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Frequency Analysis of Thunder Features

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***Abstract*—Acoustic signatures of thunder can be used in understanding some properties of lightning channels. Basic features of thunder signal are qualitatively classified as Peals, Claps and Rumble. In studies [1] and [4], attempts have been made to recognize these features quantitatively. To strengthen previous findings, above features were analyzed using S-transformation in this study. Characteristics of Peals, Claps and Rumble are directly affected by the acoustic energy, channel tortuosity, the interference of distinct parts of the channel, channel orientation relative to the observer and attenuation of high frequencies during the propagation. The fundamental frequency of audible thunder appears less than 250 Hz. S-transformation was introduced to estimate the fundamental frequencies and mean frequencies of thunder features with a level of significance. The elapsed time of peals and claps depends with the intensity level and the frequency composition of the fluctuation. The mean fundamental frequency of rumbles is 63 Hz.**

Keywords-spectrogram; peal; clap; rumble; S transformation

I. INTRODUCTION

The acoustics signatures produced by lightning discharge have been analyzed in time domain in many occasions for quantitative identification of thunder features such as peal, clap and rumbling [1, 4]. The frequency domain analysis as provided by Fourier transformation, short time Fourier transformation with various window functions have contributed considerably in analyzing the acoustic signals. However, the localization and the resolution of the frequency have been degenerated due to mathematical limitation of above methods.

Energy per unit length associated with the thunder has been studied using audible fundamental frequency of lightning discharge by introducing short time Fourier transformation [1]. The harmonic nature of audible frequencies has been inferred significantly in distinguishing the ground flashes and cloud flashes.

The audio frequency pressure variation associated with thunder has been estimated by spectral densities and dominant frequency maxima is in the range of 52 to 96 Hz and it is confirmed that the sound pressure is a function of distance and has been initiated by the cylindrical wave-fronts [2].

In general, the terms peal, clap, and rumble are specified qualitatively by listening audible sound pressure variations. A peal defines as a sudden loud burst with repetitive nature and takes a long time to return to the ambient pressure. A sudden isolated sound from main profile lasts for short time duration or impulsive nature refers as a clap and rumble is a weak sound continued over considerable time duration. The distance is also a vital parameter to distinguish the pressure fluctuation of subjective thunder terms [3].

The occurrence characteristics and the relative amplitudes have been analyzed to enlighten the features of thunder. A level of significance of relative amplitudes has been introduced by using the peak value to effectively distinguish the subjective terms, clap, peal, roll and rumble. The number of occurrence of claps has a certain confidence to identify ground flashes and cloud flashes [4].

The time duration of pressure fluctuation associated with the subjective thunder terms specially peals and claps depends on the fundamental frequency because of their impulsive nature and high intensity level change. In this study, it is intended to analyze the frequency variation of the subjective thunder terms using the time localized spectrograms generated by S-transformation. Relative signal to noise ratio and the decibel level change of signal to noise ratio have been introduced with a certain level of significance to distinguish the characteristic thunder features from the main thunder signature.

II. THEORY

A. *Audibility of thunder*

The sudden expansion of atmosphere around the lightning channel initiates a strong shock wave with extremely high pressure variation and then gradually turns into feeble shock with slow speed. Finally, the weak shock transforms into an acoustic pressure variation that propagates with the speed of sound [5].

Peals of thunder arrive directly from the lightning discharge while consecutive peals originate at different sections of the flash and claps arrive from different directions that appear from a reflection or a distant excitation of the flash [3]. The distant parts of flash forms low intense pressure variation by giving rise of rumbles associated with low frequencies because of the attenuation of high frequencies during the propagation.

