Study the Otoacoustic Emission Generation by using Nonlinear Model

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ABSTRACT

The Previous studies have shown evidence for the presence the quality factor of otoacoustic emissions models and it's role, in this work we study the effect by using different values of the quality factor, so we take the values of the quality factor (Q=5, 10, 20, 30, 40 and 50) The results suggest that reflections generation of the otoacoustic emissions from roughness are behaved two parts with respect to the value of the quality factor (Q), we found with low value (Q=5 and 10) the generation of the reflectivity is less than with high values of the quality factor (Q = 20, 30, 40 and 50) therefore the reflectivity is depend on the value of quality factor.

Introduction

Otoacoustic emissions (OAEs) are a physiological by product of the activity of the mammalian cochlea [1]. The OAE generation and backward transmission is effectively described by transmission line cochlear models, including tonotopically resonant transverse impedance terms [2]. These terms must also model the active feedback mechanism mediated by the outer hair cells (OHCs), which is responsible for the excellent threshold sensitivity and frequency resolution of the mammalian hearing system. A comprehensive cochlear model must be, to some extent, both nonlinear and non-local, and based on the knowledge of the OHC mechanoelectric behavior. Several models of the OHC feedback mechanism have been developed [3], [4], including detailed analyses of the OHC coupling to the basilar membrane (BM) and to the tectorial membrane, and they have been tested and refined in the past decades through comparison with experimental data, reaching a fairly high degree of complexity, and a correspondingly high number of free parameters [5]. Cochlear modeling is a very useful tool for understanding basic cochlear physiology, helping the researcher in the theoretical interpretation of experimental data. It also provides a necessary support for design and optimization of new diagnostic techniques of cochlear function. A cochlear model can be used to run "numerical experiments," in which some sort of stimulus is fed as an input to the model, and the output response is computed. The results of these numerical experiments can be compared with those of analog real experiments, with a twofold purpose. In a first stage, such comparisons help refining and validating the model. In a second stage, a validated model can be used to predict the cochlear behavior in different scenarios, which can also be outside the accessibility range of experimental techniques. A model capable of providing reliable predictions outside the range over which it has been directly tested must be built upon solid ground, i.e., it must be based on a coherent theoretical schematization of the cochlear function, and use a limited number of free parameters. Linear models can be effectively solved in the frequency domain, either using analytical approximations or numerically, with low computational costs. The same advantage applies to those weakly nonlinear models in which the nonlinearity can be treated as a small perturbation. Unfortunately, nonlinearity is a key feature of the cochlear physiology, strictly related to the quality of hearing, which cannot be considered a small perturbation, except, perhaps, at very low sound levels, close to the auditory threshold. Several cochlear models have been discussed and tested in the literature, which include active terms, either linear [2], [5], [6], [7], or nonlinear, to schematize the active feedback mechanism [8]. Nonlinearity is an intrinsic feature of the cochlear physiology, so the frequency-domain solutions of the linearized problem can only approximately predict the behavior of the system, and only in a perturbative regime. Much care must therefore be used when applying to such a system concepts that are fully meaningful for linear systems only, such as the complex frequency response, defined as the Fourier transform (FT) of the impulsive response, or the group delay, defined as the negative slope of the phase/frequency relation. The intrinsically nonlinear equations describing the cochlear micromechanics require, in a nonperturbative regime, a solution in the time domain. On the other hand, the time domain numerical solutions may become expensive in terms of computational time and memory demanding, if sufficient spatial and time resolutions have to be achieved. High spatial resolution is necessary because the discontinuous variation in the transverse impedance parameters caused by discretization itself must not cause significant spurious reflection of the forward traveling wave (TW). High time resolution is automatically provided by the adaptive integration time step set by the routines used to solve the differential equations, and the related computational cost depends strongly not only on the number of elements of the discretized cochlea but also on the frequency content of the stimulus and on the characteristic frequencies of the system. Elliott [9] proposed matrix formalism, applied to a finite-difference solution method of cochlear models, which is used in this study to model the propagation of the TW and the generation and backward propagation of OAEs. Elliott [9] originally applied this solution scheme to an active linear and local model developed by Neely and Kim (1986) [6]. In the Neely and Kim (1986) model [6] each micromechanical element is a two degree of freedom system of coupled oscillators, simulating some the active cochlear amplifier properties (negative resistance, or antidamping, in a limited region close to the resonant place). The same scheme can be modified to represent several different cochlear models. In the model by

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Kim and Xin (2005) [10] (adapted from Lim and Steele (2002) [11] and generalized to model cochlear impairment in Bertaccini and Fanelli (2009) [12], the forces applied by the OHCs on the BM are schematized by a nonlinear non-local feed-forward term.

