Technical University of Denmark

Spontaneous otoacoustic emissions are generated by active oscillators clustered in frequency plateaus

Epp, Bastian; Wit, Hero ; van Dijk, Pim

Publication date:
2014

Citation (APA):
Epp, B., Wit, H., & van Dijk, P. (2014). Spontaneous otoacoustic emissions are generated by active oscillators clustered in frequency plateaus. Poster session presented at 37th Annual MidWinter Meeting of the Association for Research in Otolaryngology, San Diego, CA, United States.

Spontaneous otoacoustic emissions are generated by active oscillators clustered in frequency plateaus

Bastian Epp[1], Hero Wit[2] & Pim van Dijk[2]

[1] Hearing Systems Group, Department of Electrical Engineering, Technical University of Denmark
[2] Department of Otorhinolaryngology/Head and Neck Surgery, University Medical Center Groningen, University of Groningen

Abstract

It is commonly assumed that the active process linked to hair-cell motility is an important factor contributing to SOAEs. A chain of coupled, active and nonlinear oscillators with tonotopic organization can be used to account for key aspects of cochlear processing, including SOAEs and related phenomena when random irregularities of the mechanical parameters (roughness) are introduced. It was hypothesized that this roughness leads to sudden impedance mismatches leading to multiple reflections of the travelling wave in the cochlea. Recently it was shown [Wit&van Dijk, 2012; J. Acoust. Soc. Am. 132, 918–926] that a linear array of active oscillators with nearest neighbour coupling produces clusters of oscillators with a common oscillation frequency (frequency plateaus) and a preferred frequency separation. The frequency plateaus can also be entrained to the frequency of an external tone. Both of these aspects are properties found in SOAEs. In the present study it is investigated if frequency plateaus are also found in a TM which is able to generate realistic SOAEs and if these frequency plateaus can be used to explain the formation of SOAEs.

Hypothesis

SOAEs simulated with an active and nonlinear transmission line model of the human cochlea stem from self-sustained oscillators grouped in frequency plateaus. The analogy of a model of lizard SOAE generation and human SOAE generation allow to test current theories of SOAE generation.

Models

Linear array of oscillators (LAM)

The formation of frequency plateaus was investigated using a LAM written in the normal form of a Hopf bifurcation (Vilfan & Duke, 2008; all parameters taken from Wit & vanDijk, 2012):

$$\dot{z}_j = (i\omega_j + \epsilon_j)z_j + \kappa_j(d_r + id_I)(z_{j-1} - 2z_j + z_{j+1}) - B_j|z_j|^2 z_j + F_j(t)$$

- x_j displacement of j-th oscillator
- z_j $x_j - \frac{1}{\omega_j} i\dot{x}_j$
- ϵ_j effective damping
- κ_j relative coupling strength
- d_R dissipative damping
- d_I reactive damping
- B_j nonlinearity factor
- $F_j(t)$ external force

The model equations were solved in the time domain using the forward Euler method with a time step of $\Delta t = 2\pi/(360 \cdot \overline{\omega})$ with $\overline{\omega} = (\omega_{min} + \omega_{max})/2$.

Transmission line model (TM)

A nonlinear and active TM with 1000 segments and included roughness of the cochlea was used to simulate SOAEs (all parameters taken from Epp et al., 2010):

$$p_j = m\ddot{x}_j + d_j(\dot{x}_j)\dot{x}_j + s_j\,[x_j + c_j(\dot{x}_j)\dot{x}_j(t)|_{t-\tau}]$$

- p_j pressure at j-th oscillator
- m effective mass of j-th oscillator
- x_j displacement of j-th oscillator
- $d_j(\dot{x}_j)$ nonlinear damping coefficient
- s_j linear spring constant of j-th element
- $c_j(x_j)$ nonlinear feedback stiffness term
- τ feedback time delay

The model equations were solved in the time domain with a rate of 400 kHz using a modified 4-th order Runge-Kutta method.

Methods

- Formation of frequency plateaus using the LAM model (see Wit & vanDijk, 2012).
- Simulation of SOAEs using the TM with introduced roughness (see Epp et al, 2010).
- Analysis of oscillations of all elements of the TM in the frequency domain.
- Extraction of frequency with maximum amplitude for each TN segment.