B. Spectrogram by S-transformation

S-transform is a time-frequency distribution, which generalizes the Short time Fourier transform and continuous wavelet transform. It provides frequency dependent resolution and directly relates with the Fourier spectrum. The better frequency localization has been provided in short time durations which is important in studying the characteristic features of thunder compared to the Gabor transformation in Short time Fourier transforms. The local spectrum of a signal in finite time window τ is given by

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t)\frac{|f|}{\sqrt{2\pi}} e^{-\frac{(\tau-t)^2 f^2}{2}} e^{-i2\pi ft}dt \qquad (1)$$

Where *x(t)* is the signal of interest and *f* represents the frequency. The S-transform of discrete time series can be proposed by replacing $f \to n/NT$ and $\tau \to jT$

$$S\left[jT, \frac{n}{NT}\right] = \sum_{m=0}^{N-1} H\left[\frac{m+n}{NT}\right] e^{-\frac{2\pi^2 m^2}{n^2}} e^{-\frac{i2\pi mj}{N}} \qquad (2)$$

Where *n*,*m* are the discrete frequencies and *T* is the sample time and *H* represents the discrete Fourier transform of $m+n$ shifted frequency components. The computing complexity of the S-transform coefficient has been solved using Fast Fourier transformation algorithm and the coefficients appear to directly related to the power spectrum of the signal [6,7].

III. MEASUREMENT AND DATA

Thunder signatures recorded as a voltage variation associated with the pressure change on the diaphragm of microphone. The outdoor Omni-direction microphone (Bruel & Kjaer Outdoor Microphone Unit type 4198) includes Falcon range ½"pre-amplifies type 2669 C and this preamplifier operates over wide range of temperatures, humidity and other environmental conditions. The sensitivity of the preamplifier is -26 ± 2 dB, 1 Volt per Pascal, 50 mV per Pascal. The frequency response is ± 1 dB 10 Hz to 8 kHz and lower limiting frequency is 2 Hz to 4 Hz. The recorded thunder signals are accompanied with the back ground sound noises including raining, bug screaming, birdcalls etc. The effect of the wind has been eliminated using windscreen filters to the microphones during the capturing up to the speed of 120 kilometers per hour but under heavy windy conditions there is small wobbling of the microphone poles which interfered with the signal with very low frequencies.

The captured voltage signal was transmitted to the Nexus Range of conditioning amplifier type 2690 (Bruel & Kjaer) with the frequency range of 0.1 Hz to 100 kHz for the gain (i.e. less than or equal to 60dB). The signal captured by the conditioning amplifier was sent to Data acquisition card (USB 4432 National Instruments) for the acquisition and conversion of analogue to digital. Data were recorded at 100k per second of 40k sample capacity.

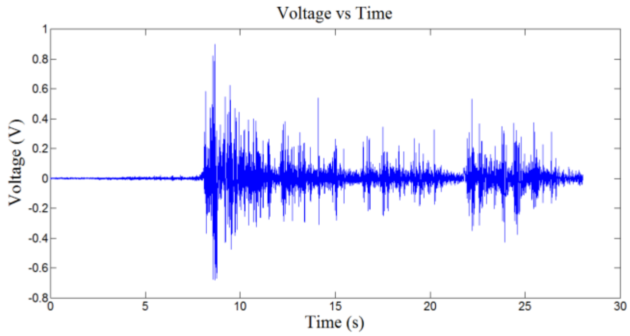

Figure 1. Recorded voltage variation of cloud flash (05092015_030131_PM)

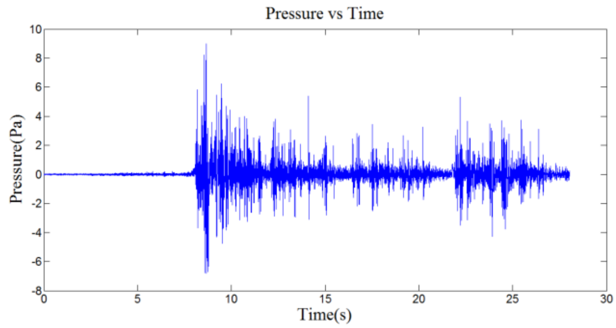

Figure 2. The pressure variation of the thunder obtained from the sensitivity of the conditioning amplifier100 mV/Pa

