Influence of stimulus parameters on amplitude-modulated stimulus frequency otoacoustic emissions^{a)}

Tiffany A. Johnson^{b)} and Laura Beshaler

University of Kansas Medical Center, Kansas City, Kansas 66160

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The present study evaluated the influence of suppressor frequency (f_s) and level (L_s) on stimulus-frequency otoacoustic emissions (SFOAEs) recorded using the amplitude-modulated (AM) suppressor technique described by Neely *et al.* [J. Acoust. Soc. Am. **118**, 2124-2127 (2005a)]. Data were collected in normal-hearing subjects, with data collection occurring in two phases. In phase 1, SFOAEs were recorded with probe frequency (f_p) = 1, 2, and 4 kHz and probe levels (L_p) ranging from 0 to 60 dB sound pressure level (SPL). At each f_p , L_s ranged from $L_s = L_p$ to $L_s = L_p + 30$ dB. Additionally, nine relationships between f_s and f_p were evaluated, ranging from $f_s/f_p = 0.80$ to $f_s/f_p = 1.16$. Results indicated that for low suppressor levels, suppressors higher in frequency than f_p ($f_s > f_p$) resulted in higher AM-SFOAE levels than suppressors lower in frequency than f_p ($f_s < f_p$). At higher suppressor levels, suppressors both higher and lower in frequency than f_p produced similar AM-SFOAE levels, and, in many cases, low-frequency suppressors produced the largest response. Recommendations for stimulus parameters that maximize AM-SFOAE level were derived from these data. In phase 2, AM-SFOAEs were recorded using these parameters for $f_p = 0.7$ -8 kHz and $L_p = 20$ -60 dB SPL. Robust AM-SFOAE responses were recorded in this group of subjects using the parameters developed in phase 1. © 2013 Acoustical Society of America. [http://dx.doi.org/10.1121/1.4812766]

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I. INTRODUCTION

Of the various types of evoked otoacoustic emissions (OAEs), distortion product otoacoustic emissions (DPOAEs), transient-evoked otoacoustic emissions (TEOAEs), and stimulus-frequency otoacoustic emissions (SFOAEs), SFOAEs may be the simplest to interpret. SFOAEs occur in response to a single pure-tone stimulus, a simpler and more frequency-specific stimulus than what is used to elicit either DPOAEs or TEOAEs. Despite the apparent simplicity in the eliciting stimulus, recording SFOAEs is more technically challenging than recording DPOAEs or TEOAEs. The SFOAE response overlaps in both time and frequency with the tone used to elicit it. Thus, separating the response from the stimulus involves more complex signal processing than is required to record DPOAEs or TEOAEs. Recently, Kalluri and Shera (2007) illustrated that, when careful attention is paid to the measurement technique, SFOAEs recorded using any of the commonly used approaches yield similar estimates of the SFOAE response in individual ears. This finding suggests that SFOAEs are not measurement artifacts but reflect cochlear processing. Not surprisingly, numerous investigators have used SFOAEs to investigate various aspects of cochlear function (e.g., Brass and Kemp, 1993; Schairer *et al.*, 2003; Schairer *et al.*, 2006; Shera and Guinan, 2003; Schairer and

Keefe, 2005; Keefe *et al.*, 2008; Bergevin *et al.*, 2012; Lichtenhan, 2012).

Despite the relative success with which SFOAEs have been used to assess cochlear function, less effort has focused on translating SFOAEs into a clinical tool for identifying and diagnosing auditory pathology. Although data have been reported from studies where SFOAEs were recorded in ears with normal hearing (NH) and in ears with hearing loss (e.g., Konrad-Martin *et al.*, 2002; Konrad-Martin and Keefe, 2005), few have recorded SFOAE responses in large groups of normal and impaired ears. Data from these large-scale studies are necessary to describe the accuracy with which SFOAEs could be used to identify differences in responses from normal and impaired ears. Currently, the only large-scale studies in both normal and impaired ears are those described by Avan *et al.* (1991) and Ellison and Keefe (2005). General applicability of the Avan *et al.* findings is limited because they reported results for a limited range of frequencies (all ≤ 1000 Hz). Ellison and Keefe reported data for a broader range of frequencies, and their data suggest that SFOAEs may have clinical utility beyond their primary use as a research tool. However, Ellison and Keefe explored a broad parametric space for each subject to determine the probe-suppressor combination resulting in the largest SFOAE response in each ear. This necessitated several hours of data collection, spread over multiple days, a time commitment that is not possible under clinical constraints. To be a viable clinical tool, appropriate stimulus parameters need to be determined in advance so that measurements can be made in a short period of time. It is unclear how well SFOAEs would have performed in the Ellison and Keefe study if a fixed set of stimulus parameters had been used for all subjects.

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^{b)}Author to whom correspondence should be addressed. Electronic mail: tjohnson7@kumc.edu

In addition to the generally encouraging results obtained by Ellison and Keefe (2005), there has been some speculation that SFOAEs may be useful in clinical applications because the cochlear mechanisms contributing to the SFOAE response are different from those contributing to other types of evoked OAEs, particularly DPOAEs. Currently, there are believed to be two fundamentally different cochlear mechanisms by which OAEs are generated (e.g., Shera and Guinan, 1999). These mechanisms include a coherent-reflection mechanism, arising from a reflection source, and a nonlinear distortion mechanism, arising from a distortion source. DPOAEs are believed to include contributions from both mechanisms (e.g., Talmadge *et al.*, 1998; Talmadge *et al.*, 1999; Shera and Guinan, 1999), while SFOAEs primarily may arise via a coherent-reflection mechanism (Shera and Guinan, 1999, 2003; Goodman *et al.*, 2003; Shairer *et al.*, 2006; Shera *et al.*, 2008; Choi *et al.*, 2008). Shera and Guinan (1999) have speculated that the two cochlear mechanisms underlying OAE generation may depend on different aspects of cochlear mechanics for their generation. Additional studies where SFOAEs and other types of OAEs are recorded in the same subject would help to explain if useful knowledge regarding auditory pathology can be obtained by comparing responses from OAEs arising through different cochlear mechanisms.

