Parametric Spectral Estimation of Transient Otoacoustic Emissions for Auditory Function Measurements

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ABSTRACT

The aim of this study is peripheral auditory function evaluation. Otoacoustic emissions (OAEs) are a remarkable and interesting auditory fact which allows us to examine peripheral hearing function in new depth and detail. OAEs have given us new intuition into hearing impaired conditions and promise for early intervention for therapy. Subjects with normal hearing and abnormal hearing recordings of TOAEs during the introduction of contra lateral stimuli at different frequencies are collected. Parametric spectral estimation method is proposed for analysis of auditory function measurements.

Keywords-Otoacoustic Emissions; Parametric Spectral Estimation; Auditory System; Cochlea;

I. INTRODUCTION

A. Otoacoustic emissions

Otoacoustic emissions are tones that can be registered in the ear canals of normal ears. They are biophysical event of compressions and rarefactions of the air in the ear channel due to action of the ear drum. New assessment in healthy ears have presented that the travelling wave within the cochlea can build up as it travels to exceed the vibration entering the cochlea at the oval window by hundreds of times. This rapid buildup in traveling wave energy is only found in normal subject cochlea where the outer hair cells are in healthy condition [1]. Any pathological condition to the cochlea or disease tends to speedily afflict the traveling wave. This leads to a reduction in receptiveness and uplift of hearing threshold. Otoacoustic emissions (OAE) are hearing energy formed by the cochlea (most perhaps by the development of the exterior hair cells). This strength can be dependent on a stimulus, e.g. transiently evoked otoacoustic emissions (TEOAE) [2]. Otoacoustic emissions are limited tones produced by motion of the ear drum in return to vibrations from deep within the cochlea. The normal cochlea generates subjective vibrations at any time it processes tone. Defective cochleae routinely do not generate this type of modulating sound. Some normal ears even generate sound automatically as internal tones are refined and amplified. As explained later, the cochlea's range to generate sound is well associated with its attainment of normal audible threshold, and the hidden mechanism is very easily damaged. To acquire and record the sounds made by the cochlea an earphone and microphone combo sensor is fitted into the ear canal. The mid ear has to be functioning well in order to handling the subtle cochlear modulations back to the ear drum interim like a stethoscope. A good fitting of the sensor is essential. Closing of the ear canal channel by the earphone-microphone combination sensor enormously amplifies the sound pressure generated by any ear drum modulation. It also ignores undesirable external sounds [2, 3].

The normal cochlea receives sound and produces a low intensity sounds OAEs. There are 4 types of OAEs

- Spontaneous otoacoustic emissions (SOAEs) - Auditory tones emitted without an hearing stimulus (that is, naturally).
- Transient otoacoustic emissions (TOAEs) or transient evoked otoacoustic emissions (TEOAEs) - Auditory modulations emanated in return to hearing stimulus of very brief duration; customarily clicks sort of sound.
- Distortion product otoacoustic emissions (DPOAEs) - Sounds generated in response to 2 customarily clicks sort of sounds of distinct frequencies.
- Sustained-frequency otoacoustic emissions (SFOAEs) - Sounds emanated in return to a continuous sound.

B. Objectives

Study is concerning mechanical activity and clinical method for auditory measurement of the status of peripheral auditory system can be derived. OAEs reflect a leakage of energy from non linear biomechanical gain process based on outer hair cells [4]. Otoacoustic emissions can thus give remarkably frequency distinct knowledge about the cochlear feedback. An individual's otoacoustic emission response is greatly individual and very distinct to the strength and spectrum of the stimulus sound [5]. If the latter two are kept constant then changes in the acoustic emission with time are an assured measure of variations in the physiological condition of the peripheral hearing system. This information has been used as a sensitive indicator of changes produced by noise or treatment on a patient's ear. The need for the OAE test is to detect cochlear condition, specifically auditory hair cell function. This diagnostic feature is to be used to

1. Screening of auditory impairment in newborns, infants or subjects with progressive disabilities.
2. Estimation of hearing acuity up to some extent partially.
3. Distinguish between the hearing sensitivity and neural factors of sensory neural hearing loss, and
4. Tests for occupational hearing loss.

C. Scope of the research

Pure tone audiometry is conventional screening method; measures peripheral ear, middle ear, cochlea, cranial nerve (CN) VIII, and central hearing system. OAEs do not quantify hearing loss but simply detects its presence and ideal means for screening of infants and children [5]. OAEs measure only the peripheral auditory system that comprises the outer ear, middle ear, and cochlea. The feedbacks only originate from the cochlea, but the outer and middle ear must be capable to convey the emitted sound return to the recording microphone. OAE testing often is used as a screening tool to take a decision, presence or absence of cochlear function, although analysis can be performed for sole cochlear frequency bands. OAEs cannot be used to entirely explain an individual's hearing thresholds, but they can assist to verify other threshold measures or they can give knowledge about the location of the lesion.