Results: Self-sustained oscillations and SOAE

Transmisson line (TM)

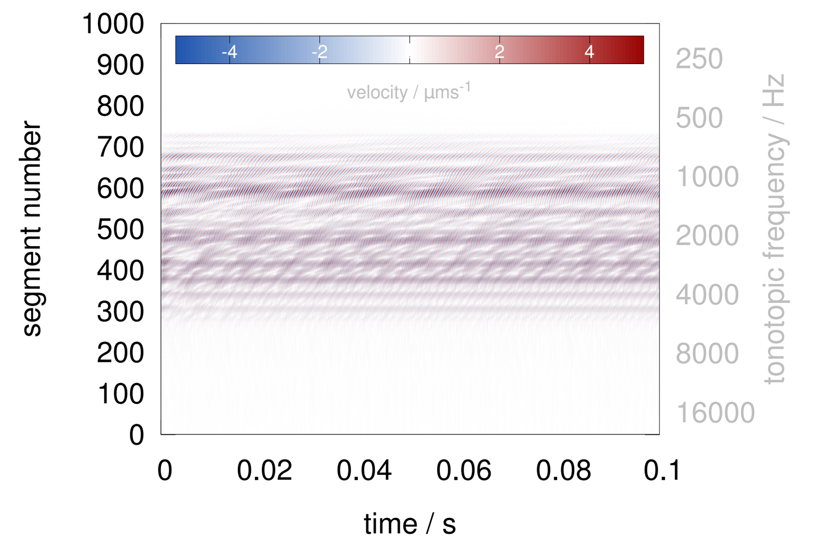

FIGURE: Oscillations of the cochlear partitions without external excitation. Segments located in the middle of the simulated cochlea show self-sustained oscillations.

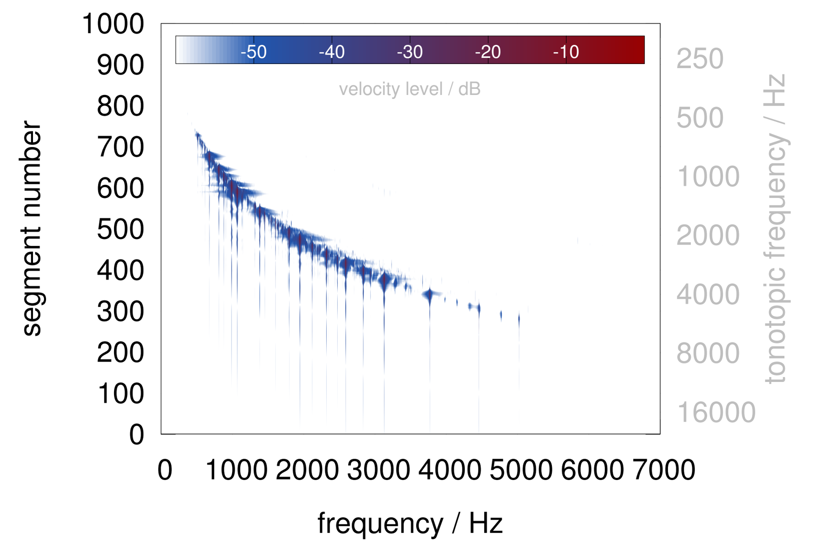

FIGURE: Frequency analysis of the self-sustained oscillations. The maximum frequencies reflect the tonotopic organization of the simulated cochlea. Vertical stripes show the energy of oscillations at specific places traveling from base to apex.

