# Otoacoustic Emissions as a Compositional Tool

By Jonathon Kirk, Eastern Illinois University Department of Music
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This paper describes various compositional attempts at initiating otoacoustic emissions through electronic music composition. Otoacoustic emissions (OAE) are sounds that arise in the inner ear and which are related to the process of amplification in the cochlea. While the physiological processes involved with OAEs are not entirely understood, scientists now have a better comprehension of how they work within the inner ear. This paper will provide a basic overview of OAEs along with their compositional applications by assessing particular works of Maryanne Amacher, Jacob Kirkegaard, and Phill Niblock.

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*Jonathon Kirk*

Eastern Illinois University
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## ABSTRACT

This paper describes various compositional attempts at initiating otoacoustic emissions through electronic music composition. Otoacoustic emissions (OAE) are sounds that arise in the inner ear and which are related to the process of amplification in the cochlea. While the physiological processes involved with OAEs are not entirely understood, scientists now have a better comprehension of how they work within the inner ear. This paper will provide a basic overview of OAEs along with their compositional applications by assessing particular works of Maryanne Amacher, Jacob Kirkegaard, and Phill Niblock.

## 1. INTRODUCTION

Otoacoustic emissions (OAEs) are physical sounds that arise in the ear canal when the tympanum receives vibrations transmitted backwards through the middle ear from the cochlea [2]. While aural harmonics and subjective distortion products have been understood as psychoacoustic phenomena since the eighteenth century, by the mid twentieth century there had not been an adequate explanation to account for a physical appearance of these tones in relationship to the processes of the inner ear. OAEs were first predicted by NASA scientist Thomas Gold in 1948 and later discovered by auditory physicist David Kemp in 1977 [10]. Gold based his cochlear model on his experience with radio technology and the transduction of frequency information by regenerative receivers. Kemp followed Gold's model by suggesting that distortion products could be generated within the ear, and that these products could be described as 'evoked cochlear mechanical responses' or 'echoes' [7]. Scientists then began to infer connections between perceivable internal oscillations in the ear and physical emissions from within the inner ear.

Eventually these responses would be described as OAEs, and it would be shown that the sound produced by the ear could be measured and recorded in the human ear canal. With the knowledge that the inner ear could indeed generate sound, Davis (1983) described the presence of a 'cochlear amplifier' and it was later demonstrated that the outer hair cells were capable of receiving and transducing energy [3]. Ultimately it was shown that OAEs could be generated as distortion products by the application of two sinusoidal stimuli, and it was also recognized that one could record OAEs by placing a small microphone inside the ear canal. As the reality of OAEs were confirmed and the processes of the inner ear became better linked to physical sound, we now understand that the cochlea uses active processes to detect the phenomenally faint sounds (measured in micropascals) that our ears routinely hear [2].

## 2. OAE CATEGORIZATION

OAEs are generally categorized in three types: spontaneous otoacoustic emissions (SOAE), transient evoked otoacoustic emissions (TEOAEs), and distortion product otoacoustic emissions (DPOAEs). DPOAEs are generated by the simultaneous presentation of two closely spaced sinusoidal frequencies where the two frequencies activate the cochlea in the same region of the basilar membrane [5]. It was implied early on that OAEs were consistent with the appearance of subjective combination tones and in some cases with the resultant sounds caused by diplacusis, but it was shown by Kemp (1977) that the mechanical process of intermodulation distortion parallels the stimulus parameters involved in the generation of OAEs: the quadratic difference tone (QDT) appears at frequency $f_{QDT} = f_2 - f_1$ where $f_2 > f_1$. While other distortion product (DP) frequencies are possible of being generated, the strongest additional DP in humans is defined by the cubic difference tone (CDT), $f_{CDT} = 2f_1 - f_2$. While nonlinear distortion should generate the sum tone as well, it is much more difficult to hear because it can be masked by the original tones. Furthermore the ordinary difference tone can be difficult to detect when it lies between $f_1$ and $f_2$ [4]. Emergence of DPOAEs in the cochlea show that when there is nonlinearity anywhere in the sound transmission path it should generate an additional sounding element.

