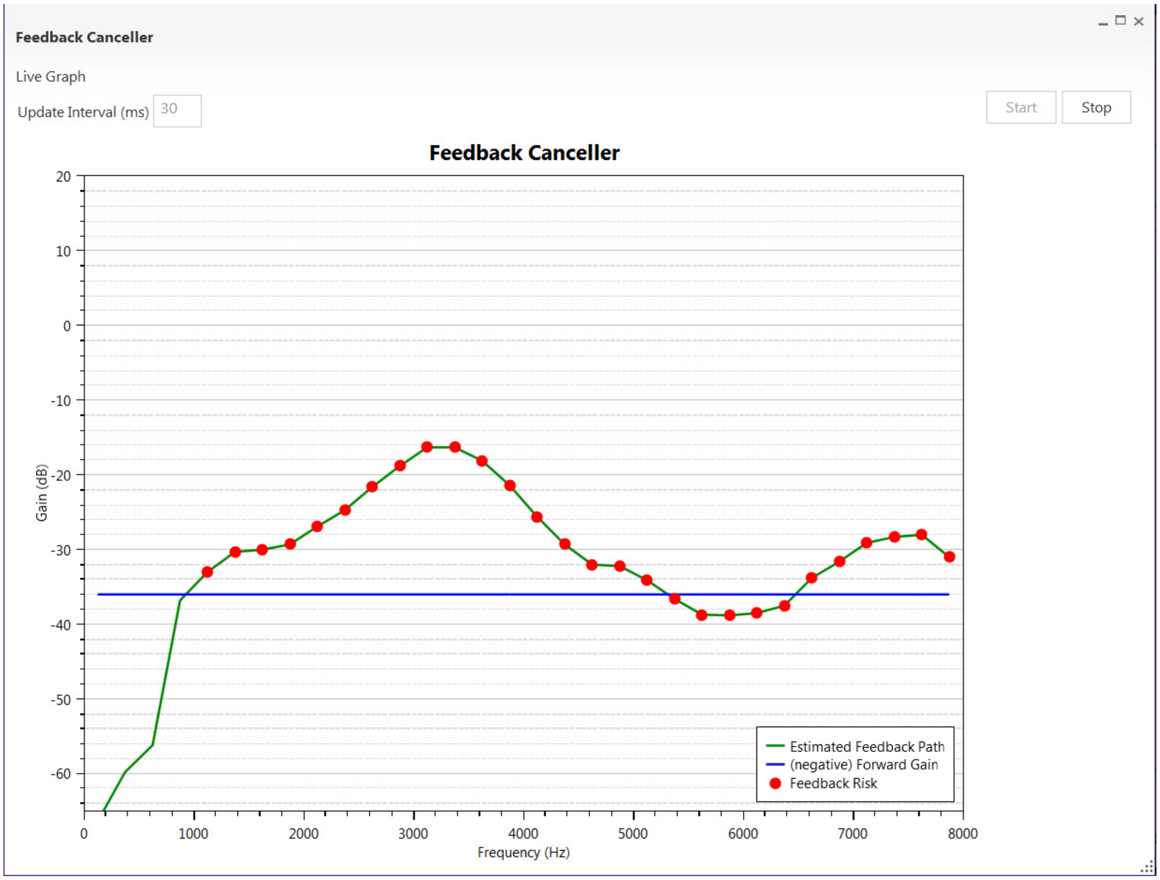

Figure 8. Sample Screenshot of Feedback Canceller Live Display Graph. Gain is 20 dB above MSG and Gain Management is Disabled.

The estimated feedback path is extracted in real time from the current state of the Feedback Canceller algorithm. It is shown as the green curve in Figure 8. It represents the level of the feedback path as seen by the Feedback Canceller algorithm in each frequency band. Since the algorithm operates in the digital domain of the DSP, the feedback−path estimate includes both the transducer responses as well as the gain of the microphone preamplifier.

For example, in Figure 8 the estimated feedback path is approximately −33 dB at 1250 Hz (left−most red circle). The hearing−aid output signal feeds back to the microphone signal at a level 33 dB below the current output. Consequently, 33 dB of gain can be added to the audio path before a risk of feedback is encountered at 1 kHz. The graph also shows that the highest feedback−path estimate over all frequencies occurs at a frequency of 3250 Hz where the estimate is −16 dB. At this frequency, the maximum gain that can be applied is 16 dB. Since this is the highest flat gain that can be applied to the device, it is also an estimate of the current MSG.