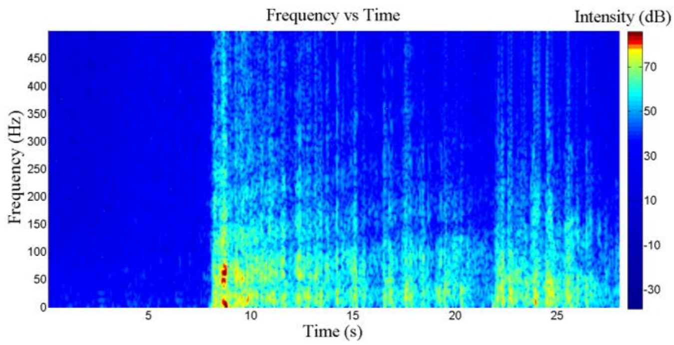

Figure 3. The frequency variation of the recorded thunder signal represents with time. All the frequency components less than 500 Hz are analyzed in this study by the relative power and the dominant frequencies are obtained from the maximum power dissipation.

The spectrogram of the thunder signature has been estimated to get the frequency localization by introducing short time Fourier transformation. The fundamental frequency of thunder is obtained from the maximum intensity level change or maximum audible power dissipation determined by the power spectrum. Fig. 3 represents the fundamental frequency variation of the thunder signal labeled as 05092015_030131_PM and all signals analyzed in the study contain the frequencies below 200 Hz. The subjective thunder features have been separated from the main thunder profile and introduced S-transformation based spectrogram to estimate the fundamental frequencies below 250 Hz. Cloud flashes lasts longer duration compared to the ground flashes due to the difference in propagation distance. The distance of the thunder has been approximated by the change in intensity level and measuring the time to thunder.

IV. Results and Discussion

The study is mainly focused to describe the frequency variation of audible thunder features peal, clap and rumble irrespective of the flash type. The intensity level change of thunder provides reasonable information about the distance of the sound source and can be used to distinguish the close flashes and distant flashes respectively. Time domain analysis of the pressure fluctuation of thunder reveals that the initiation of close flashes is a sudden loud burst and continues with consecutive peaks and turn into feeble pressure fluctuations. The distance flashes are initiated by feeble pressure fluctuations and gradually turn into a loud burst which takes considerable time to reach the peak. The dominant frequency of close flashes associated with the loud burst appears to be relatively high compared to the distant flashes due to the attenuation of high frequencies in the atmosphere.

In this study, twenty-three thunder recordings were analyzed to categorize the characteristic thunder features into peals, claps and rumbles by listening to the recordings and comparing the signal to noise ratio during the activity. The background noise is recorded and then recorded thunder signals are analyzed relative to the average background noise. This technique can effectively be used to separate the subjective thunder features from peal and claps or sudden pressure fluctuations. The rumbles or feeble pressure variations usually occur at the beginning and the lasting parts of the thunder recordings.

A. Peal

Fifty pressure pulses, which have been identified as peals from different flashes have been considered in the study to perform the frequency analysis by S-transform. By using the spectrogram of each pressure fluctuation, the fundamental frequency which provides the maximum intensity level obtained and other intensities represented as a relative intensity level. Fig. 4 represents the pressure variation produced by a peal obtained from 04172014_080916_PM. A long time duration and gradually developing to the maximum pressure are the basic features of peals.

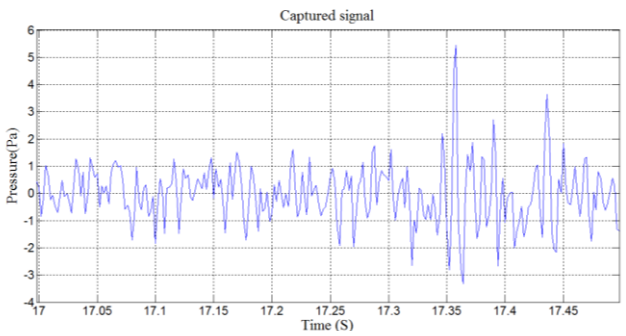

Figure 4. The pressure variation of a peal separated from the main thunder signature labeled as 04172014_080916_PM