Exploration of these clinical questions requires an efficient and reliable technique for recording SFOAEs. Neely *et al.* (2005a) recently described a technique for recording SFOAEs using an amplitude-modulated (AM) suppressor that may be more efficient than other approaches to recording SFOAEs. This technique is a variation of the classic

two-tone suppression approach to extracting the SFOAE response from the pure-tone stimulus (e.g., Kemp and Chum, 1980; Brass and Kemp, 1993; Keefe, 1998). In this approach, an AM suppressor is presented in conjunction with a probe tone that is either fixed or modulated in level. Details of this technique will be described further in Sec. II. Briefly, the AM-suppressor interacts with the SFOAE elicited by the probe stimulus resulting in AM in the SFOAE response. The AM of the SFOAE response is then detectable in sidebands that occur at frequencies just higher and just lower than the probe frequency (see Fig. 1). Spectral techniques can then be used to estimate the SFOAE response present in these sidebands.

Potential gains in efficiency for the AM-SFOAE technique relative to other approaches come from the fact that the suppressor and probe are presented simultaneously in a single recording interval. In contrast, the more common implementation of the suppression technique involves multiple recording intervals, some containing the probe stimulus presented alone and others containing the probe in combination with a suppressor (e.g., Brass and Kemp, 1993; Souter, 1995; Keefe, 1998; Kalluri and Shera, 2007; Keefe *et al.*, 2008). In this approach, the SFOAE is obtained by subtracting the intervals with the suppressor from the intervals without the suppressor, essentially requiring multiple measurements to determine the response for a single condition. The AM-SFOAE technique does not require separate recordings for a probe alone and a probe plus suppressor condition.

Another potential benefit of the AM-SFOAE technique is that the use of spectral techniques to estimate the response allows for the exclusion of some non-cochlear, physiologic

FIG. 1. Demonstration of the AM-SFOAE response in an acoustic cavity and a NH ear. In both columns, $f_p = 2$ kHz and $f_s = 2.16$ kHz. Left column: Spectra of the AM-SFOAE stimuli and response for $L_p = 40$ dB SPL and $L_s = 54$ dB SPL (measured level, nominal level = 60 dB SPL; see text for the distinction between measured and nominal levels). The gray shading near the bottom of each panel represents the maximum noise level observed for the frequency interval 1992–2008 Hz (i.e., the interval encompassing f_p and the spectral sidebands). Evidence of AM in the suppressor is apparent in the sidebands surrounding f_s , which are present in both the cavity and in the NH ear. Evidence of the suppressor modulating the response to the probe is present in the NH ear where large sidebands representing the AM-SFOAE response are present at $f_p \pm 8$ Hz. The sidebands at $f_p \pm 8$ Hz are not seen in the acoustic cavity. Right column: Data plotted as input/output functions. The open symbols represent the response level in each sideband, the filled circles represent the response level after summing the sidebands, and the solid lines represent the associated noise levels (3 lines are plotted, one for each sideband and one representing the average sideband noise).

noise sources. For example, Neely *et al.* (2005a) showed evidence of spectral components that were believed to arise from a physiologic process such as the heartbeat. These biologic (non-OAE) components could be excluded from the AM-SFOAE response because their frequency content differs from the frequencies where the AM-SFOAE response occurs.

These factors suggest that the AM-SFOAE approach may be an efficient technique for recording SFOAE responses, particularly if stimulus parameters yielding robust responses are known in advance. The parametric space has been thoroughly investigated for DPOAEs (e.g., Gaskill and Brown, 1990; Harris *et al.*, 1989; Kummer *et al.*, 1998; Neely *et al.*, 2005b; Johnson *et al.*, 2006) but has received less attention in the SFOAE literature. Neely *et al.* (2005a) demonstrated the feasibility of the AM-SFOAE technique but did not explore the suppressor-probe parametric space. Therefore the optimal frequency and level relationships for the probe and AM-suppressor tones are not known.

The purpose of the present study was to define stimulus parameters for recording AM-SFOAEs using the Neely *et al.* (2005a) method with the idea that these predefined stimulus parameters could be used in future investigations into the clinical applications of AM-SFOAEs. More specifically, the goals of the present project were (1) to explore the influence of manipulating the suppressor frequency and suppressor level on the AM-SFOAE response recorded in NH ears, (2) to develop stimulus parameters that are expected to produce robust AM-SFOAE responses in NH ears, and (3) to evaluate the extent to which these stimuli generalized by recording AM-SFOAEs using these parameters in a new group of NH subjects.

II. METHODS

A. Subjects

Data were collected from one ear of 40 NH adult subjects (30 females, 10 males). Subjects ranged in age from 18 to 28 yr (mean = 22 yr). NH was defined as pure-tone behavioral thresholds ≤ 20 dB hearing level (HL) (re: ANSI, 2004) for the octave frequencies from 250 to 8000 Hz. Pure-tone behavioral thresholds were evaluated on the first day of data collection. Subjects were required to have a normal 226-Hz tympanogram in the test ear prior to each test session. Data collection occurred in two phases (described in the following text) with 20 subjects (15 females, 5 males) participating in each phase. During data collection, subjects reclined in a comfortable chair and were free to sleep, read, or watch a silent, captioned movie. Phase 1 data collection required approximately 7-8 h of participation from each subject; data collection was spread over three to four 2-h sessions. Phase 2 data collection was completed in a single 1.5-2 h session for each subject. The subjects participating in phase 2 differed from those participating in phase 1.

B. Procedures

1. Equipment and calibration

All AM-SFOAE data were collected using custom-designed software (EMAV; Neely and Liu, 1993) that controlled

a 24-bit sound card (CardDeluxe, Digital Audio Labs) housed in a PC. Stimuli were presented, and responses were recorded through an ER-10C (Etymotic Research) probe-microphone system. The ER-10C was modified to remove 20 dB of attenuation from each channel. As a result, it was possible to achieve stimulus levels as high as 80 dB sound pressure level (SPL) in each subject's ear canal. Stimulus levels were calibrated *in situ* in sound pressure at the plane of the ER-10C probe. Equipment and calibration approaches were identical for the two phases of data collection.

2. The AM-SFOAE technique

In the AM-suppressor approach used here, an AM suppressor is presented in conjunction with a probe tone that is fixed in level. This differs from the original description of the AM-SFOAE technique (Neely *et al.*, 2005a), where the probe tone was modulated slowly in level. Modulation of probe level is not a critical feature of the technique. In other words, to implement the technique, the suppressor must be AM, but the probe can remain fixed in level as was done in the present study.