Forward gain is a snapshot of the current gain of the device in each frequency band. It includes the combined effects of all algorithms and it is updated frequently to account for dynamic or adaptive features (e.g. WDRC and noise reduction). On the Live Display graph, it is plotted as the negative Forward Gain for direct comparison with the estimated feedback path. In the example provided in Figure 8, algorithms, such as WDRC and noise reduction, are disabled so the Forward Gain is a constant 36dB across all frequencies as shown by the blue line. In this example, it represents the settings of the wideband gain and volume control only.

Feedback can occur anytime the hearing aid's gain exceeds the maximum stable gain. In the Live Display data, this means that a risk of feedback exists whenever the Estimated Feedback Path approaches or exceeds the negative Forward Gain. Frequencies where the Feedback Canceller identifies a risk of feedback are indicated by the red circles superimposed on the Estimated Feedback path curve in the Live Display plot.

Note that, in some cases, a risk of feedback is identified where the gain does not strictly exceed the estimated feedback path (for example, 5400 to 6400 Hz). This is to allow for natural variations in the feedback estimate at certain frequencies. Feedback may occur at a gain that is lower than the current estimate due to such variations in feedback. Figure 9 provides another example of the Live Display feature. This graph was obtained for the same hearing aid and acoustical conditions as used in Figure 8 but with the Gain Management Feature enabled with a Gain Limit of 10 dB. In this case, the hearing−aid gain curve (blue line) is no longer flat owing to the limiting action of the gain manager, A risk of feedback still exists at many frequencies, however, since the gain is allowed to exceed the current feedback estimate (green curve).