D. Anatomy and Physiology basic of OAEs

OAEs are recent to some doctors, a concise report of the proper anatomy and physiology of basic auditory system is presented. When tone is used to evoke an emission, it is broadcast over the outer ear, where the auditory stimulus is transformed from an auditory signal to a vibration signal at the tympanic membrane and is passed through the middle ear ossicles; the stapes footplate moves at the oval window, causing a transformed wave in the fluid-contained cochlea. The cochlear fluid's passing wave moves the basilar membrane; each portion of the basilar membrane is largely sensitive to only a defined frequency band. The arrangement is a tonotopic elevation. Regions closest to the oval window are deeper sensitive to larger-frequency stimuli. Regions further away are better sensitive to lower-frequency stimuli. Thus, for OAEs, the first feedback returned and recorded by the probe microphone radiate from the largest-frequency cochlear regions because the transit span is less. Feedbacks from the lower frequency bands, nearer to the cochlear apex, arrive later. When the basilar membrane moves, the hair cells are set into action and an electromechanical feedback is elicited, while an auditory signal is transported and a radial signal is emitted. The efferent signal is transported back through the auditory pathway, and the signal is measured in the outer ear canal. As explained above, the feedbacks from the lager-spectral region arrive first, increasingly succeeded by return responses from lower-spectral bands.

Outer hair cells are placed in the organ of Corti on the basilar membrane. These hair cells are unsteady; an electrochemical auditory feedback evokes a generator response. The three rows of peripheral hair cells have stereocilia aligned in a passion. The stereocilia are associated to each other and, thus, measure as a unit. These are the outer hair cells have to inhibit OAE propagation. As described in the section D, the principle of recording OAEs are shown in *Fig. 1*.

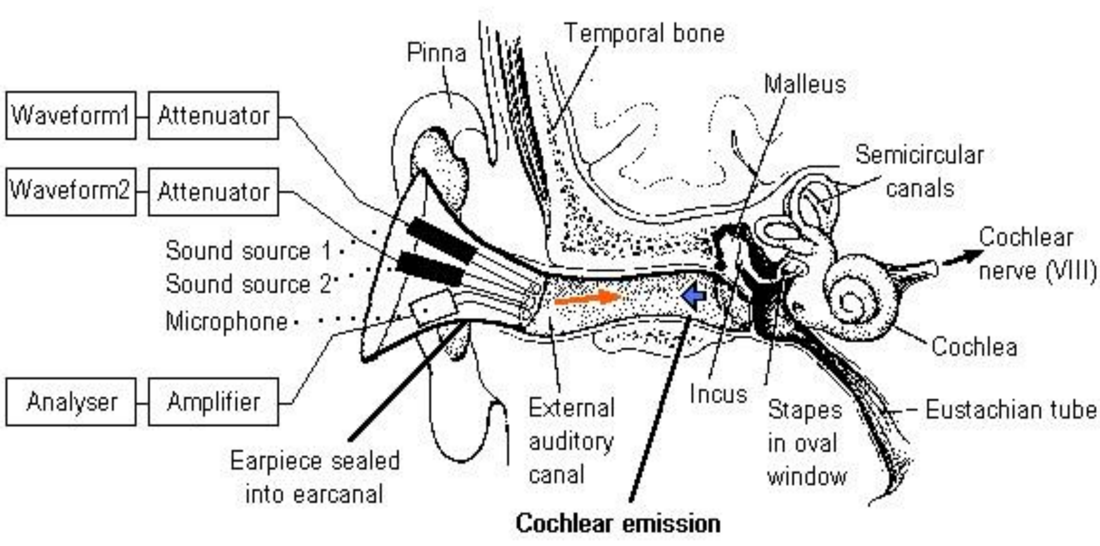

Figure: 1 Otoacostic emissions

(Image: Resource for DNB residents, wordpress.com 2011)

E. Merits of Otoacoustic Emissions diagnostic testing

OAE is noninvasive test for auditory measurements; the merits of OAE versus Auditory Brain Response are given in *Table I* From the table it can be clearly seen that auditory screening usefulness using OAE analysis.

Table: 1 Advantages and features of Otoacoustic Emissions

Features of diagnostic test	
Testing parameter	***OAE***
Preparation time	Minimal
Cost	Cost-effectiveness of newborn hearing screening anywhere approximately 100 in Indian Rupee (up to $1.00 USD)
False negative	Rare
Measures	Function of outer hair cells in cochlea
Frequency response	Responses obtained in the range 500 – 5000 Hz, the best responses are noted above 1000-1500 Hz.