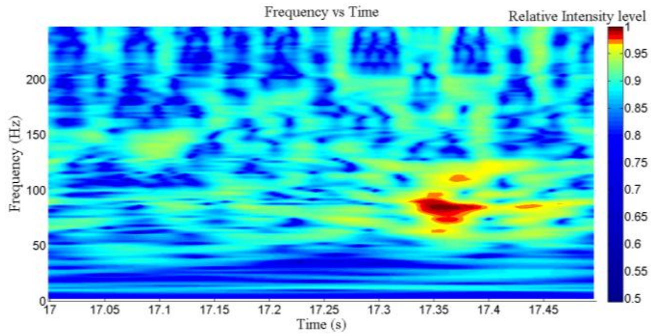

Figure 5. The frequency variation of the recorded peal obtained from the spectrogram generated by S-transformation

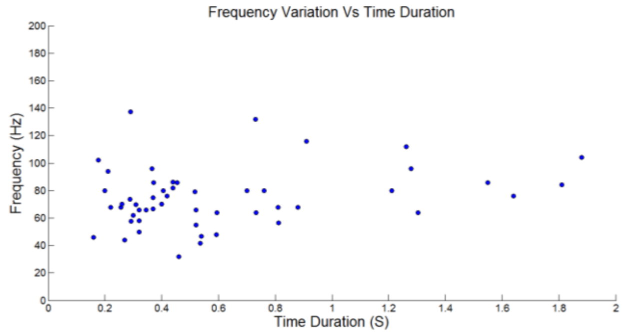

Figure 6. The fundamental frequency varaition of peals arranged relative to the time duration

The frequency spectrogram of the same pressure fluctuation is represented in Fig. 5 and all the frequencies less than 250 Hz been analyzed. The Harmonic nature can be observed for close flashes while the distant flashes basically converged to the fundamental frequency because of the attenuation of high frequencies during the long distance propagation. The fundamental frequencies of peals can be distinguished by the maximum relative intensity level in the spectrogram. The frequency composition of peal appears to be a representation of the localized acoustic energy produced by the expansion of air around the return stroke.

The fundamental frequency variation with the time duration of peals captured from distinct parts of same flash and different flashes are represented in Figure 6 and the frequency range 32 to 137 Hz. More than 80% of recorded frequencies are scattered around the frequencies between 40 to 100 Hz with accordance to the sample considered. The intensity level change and the fundamental frequencies of peal associated with ground flashes and cloud flashes appear to have a significant variation because of the tangential propagation and normal propagation of sound wave in atmosphere.

B. Clap

An abrupt isolated pressure variation which persists for short time duration in thunder can be identified as a clap. Its sound quality is based on the impulsive nature associated with short time duration and superimposition of few feeble pressure fluctuations. Pressure variation of claps can be distinguishable associated with a peal by its time duration. Fig. 7 represents the pressure variation which identified as a clap taken from the thunder label as 04172014_081013_PM. The frequency of occurrence of claps in cloud flashes is relatively high compared to the ground flashes because of the torturous nature of propagation of cloud flashes.

The spectrogram which includes all the frequencies less than 250 Hz within a selected time window has been introduced to the pressure fluctuation initiated by clap. Figure 8 represents the spectrogram of claps taken from Fig. 7 and it contains two close consecutive claps with similar frequency signature. In accordance with the spectrogram, the fundamental frequency has been obtained and there is a significant effect from low frequency components to the clap. The fundamental frequencies of the distinct claps appear in the same flash is changed from low frequency to high and high frequency to low irrespective to the flash type. Generally, high frequencies rapidly attenuate during the propagation and therefore claps with low fundamental frequencies are from distance parts of the stroke or less energy strokes. Closest claps composites with high frequencies and distinct claps from the same thunder degenerates the fundamental frequency. The number of claps in a thunder appears not to vary with the fundamental frequency variation.

The sample size of the claps included to the study is thirty-seven and the fundamental frequency variation with the time duration of the pressure variation has been represented in Fig. 8. The time duration of 90% of analyzed pressure fluctuation as clap is less than 0.25 seconds and the fundamental frequencies of more than 90% of pressure fluctuation are spread in the range of 40 to 160 Hz.