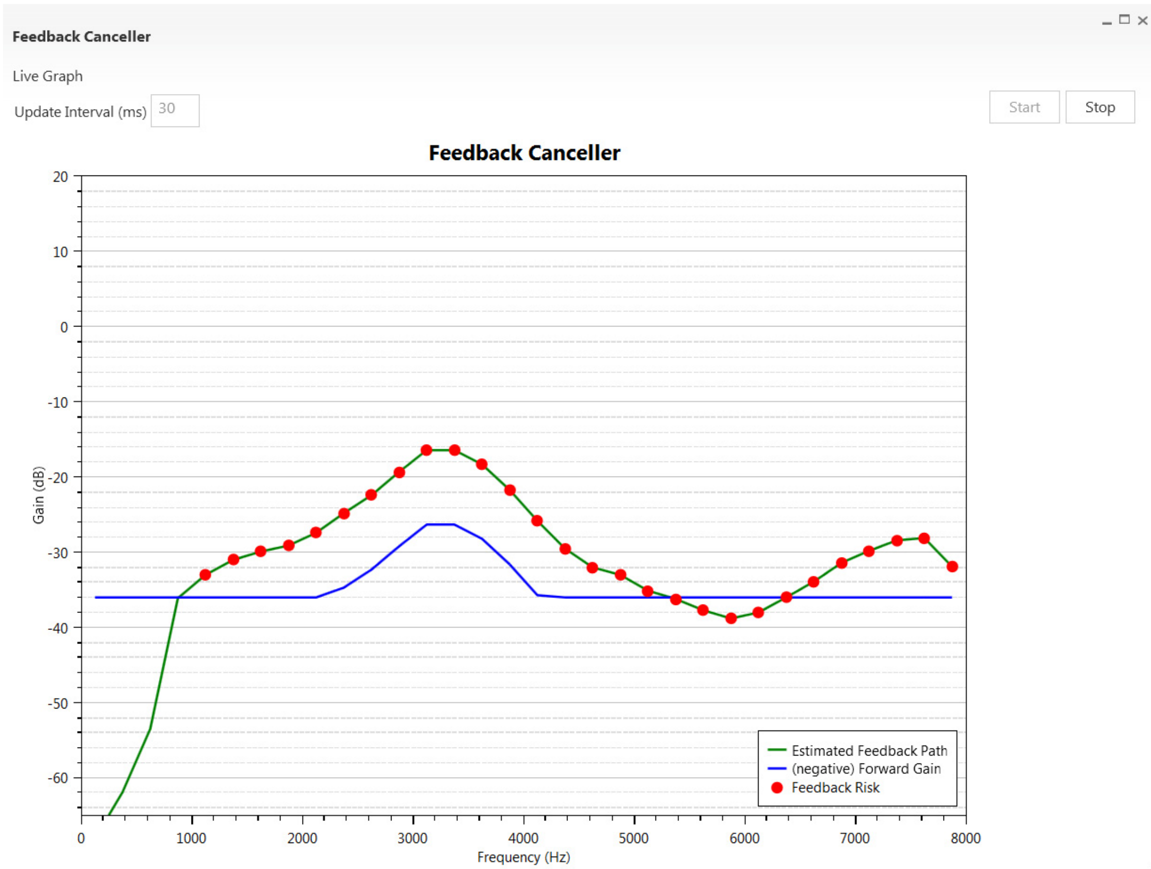

Figure 9. Sample Screenshot of Feedback Canceller Live Display Graph. Target Gain is 20 dB above MSG and Gain Management is Enabled with a Gain Limit of 10 dB.

As a final example, setting the Gain Limit to −10 dB results in the Live Display graph shown in Figure 10. As shown, the lower gain limit imposed by this setting restricts gain to 10 dB below MSG and effectively removes all risk of feedback, as indicated by the absence of red dots in the Live Display graph.