SOAEs, faint, pure sounds from within the ear, were the first to be reported and are generally used in the testing of infant hearing, while TEOAEs are similar to DPOAEs and are recorded in response to a very abrupt (click) stimulus [5]. Because acoustic stimuli are easily controlled and the resultant tones are mathematically predictable, DPOAEs are perhaps the most advantageous to record and measure.

## 3. DISTORTION PRODUCTS

There is wide acceptance that the cochlea is a frequency specific organ and DPOAEs should be considered on a frequency by frequency basis. Because TEOAEs involve clicks, which contain all frequencies, DPOAEs can be and are used to control frequency/pitch material in the listener's ear. DPOAEs involve a more restricted part of the cochlea so that the outer hair cells become active in their working state [7]. The precise 'tuning' of DPOAEs can be a very important facet for the composer to consider. OAEs are highly frequency specific: each frequency component can be directly traced to a frequency component in the stimulus.

By considering the active listening processes involved in the inner ear, intentional creation of DPOAEs can bring about dynamic musical possibilities due to the external ear containing both physiologic sound generated by the listener and the ambient environment. This of course can result in very complex interactions including the generation of nodes and antinodes (via standing waves) and the stimulus sound wave moving outward from the tympanic membrane [11].

## 4. MUSICAL EXAMPLES OF DPOAE

While many composers working within an electronic medium have used aural harmonics or combination tones intentionally or involuntarily, some have purposefully used the creation of distortion products (DP) as an independent musical element. As the process of harnessing both the synthesis and recording of OAEs has become better documented in the past twenty years, composers have been able to organize DPs within a temporal framework so that the listener's ear becomes an active layer in a composition's structure.

### 4.1. Phill Niblock

Composer Phill Niblock (b. 1933) has become known for intensely loud pieces that involve live, amplified instruments being performed alongside dense, microtonal layers of sound. These microtonal drone-like layers usually involve overlapping recordings of the amplified instruments, carefully processed to create a new level of aural complexity. A typical concert of his music involves the screening of any number of his minimalist, quasi-documentary films integrated with a surround sound speaker array. Niblock carefully maps out the behavior of the combination tones so that the audience is saturated by the total space, "engaging the air" [9].

Niblock is primarily concerned with the construction of a multi-layered texture that is realized by the interaction of carefully chosen individual frequencies. Niblock's earlier work exploited the listener's own experience with the critical band by layering the frequencies so that the presence of aural beating becomes a prominent compositional layer. It is because of this that Niblock commonly refers to his music as 'architectural,' creating an aural geography in space created by a single sound source [12].

*3 to 7 – 196* is a work for cello and tape that uses sampled sustained tones from the cello at varying lengths. The title refers to the pitch G3 (196 Hz) and seven higher pitches in steps of 3 to 7 Hz (200, 207, 213, 216, 221 225, 228 Hz). In the two-channel mix, the first four frequencies are heard in one channel and the second four are heard in the other. While this creates a number of dense layers of audible beating, Straebel (2008) points out in his analysis that Niblock aims for 28 combination tones or beating patterns of 21 frequencies between 3 Hz and 32 Hz to emerge, even though many of these would be inaudible because of their low frequency [12]. However DPs would arise when played at a very high volume—Niblock requests the amplitude at 90 to 100 dB (SPL).

### 4.2. Maryanne Amacher: Sound Characters

Composer Maryanne Amacher (1938-2009) became interested in the physicality of sound while she began composing electronic music in the mid 1960s. Later and after confirming that OAEs where in fact physical sounds inside the ear, she indicated a desire to create a kind of music where the listener would have vivid experiences while contributing another sonic dimension to the music that their ears were making [1]. Amacher described OAEs as indicative of 'perceptual geographies,' or ways of hearing that she understood as being experienced primarily as subliminal. Because Amacher realized that first, second, and third order difference tones were common in much of the electronic music she was creating, she set out to compose music that would not allow the listener to become desensitized to this other sonic dimension.

