Simulated performance of an acoustic modem using phase-modulated signals in a time-varying, shallow-water environment

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Published in:
Acoustical Society of America. Journal

Link to article, DOI:
10.1121/1.417508

Publication date:
1996

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

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Error in the calculation of synchronized spontaneous otoacoustic emission frequencies measured with the ILO88 system [43.64.Jb, 43.64.Yp]

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High-level spontaneous otoacoustic emissions (SOAEs) were measured from 16 ears using both spectral and time averaging. The purpose was to determine the source of an upward shift in frequencies of synchronized SOAEs (SSOAEs) observed while using a subroutine of the ILO88 system of Otodynamics Ltd. An HP3561A signal analyzer performed spectral averaging to extract SOAEs with no external stimulation applied to the ear canal. Synchronized SOAEs were derived using the ILO88 system performing time averaging following click stimulation. The frequencies of all SSOAEs were shifted upwards by 6 to 21 Hz when compared to corresponding SOAE frequencies determined with spectral averaging. Additional measurements of signals in a cavity and of click-evoked otoacoustic emissions in selected ears indicated that the frequency shift is the result of an error in the ILO88 software. Incorrect cursor readouts in the program cause an apparent upward shift in frequency of 12.2 Hz. This error was confirmed by the manufacturer.

Spontaneous otoacoustic emissions (SOAEs) represent narrow-band signals that can be recorded in the outer ear canal when no external acoustic stimulation is presented (see Probst et al., 1991 for a review). In general, two methods have been used to record them. In the first, the sound-pressure level in the ear canal is measured by a low-noise microphone with no stimulation applied. The microphone signal is averaged in the frequency domain (e.g., Whitehead et al., 1993). The second method consists of recording SOAEs synchronized by acoustic stimuli, for example clicks, using averaging in the time domain. This enables the detection of long lasting oscillations following click-evoked otoacoustic emissions (CEOAEs). It has been shown that for an ear with strong SOAEs, a CEOAE spectrum exhibits peaks corresponding to SOAE frequencies (Probst et al., 1986; Gobsch and Tietze, 1993). Software of a widely used commercially available instrument for measuring OAEs, the ILO88 (Otodynamics Ltd., Hatfield, UK), includes a subroutine for measuring synchronized spontaneous otoacoustic emissions (SSSOAEs). Several recent studies have reported SSOAE data collected with the ILO88 system (Wable and Collet, 1994; Kulawiec and Orlando, 1995; Prieve and Falter, 1995). As part of an ongoing study of otoacoustic emissions in normal-hearing humans in our laboratory, we have measured SOAEs using both spectral averaging and the synchronization technique of the ILO88. In comparing the two results from the same ear, we have observed a slight but consistent difference in the frequencies of SSOAEs and SOAEs. Therefore, we sought to characterize this discrepancy further and to determine its source. Because of the widespread use of the ILO system, we believe that it is important that our findings be reported.

Both ears of eight subjects from our laboratory pool who had known SOAEs that were at least 10 dB above the noise floor of the instrumentation were tested with two methods. In the first method, the sound-pressure level in the ear canal was measured by a low-noise microphone (Etymotic Research, ER10A) with no stimulation applied. The microphone output was connected to a custom-made low-noise preamplifier with a gain of 20 dB and a high-pass filter with a cutoff frequency of 400 Hz. The signal was led to a dynamic signal analyzer (Hewlett-Packard 3561A) and was analyzed from 0.5 to 10 kHz in 500-Hz Hanning windows. For each frequency span, a spectrum with an analysis bandwidth of 1.875 Hz was obtained based on the average of 20 fast Fourier transforms (FFTs) of the microphone signal. Automatic artifact rejection of the spectrum analyzer with the rejection threshold set at 50 dB SPL was used to eliminate samples contaminated by high-level physiological noise resulting from swallowing, noisy breathing, and muscle and joint movements. Individual traces were stored in the bubble memory of the instrument for further analysis. A high-level SOAE was defined as any narrow-band, i.e., a spectrum obtained over noise floor by >10 dB and was present in two consecutive average spectra of the signal from the ear under test. The cursor on the display of the instrument was used to determine the frequency of the SOAE.