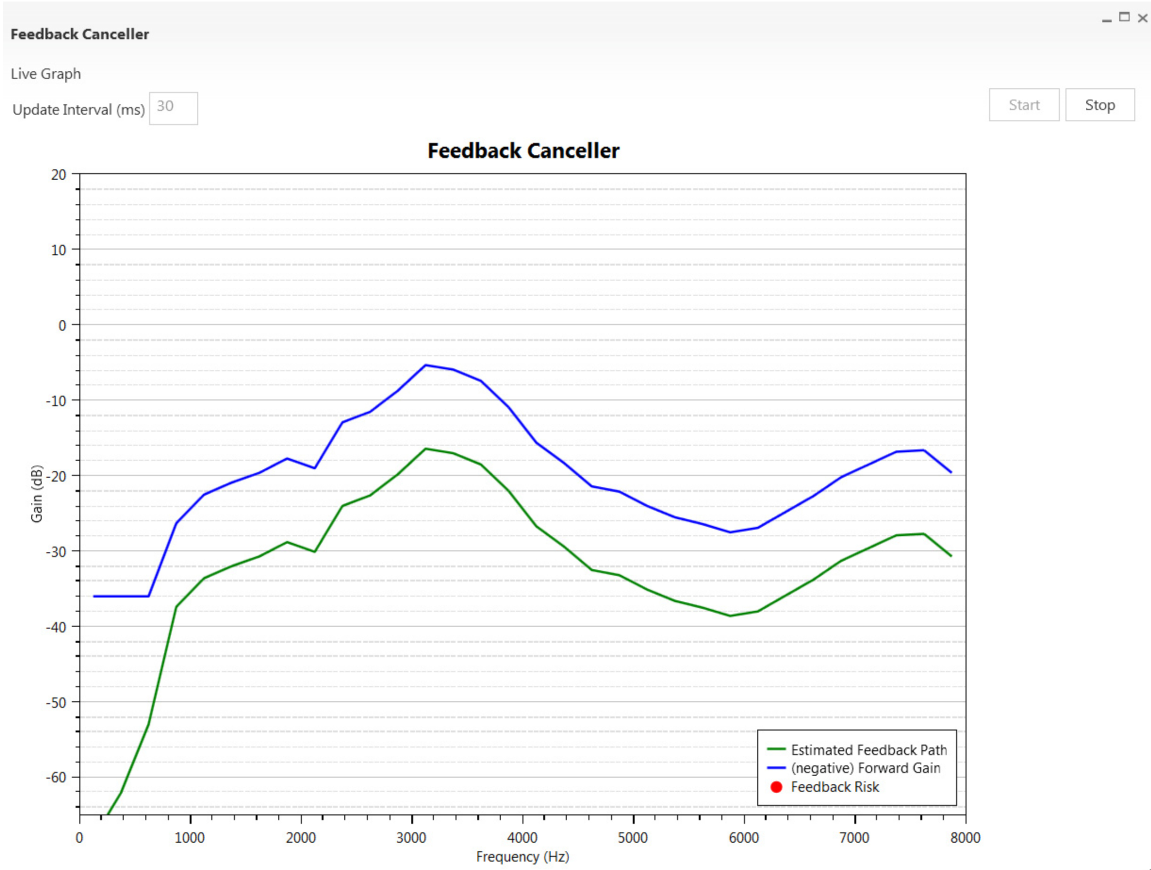

Figure 10. Sample Screenshot of Feedback Canceller Live Display Graph. Target Gain is 20 dB above MSG and Gain Management is Enabled with a Gain Limit of −10 dB.

All Live Display parameters are made available to the Sound Designer API. For complete details, refer to the Firmware Bundle User's Guide.

Adaptation Speed

To demonstrate the adaptation speed controls, a movable acoustic reflector was used to create a second, temporary feedback path. When it was fully in place, the reflector caused a reduction of about 6 dB in the measured MSG of the hearing aid. The reflector was mounted in such a way that it could be easily moved towards and away from the hearing aid, causing a rapid change in feedback.

Adaptation speed was measured by mounting the hearing aid on the mannequin, as previously described. The MSG was determined without the presence of the reflector and the hearing aid gain was set to that value, with the Feedback Canceller enabled. The adaptation speed controls were then set to their desired values and a recording of the ear−canal microphone was initiated. The reflector was then moved to a position close to the hearing aid, reducing the MSG and causing a feedback event. The recording captured the feedback event which was then analyzed to determine adaptation speed.

An example recording is shown in the top graph in Figure 8. This recording was obtained by setting the Active Speed to 1, the Active Sensitivity to 5 and the Active Time to 1500ms. Referring to the graph, the acoustic reflector is moved toward the hearing aid at time A. After approximately 200ms, the reflector is in place causing a feedback event which peaks at time B. The algorithm detects the feedback event in about 50 ms and begins to update the internal estimate at time C. By time D, the adaptation is sufficiently complete to eliminate the feedback event, about 150 ms. The feedback event develops, is detected and is cancelled within a time window of 400 ms.

The lower graph of Figure 8 shows a second example but with an Active Speed of 5. In this case, the feedback occurs as before and the algorithm detects the feedback at time C. Since the Active Time is set to 5, however, the internal feedback estimate is updated much more slowly resulting in a longer time to eliminate the feedback event, in this case 1.8 s.

While a slower Active Speed can result in slower feedback elimination, it can also result in improved audio quality for tonal input signals.