In 1999, Tzadik released *Sound Characters (Making of the Third Ear)*, which contained the music from a variety of site-specific sound installations and was also the first full-length recording of her musical works. Many of these pieces rely on the DPOAE sound layer to play an active role in the experience of the listener. Pieces like *Head Rhythm 1*, *Chorale 1*, and *Dense Boogie* all present fast, uninterrupted looping of up to 4 sinusoidal stimulus frequencies (2 in each channel) at the same time, and lead to the emergence of an inner ear counterpoint. Redundancy and repetition are important to her musical process; this allows for the DPs to become more embedded within the external sound layers, and in a sense, create a perceivable tonality.

Amacher's OAE compositions put significant focus on audible beating created by relatively high frequencies. For instance, *Chorale 1* presents an arpeggiated and microtonal F triad (seemingly major) through the creation of QDTs.

The piece opens with two simultaneous sinusoidal chords resulting in QDTs of an alternating fifth in the left channel and an alternating third in the right channel (left channel: $f_2$ = 3026 Hz and $f_1$ = 2762 Hz yielding $f_{DT}$ of 264 Hz and $f_2$ = 2016 Hz and $f_1$ = 1841 Hz yielding $f_{DT}$ of 175 Hz; right channel $f_2$ = 2234 Hz and $f_1$ = 2144 Hz yielding $f_{DT}$ of 90 Hz and $f_2$ = 2680 Hz and $f_1$ = 2572 Hz yielding $f_{DT}$ of 108 Hz). As the piece progresses, Amacher maintains the low F 'tonality,' but tunes the right channel frequencies much closer so that the audible beating slows thus creating a rougher texture. While the CDTs are significantly masked at the beginning, they become more prevalent as the piece progresses, adding to its sonic complexity and leading to a more interesting interplay within the ear.

### 4.3. Jacob Kirkegaard: Labyrinthitis

Like Amacher, the work of composer and sound artist Jacob Kirkegaard (b. 1975) is rooted in architecture of buildings as well as the inner architecture of the human ear. In 2007 the Medical Museion in Copenhagen commissioned him to create a work related to topics discussed at the *Art and Biomedicine: Beyond the Body* Conference held that same year. Kirkegaard set out to create a piece that would rely on the nonlinearities of both his own ears and that of the audience.

Kirkegaard had a range of DPOAEs recorded from within his own ear in the anechoic chamber at the Centre for Applied Hearing Research in Copenhagen, and then used these recordings as the basis for a piece entitled *Labyrinthitis*. The title comes from a syndrome of inner ear ailments caused by various balance disorders, however the title is also used as a metaphor to describe the structure of the sound installation used to perform the work. Sixteen speakers are placed in a downward spiral anchored to the ceiling of an old auditorium, reflecting the labyrinth like shapes of the inner ear, and the gradually narrowing basilar membrane. Kirkegaard describes the process as a systematic balance distortion, where the audience can experience the ear as an 'active organ' [8].

*Labyrinthitis* consists of a gradual, descending layer of sinusoidal-like tones—the source material being the layering of the composer's own recorded DPOAEs so as to create DPOAEs in each listener of the audience. Once the DPOAEs are established, the stimulus frequencies are gradually faded out so that a new tone, matching the frequency of the DPOAE, can be faded in to create a DPOAE with another frequency. Kirkegaard describes the compositional process as a descending tonal structure based on the resonant spectrums of the human ear. The piece is an experiment in counterpoint between the stimulating frequencies and the resultant DPs. When the resultant tone emerges in the ear of the listener the synthesized tone will emerge organically. Kirkegaard takes great care in eliding both of these tones so that the DPOAEs naturally become part of the same musical texture as the stimulus frequencies. One could argue that the harmonic effect metaphorically transplants the electroacoustic domain onto the physiological domain, or more specifically, reflects the architecture of the cochlea itself.

## 5. CONCLUSION

OAEs and particularly DPOAEs introduce both composer and listener to a unique, physical sound layer that travels well beyond the psychoacoustic layers possible in the vast spectrum of electronic musical texture and timbre. Niblock, Amacher and Kirkegaard reveal that the otoacoustic musical dimension is one of extreme physicality, heightening the listener's active process of hearing.

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