The second method used the SSOAE subroutine of version 4.2 of the ILO88 system’s software run on a Pentium computer. In this mode, a single 80-μs pulse was presented every 80 ms at a peak level of approximately 72 dB SPL through a probe fitted in the external ear canal. The microphone signal was averaged over a 20- to 80-ms poststimulus time interval. Five hundred responses were averaged. The FFT resolution was approximately 12.2 Hz. Data were stored on a disk for further analysis. The characteristics of the SSOAEs were determined after examining two spectra, i.e., signal spectrum and noise spectrum, that were calculated and displayed by the ILO88 system. The frequency of the SSOAEs corresponding to the maximum level of the narrow-band signal in the targeted frequency range was determined using a cursor. Testing using both methods was performed in a sound-treated room with the subject seated quietly. Each session started with SSOAE testing for both ears of one subject followed by SOAE testing.

The total number of high-level SOAEs ranged from 1 to 7 per ear (with the total number of 41 in 16 ears). There was generally good correspondence of the SOAEs and SSOAEs obtained from the same ears with the two methods of recording, i.e., a spectrum obtained with the ILO88 system exhibited peaks in the same frequency regions as detected by the HP3561A analyzer. Similar findings have been obtained previously by Gobsch and Tietze (1993) who used a laboratory system for data collection. Their Fig. 1, which depicts a representative example of SOAEs and SSOAEs, showed the presence of SSOAEs at exactly the same frequencies as SOAEs. A detailed analysis of our own data revealed, however, an evident shift between SSOAE and SOAE frequencies. For all 41 SOAEs, the corresponding SSOAE frequencies were higher by 6 to 21 Hz. The observed difference between the frequencies is not due to differences in the frequency resolution (two methods of recording) or to stimulus level (75.75 Hz versus 12.2 Hz) because in all cases the frequency shift was in the same direction. Therefore, we sought to determine the source of the error. One possible explanation for the differences might be that synchronizing clicks change the mechanical properties of the cochlea, which could result in a frequency shift. Interactions between SOAEs and external pure tones are known to exist (e.g., Long et al., 1991). Another possibility would be an artifact in the ILO system. Additional measurements were performed to evaluate these potential causes.

Figure 1 displays a set of results obtained from the left ear of one of the subjects. The data are for the 1750- to 2250-Hz frequency region. The output recorded using spectral averaging with the HP3561A analyzer is presented in Fig. 1(a). Note the dominant SOAE at 2035 Hz with a level of +1.9 dB SPL (approximately 21 dB above the noise floor). Using the ILO88 system in SSOAE mode, a spectrum with several local peaks (SSSOAEs), one of them at 2051 Hz with a level of ~8.1 dB SPL was obtained [Fig. 1(b)]. In this case, there was an upward shift of the SSOAE frequency by 16 Hz when compared to the SOAE frequency. Without removing the ILO88 probe from the ear canal and without changing the stimulus level, a CEOAE was recorded using the “nonlinear” operational mode (Kemp et al., 1990). This consists of a stimulus set of four clicks, delivered three at the same level and polarity and the fourth three times greater in level and inverted in polarity. The sweep time clock was set to 120 μs. The poststimulus analysis time window was 60 ms, and the frequency resolution of the CEOAE spectrum was 16.3 Hz. The CEOAE spectrum exhibited several local peaks with a strong narrow component at 2034 Hz [Fig. 1(c)], which corresponded
almost exactly to the frequency of the SOAE determined using spectral averaging [Fig. 1(a)]. Note: The difference of 1 Hz is lower than the frequency bandwidth of the spectrum analyzer. A comparison of the two spectra collected with the ILO88 system in the two different operational modes showed an obvious difference [Fig. 1(d)]. Similar results were obtained from four other ears. This finding does not support the hypothesis that syn- 

tra collected with the ILO88 system in the two different operational modes 

The spectrum collected with the SSOAE mode of the ILO88 system exhib-

phone was removed and the ILO88 probe was then sealed into the cavity. 

SOAE from the human ear as displayed in Fig. 1 

of the pure tone in the spectrum recorded from the cavity matched the 

method of spectral averaging as used for the SOAE testing. The frequency 

into the cavity, and the signal spectrum was measured using the same 

SSOAE search mode with a 12.2-Hz frequency resolution. The response 

dotted line in panels (b) and (c) corresponds to the frequency of the SOAE 

at 2035 Hz determined by the spectrum analyzer. (d) The SSOAE spectrum 

(solid line) overlaid on the CEOAE spectrum (dashed line).