The suppressor frequency (f_s) and level (L_s) are chosen so that the suppressor will interact with the cochlear response to the probe tone (the SFOAE) causing the SFOAE to alternate between suppression and no suppression at a rate equal to the suppressor modulation frequency (mf). In other words, the suppressor produces AM in the SFOAE and, as a result, the SFOAE response will be apparent in spectral sidebands present at frequencies both higher and lower than the probe frequency (f_p). Specifically, the sideband components will be present at $f_p \pm mf$. Spectral techniques can then be used to estimate the SFOAE response present in these sidebands.

3. Stimulus conditions

The stimulus conditions differed across the two phases. Phase 1 primarily was a stimulus-development phase where the influence of a range of f_s and L_s conditions on the AM-SFOAE level was evaluated. Phase 2 primarily was a stimulus-validation phase where the stimulus parameters developed during phase 1 were tested in a new group of subjects.

During phase 1, AM-SFOAE responses were recorded in the form of input-output (I/O) functions for probe levels (L_p) ranging from 0 to 60 dB SPL in 10-dB steps. The I/O functions were recorded at 3 f_p 's: 1, 2, and 4 kHz. The influence of f_s and L_s on the level of the AM-SFOAE was explored by recording responses to nine different suppressor-probe frequency ratios (f_s/f_p) and four different suppressor-probe level relationships (L_s, L_p). The stimulus conditions are summarized in Table I. The test stimuli included conditions where f_s was lower in frequency than f_p ($f_s/f_p < 1.0$) and conditions where f_s was higher in frequency than f_p ($f_s/f_p > 1.0$). For each f_p and f_s/f_p combination, the L_s, L_p relationship ranged from one where L_s was equal to L_p ($L_s = L_p + 0$) to one where L_s was 30 dB higher than L_p ($L_s = L_p + 30$). In all cases, the suppressor was 100% AM at a rate of 8 Hz (i.e., mf = 8 Hz).

It should be noted that our software (EMAV) sets signal level for both the probe and suppressor stimuli before AM is

TABLE I. Summary of stimulus conditions for phase 1.

f_p (kHz)	L_p (dB SPL)	f_s/f_p	L_s, L_p
1, 2, 4	0-60	0.80, 0.84, 0.88, 0.92, 0.96	$L_s = L_p + 0$
	10-dB steps	1.04, 1.08, 1.12, 1.16	$L_s = L_p + 10$
			$L_s = L_p + 20$
			$L_s = L_p + 30$

added to the suppressor. With the addition of AM, the average level of the suppressor is lower than it would be if it were unmodulated. Therefore the recorded levels for the suppressor tone were lower than the nominal levels used as the target during the calibration stage. For example, if the nominal (target) level for L_s was 40 dB SPL, the recorded level was lower (approximately 34 dB SPL) because the recorded level includes the reduction in energy that occurs with the addition of AM. Unless otherwise noted, the levels reported for the suppressor tones in this manuscript are the nominal levels. For cases where L_s was 30 dB higher than L_p , the maximum level of the suppressor was limited to 80 dB SPL (nominal level). This was done to limit the exposure of the subjects to high levels of sound and to minimize the contribution of system distortion (discussed in the following text) to the recorded response.

During phase 2, AM-SFOAE responses were again recorded as I/O functions with L_p ranging from 20 to 60 dB SPL in 5-dB steps. Here, f_p ranged from 0.7 to 8 kHz in half-octave steps. During this phase, L_s and f_s/f_p were set to those values identified in phase 1. Specific information regarding the L_s and f_s/f_p values used in phase 2 are described in Sec. III.

4. Measurement-based stopping rules

During data collection, EMASV alternately stored 0.25-s samples of the recorded response in one of two buffers. These buffers were summed to provide an estimate of stimulus and response level and were subtracted to provide an estimate of noise level at the same frequencies. Measurement-based stopping rules were used during both phases of data collection. Using these rules, averaging continued until the noise level was ≤ -25 dB SPL or until 32 s of artifact-free averaging was completed, whichever occurred first. Because averaging time was allowed to vary according to the noise level for a given condition, it was possible to obtain more consistent and lower noise levels across conditions and across subjects. For the purposes of the measurement-based stopping rules, noise level was estimated from the $f_p - 8$ Hz frequency bin (i.e., from the lower frequency sideband in the AM-SFOAE response).

5. Quantification of AM-SFOAE response and noise levels

The spectrum of an AM-SFOAE stimulus and response is plotted in the left column of Fig. 1, where component level (dB SPL) is plotted as a function of frequency (Hz) for data collected in an acoustic cavity (IEC 711 coupler, top panel) and in a NH ear (bottom panel). In both the acoustic cavity

and the NH ear, spectral components are seen at 2.16 kHz, which correspond to f_s , along with sidebands ± 8 Hz re: f_s that reflect the 100% AM of f_s . Likewise, spectral components are observed at 2 kHz in both the acoustic cavity and in the NH ear, which corresponds to f_p . In the NH ear, spectral sidebands with levels of approximately -1 dB SPL and signal-to-noise ratios (SNRs) of nearly 30 dB are evident at $f_p \pm 8$ Hz. In contrast, for the acoustic cavity, the spectral sidebands at $f_p \pm 8$ Hz have levels of approximately -30 dB SPL and SNRs ≤ 0 dB. The presence of sidebands with positive SNRs in the NH ear, and their absence in the acoustic cavity, provides evidence that the suppressor produces AM of the SFOAE in the NH ear but that there was no interaction of the suppressor and probe in the measurement system, at least for these conditions.

The growth of sideband level as a function of L_p is plotted in the right column of Fig. 1, for the acoustic cavity (upper panel) and the NH ear (lower panel). In the acoustic cavity, the sideband level (open circles) is relatively constant across L_p , with levels between -20 and -30 dB SPL observed for most conditions. Noise levels (solid lines) in the cavity were typically less than -25 dB SPL for all L_p . In the NH ear, sideband level emerged from the noise for $L_p > 10$ dB SPL, reaching a maximum of nearly 9 dB SPL for $L_p = 60$ dB SPL. The difference in response behavior for the NH ear compared to the acoustic cavity was taken as further evidence that, for these conditions, there was no interaction between the suppressor and probe in the measurement system.