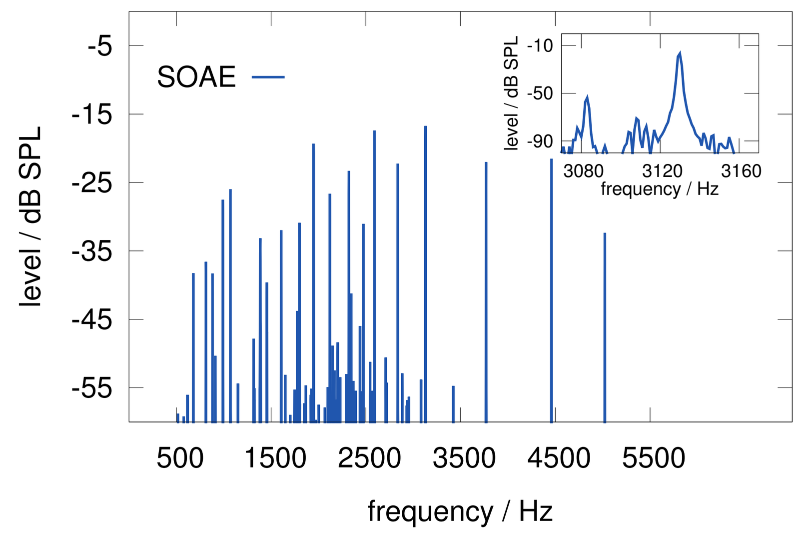

FIGURE: Spectrum of the simulated ear canal pressure corresponding to the self-sustained oscillations of the cochlear partitions. Frequencies in the ear canal exactly match the frequencies of the self-sustained oscillators. The inset shows the characteristic spectral width of SOAEs.

Results: Frequency clustering

Linear array of oscillators (LAM)

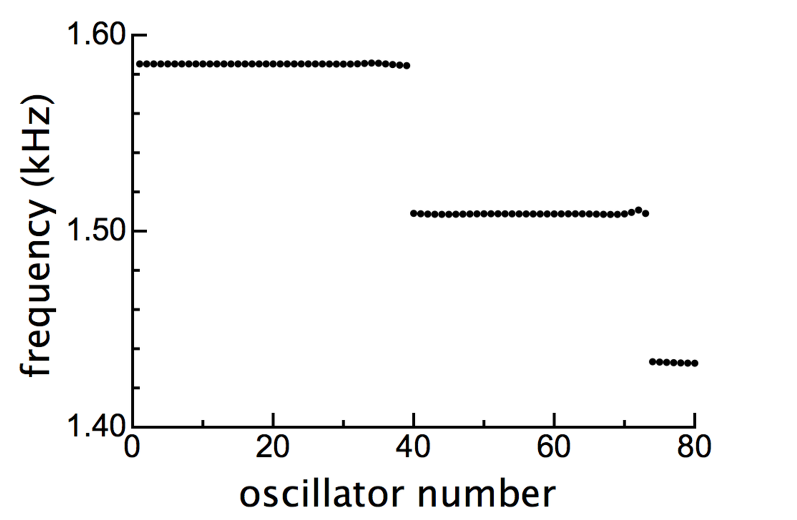

FIGURE: Frequency plateaus of the array of coupled oscillators. Neighbored oscillators tend to cluster to the same frequency. The separation of the frequency plateaus depends on the coupling strength between oscillators.

Transmission line (TM)