FIG. 1. Microphone signal spectra for a normally hearing ear collected 

using different methods of recording. (a) Spectral average (n = 20) obtained 

with the ER10A microphone and the Hewlett-Packard 3561A dynamic sig-

nal analyzer with an analysis bandwidth of 1.875 Hz depicts an SOAE at 

2035 Hz. (b) Time-averaged spectra obtained with the ILO88 system using 

the SSOAE search mode with a 12.2-Hz frequency resolution. The response 

spectrum (thin line) depicts an SSOAE at 2051 Hz clearly detectable above 

the background noise (thick line). (c) Time-averaged spectra obtained with 

the ILO88 system using the nonlinear CEOAE mode and a 16.3-Hz fre-

quency resolution. The response spectrum (thin line) depicts a strong narrow 

component at 2034 Hz. Thick line represents background noise. The vertical 

dotted line in panels (b) and (c) corresponds to the frequency of the SOAE 

at 2035 Hz determined by the spectrum analyzer. (d) The SSOAE spectrum 

of the pure tone in the spectrum recorded from the cavity matched the 

frequency depicted by the cursor would be shifted upwards in relation to 

its actual value. An inquiry to the manufacturer of the equipment (Otody-

amics Ltd.) led them to examine the source code of their software, and the 

error was detected and confirmed. The leftmost position of the cursor was 

set incorrectly to 12.2 Hz rather than to zero as it should have been. This 

accounts for the 12.2-Hz frequency shift of the cursor readout. After cor-

recting for this error, the difference between the frequencies of the 41 

SOAEs and SSOAEs recorded from the group of 16 ears would range from 

-6 to +9 Hz.

The data shown in Fig. 1 illustrate additional findings (currently under 

further exploration) that are outside the main focus of this study but need 

some clarification in this paper. For all 16 ears, the SOAEs exhibited higher 

levels than corresponding SSOAEs. For example, there was a 10-dB differ-

ence in the level of the SOAE shown in Fig. 1(a) compared to its SSOAE 

counterpart shown in Fig. 1(b). The reason of that difference is somewhat 

unclear. A set of SOAE and SSOAE recordings is planned using the same 

ER10A probe and our own software to control data acquisition via a 16-bit 

A/D converter for both methods. These measurements would also allow 

a direct comparison of S/N for SOAE and SSOAE recordings. Such a com-

parison based on the present data is difficult due to unknown characteristics 

of the ILO88 probe. Finally, in almost all of the 16 ears, the spectra obtained 

with the ILO88 system exhibited additional peaks (SSOAEs) that were not 

observed on the spectra recorded with the HP3561A analyzer (e.g., Fig. 1). 

It is believed that those peaks represented synchronized sound-evoked com-

ponents with a long duration but without spontaneous oscillations. Similar 

findings were previously reported by Wable and Collet (1994).

In conclusion, the ILO88 system, which is commercially available and 

widely used to measure CEOAEs in clinical settings, is also valuable for 

screening for the presence of SSOAEs. For such screening purposes, the 

frequency discrepancy of 12.2 Hz is not of critical importance. However, 

when detailed information regarding SOAEs is required SSOAE data should 

be corrected accordingly when version 4.20 (or earlier) of the software is 

used. Frequencies of SSOAEs are incorrectly displayed on the computer 

screen and should be corrected by shifting frequency downward by one step, 

i.e., 12.2 Hz.

ACKNOWLEDGMENTS

This study was supported by a grant from Swiss National Foundation 

(project Nr. 3200-042241.94/1). We thank Dr. Dennis McFadden for stimu-

lating discussions via the Internet, Dr. David Kemp for helping us to solve 

the “mystery” of the frequency shift, and Dr. Frances Harris for comments 

on the manuscript.


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Advanced-degree dissertations in acoustics

Editor’s note: Abstracts of Doctoral and Master’s theses will be welcomed at all times. Please note that they must be double spaced, limited to 200 words, must include the appropriate PACS classification numbers, and be submitted to the address for obtaining a copy of the thesis is helpful. Please submit two copies.

Multiple-reference adaptive noise control in enclosures[43.40.Qi, 43.50.Ki, 43.60.Lq]—Zane Michael Rhea, Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA 16802, May 1996 (M.S.). Noise control of multiple noise sources in three-dimensional enclosures remains a concern in many applications. This is of particular interest in vehicles, such as twin-engine propeller-driven aircraft, where multiple primary sources contribute to the sound field inside the enclosure. When utilizing active noise control (ANC) systems in these applications, multiple reference inputs are required. A comparison of ANC of multiple noise sources with multiple and single reference inputs is presented in a case format. The enclosure walls were excited at four pairs of frequency sets: (1) with both frequencies on-resonance for both the structure and the enclosure, (2) with both frequencies at structurally dominated modal frequencies (on-structural off-enclosure resonance), (3) with both frequencies at acoustically dominated modal frequencies (off-structural on-enclosure resonance), and (4) with both frequencies off-resonance for both the structure and enclosure. The purpose of this study is to determine if the enclosed sound field from multiple noise sources can successfully be controlled with (1) a single reference input which contains information from only one primary noise source, (2) a single reference input which contains information from both primary sources, and (3) multiple reference inputs; at frequencies on and off resonance for the structure and enclosed space.