In the NH ear, the response levels in the two sidebands were within 1 dB of each other for all cases where the response had emerged from the noise. Evaluation of the responses from other ears and for other conditions suggested no systematic difference in response behavior between the two sidebands. As a result, the sidebands were summed (using vector summation) to yield a single estimate of SFOAE level. In the right column of Fig. 1, the summed response is plotted as filled circles. As expected, the summed response level is approximately 6 dB higher than the response in an individual sideband. Deviations from the expected 6-dB increase for the summed response were observed when either the level or the phase differs between the two sidebands, an occurrence that was common in the cavity and when the response was not well separated from the noise. To derive a single estimate of the noise, the noise levels observed at the two sideband frequencies were averaged to yield a single value. In all subsequent figures and in all further analyses, only the summed response levels and averaged noise levels are considered.

III. RESULTS

A. System distortion and valid emissions

In a linear measurement system, there should be no interaction between the probe and the suppressor, regardless of the frequencies or levels tested. The data shown in Fig. 1 for the acoustic cavity suggest that for some frequencies and levels, this assumption is true. However, it appears that the assumption was not valid for the measurement system across

all conditions evaluated. To quantify the dynamic range of the system, a modified version of the approach for quantifying system distortion described by Dorn *et al.* (2001) was used. Here responses were recorded in four cavities: (1) An IEC 711 coupler, (2) a standard 2-cm³ coupler, (3) a 10-m PVC tube (internal diameter = 8 mm), and (4) an open syringe with the plunger in close proximity to the ER-10C probe tip (enclosed volume of air approximately 0.1 cm³). The IEC 711 and standard 2-cm³ couplers were included as cavities that provide an approximation of an average human ear. The syringe and 10-m PVC tube were included to represent extremes of cavities sizes. The syringe represents a smaller cavity than would be encountered in a human ear but represents a case where high signal levels could be achieved for low driving voltages. Conversely, the 10-m PVC tube represents a cavity much larger than the human ear where higher driving voltages were necessary to achieve target signal levels. These cavities were intended to span the range of acoustic conditions that might be expected across a group of subjects and would allow insight into those conditions where nonlinearities (non-biologic contributions) from the measurement system were present in the measured response. The response levels recorded in these cavities were taken as an indication of the level of system distortion. Data were collected in each of these four cavities for the stimulus combinations described in Table I.

As shown in Fig. 1, for many conditions, nonlinear contributions did not emerge from the noise floor. For other conditions, however, nonlinear contributions were observed that equaled the responses observed in NH ears. An example of this is shown in Fig. 2. Here, response level is plotted as a function of L_p . The response in the NH ear (bottom panel) suggests a robust SFOAE response that emerges from the noise floor and grows to a maximum of approximately 12 dB SPL for probe levels between 50 and 60 dB SPL. Examination of the response in the IEC 711 coupler (middle panel) suggests a nearly identical growth function with response levels in the coupler falling within 1 dB of the levels observed in the NH ear for $L_p = 40$ to 60 dB SPL. For these conditions, it appears that the response recorded in the NH ear may be largely (or entirely) non-biologic in origin. Examination of the results recorded by connecting the soundcard DAC directly to the ADC (top panel) suggest the origin of the nonlinearities primarily resides in the ER-10C transducers as the response level at the soundcard output never exceeds -25 dB SPL, even for $L_p = 60$ dB SPL. This pattern of findings is similar to what was reported by Neely *et al.* (2005a) in the original description of the AM-SFOAE technique. Neely *et al.* attributed the nonlinearities to those arising through intermodulation distortion in the ER-10C. Cross-talk in the ER-10C could also contribute to artifacts in the measured response, although cross-talk in the ER-10C would be expected to be a factor at frequencies higher than the frequency where this measurement was made (Siegel, 2007).

Figure 2 represents one of the most extreme examples of system distortion observed in the data; however, non-biologic energy that exceeded the noise floor was observed for other combinations of f_s , f_p , and L_s , L_p . Data representing

FIG. 2. Input/output functions recorded with $f_p = 1$ kHz, $f_s/f_p = 1.04$, and $L_s = L_p + 30$ dB. Because the maximum stimulus level was limited to 80 dB SPL, when $L_p = 60$ dB SPL, a lower L_s was used ($L_s = L_p + 20$). Data in the top panel were recorded by connecting the DAC output of the sound card directly to the ADC input of the sound card; data in the middle panel were recorded in the IEC 711 coupler; and data in the bottom panel were recorded in a NH ear. The filled symbols represent the summed sideband response (the AM-SFOAE) and the solid line represents the average noise floor for the two sidebands.

the range of system distortion observed in the data are plotted in Fig. 3 as cumulative distribution functions. The data plotted here suggest that system distortion decreases as f_p increases from 1 to 4 kHz and that system distortion increases as suppressor level increases from top to bottom in the figure. Although in many cases, it is not possible to distinguish the functions across the different f_s/f_p 's (see, for example, the upper right panel), in other cases, the level of system distortion varied across f_s/f_p . Specifically, when $f_p = 1$ and 2 kHz, $f_s/f_p = 0.96$ and 1.04 produced higher levels of system distortion than other ratios. This is evident in Fig. 3

FIG. 3. Cumulative distributions for system distortion measured in the four acoustic cavities described in the text. As indicated on the figure, each column represents a different f_p and each row represents a different L_s , L_p relationship, with L_s increasing from top to bottom. Within each panel, the individual curves represent the data recorded for a given f_s/f_p as L_p is increased to a maximum of 60 dB SPL. Additionally, each curve represents the data recorded across all four cavities for a given combination of f_p and f_s/f_p . Cases where $f_s/f_p < 1.0$ are plotted with dashed lines, and cases where $f_s/f_p > 1.0$ are plotted as solid lines. Line thickness is used to indicate the spacing between f_s and f_p . The thickest lines indicate the narrowest spacing ($f_s/f_p = 0.96$ and 1.04) with decreasing thickness indicating broader spacing. Also shown in each panel is a vertical reference line at -20 dB SPL, which marks the point above which system distortion levels would exceed the biologic noise floor observed in ears.

in that the cumulative distribution functions corresponding to these ratios (thickest lines) were associated with the highest system distortion levels at each cumulative percentile when $f_p = 1$ and 2 kHz. For the condition where $f_p = 1$ kHz and $L_s = L_p + 30$ (bottom left panel), $f_s/f_p = 0.92$ and 1.08 also produced higher system distortion levels than was observed with other ratios. These findings are consistent with the idea that higher levels of system distortion were observed when f_s and f_p were more closely spaced compared to conditions where they were more broadly spaced, particularly when high L_s were used.