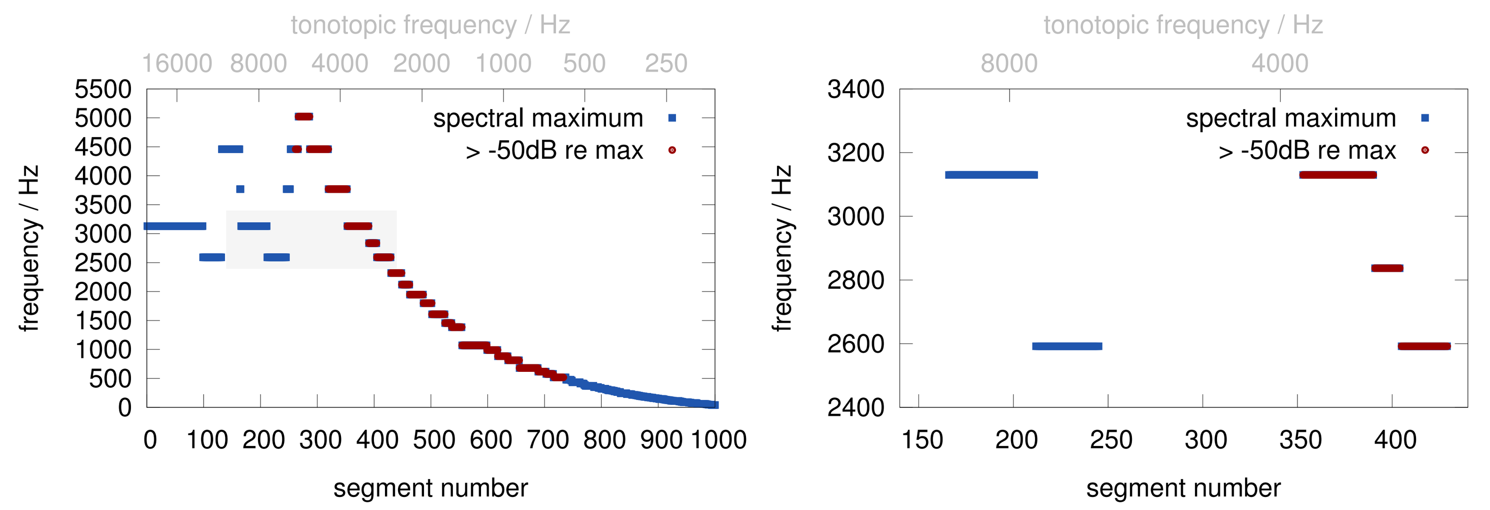

FIGURE: **Left:** Frequency plateaus of the TM. Blue dots indicate the spectral maximum of each cochlear partition. Red points indicate spectral peaks with amplitudes of -50 dB or higher relative to the maximum amplitude of all partitions. Neighbored partitions tend to cluster into similar frequencies. **Right:** Segments tuned to higher frequencies (low numbers) tend to cluster with segments tuned to relatively low frequencies oscillating with high energy, leading to multiple plateaus at the same frequency.

Results: Traveling vs. standing waves

Linear array of oscillators (LAM)

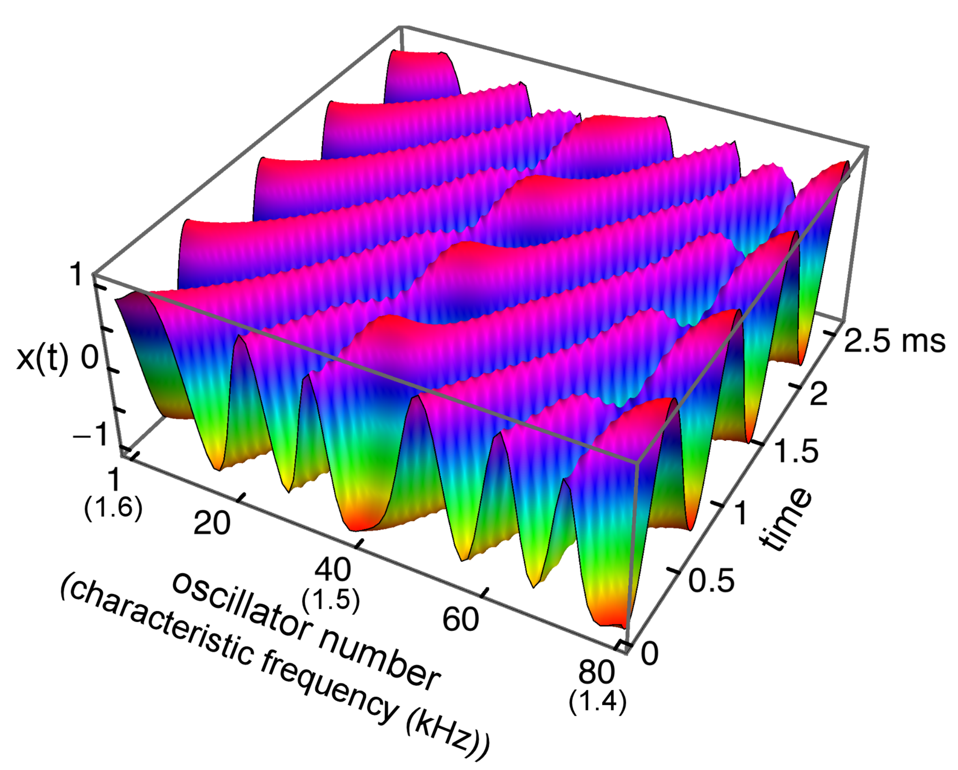

FIGURE: Normalized amplitudes of single oscillator displacement over time. The pattern shows traveling-wave like behavior from high-frequency segments towards low-frequency segments of the array. Frequency plateaus are visible in regions of high amplitude with different slopes along time.