II. LITERATURE REVIEW

In the health care, TOAEs generally are used to screen infant auditory, to verify observable or electrophysiological hearing thresholds, and to determine cochlear action corresponding to the spot of the lesion. By characterization, TOAEs are acquired only in response to true short or transient stimuli. Thus, the stimulus has bound spectral band specificity, and the TOAE propagates from a almost vast cochlear region. However, current analysis methods let on the response to be separated into various spectral bands for investigation. In routine, the existence of a TOAE in an appropriate frequency band prefer that cochlear acuity in that region is generally 20-40 dB HL or superior, depending on the consider ration cited. Most audiologists use the existence of a TOAE in a particular octave band to propose that hearing threshold should be 30 dB HL or higher, except a functional or neural component is present.

Sliwinska et al. (2002) proposed method to confirm the high acuity of TEOAEs in estimate the shift to the cochlea after short risk to industrial noise, the conclusion of the study recommend that OAEs, are expected to turn into a valuable technique for assessing early hearing damage caused by exposure to noise. This method is important to use in an auditory care program for the early findings [6].

Shera and Abdala reported have recommended using a low-level click for neonatal hearing screening and including the high-level click condition only if the infant does not pass the initial screen. By using multiple stimulus levels, it may be possible to differentiate between individuals with slight or mild hearing loss and those with a greater degree of loss [7].

Discrete Fourier Transform (DFT) method has lack of resolution in representing peaks and nulls [8, 9]. Thus parametric spectral estimation model the signals (TOAE) in the sample as the gain of a continuous scheme stimulate by white noise (noise with zero mean and constant PSD). Spectra with pair of limited spike and plane flat cannot be characterized with single AR model or the MA model (at least with the definite length). Hence estimation of power spectral computation using AR or MA (models) alone fails to model the TOAE signals. In those cases, the ARMA model is a good substitute. There is a computational question with the ARMA model though, namely computing the optimum filter coefficients is a difficult task computationally. There is an algorithmic method that finds the solution iteratively [10].

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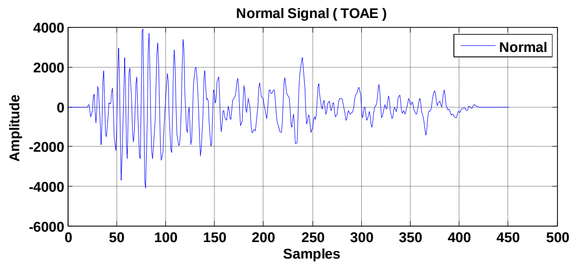
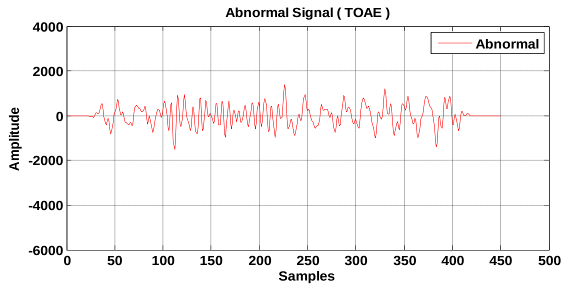
III. METHODOLOGY

3.1 Description of the data

In this work recorded segments of TOAE, 17 normal 21 abnormal signals are used. Exemplary recordings of normal and abnormal (hearing impaired condition) signals are shown in *Fig. 2 (a) and (b)* respectively.



(a)



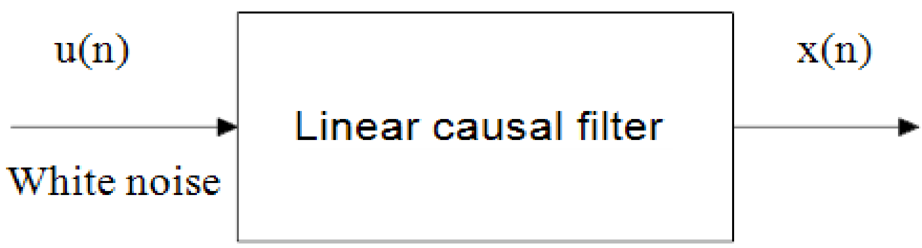
(b)

Figure 2: (a) Normal TOAE signal and (b) Abnormal (hearing impaired condition) TOAE signal

3.2 Parametric spectral estimation

Parametric methods for the cases of short data, the good resolution techniques tend to give better outcomes than traditional discrete Fourier transform- frequency domain based methods. This good resolution method uses a priori knowledge of the spectral information of the signal to develop a model of the signal. Parametric methods in spectral method have been the subject of demanding research, and many different methods have been proposed. In this work OAEs are analyzed using simplest cases only, which is related to the Yule-Walker equations [11], [12].

Linear predictors are used in application of otoacoustic signal analysis. A time series representation that relative discrete time deterministic or stochastic process is represented by filter shown in *Fig. 3*, and the difference equations of complex coefficient are given.