The Theory

As in Moleti et al. 2009 [5], we refer, as a first approximation, to a simple passive 1-d transmission line cochlear model described by the equations:

$$\frac{\partial^2 p(x,0,t)}{\partial x^2} = \frac{2p}{H}\ddot{\xi}(x,t) \ldots\ldots\ldots\ldots 1$$

$$\ddot{\xi}(x,t) + \gamma_{bm}(x)\dot{\xi}(x,t) + \omega^2{}_{bm}(x)\xi(x,t)A = \frac{p(x,0,t)}{\sigma_{bm}} \ldots\ldots\ldots 2$$

Where (p) is the fluid density, σ_{bm} is the BM surface density, ξ is the (BM) transverse displacement at the longitudinal position (x) and time (t).

Equation(2) describes, for each cochlear position (x), the dynamics of a passive oscillator driven by differential fluid pressure only, Active terms, either proportional to (p) or to ($\ddot{\xi}$), will be added later to this basic equation, to schematize the additional forces on the BM associated with the OHC mechanism. In a tonotopically resonant cochlea, the relation between longitudinal position(x), angular frequency and passive damping constant are set by Green Wood (1990) map

$$\omega_{bm}(x) = \omega_0\, e^{-k_\omega x} + \omega_1 \ldots\ldots\ldots 3$$

$$\gamma_{bm}(x) = \gamma_0\, e^{-k_\gamma x} + \gamma_1 \ldots\ldots\ldots 4$$

The local passive quality factor defined as;

$$Q(x) = \frac{\omega_{bm}(x)}{\gamma_{bm}(x)} \ldots\ldots\ldots 5$$

In the limit $k_\omega = k_\gamma$ and $\omega_1 = \gamma_1 = 0$, Q(x) = $Q_0 = \frac{\omega_0}{\gamma_0}$ is a constant and the maps of equations (3, 4 and 5) do not explicitly break the scale invariance symmetry because Q does not depend on the frequency scale, and there is no characteristic frequency scale such as (ω_1). We have not introduced scale invariance breaking. Although the scaling symmetry does not fully holds in the real cochlea. We have not introduced scale invariance breaking terms in model to preserve some useful properties of scaling symmetric models (e.g., latency inversely proportional to (ω)) that make it easier to evaluate the stimulation results.

Result and Discution

OAE spectral latency is the delay due to the round-trip acoustic transmission to the OAE generation place and back to the detector. This delay is dominated by the cochlear contribution, which can be computed for each frequency as the integral over the cochlear path of the inverse group velocity, the group velocity is computed from the relation between the wave vector (k) and the angular frequency (ω).

However, in any reasonable model the relation between (k) and (ω) has a resonance at the tonotopic place.

The traveling wave velocity decreases when approaching the tonotopic place proportionally to the sharpness of the resonance. Thus, the total delay is dependent on the sharpness of the resonance, expressed by the quality factor Q, which is defined as the ratio between the frequency (ω) and the bandwidth of the resonance itself.

Time-domain numerical solutions of a nonlinear active cochlear model forced by click stimuli are analyzed with a time-frequency wavelet technique to identify the components of the otoacoustic response.

There are many parameters are used in the non-linear model of the otoacoustic emissions and the calculations are depend upon these parameters, the quality factor (Q) is one parameter from these parameters, the previous studies have shown the dependence of many parameters like the stimulus level and discussed the numerical simulations in order to study the generation of the otoacousti emissions. In this work, we study the role of the quality factor (Q) and we discuss the effect of the model calculations, we found that the quality factor is very important and the results of the otoacoustic emissions in this model are depend on the value of this parameter. We used different values of quality factor (Q=5, 10, 20, 30, 40 and 50) to show the effect of this parameter and discuss this effect of the reflectivity phenomenon of the otoacoustic emission generation. According to Green map, we use the (Q) for different position of the basilar membrane from the basal to the end of the basilar membrane (positions (x) = 0.035, 1.955, 3.99, 5.98, 8.015, 10.01, 15.01, 19.98, 24.99 and 29.99 mm), the finding frequencies are (f= 20.2, 15.5, 11.7, 8.8, 6.6, 5.04, 2.4, 1.15, 0.5 and 0.18 kHz). According to our results, we concluded that the quality factor is divided two categories, the first category is the low value of quality factor and the second category is high value of the quality factor. The main result shows that the reflectivity of the otoacoustic emissions depend on the value of the quality factor, we found that the reflectivity increase with high value and decrease with low value of the quality factor. Time-domain numerical solutions of a nonlinear active cochlear model forced by click stimuli are analyzed with a time-frequency wavelet technique to identify the components of the otoacoustic, such as the reflectivity component, the results of the numerical simulations illustrate the effect of the quality factor, for example with low values of quality factor (Q=5, 10) gives results are different with respect to the high values such as (Q=20, 30, 40 and 50), so we can divide the results two parts, the first when the quality factor is low and the second when the quality factor is high.