Thesis co-advisors: Courtney B. Burroughs, Scott D. Sommerfeldt.

Remote estimation of sound speed in an elastic medium [43.30.Es, 43.30.Pc, 43.58.Dj]—Todd A. Matthias, Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA 16802, December 1995 (M.S.). Remotely determining the acoustic properties of an unknown medium such as the ocean sediment is a fundamental problem of interest to ocean acousticians. This thesis describes several nondestructive, remote methods for finding the sound speed in a medium that is adjacent to a medium of known sound speed. The methods are developed and examined for accuracy. An experiment is performed in which one of these methods is used to determine the sound speed in an elastic medium submerged in water.


Active control of discrete-frequency noise from small subsonic fans[43.50.Ed, 43.50.Ki, 43.28.Ra]—John MacGilivray, Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA 16802, May 1996 (M.S.). This research investigates the use of active noise control to reduce the emissions of small subsonic axial flow fan units typically found in computer enclosures and printers. Aerodynamic noise generated by an axial flow fan is reduced using active noise control where sources of tonal sound in the primary noise field are coupled to a secondary source created by physically shaking the fan unit. The nature of the control method essentially colocalizes the primary and secondary sources at frequencies for which the fan acts as a compact source. Feasibility studies are used to predict potential fan and shaker combinations that would be effective and to determine which implementations of control are viable. Simulations of the proposed control scheme are presented and an experimental demonstration of the concept using a 92-mm axial flow fan which is baffled is conducted. Sound power level reduction of 14 dB at the blade passage frequency of a baffled fan unit is achieved, and additional measurements show that sound pressure level reductions as great as 21 dB can be demonstrated for a fan surrounded by a computer enclosure.

Thesis advisor: Gary H. Koopmann.

Gender differences and the development of the frequency importance functions using the articulation index[43.71.Bp, 43.71.Es, 43.71.Gv]—Mary Colleen Herr, Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA 16802, December 1995 (M.S.). Since the early study by French and Steinberg (1947), there has been little female data involved in frequency importance function calculations. This research investigated the frequency importance function development for words spoken by male and female speakers. The
highly controlled experimental conditions ensured that differences in FIF were attributed to gender alone. Twenty-two normal hearing listeners were asked to identify words presented under 60 filtering and noise background conditions for each gender of speaker. The frequency importance functions for words spoken by both speakers were derived and graphically presented. The most important frequency band for understanding male and female produced speech, was in the 1400- to 3000-Hz frequency band. A statistical analysis on the differences between the FIFs was also conducted using a one-way ANOVA and one-sample runs test. The statistical analysis found that there was no significant difference between the frequency importance functions for words spoken by the two speakers. It was concluded that gender did not play a role as a distinguishing characteristic in frequency importance functions for words spoken by the particular set of speakers participating in this study. Future studies may include the utilization of child speakers to obtain frequency importance function information for various speech types.

Thesis advisor: Claus P. Janota.

A superposition model for the study of acoustic radiation by finite length cylinders

Mark J. Bregar, Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA 16802, May 1995 (M.S.). Cylinders, one of the fundamental geometric shapes, are found in many physical devices. In applied engineering and acoustics, the study of vibrating cylinders becomes important in structural analysis and noise control. Cylinder modeling, therefore, becomes an important tool in determining their behavior. Exact solutions to their acoustic field patterns become unmanageable due to the mathematical complexities. Boundary element models are available commercially, but a simple model that can be run on a small digital computer is desired. The superposition principle arises as a plausible candidate. In order to confirm its appropriateness and discover the limitations of the model, a study was undertaken. The following five steps were taken: (1) formulate and justify the model mathematically; (2) prove, by a comparison of two-dimensional exact and superposition model solutions, that indeed the representation provides acceptable results; (3) extend the model to the more practical three dimensions; (4) apply it to “real world” problems and (5) compare the results to available empirical data. A review is then made which exhibits the strengths and weaknesses of the superposition formulation.

Thesis advisor: Oliver McDaniel.