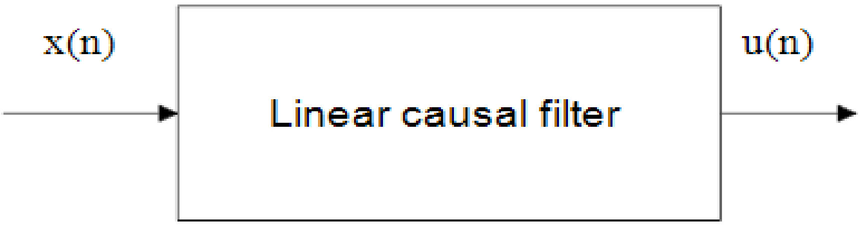


Figure 3: Linear prediction

$$x(n) = -\sum_{k=1}^{p} a[k]x(n-k) + \sum_{k=0}^{q} b[k]u(n-k)$$

(1)

$$x(n) = -\sum_{k=0}^{\infty} h(k)\, u(n-k)$$

(2)

The Z transform of output sequence x (n), autocorrelation is related. Location of the zeroes and poles of H(Z) respectively. The system function H(Z) between input and output has the rational form. The polynomials are

$$A(Z) = 1 + \sum_{k=1}^{p} a[k]Z^{-k}$$

(3)

$$B(Z) = 1 + \sum_{k=0}^{q} b[k]Z^{-k}$$

(4)

$$H(Z) = 1 + \sum_{k=1}^{\infty} h[k]Z^{-k}$$

(5)

Both polynomials A(Z) and B(Z) will be assumed to have all of their zeroes within the unit circle in the Z-plane to guarantee q.

$$H(Z) = \frac{B(Z)}{A(Z)} = \frac{\sum_{K=0}^{q} b[k]u(n-k)}{1+\sum_{k=1}^{p} a[k]x(n-k)} \;\; ;|Z| > r1$$

(6)

Where a[k], b[k] are filter coefficients, that determines the

H (z) is a well controlled least possible phase casual filter. The Z-transform of the output sequence x (n) autocorrelation is related to the z-transform of the input random process u(n) autocorrelation by

$$P_{xx} = P_{uu}(Z)H^{*}(\tfrac{1}{Z}) = P_{uu}(Z) = \frac{B(Z)B^{*}(\frac{1}{Z^{*}})}{A(Z)A^{*}(\frac{1}{Z^{*}})}$$

(7)

3.3 The Mixed Autoregressive Moving average (ARMA) Model.

The input driving process u (n) is not usually available for the purposes of frequency domain estimation. Many things could be assumed for the driving process. It could be a unit impulse, an impulse train, or white noise. Here it is assumed that driving sequence is a white noise process of zero mean and variance (ρ_{ω}). Thus,. An Autoregressive Moving Average (ARMA) model for the time series is determined by *Eq. (8)*, with white noise sequence. The ARMA power spectral density is obtained by substituting

$Z = \exp(-j2\pi$ into *Eq. (7)* and scaling by the sampling interval T yielding

$$P_{ARMA}(f) = T\rho_{\omega}\,|\mathrm{B(f)}/\mathrm{A(f)}|^2 = \mathrm{T}\rho_{\omega}\,\frac{e_q^H(f)\,bb^H e_q(f)}{e_{pq}^H(f)\,aa^H e_p(f)}$$

(8)

In which the polynomials and are defined as,

$$A(f) = 1 + \sum_{k=1}^{p} a[k]\exp(-j2\pi fkT)$$

$$B(f) = 1 + \sum_{k=1}^{q} b[k]\exp(-j2\pi fkT)$$

(9)

$$e_p(f) = \begin{bmatrix} 1 \\ \exp(-j2\pi fT) \\ \vdots \\ \exp(-j2\pi f_p T) \end{bmatrix}, \quad a = \begin{bmatrix} 1 \\ \mathrm{a}[1] \\ \vdots \\ \mathrm{a}[\mathrm{p}] \end{bmatrix}$$

$$e_q(f) = \begin{bmatrix} 1 \\ \exp(-j2\pi fT) \\ \vdots \\ \exp(-j2\pi f_q T) \end{bmatrix}, \quad \mathrm{b} = \begin{bmatrix} 1 \\ \mathrm{b}[1] \\ \vdots \\ \mathrm{b}[\mathrm{q}] \end{bmatrix}$$

(10)

3.4 Autoregressive (AR) Model

If all the moving average parameters are zero, except $b[0] =$, then

$$x(n) = -\sum a[k]x(n-k] + u(n)$$

(11)

Eq. (11) is strictly a autoregressive (AR) process of order p, or simply an AR(p).Then AR power spectral density, obtained by setting , in *Eq. (8)*, is

$$P_{AR}(f) = T\rho_{\omega}\left[\frac{1}{A(f)}\right]^2 = \frac{T\rho_{\omega}}{e_p^H(f)\,aa^H e_q(f)}$$

(12)

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3.5 .Moving average (MA) Model

If all the autoregressive parameters are zero, except $a[0] =$, then

$$x(n) = \sum b[k]u(n-k) + u(n)$$

(13)

Eq. (13) is a strictly a moving average(MA) process of order q, or simply an MA(q).The Ma power spectral density by setting in *Eq.(8)*, is

$$P_{MA}(f) = T\rho_{\omega} |B(f)|^2 = T\rho_{\omega}\, e_q^H(f)\, bb^H\, e_q(f)$$

(14)

The following algorithm is to find the spectrum from the TOAE signals.