We found that the reflectivity with the high values is more than the low values this means that the reflectivity is increased with the high values of the quality factor.

We illustrate these results by study many examples for different values of the quality factor.

The first example

We study the frequency (f= 6.6 KHz) as example, by using different values of the quality factor (low and high values of the quality factor), we found that the behavior of the otoacoustic emission generation is depend on the value of the quality factor.

The first case, we used low value (Q=5), figure (1) shows the otoacoustic emissions generation, in this case the value of latency of the otoacoustic emissions of the frequency (6.6921 kHz) is (5 ms).
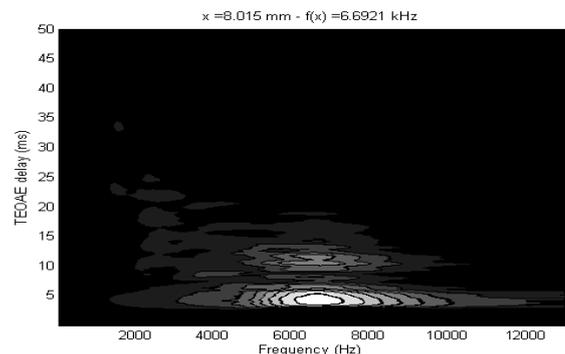

Figure 1. Time-frequency representation of the simulated TEOAE using Q =5

In general the generation of the otoacoustic emissions for different values of the low quality factor (Q = 5 and 10) is approximately the same so for this example we choice (Q=5). The second case (high values of the quality factor) we used, (Q=20, 30, 40 and 50) the results of the otoacoustic emissions generation are clearly different with respect to low values, for the high values of the quality factor we choice the value (Q=50). Figure (2) illustrate the otoacousti emissions generation when Q=50, we can see clearly in this case the reflectivity of the otoacoustic emissions, the values of the latencies of the otoacoustic emissions are 5, 10 and 15 ms for the same frequency.
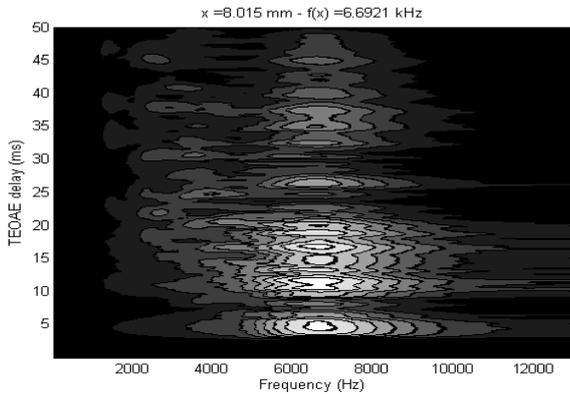

Figure 2. Time-frequency representation of the simulated TEOAE using Q = 50

The comparison between the two cases the low and high vales of quality factor (figure (1) and figure (2)), we can see the difference between the two cases, the generation of the reflectivity of the otoacoustic emissions is shown in the figure(2) clearly, the values of the latencies are (5, 10 and 15 ms), in this case we have the first reflectivity when the latency is 10 ms and the second reflectivity when the latency is 15 ms, figure (2) shows the reflectivity of the otoacoustic emission generation when we used high values of the quality factor, but this generation of the reflectivity does not find in the first case (low vale).

The difference of the reflectivity of the otoacoustic emissions generations between the two cases is shown by figure (1) and figure (2).

Table (1) shows the values of the latencies of the frequency of the two cases of the same frequency (6.6921 kHz, for the first case, the quality factor (Q)= 50, the value of latency (5 ms) represents the main latency of the otoacoustic emission of the frequency 6.6921 kHz, the second value of the latency (10 ms) represents the first reflectivity of the main wave and the third value of the latency (15 ms) represents the second reflectivity of the main wave, but for the second case, table (1) and figure (1) show only one value of the latency (5 ms) of the otoacoustic emissions of the frequency (6.9621 kHz) for the value of the quality factor (Q= 5).