Although the influence of L_p on these data is not apparent in Fig. 3, the conditions associated with the highest levels of system distortion (the 100% point on the cumulative distribution function) were those recorded with the highest L_p (50 or 60 dB SPL). In other words, in all cases, the highest levels of system distortion were observed when L_p was at or near its maximum level, which was when L_s also was at its

maximum level. Please note that due to the decision to limit the maximum stimulus level used during data collection in ears to 80 dB SPL, no data were collected with $L_p = 60$ for the $L_s = L_p + 30$ conditions. In some cases, this produced the impression that less system distortion was obtained for the $L_s = L_p + 30$ condition than for the $L_s = L_p + 20$ condition (compare the maximum system distortion recorded with $f_p = 2$ kHz in the bottom 2 rows). The apparently lower levels of maximum system distortion for the highest suppressor levels is a result of the decision to not test $L_p = 60$ dB SPL for this condition.

It should be noted that the biologic noise floor in ears varied across f_p but was generally between -20 and -30 dB SPL. Therefore the system distortion would not be expected to influence the SFOAE level recorded in ears until it exceeded -20 to -30 dB SPL. The system distortion values recorded in the acoustic cavities were frequently lower than -20 to -30 dB SPL; however, the data plotted in Fig. 3

suggest that system distortion exceeding the biologic noise floor may be present under some conditions, particularly when recording with high L_p and L_s and when f_s and f_p are closely spaced.

Given these observations, inclusion criteria were developed and data were required to meet these criteria to be considered primarily biologic in origin. Before applying these inclusion criteria to the data collected in phase 1, the mean AM-SFOAE response level for the 20 subjects participating in this phase was computed. Likewise, the mean noise level across the 20 subjects was calculated. After averaging the data across the 20 subjects, the following inclusion criteria were applied. First, the mean response level in ears must exceed the mean noise level in ears by 6 dB (the SNR must exceed 6 dB). Second, for those cases where the SNR was >6 dB, the response must also exceed the maximum system distortion level observed across all four cavities by 6 dB (the signal-to-distortion ratio, SDR, must exceed 6 dB). The SNR criterion was always invoked first because the SDR is of little interest for responses that are in the noise floor, i.e., these responses are not interpretable regardless of their origin, biologic or otherwise. Responses meeting these inclusion criteria were considered to be “valid” responses, where the average response in NH ears exceeded the noise floor by more than 6 dB and also exceeded the maximum response in cavities by more than 6 dB. More stringent inclusion criteria were used when making the determination of stimulus parameters for use when recording AM-SFOAEs. These more stringent criteria are described in Sec. III C.

B. Influence of suppressor frequency and level

The influence of f_s and L_s on AM-SFOAE level is plotted in Figs. 4 and 5. In Fig. 4, mean AM-SFOAE and noise levels (and standard errors) were obtained by averaging the responses obtained in the 20 subjects participating in phase 1 (15 females and 5 males). Data plotted on this figure represent cases where both the SNR and SDR were >6 dB. Missing data are observed in most panels. In the case of the lowest L_p 's (0–10 dB SPL), data typically were excluded for not meeting the SNR criterion. In contrast, at higher L_p 's and at narrow f_s/f_p spacing (i.e., $f_s/f_p = 0.96$ and 1.04), data more frequently were excluded for failing to meet the SDR criterion. These missing-data trends can be seen in the leftmost column ($f_p = 1$ kHz) in the $L_s = L_p + 20$ panel. Here data are plotted for $L_p = 10$ –60 dB SPL. No data are shown for $L_p = 0$ dB SPL because for all f_s/f_p 's, this L_p resulted in AM-SFOAEs with SNR <6 dB. Likewise, in this panel, data points are missing for $f_s/f_p = 0.96$ and 1.04 when $L_p = 50$ and 60 dB SPL. These data were excluded for not meeting the SDR inclusion criterion.

For low L_s (top 2 rows), f_s/f_p influences the level of the recorded SFOAE. For a fixed L_p , suppressors higher in frequency than the probe ($f_s/f_p > 1.0$) resulted in higher SFOAE levels than suppressors lower in frequency than the probe ($f_s/f_p < 1.0$). However, at higher L_s (bottom 2 rows), for any given L_p , similar AM-SFOAE levels were observed for suppressors both higher and lower in frequency than f_p and in some cases $f_s/f_p < 1.0$ produced larger AM-SFOAEs.

The influence of L_s and f_s on AM-SFOAE level for a fixed L_p is shown in Fig. 5. As was the case for Fig. 4, the data plotted in Fig. 5 represent the mean SFOAE levels for the 20 subjects participating in phase 1. These mean SFOAE levels are plotted as a function of L_s (in dB re: L_p). As in Fig. 4, all data plotted here met the inclusion criteria of SNR >6 dB and SDR >6 dB. The trends shown in Fig. 5 are consistent with those shown in Fig. 4, although the relative influence of L_s and f_s at a fixed L_p are seen more easily here. The data are consistent with the idea that for a given L_p , suppressors higher in frequency than the probe were more effective at suppressing the AM-SFOAE response when L_s is low (<20 dB re: L_p). However, for $L_s \geq 20$ dB re: L_p , suppressors lower in frequency than the probe result in AM-SFOAE levels that were equal to or slightly higher than those observed with a high-frequency suppressor. For most L_p 's, the SFOAE level saturated indicating that a range of f_s/f_p and L_s combinations are equally effective at suppressing the SFOAE, which results in equal AM-SFOAE levels across multiple stimulus combinations.