3.6 Algorithm of the proposed Parametric Spectral method

Step 1: Calculate the autocorrelation matrix

Step 2: Computed Matrix to be Toeplitz

Step 3: Find the variance vector

Step 4: Estimate, a and b coefficients

Step 5: Obtain the AR, MA and ARMA spectrum

Analysis of signals is carried out using Mat lab programming [9]. *Fig. 4* showing the results of noise mixed with the TOAE signal for the normal case subsequent *Fig.5* is the computed parametric model coefficients for AR, MA and ARMA models. Similar way *Fig. 6* and *Fig.5*, for abnormal condition exemplary signal.

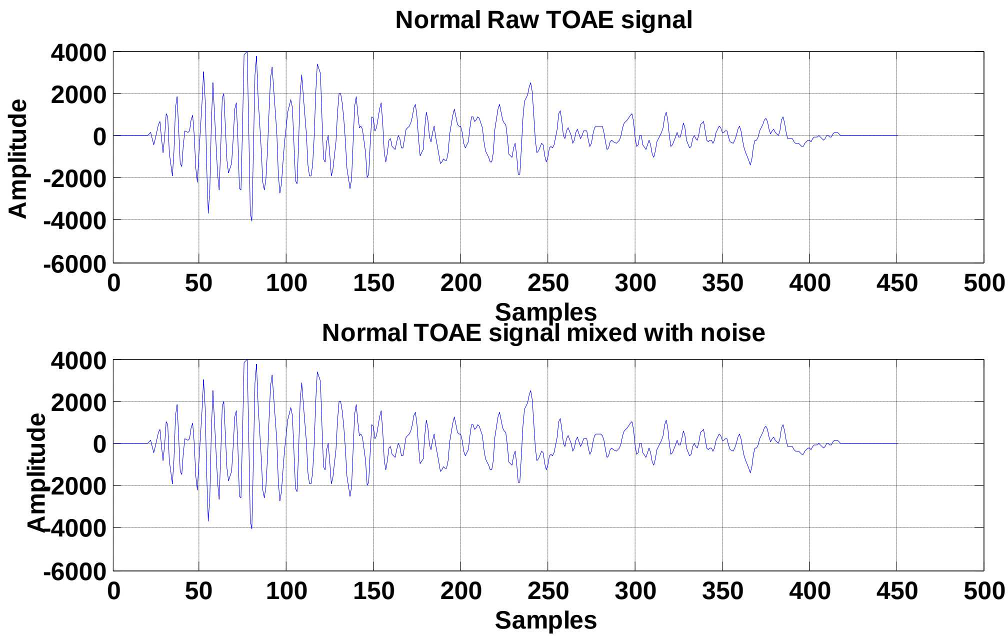

Figure: 4 Showing normal TOAE signal and with white noise

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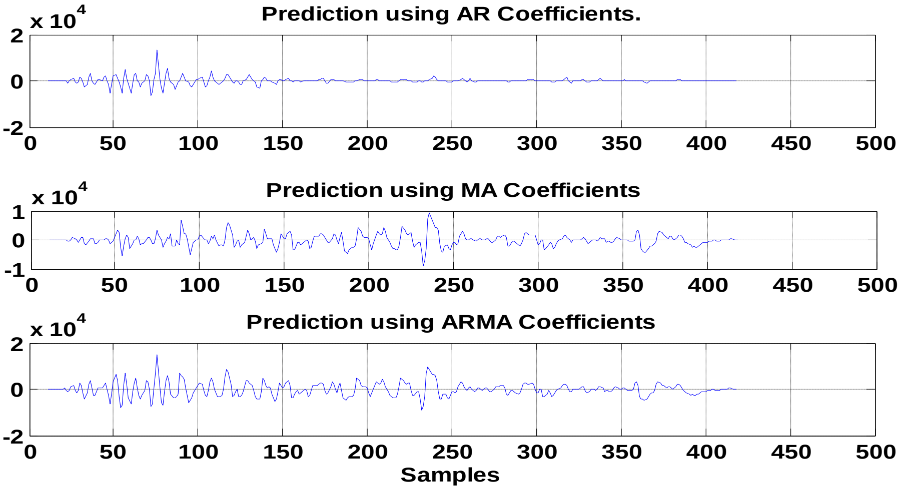