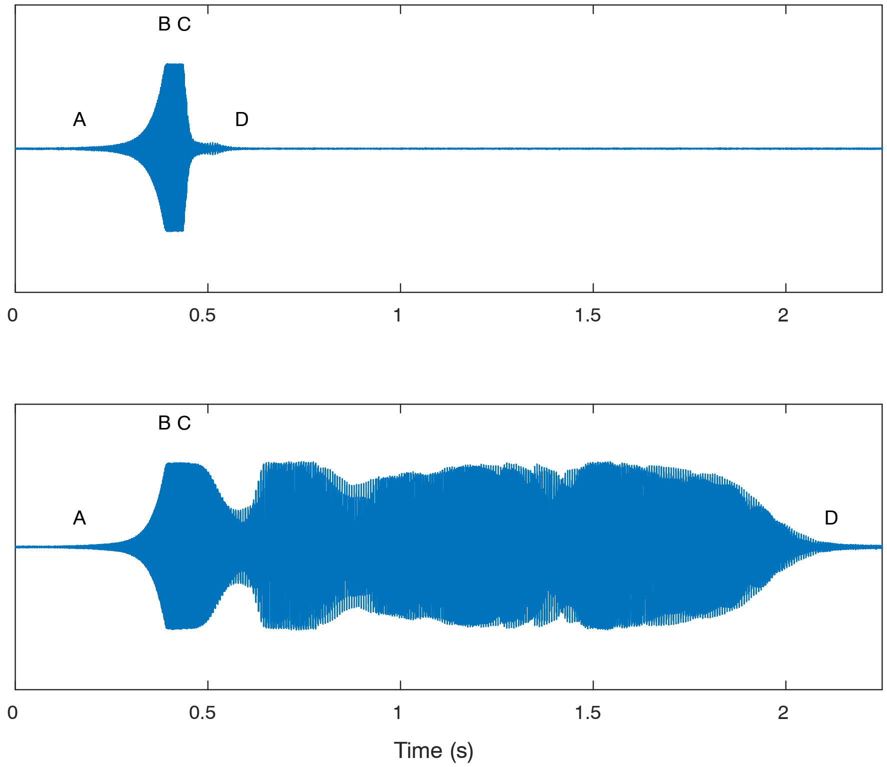

Figure 11. Measuring Adaptation Time. Top Graph: Active Speed of 1. Bottom Graph: Active Speed of 5.

The same set up can also be used to illustrate the behavior of the Active Sensitivity parameter. The top graph of Figure 9 shows the same recording as the top graph of Figure 8, on a slightly different time scale. The recording was obtained by setting the Active Speed to 1, the Active Sensitivity to 5, and the Active Time to 1500 ms. The bottom graph shows the recording obtained by increasing the Active Sensitivity to 40. The increase in Active Sensitivity causes the algorithm to delay its response to the feedback event for an additional period of time before beginning the adaptation process. In this example, feedback detection time increases to approximately 300 ms. Once adaptation begins, however, feedback is eliminated just as quickly since the Active Speed is set to 1.

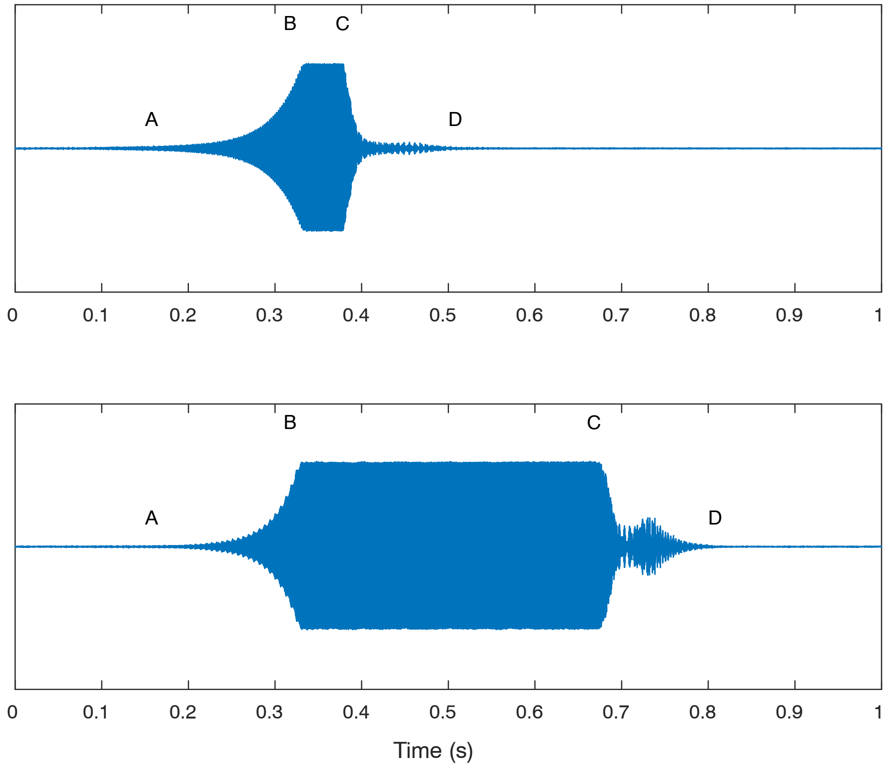

Figure 12. Illustration of Active Sensitivity. Top Graph: Active Sensitivity of 5. Bottom Graph: Active Sensitivity of 40.

Audio Quality Considerations

The Feedback Canceller algorithm is able to eliminate many instances of feedback quickly providing excellent audio quality under many conditions. When the Feedback Canceller is enabled, however, there are some situations when audio quality may be reduced unless specific measures are taken. This includes receiver saturation, fast adaptation speeds during music or tones and extreme feedback events.

Receiver Saturation

The internal feedback estimate maintained by the algorithm is intended to model transducer responses under normal conditions. Under extreme conditions, such as receiver saturation, the algorithm may not be able to accurately estimate the feedback path and audible artefacts may result.