C. Stimulus parameters for recording AM-SFOAEs

The data plotted in Figs. 4 and 5 describe the influence of f_s and L_s on the mean AM-SFOAE response. Because exploration of this parametric space is time consuming, one goal of this study was to develop a set of stimulus parameters that would be expected to produce robust AM-SFOAE responses in individuals with NH. This was accomplished by first imposing more stringent inclusion criteria on the data to be included in this analysis. Data used for the purpose of identifying optimal stimulus parameters were required to meet the following three criteria: (1) The SNR must exceed 6 dB, (2) the AM-SFOAE level must exceed the maximum level of system distortion measured across all cavities by ≥ 10 dB, and (3) the AM-SFOAE level must exceed the maximum level of system distortion measured in the “ear-like” cavities (IEC 711 coupler and 2-cm³ coupler) by ≥ 15 dB. As was done with the data plotted in Figs. 4 and 5, the inclusion criteria were applied to the SFOAE data after the SFOAE data had been averaged across subjects. This resulted in the exclusion of the same conditions producing missing data points in Figs. 4 and 5 along with several additional conditions. These additional excluded conditions included data recorded with $f_p = 1$ kHz when $f_s/f_p = 0.96$ and 1.04 for all L_p and L_s . Data recorded at these ratios with $f_p = 2$ kHz for the highest L_s conditions ($L_s = L_p + 20$ and $L_s = L_p + 30$) also were excluded. Recall that these were the conditions where the cumulative distribution functions indicated higher system distortion levels than those obtained with other f_s/f_p 's (see Fig. 3). These more stringent criteria were imposed to reduce the likelihood that the conditions producing the highest AM-SFOAE levels included contributions from non-biologic sources.

After the data set was reduced through the more stringent inclusion criteria, the averaged data were examined to identify those suppressor frequencies and levels that resulted in the largest AM-SFOAE responses at each f_p and L_p . Because we observed differences in the L_s at which the

FIG. 4. AM-SFOAE level is plotted as a function of f_s/f_p for the three f_p 's evaluated in phase 1. Suppressor level increases from top to bottom in the figure as indicated within each panel. The symbols represent mean AM-SFOAE level (± 1 standard error). The parameter in each panel is L_p , decreasing in 10-dB increments from a maximum of 60 dB SPL, indicated with decreasing line thickness and change of symbol (as indicated on the figure). The dashed vertical line in each panel represents the division between conditions where $f_s < f_p$ and $f_s > f_p$. See text for discussion of missing data points in this figure. Note that maximum stimulus level was limited to 80 dB SPL. Because of this limitation in maximum level, when $L_p = 60$ dB SPL, no data were collected for $L_s = L_p + 30$. Therefore the highest L_p plotted in the bottom row of the figure is 50 dB SPL.

largest AM-SFOAE responses were observed when $f_s < f_p$ compared to $f_s > f_p$, we determined the L_s associated with the highest AM-SFOAE level for the low-frequency suppressors separately from the high-frequency suppressors. Figure 6 summarizes the data obtained through this analysis. In Fig. 6, the symbols represent the combination of L_s (top row) and f_s/f_p (bottom row) that produced the highest average AM-SFOAE level for each f_p and L_p . For both $f_s < f_p$ and $f_s > f_p$, the relationship between L_s and L_p was statistically significant suggesting that the highest AM-SFOAE levels were obtained when L_s was set higher than L_p and increased as L_p increased according to the best fit equation shown in each panel. As expected from the data plotted in Figs. 4 and 5,

when $f_s < f_p$, the largest AM-SFOAE response required a higher L_s than was required to record the largest response for $f_s > f_p$. In contrast to the results suggesting L_s should vary with L_p , the relationship between f_s/f_p and L_p was not statistically significant. This suggests that f_s/f_p should remain fixed across L_p .

Based on this regression analysis, the recommended stimulus parameters for recording AM-SFOAEs are shown in Table II. The recommendations for L_s were taken directly from the best fit equations shown in the upper row of Fig. 6. The recommendations for f_s/f_p were determined by taking the intercepts of the best fit lines in the bottom row of Fig. 6 and rounding to the nearest f_s/f_p that was used during data

FIG. 5. Average AM-SFOAE level as a function of L_s for the three f_p 's evaluated in phase 1. Each column represents data for a different f_p , with L_p increasing from top to bottom in the figure. The parameter within each panel is f_s/f_p . As in Fig. 3, cases where $f_s/f_p < 1.0$ are plotted with dashed lines and cases where $f_s/f_p > 1.0$ are plotted as solid lines. Line thickness is used to indicate the spacing between f_s and f_p . The thickest lines indicate the narrowest spacing ($f_s/f_p = 0.96$ and 1.04) with decreasing thickness indicating broader spacing. As in Fig. 4, when $L_p = 60$ dB SPL, no data were collected with $L_s = L_p + 30$. As a result, data for this condition are not plotted (see bottom row).

collection and that passes through the individual data points plotted in the lower row. In other words, for $f_s > f_p$, the intercept of 1.1 was rounded down to 1.08 and not up to 1.12 because 1.08 represents the individual data better than 1.12. The stimulus conditions specified in Table II are expected to produce robust AM-SFOAE responses across a range of frequencies. Furthermore, slightly higher response levels might be expected by using the conditions specified for $f_s < f_p$ than for the conditions specified for $f_s > f_p$ (see Figs. 4 and 5). These predictions were directly evaluated in phase 2.

D. Stimulus parameters in new subjects

In phase 2, a new group of 20 NH subjects (15 females, 5 males) participated in data collection. Data were collected in this group of subjects for $f_p = 0.7$ – 8 kHz in half-octave steps with L_p ranging from 20 to 60 dB SPL using the stimulus conditions specified in Table II. Figure 7 summarizes the

data collected in these subjects. The data plotted in Fig. 7 represent the median and interquartile ranges for AM-SFOAE and noise levels. Also shown in Fig. 7 is a thick slanting line, which represents the estimate of system distortion. This estimate was obtained by recording responses in the four cavities described previously (IEC 711 coupler, 2-cm² coupler, 10-m PVC tube, and a syringe) and developing a regression model to predict system distortion levels based on stimulus conditions.

The data plotted in Fig. 7 suggest we were able to record AM-SFOAEs that exceed both the noise level and the estimate of system distortion across a range of L_p 's for the majority of the new group of subjects. Positive SNRs and SDRs were observed across all frequencies, even those not evaluated during phase 1. The stimulus conditions derived in phase 1 appear to have generalized to a new group of subjects. Across most f_p 's, AM-SFOAE levels recorded using $f_s/f_p = 0.88$ were slightly higher than those recorded with

FIG. 6. The approach to specifying stimulus parameters for recording AM-SFOAEs. The symbols represent the L_s (top row) and f_s/f_p (bottom row) associated with the highest AM-SFOAE level at each L_p . The determination of parameters associated with the highest AM-SFOAE level was restricted to conditions where $f_s < f_p$ in the left column and $f_s > f_p$ in the right column. The solid lines in each panel represent the best fit line with the results of the regression analysis shown as insets in each panel. Note that the symbols are offset slightly in the figure for clarity. See text for information regarding inclusion parameters that were imposed on the data included in this figure.