Figure 5: Showing normal TOAE signals' computed coefficients

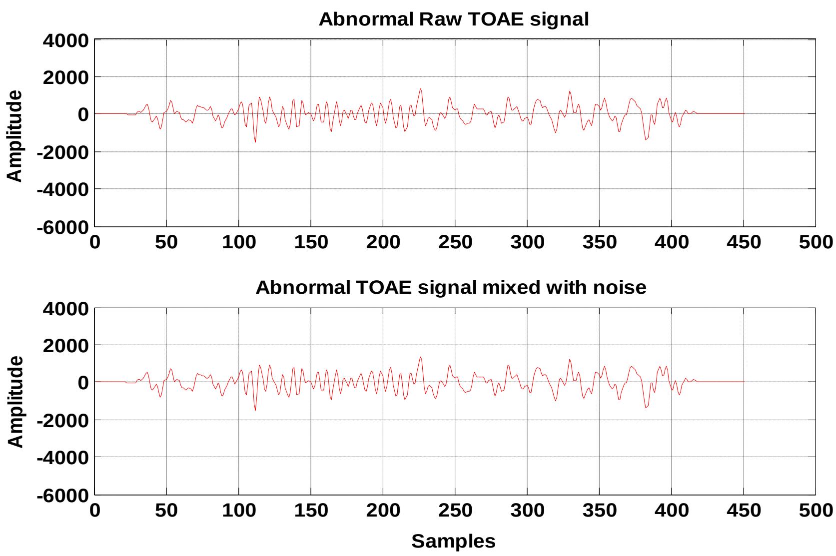

Figure 6: Showing Abnormal TOAE signal and with white noise

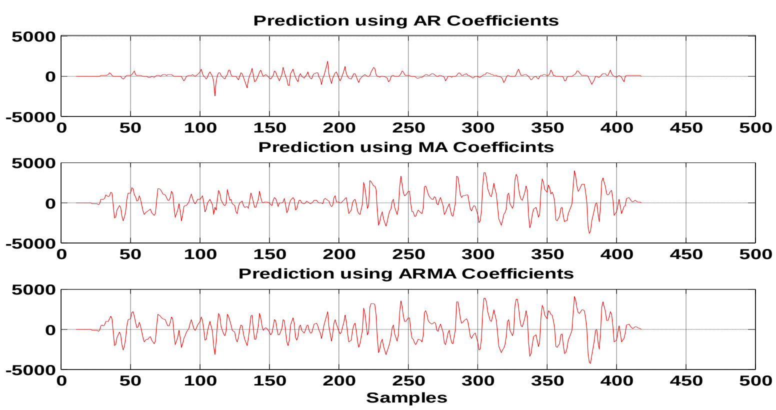

Figure 7:Showing Abnormal TOAE signals' computed coefficients

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***Fig. 8* and *Fig.9* parametric spectrum obtained by impleting the algorithm as steps explained in section *C*.**

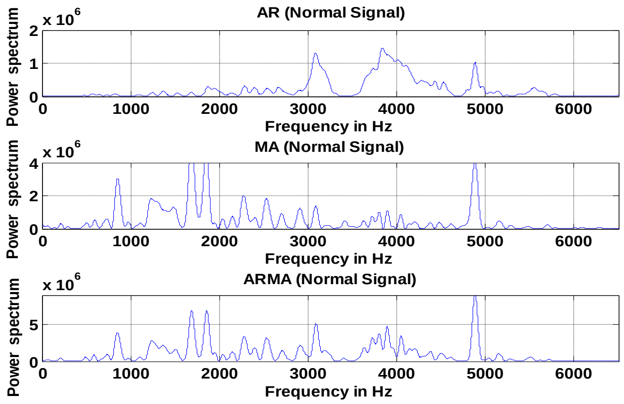

Figure 8: Showing PSD for normal signal

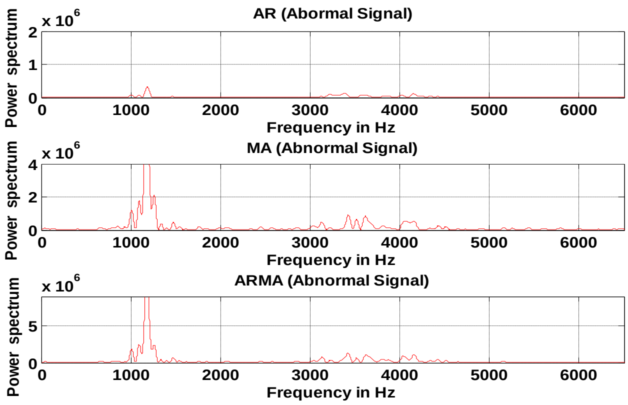

Figure 9: Showing PSD for Abnormal signal

Fig.10 and Fig. 11, the power of HL in dB is tabulated in Table 2.