Table 1. The values of the latencies for the two cases low and high quality factor of the frequency (6.6921 kHz)

The Quality factor (Q= 50)		The Quality factor (Q= 5)	
Latency(ms)	Frequency(kHz)	Latency(ms)	Frequency(kHz)
5	6.6921	5	6.6921
10			
15			

The second example

We study another example to improve this result with the same values of the quality factor, the second frequency is (f = 5.041 kHz).

Like first frequency, we study the two cases of the frequency (f = 5.041 kHz) of the generation of the otoacoustic emissions for different values of the quality factor, low vales (Q = 5 and 10) and high values of the quality factor (Q=20, 30, 40 and 50).

The first case, we used low value (Q=5 and Q=10) because the results for Q=5 and Q=10 approximately are not different, we choice Q=5 and we choice Q=50 for high values.

The first case (low value Q=5), figure (3) shows the otoacoustic emissions generation, in this case the value of latency of the otoacoustic emissions of the frequency (f = 5.041 kHz) is 6 ms.

The second case (high vales, figure (4) illustrate the otoacousti emissions generation when Q=50, we can see clearly in this case the reflectivity of the otoacoustic emissions, the values of the latencies of the otoacoustic emissions are 6, 12 and 18 ms for the same frequency.

The comparison between the two cases the low and high vales of quality factor (figure (3) and figure (4)), we can see the difference between the two cases, the generation of the reflectivity of the otoacoustic emissions is shown in the figure(4) clearly, the values of the latencies are (6, 12 and 18 ms), in this case we have the first reflectivity when the latency is 12 ms and the second reflectivity when the latency is 18 ms, figure (4) shows the reflectivity of the otoacoustic emission generation when we used high values of the quality factor, but this generation of the reflectivity does not find in the first case (low value).

The difference of the reflectivity of the otoacoustic emissions generations between the two cases is shown by figure (3) and figure (4).

Table (2) shows the values of the latencies of the frequency of the two cases of the same frequency (5.041 kHz), for the first case, the quality facotr (Q= 50), the value of latency (6 ms) represents the main latency of the otoacoustic emission of the frequency 5.041 kHz, the second value of the latency (12 ms) represents the first reflectivity of the main wave and the third value of the latency (18 ms) represents the second reflectivity of the main wave, but for the second case, table (2) and figure (3) show only one value of the latency (6 ms) of the otoacoustic emissions of the frequency (5.041 kHz) for the value of the quality factor (Q= 5).
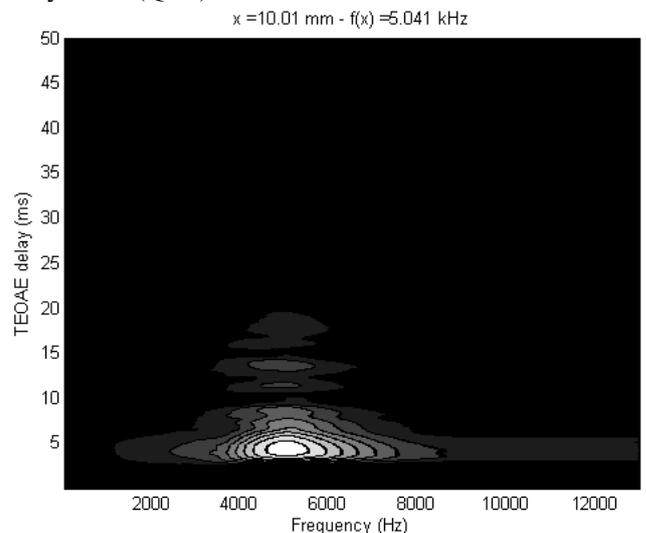

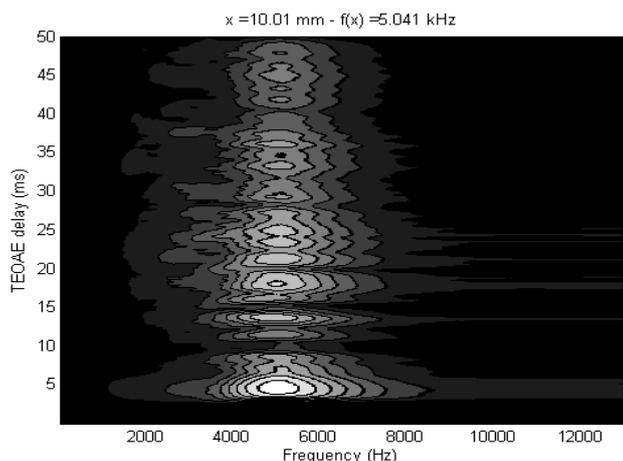**Figure 3. Time-frequency representation of the simulated TEOAE using Q = 5**

Figure 4. Time-frequency representation of the simulated TEOAE using Q = 50

Table 2. The values of the latencies for the two cases low and high quality factor of the frequency (5.041 kHz)

The Quality factor (Q= 50)		The Quality factor (Q= 5)	
Latency(ms)	Frequency(kHz)	Latency(ms)	Frequency(kHz)
6	5.014	6	5.014
12			
18			

The Third Example

The our third frequency is (f = 2.4536 kHz)

1 – With low value of quality factor (Q=5)

We used the frequency (f=2.536 kHz) to show the effect of the quality factor.