When the Feedback Canceller is enabled, it is recommended to also enable the wideband AGCO (output limiter), even if it is not required for audiological purposes. The AGCO threshold should be set to a value that prevents saturation of the receiver, thereby allowing the Feedback Canceller to properly update the feedback estimate.

Music Signals

Music signals represent a difficult environment for the Feedback Canceller since they can erroneously be detected as feedback and trigger a rapid adaptation. Rapid adaptation during music causes algorithm mis−adjustment and may lead to audible artefacts also known as entrainment.

For situations where music is expected to be encountered, it is recommended to reserve a specific program memory for music listening. If the Feedback Canceller is required, its parameters can then be tuned within that memory to provide improved behavior with music signals. The key parameters are: Active Sensitivity, Idle Speed, Active Time and Active Speed.

Active Sensitivity can be tuned to make the Feedback Canceller less sensitive to detecting feedback. As shown above, this delays the start of rapid adaptation unless the feedback events persists for a longer amount of time. This has the effect of getting the Feedback Canceller to ignore brief tonal signals thereby reducing entrainment events.

Even when there is no active feedback, the Feedback Canceller continues to update its internal estimate at a rate determined by the Idle Speed parameter. Setting the Idle Speed to a slow value will reduce Feedback Canceller adjustment making the system more immune to disturbances during music.

If a feedback event is detected, the algorithm switches to rapid adaptation by activating the Active Speed parameter for a time period dictated by Active Time. A fast setting for Active Speed will make any feedback disappear quickly but may lead to entrainment if no feedback is present. A longer duration for Active Time will lead to more complete elimination of feedback but may also lengthen entrainment if no feedback is present.

In general, slower Active Speeds and shorter Active Time settings will lead to improved audio quality during music. This choice is suitable if the risk of feedback is known to be low (e.g., well−sealed earmold or low gain). If the risk of feedback is known to be high (e.g., for open canal or high gain devices), then a faster Active Speed may be more suitable. This will lead to faster elimination of annoying feedback which might be more of a concern than entrainment.

Extreme Feedback Events

Extreme feedback refers to situations where the feedback is so severe that the Feedback Canceller is unable to compensate for it. This can happen, for example, if a hand is cupped over the hearing aid. The Feedback Canceller will attempt to cancel the feedback continuously often resulting in loud, annoying artefacts. The artefacts will continue until the obstacle causing feedback is removed or until the gain of the device is reduced. The Gain Management feature offers an automatic way to provide such a gain reduction.

An example of severe feedback was created by configuring the above hearing aid with a gain that was 10 dB above the maximum stable gain. With no obstacle near the hearing aid, the Feedback Canceller is able to maintain stability with no feedback. When a hand is placed over the hearing aid, however, the Maximum Stable Gain is drastically reduced and the Feedback Canceller is not able to restore stability. The recorded output from the hearing aid is plotted in Figure 11. The hand is placed over the hearing aid around 0.3 s and the high−level feedback continues until a time of 7.5 s when the hand is removed.