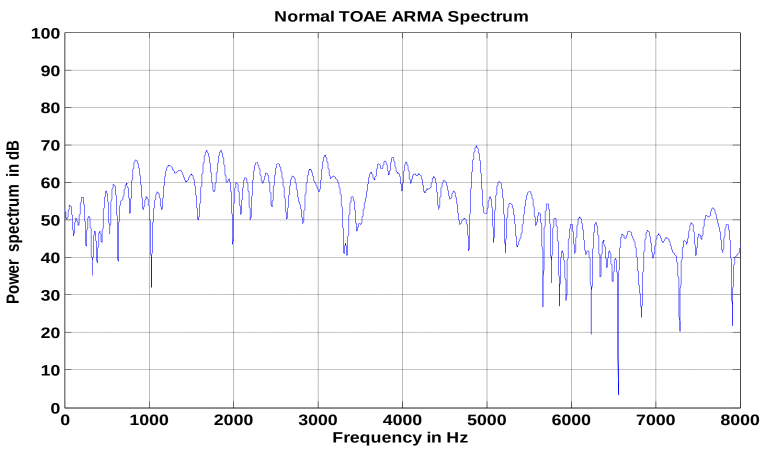

Figure 10: Showing normal TOAE ARMA Spectrum

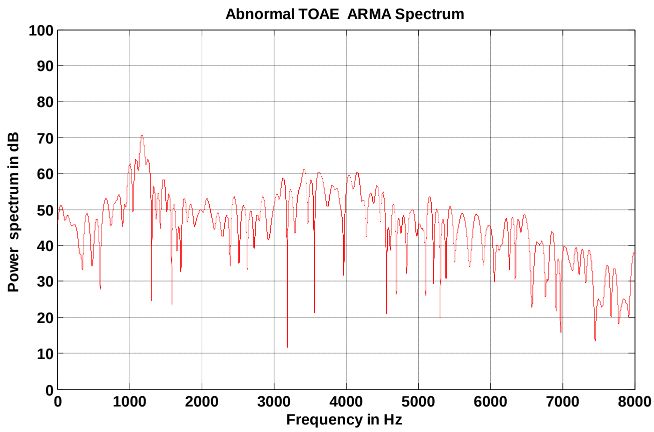

Figure 11: Showing Abnormal TOAE ARMA Spectrum

Table 2: Normal and abnormal signal AR spectral values

Frequency	AR Spectrum	
	Mean Power in dB	
	Normal	Abnormal
1Hz-1kHz	39.95	31.60
1kHz-2kHz	46.23	38.48
2kHz-3kHz	50.92	32.68
3kHz-4kHz	54.67	43.46
4kHz-5kHz	54.30	38.36
5kHz-6kHz	46.43	33.59
6kHz-7kHz	40.80	30.80
7kHz-8kHz	41.18	30.14
Mean	46.81	34.89

The audiometric profiles for exemplary signals; normal and abnormal analysis results are presented in *Table II*. From the *Table II* and *Fig. 12* it can be clearly seen that there is power level in the spectrum on comparison between normal signal and hearing impaired signal. Mean power hearing level (HL in dB) is < 3 dB in almost all octave frequencies, the subject is grouped objectively.

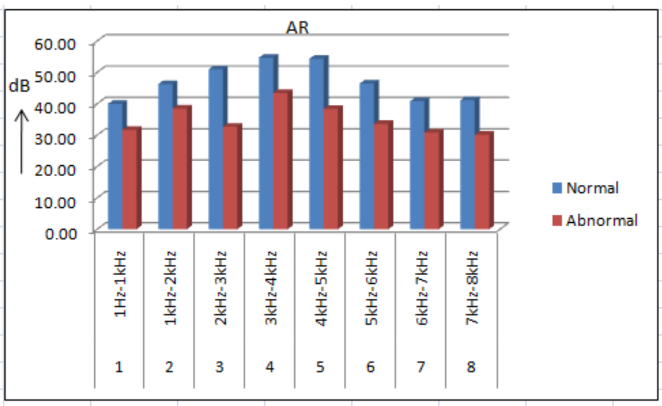

Figure 12: Comparison of Normal and Abnormal (AR) TOAE responses

Fig. 12 showing bar chart of such exemplary condition normal and abnormal condition, power spectral values are derived from responses from AR spectrum. In similar way *Table III*, *Fig. 13* from MA model spectrum and *Table IV, Fig. 14* from ARMA model spectrum are computed and tabulated.