$f_s/f_p = 1.08$. This observation was tested using repeated-measures analysis of variance (RMANOVA) with three factors, ratio (f_s/f_p), frequency (f_p), and level (L_p). Only response levels recorded for $L_p = 40$ – 60 dB SPL were included in the RMANOVA. We excluded the data for $L_p < 40$ dB SPL to reduce the influence of noise at these lower probe levels where poor (< 6 dB) SNRs were observed for many subjects. The results of this analysis are summarized in Table III. The results of the RMANOVA suggest that SFOAE level varies significantly with both L_p and f_p . These findings are not surprising and are consistent with similar observations made for DPOAEs (e.g., Gorga *et al.*, 1993; Dorn *et al.*, 2001) and for SFOAEs (e.g., Kemp and Chum, 1980; Schairer *et al.*, 2003; Schairer and Keefe, 2005).

For the purposes of determining stimulus parameters to be used in future studies with AM-SFOAEs, the significant results for the main effect of f_s/f_p and for the interaction of f_s/f_p and f_p are of interest. These results suggest that when the data were collapsed across both f_p and L_p , higher AM-SFOAE levels were recorded with $f_s/f_p = 0.88$ than for $f_s/f_p = 1.08$. The significant interaction of f_s/f_p and f_p , however, suggests that this trend was not present across all f_p 's. Examination of the data in Fig. 7 suggests that AM-SFOAE level was higher when recorded with $f_s/f_p = 0.88$ at all f_p 's

except 8 kHz, where AM-SFOAE level for $f_s/f_p = 1.08$ was 3.4 dB higher, on average. For all other f_p 's, the average (across L_p) AM-SFOAE level was higher with $f_s/f_p = 0.88$. The higher average level for $f_s/f_p = 0.88$ ranged from as little as 0.763 dB when $f_p = 2$ kHz to as much as 3.472 dB when $f_p = 1$ kHz. These data suggest that, for most frequencies, higher AM-SFOAE levels would be expected for $f_s/f_p = 0.88$ than for $f_s/f_p = 1.08$.

IV. DISCUSSION

The data plotted here extend the original report by Neely *et al.* (2005a) describing the AM-SFOAE technique by demonstrating the AM-SFOAE response in a larger group of NH subjects across a broader range of stimulus conditions. These data suggest that it is possible to obtain AM-SFOAE responses that exceed the estimates of both noise and system distortion for a range of stimulus frequencies and stimulus levels. We were able to develop a set of stimulus parameters (L_s , L_p and f_s/f_p relationships) that are expected to result in large SFOAE responses in NH ears. The data reported for phase 2 suggest that these stimulus parameters generalized to a new group of subjects; this suggests that the stimuli could be used in future investigations into clinical applications of AM-SFOAEs using large groups of NH and hearing impaired ears where an efficient protocol is necessary.

A. Contribution of system distortion to the AM-SFOAE response

All measurement systems have a limited dynamic range. Observations like those shown in Fig. 2, where the cavity

TABLE II. Stimulus parameters for recording AM-SFOAEs.

	$f_s < f_p$	$f_s > f_p$
L_s	$0.6L_p + 42$	$0.5L_p + 38$
f_s/f_p	0.88	1.08

FIG. 7. Input/output functions for AM-SFOAE and noise levels recorded using the stimulus parameters developed in Fig. 6 and specified in Table II. Probe frequency increases from top to bottom in the figure as indicated within each panel. Solid lines represent median levels, with the dashed lines representing the interquartile range. The thick, solid line within each panel represents the estimate of system distortion.

response was identical to the response from the NH ear, suggest it is important to define those conditions under which system nonlinearities may contaminate the response. The data shown in Fig. 2 suggest that the major source of

TABLE III. Results of the RMANOVA for AM-SFOAE Level. The asterisk (*) denotes conditions reaching statistical significance ($p < 0.05$).

Source	df	F ratio	p value
Main effects			
*Ratio (f_s/f_p)	1, 17	46.06	<0.001
*Frequency (f_p)	4.3, 72.4	5.07	0.001
*Level (L_p)	2.2, 38	184.84	<0.001
Interactions			
* f_s/f_p and f_p	3.8, 63.8	6.63	<0.001
f_s/f_p and L_p	2.4, 41.5	1.62	0.206
f_p and L_p	28, 476	0.82	0.730
f_s/f_p , f_p , and L_p	28, 476	1.486	0.054

nonlinearities is the ER-10C probe-microphone system. Examination of the responses recorded across the four cavities suggests that a large portion of the distortion components arise from the AM suppressor tone. Examination of the spectrum of the AM suppressor indicated the presence of the expected sidebands at $f_s \pm mf$, along with additional distortion components. The amplitude of these distortion components grew as suppressor level increased. When f_s and f_p are closely spaced, such as when $f_s/f_p = 0.96$ and 1.04 , the energy from the distortion components may overlap the sideband frequencies at which the determination of the SFOAE response is made. These additional distortion components more frequently were observed when recording low- and mid-frequency AM-SFOAEs ($f_p = 1$ and 2 kHz) than when recording higher frequency AM-SFOAEs ($f_p = 4$ kHz), consistent with the trends observed in Fig. 3. They also were more apparent at the highest suppressor levels.

It appears that this source of system distortion may be specific to the AM-SFOAE technique because it was observed for the AM suppressor more frequently than for the probe, which was fixed in level in this implementation of the AM-SFOAE technique. Other suppression approaches that used fixed-levels for both the probe and suppressor would not be expected to be contaminated by this type of system distortion. It appears that when using the AM-SFOAE technique, care must be given to the spacing of the suppressor and probe frequencies to avoid interference from the distortion components introduced to the AM suppressor by the ER-10C system. These distortion components were observed across the three models of the ER-10C that are used in the laboratory. It is not clear if another probe system would be less susceptible to this type of nonlinearity.

Although we have attempted to minimize the influence of system distortion on the AM-SFOAE data through cavity measures and the implementation of inclusion criteria, an additional level of verification would include recording the AM-SFOAE response in NH and hearing-impaired ears to evaluate the extent to which responses differ in these groups. Although it is difficult to fully capture system distortion for all possible acoustic environments, we believe the stringent inclusion criteria used when developing the stimulus parameters eliminated the majority of the non-biologic contributions to the measured response.