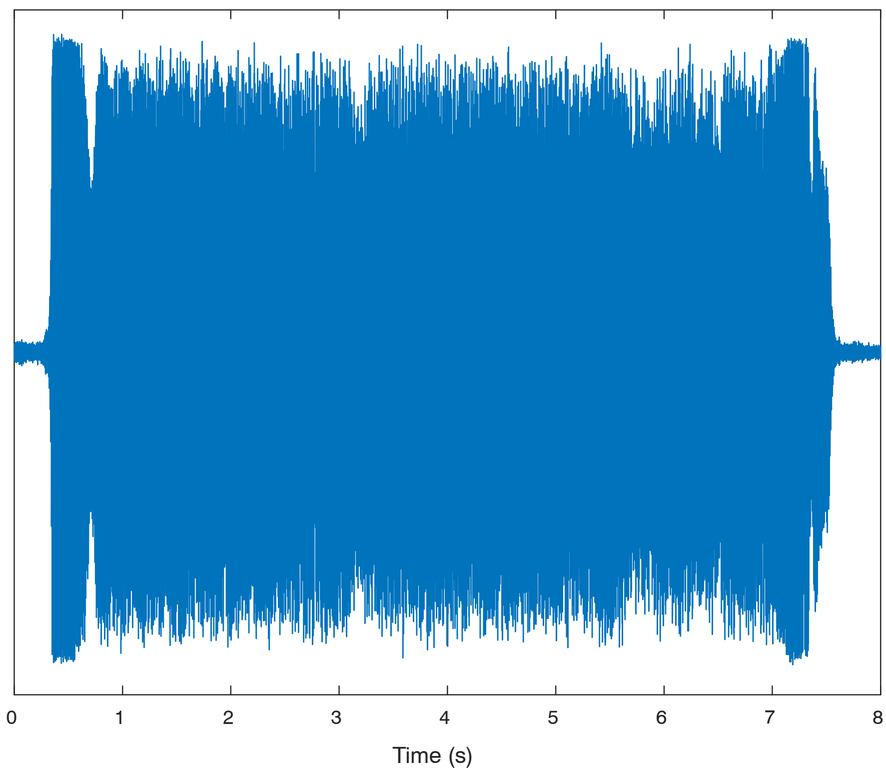

Figure 13. Output Signal from Hearing Aid under Severe Feedback Condition. A Hand is Brought near the Hearing Aid at a Time of 0.3 s and is Removed at a Time of approximately 7 s. The Gain Management Feature is Disabled.

The severe feedback condition described above was re−created as closely as possible but with a Gain Limit of 10 dB. The recorded output from the hearing aid is plotted in Figure 12. The hand is placed over the hearing aid at around 0.3 s and it is held in place until a time of approximately 6 s. After the initial hand placement, feedback does occur but is eliminated quickly by a combination of rapid adaptation and fast−acting gain management. Even the though the hand is keep in place, sustained feedback does not occur. A second, brief feedback event occurs when the hand is removed but is also eliminated quickly.

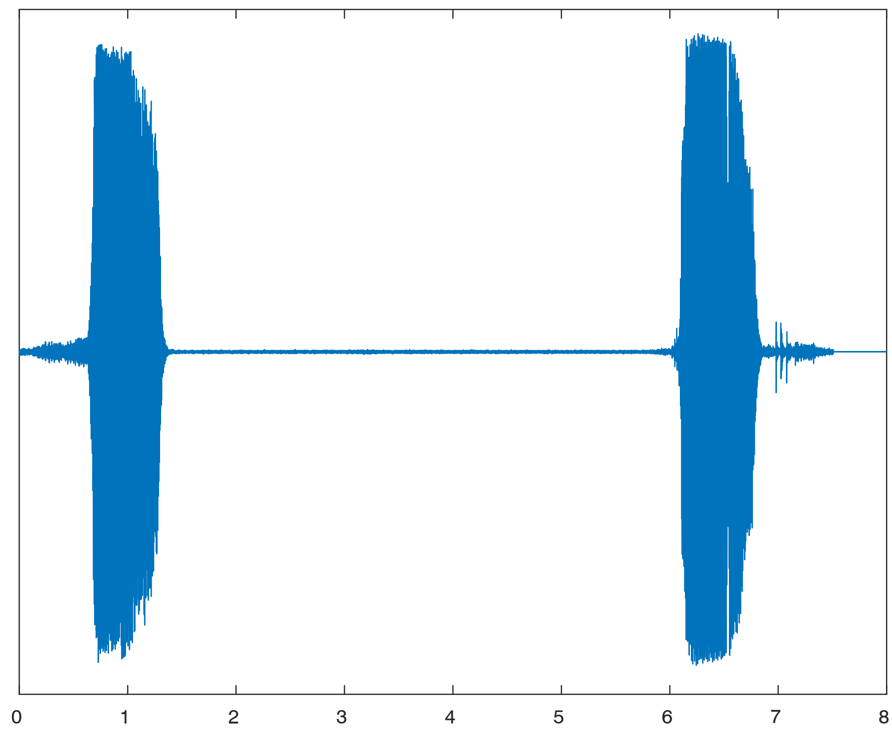

Figure 14. Output Signal from Hearing Aid under Severe Feedback Condition. A Hand is Brought near the Hearing Aid at a Time of 0.3 s and is Removed at a Time of approximately 6 s. The Gain Management Feature is Enabled with a Gain Limit of 10 dB.

PUBLICATION ORDERING INFORMATION

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