Table:3 Normal and abnormal signal MA spectral values

Frequency	MA Spectrum	
	Normal	Abnormal
1Hz-1kHz	52.22	46.32
1kHz-2kHz	58.55	52.19
2kHz-3kHz	55.71	46.21
3kHz-4kHz	53.07	52.06
4kHz-5kHz	52.94	47.96
5kHz-6kHz	46.27	44.42
6kHz-7kHz	43.72	40.88
7kHz-8kHz	45.86	35.50
Mean	51.04	45.69

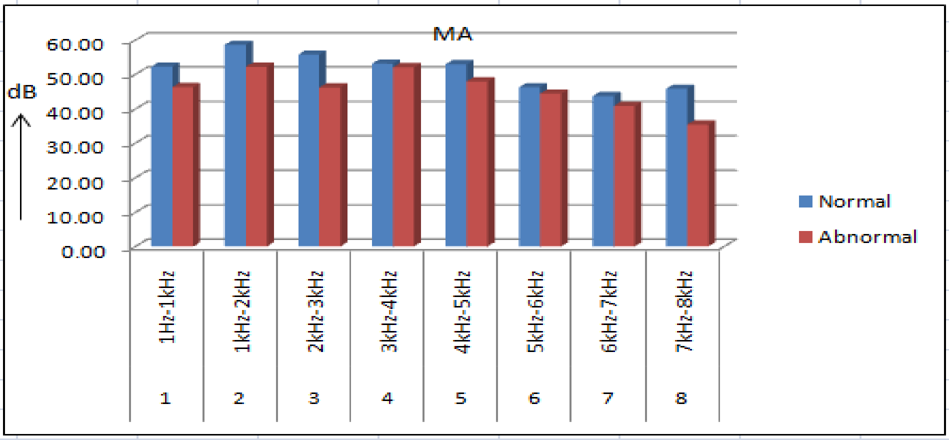

Figure 13: Comparison of Normal and Abnormal (MA) TOAE responses

Table:4 Normal and abnormal signal ARMA spectral values

Frequency	ARMA Spectrum	
	Mean Power in dB	
	Normal	Abnormal
1Hz-1kHz	53.00	46.83
1kHz-2kHz	60.08	53.38
2kHz-3kHz	59.04	47.26
3kHz-4kHz	58.78	53.73
4kHz-5kHz	58.37	50.08
5kHz-6kHz	49.31	44.12
6kHz-7kHz	42.09	39.17
7kHz-8kHz	44.51	30.76
Mean	53.15	45.67

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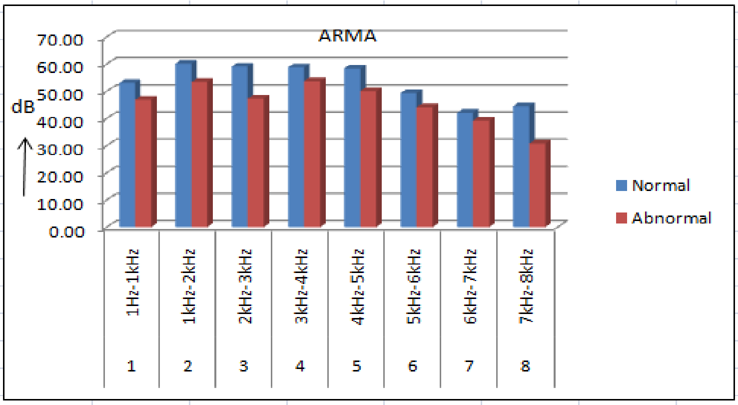

Figure 14: Comparison of Normal and Abnormal (ARMA) TOAE responses

IV. CLINICAL IMPLICATION AND DISCUSSION

OAE being generated by a stimulus resonant sound and propagating back via a reverse traveling wave recording would be supported by these results. TOAE is always carried offline data analysis objectively. The sharp peaks that characterize AR spectra and deep nulls that characterize moving average spectra. The ARMA spectra are able to model both sharp peaks and deep nulls. Subjects with normal hearing produce emissions, those with hearing impaired do not produce these emissions. *Fig. 8* showing one such normal exemplary TOAE signals' parametric spectrum plot for AR, MA and ARMA. The following features are computed and counted after the response: TOAE level, response levels in the band of frequencies 1- 8 kHz, and degradations in the magnitude of the responses in the abnormal condition. It is clearly observed that peaks and nulls are presented in the audio frequency range 1000 Hz to 6000 Hz. In similar way analyzing TOAE for an exemplary abnormal signal peak is present only at 1000 Hz.

This signifies the objective analysis of hearing loss. Tests are conducted on remaining normal and hearing loss signals TOAE failed to detect hearing loss in all the cases, test performance is greatest at low frequency and decreased as frequency increased in hearing loss conditions. Since hearing loss vary and also it is subject independent with octave frequency bands test performance measures best when audiometric thresholds at 30-40dB HLL at 4 kHz.

V. CONCLUSION AND FUTURE DEVELOPMENT

In the Normal cases maximum power lies in the frequency range above 3 kHz. In the abnormal cases maximum power lies in the range below 3 kHz. The spectral variations are subject independent and analysis of the recording is offline reviewed by an expert audiologist, who actually does the screening and detecting hearing loss or impaired.

Here in this work normal and abnormal signals are presented plot of ARMA model spectrum and assessing auditory function objectively.

In future work it is proposed to apply wavelet filter and analyzing TOAE and DPOE signals in time-frequency and also by computing auditory response in contour plot with its variance. Hence decision analysis can be done based on the level of hearing loss.

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