Figure (5) shows the time-frequency energy to the otoacoustic emissions of the frequency (2.4536 kHz).

2 – With high value of the quality factor (Q= 50)

We used the frequency (f=2.536 kHz) to show the effect of the quality factor.

Figure (6) shows the time-frequency energy to the otoacoustic emissions of the frequency (2.4536 kHz).
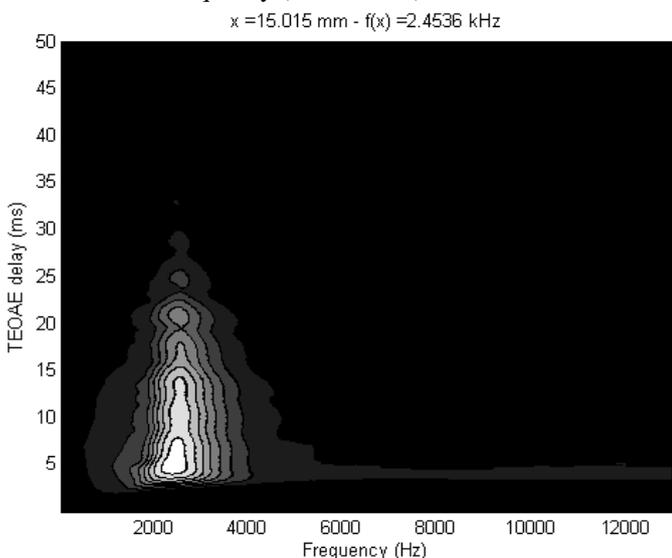

Figure 5. Time-frequency representation of the simulated TEOAE of the frequency (2.4536 kHz)

To compare the time frequency to the otoacoustic emission between the figure (5) and figure (6), we found the result the same of example (1) and (2), that the reflectivity is also appear in the second cases with high value of the quality factor (Q=50), is shown in figure (6) and the latency is (14 ms), but didn`t

appear with low value of the quality factor (Q=5) and the latency approximately (7 ms).
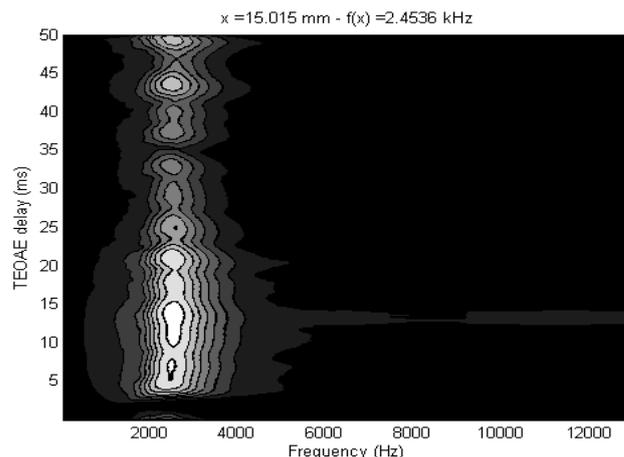

Figure 6. Time-frequency representation of the simulated TEOAE of the frequency (2.4536 kHz)

According to these three examples, we can conclude that the generation of the otoacoustic emissions is different between the two types (low and high quality factor) and the, this is mean that the behavior of the otoacoustic emission in the non-linear model depend on the quality factor with respect to reflectivity, so we found the reflectivity when we use high value of the quality factor, but with low value of the quality factor we didn`t find the reflectivity.

The our results specially in regard to the reflectivity in agreement with the previously studies[14][15][16] (Giuseppe Notaro 2007,Moleti 2003, Moleti 20013).

Conclusions

In this work and according to our results, we conclude that the behavior of the generation of the otoacoustic emissions (the reflection generation) depends on the value of the quality factor.

We found that relation between the reflection generation of the otoacoustic emissions and the quality factor as following;

1-The reflection generation of the otoacoustic emissions decreases with the low   values of the quality factor.

2- The reflection generation of the otoacoustic emissions increases with the high values of the quality factor.

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