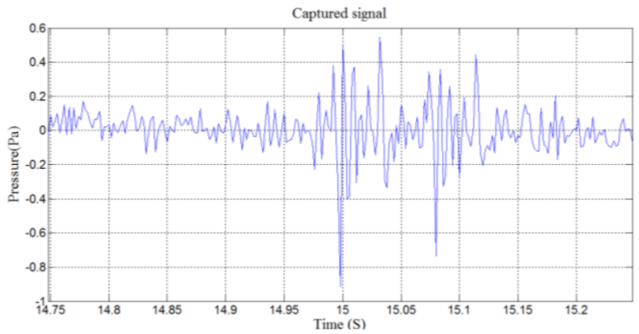

Figure 7. The pressure variation of two consecutive claps or a relection been captured from the thunder recorded as 04172014_081013_PM

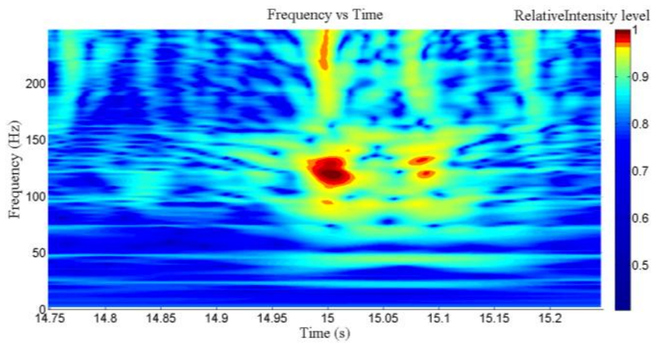

Figure 8. The frequency spectrum confirms the identical nature of the frequency composition of claps

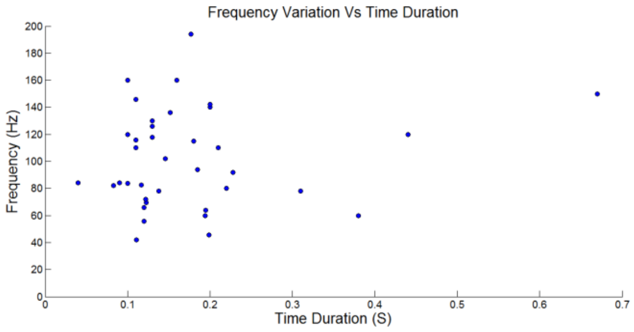

Figure 9. The fundamental ferquency variation claps initiated by diffenrt flashes

C. *Rumble*

The pressure fluctuations from the closest part of the channel and the fluctuations initiated by closest branches of the distant flashes arrive to the observer first. The pressure fluctuation from the very distant flashes produces rumbles with low frequencies because of the rapid attenuation of the high frequencies with the propagation and the small variation of the intensity level relative to the back ground noises.

The pressure variations recognized as rumbles are selected from different flashes irrespective to the flash types and the intensity level variations have been used to get an idea about the distance. Forty-three pressure fluctuations are carefully separated from the background noise and measure the time taken to initiate a peal or a clap. Generally, rumbles appear initial part and later part of the thunder that infers the distance is one of the factors. A segment of a recoded rumble has been represented in Fig. 10 and can be distinguished from the background noise by a considerable rapid variation of the associated pressure.

The pressure fluctuations initiated by rumbles can be easily recognized from the spectrogram and the fundamental frequencies have been obtained from the highest intense sound recorded in the time duration. The existence of fainted color band corresponds to high frequencies in the spectrogram strengthens the idea about the distance part of channels gives rise rumbles and these high frequency harmonics can be used to verify whether the rumble is a degeneration of peals or claps.