Transmission line (TM)

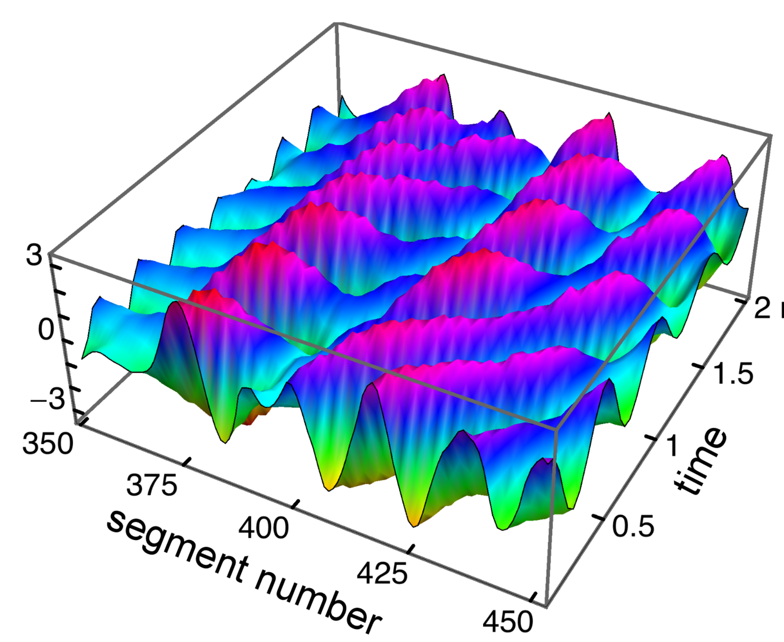

FIGURE: Amplitudes of cochlear partitions 350-450 over time. Similar to the LAM, waves travel from base (low numbers) to apex (high numbers). The frequency plateaus are separated by valleys in the amplitudes between neighbored oscillators. The clusters of segments with high amplitude correspond to the segments within a frequency plateau.

Discussion

Self-sustained oscillations in LAM and TM

- Self-sustained oscillations with properties similar to SOAEs of humans found in a linear array of coupled oscillators.
  → Indicates similar underlying physical mechanisms of SOAE generation.
- Tonotopically arranged self-sustained oscillations observed in TM as SOAEs and as self-sustained oscillations of the segments.
- Frequencies of SOAEs match exactly with frequencies of the self-sustained oscillators.
  → In line with the theory of multiple reflections underlying SOAE generation (Shera et al., 2003).

Frequency clustering in LAM and TM

- Frequency clusters of LAM tonotopically arranged with frequency separation similar to spectral spacing of SOAEs in humans .
  → Supports hypothesis of common underlying mechanisms of SOAE generation in Lizards and humans.
- Frequency clusters in TM tonotopically arranged with multiple plateaus at same frequency across segments.
  → Generation of frequency plateaus indicates similar nonlinear interactions between oscillators in LAM and the TM.

Traveling vs standing waves and local oscillations

- Traveling wave pattern can be found in LAM model (array of coupled oscillators with gradually varying parameters).
- Frequency clusters in the TM also show traveling wave behavior.
- According to the multiple reflection theory, standing wave pattern could be expected.
  → Due to active process in the cochlea, amplification of forward-traveling wave might however dominate the oscillation pattern.

Conclusion

⇒ Comparison of LAM with TM approaches are helpful to investigate the generation and theories of SOAEs.

⇒ Similarity between model of Lizard and human SOAE generation suggests common mechanisms underlying SOAE generation.

⇒ Multiple oscillators clustered in frequency plateaus are potential sources of SOAEs measured outside the inner ear.

⇒ The LAM and TM suggest that SOAEs are mainly due to inward traveling waves into the cochlear rather than standing waves.

Acknowledgements

This work was supported by the Oticon Centre of Excellence for Hearing and Speech Sciences (CHeSS) at the Technical University of Denmark (DTU).

References

Wit, HP, and van Dijk, P (**2012**) "Are human spontaneous otoacoustic emissions generated by a chain of coupled nonlinear oscillators?" *J Acoust Soc Am 132:918–926*

Vilfan, A, and Duke, T (**2008**) "Frequency clustering in spontaneous otoacoustic emissions from a lizard's ear," *Biophys J 95:4622–4630*

Epp, B, Verhey, JL and Mauermann, M (**2010**) "Modeling cochlear dynamics: interrelation between cochlea mechanics and psychoacoustics," *J Acoust Soc Am 128:1870–1883*

Shera, C (**2003**) "Mammalian spontaneous otoacoustic emissions are amplitude-stabilized cochlear standing waves," *J Acoust Soc Am 114:244–262*