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Study of Acoustic Principles in Nadaswaram using Spectral Analysis and Wave Functions

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Abstract: The Nadaswaram (a.k.a Nagasuram, Nagaswaram, Nayanam, Vangiyam) is one of the most ancient wind instruments of India. It is also the world's loudest non-brass wind instruments whose acoustic characteristics need to be studied along with other wind instrument such as trumpet, oboe, bassoon etc. Scope of this paper is to introduce for the first time the various definition governing acoustic engineering such as Input impedance, wave equation, pressure vs. flow velocity, horn equation and vibrating double reed with respect to design (construction) of Nadaswaram.
To prove high amplitude sound waves originating from flaring bell, spectral content and frequency analysis were carried out on audio signals using specific type of Nadaswaram called Paari and its scale is $2\frac{1}{2}$ ***with audio signal processing tools such as Sonic Visualizer and Matlab's audio toolbox. Nadaswaram's sound intensity(decibels) under various spectra were also simultaneously investigated and all of these measurements were used to conclude that high pitch and high amplitude sound wave originating from this instrument is directly attributed to its current structural design or construction. Experiments to measure frequency, pitch and intensity were done in normal room environment hence its assumed that their values are affected by environment noise and other acoustic attenuation.***
Keywords: Nadaswaram, Acoustics, Bessel horn, Flaring Bell, Acoustic input impedance, Anasu

I. INTRODUCTION

The Nadaswaram is a double reed wind instrument from South India. It is one of the oldest musical instrument whose usage and its mention dates back to 300 BC – 200 AD. Its original name in ancient Tamil literature was Peruvangiyam or Neduvangiyam. Earliest mention of this instrument can be found in classical Tamil poetic work called Purananooru (1:52)[8] and Agananooru (111:8-9, 301:16-17)[9]. It is a wind instrument similar to the North Indian shehnai or other western instruments such as oboe and bassoon but much longer, with a hardwood body and a large flaring bell made of wood.

Traditionally the body of the Nadaswaram is made out type of tree called Aacha whose botanical name is Hardwickia binata. While other wood types such as Rosewood, Sandal were rarely used in olden days and its impact in acoustic behavior is not known. The Nadaswaram has seven finger-holes, and five additional holes drilled at the bottom which were closed to modify the tone and match it to the scale.

Nadaswaram is a versatile instrument whose Sruthi or scale has a range of $1, 1\frac{1}{2}, 2, 2\frac{1}{2} \ldots upto\ 5$. Higher scale Nadaswaram(starting from scale 3) due to its intense sound and energy were largely suited for open spaces and lower scales were adopted for indoor concerts.

The top portion has a metal staple (mel Uzhavu) into which is inserted a small metallic cylinder (kendai) which carries the mouthpiece made of reed. Besides spare reeds, a small ivory or horn needle is attached to the instrument, and used to clear the reed of saliva and other debris and allows free passage of air. A metallic bell (keezh anasu) forms the bottom end of the instrument.

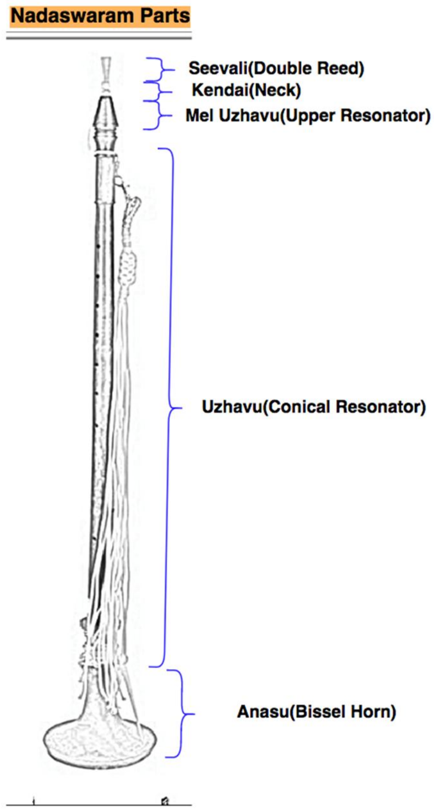

Fig .1 Parts of Nadaswaram

Any wind instruments irrespective of its wood or brass making; are ideally used to create displacement of air within cylindrical or conical tube. Based on above figure: Nadaswaram's internal bore can be assumed as a linearly behaved resonator closely coupled to a nonlinear acoustic generator which is the reed, lips or air jet produced by the player. The resonator is usually a tube, in which a column of air is set into vibration by the player blowing into a mouthpiece set at the end of the resonator. The playing frequency is determined, to first order, by the resonances in the bore of the instrument and the frequency of the vibrating lips. Upstream from the lips lies the player's vocal tract with acoustic resonances that has a large effect on performance technique.