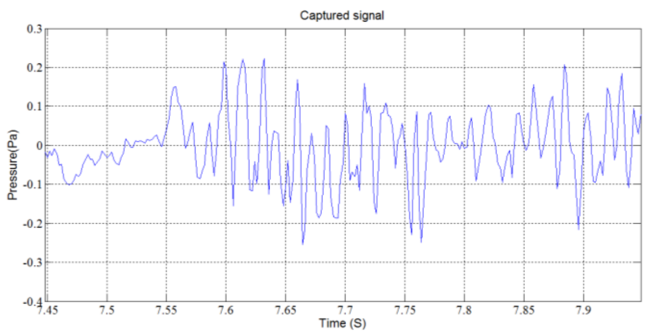

Figure 10. Prssure fluctuation associated by the rumble captured from the thunder labeled as 05102015_084917_PM

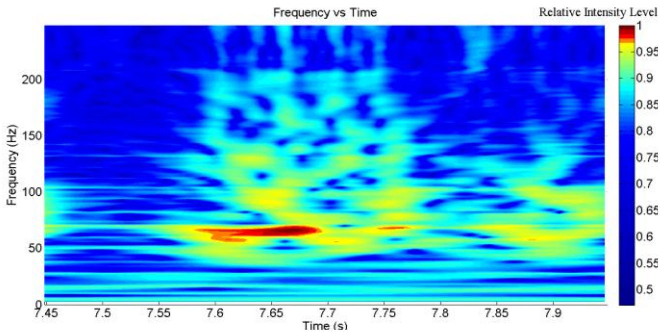

Figure 11. The frequency variation associated with a rumble captured from thunderlabeled as 05102015_084917_PM

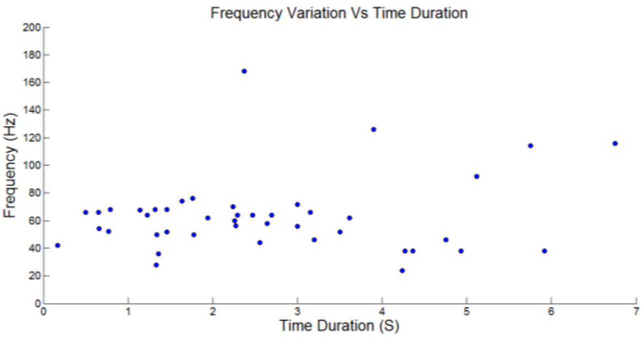

Figure 12. The fundamental frequncy variation of rumbles arranged rlative to the time duration

Fig. 11 represents the frequency variation of the selected part of the rumble in Fig. 10 and the high frequency harmonics appear with relatively low intensities because of the attanuation. Rumbles appear for closer part of the channel with high frequency harmonics while distant flashes provides feeble intensities for harmonics with low fundamental frequency.The frequncy variation and time duration of the recoded rumbles has been represented in Fig. 12 and the rumbling duration is comparatively long. The frequncy above 80 Hz recoded 10% of the sample and remaining 90% of ocurrences appears in the frequencies between 25 Hz to 80 Hz of the sample with fourty three rumbles selected from distinct flashes. The frequencies less than 25 Hz is rarely recorded and it is difficult to decide whether the sound is from thunder or some noises initiated during the recording.

V. Conclusion

The time duration of subjective thunder term, peal appears to be a function of distance to the sound source. The peals initiated by close flashes associated with short time duration and high intensive nature while distant flashes with long time duration and low intensity. The associated fundamental frequencies of peals appear to be an invariant property from the time duration. The average time duration of peals spread in the range 0 to 2 seconds and long lasting peals contains high frequency fundamental while the peals with short time duration contains low frequency fundamentals. There is a trend for the fundamental frequency of peals with the mean value of 75 Hz for the sample and its standard deviation is 22 and than 70% of recorded peals in the study appears in the range suggested by the above values.

According to the sample selected in the study, it appears no significant variation of the time duration of claps with the distance and retains its impulsive nature associated. The energy per unit length of the channel associated with the fundamental frequency of claps analyzed is deviated by the theoretical value proposed by the equation discussed in [2, 3]. The mean fundamental frequency of a clap appears to be 102 Hz in the study and its standard deviation is 36 Hz and more than 65% of recorded claps appear in the suggested range.

By the consideration of long lasting time duration and low intensive nature of sound level, rumbles appear due to the attenuation of high frequency during the propagation of distant parts of the lightning stroke. The mean fundamental frequency of recoded rumbles is 63 Hz and the standard deviation is 27 Hz. More than 85% of recorded rumbles are in the range suggested by mean and standard deviation.

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