B. Influence of suppressor frequency and level on the AM-SFOAE

The data plotted in Figs. 4 and 5 suggest that the AM-SFOAE response is influenced by the frequency and level relationships between the suppressor and probe tones in a manner that is consistent with what would be expected from mechanical two-tone suppression data. For a fixed L_p , the response to f_p that is generated by the cochlea (the cochlear SFOAE) is constant. Thus, in Fig. 4, the cochlear SFOAE response for any single curve within each panel is constant because all points on the curve were recorded with a fixed L_p . Likewise, the cochlear SFOAE response within each panel of Fig. 5 is fixed due to the common L_p in each panel. For a fixed L_p , deviations in the measured AM-SFOAE response level, therefore, indicate variations in the extent of interaction between the probe and suppressor responses along the basilar membrane. In other words, although the cochlear SFOAE is constant for a given probe level, measurement of the response depends on the interaction between the suppressor and probe responses; therefore, variability in the measured AM-SFOAE levels for a given probe level must be due to variability in the extent to which the suppressor and probe interact.

For the lowest suppressor levels ($L_s = L_p + 0$ or 10), the highest AM-SFOAE levels were observed for suppressors that were higher in frequency than the probe ($f_s/f_p > 1.0$). This pattern is consistent with mechanical two-tone suppression data that suggest suppression is observed at lower suppressor levels when the suppressor is higher in frequency than the probe compared to when the suppressor is lower in frequency (e.g., Cooper, 1996; reviewed in Robles and Ruggero, 2001). Similar patterns also have been reported for SFOAE data (e.g., Brass and Kemp, 1993; Keefe *et al.*, 2008).

For the higher suppressor levels in Figs. 4 and 5 ($L_s = L_p + 20$ or 30), the AM-SFOAE response recorded for the suppressors lower in frequency than the probe ($f_s/f_p < 1.0$) are equal to or, in some cases, larger than those observed with the high-frequency suppressors. This finding suggests that once an effective suppressor level is used, the low-frequency suppressor yielded a more fully suppressed SFOAE. These patterns also were observed in Fig. 7 and were confirmed in the statistical analyses completed for those data. Ruggero *et al.* (1992) reported similar observations in their data on mechanical two-tone suppression in chinchilla where suppressors that were lower than the characteristic frequency resulted in greater suppression magnitude than suppressors that were higher in frequency. Brass and Kemp (1993) and Keefe *et al.* (2008) reported a similar pattern in their SFOAE data.

Brass and Kemp (1993) provide a simple explanation of this pattern that is based on consideration of the relative overlap of the probe and suppressor tones along the basilar membrane. When presented at equivalent low levels, a high-frequency suppressor will more fully overlap the probe traveling wave than a low-frequency suppressor. As a consequence, the high-frequency suppressor will provide more complete suppression, particularly in the region just basal to the peak of the probe traveling wave. As suppressor level is

increased, however, the low-frequency suppressor becomes more effective due to the basal spread of its tail which produces increasing overlap (and suppression) of the response to the probe. In contrast, for all but the narrowest f_s/f_p 's, a high-frequency suppressor is more restricted in the extent of overlap with the probe because traveling-wave spread in the apical direction is more limited.

C. Stimulus parameters for recording AM-SFOAEs

The stimulus parameters identified in Table II can be used in future work with AM-SFOAEs. Slightly (but significantly) larger response levels are expected for the parameters associated with $f_s < f_p$ compared to $f_s > f_p$. It should be noted that the largest f_s/f_p evaluated was 1.16. Keefe *et al.* (2008) have noted that the most sensitive region for suppressors higher in frequency than the probe occurs in the vicinity of $f_s/f_p = 1.19$, a slightly larger value than the maximum used in this study. It is possible that the differences in SFOAE level observed for $f_s < f_p$ compared to $f_s > f_p$ may have been reduced if we had collected data for $f_s/f_p > 1.16$. In any case, for the stimulus parameters described here, slightly larger SFOAE levels would be expected at most frequencies when using $f_s/f_p = 0.88$ compared to $f_s/f_p = 1.08$.

Data shown in Fig. 7 suggest that the stimulus parameters described in Table II generalized to new subjects and are expected to produce robust SFOAEs in NH ears. The validation of these stimulus parameters in a new sample of subjects during phase 2 is an important aspect of the work describe here, suggesting that the stimulus parameters were not idiosyncratic to the ears on which they were developed. Additionally, although the stimulus parameters were based on data collected in ears that primarily were females, examination of the responses recorded in the five males participating in phase 2 suggested that their responses were distributed throughout the interquartile ranges plotted in Fig. 7. These stimulus parameters appear to produce robust responses in both male and female ears.

Based on the results of phase 2, where robust AM-SFOAEs were observed in a new group of subjects, future work could focus on questions related to the accuracy with which AM-SFOAEs identify auditory pathology. Some have speculated that OAEs arising from a single cochlear-source mechanism may more accurately identify auditory pathology than OAEs arising from multiple cochlear-source mechanisms (e.g., Shera and Guinan, 1999; Dhar and Shaffer, 2004; Vetesnick *et al.*, 2009). Although this has been a matter of some debate (compare Siegel *et al.*, 2005 and Shera *et al.*, 2008), low-to-moderate level SFOAEs are believed to primarily arise through the reflection-source mechanism (Shera and Guinan, 1999, 2003; Goodman *et al.*, 2003; Schairer *et al.*, 2006; Choi *et al.*, 2008). The use of suppressors that are within $\frac{1}{2}$ -octave of the probe frequency, as is the case for all f_s/f_p combinations used in the present study, may also help to restrict the cochlear contributions to a single source mechanism (Shera *et al.*, 2004; Kalluri and Shera, 2007). It remains to be seen if SFOAEs could be used to provide any additional information beyond what is currently obtained from DPOAE or TEOAEs.

V. CONCLUSIONS

AM-SFOAEs can be recorded across a range of frequencies and levels. Variations in suppressor-probe frequency and level relationships influence the AM-SFOAE level in a manner that is consistent with mechanical two-tone suppression data. The stimulus parameters developed in phase 1 of this project generalized to new subjects in phase 2. These stimuli could be used in future investigations with AM-SFOAEs.

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