II. METHODOLOGY : ACOUSTIC INPUT IMPEDANCE:

In the process of developing or designing any wind instrument, performer is mainly interested in tuning, timber and ease of playing of that instrument. These characteristics can be predicted by measurement of Acoustic input impedance. This impedance value shows the acoustic response of that instrument for whole range of possible frequencies. Definition of impedance is vital here to characterize the performance of the instrument, independent of the player[3]. Its a complex ratio of the pressure difference across a section of pipe over the volume flow rate through it, or

$$Zin = \frac{p_{in}}{U_{in}} \text{ at the mouthpiece or reed end.} \quad (1)$$

p_{in} - Input acoustic pressure

Z_{in} - Input Impedance

U_{in} - Acoustic volume flow

Acoustic impedance at a particular frequency indicates how much sound pressure is needed to generate provided air vibration at that frequency in a specific point. The units for impedance are $kg\ /\ m^4$swhich we call the acoustic ohm Ω. Since volume flow (U_{in}) is related to particle velocity, u of the air in the pipe it can be defined as U_{in} = uS

$$Z_{in} = \frac{p_{in}}{uS} \qquad (2)$$

with S as a cross sectional area of the pipe. A simple case is a plane wave propagating through cylindrical pipe, since there is no reflected wave, only outgoing wave must be considered and we get

$$Z_o = \frac{\rho c}{S} \qquad (3)$$

Here ρ is the density of air and c is the speed of air. This is also referred as characteristic impedance of the pipe. Thus characteristic impedance changes or is inversely proportional to cross section area of pipe.

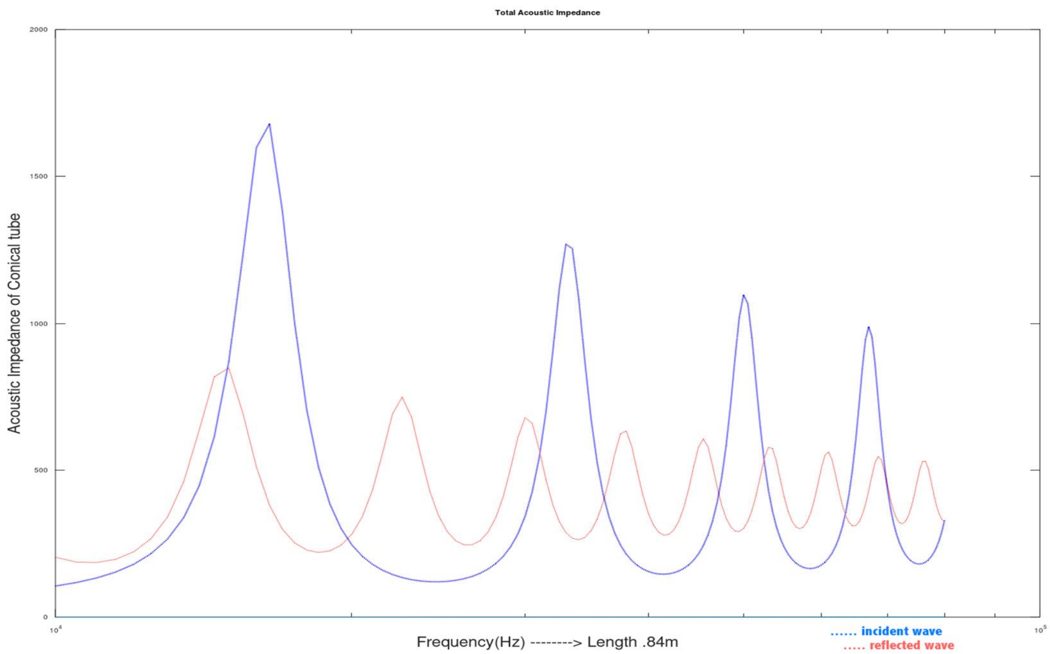

Fig.2 Acoustic input impedance of a Nadaswaram of length L = 0.84 m as a function of frequency. The case shown here includes thermal and wall losses.

From the diagram above(Fig.2), we can see that, when the incident wave reaches the transition from high impedance in the duct to low impedance in the radiation field. Higher transmission can be achieved by inserting a bell between the two regions of intermediate impedance. A flaring bell on a Nadaswaram hence functions as an impedance transformer. This can readily be demonstrated by disconnecting the bell, which makes the instrument much softer. It also changes the timbre substantially, because the bell transmits waves whose wavelength is small compare with the radius of curvature of the bell profile.

Initially without considering the bell at one end, lets assume a situation when we consider a finite pipe of length L. We excite an outgoing plane wave at the beginning of the pipe at x =0. The end of the pipe at x = L represents an abrupt change of the acoustic impedance and we get a reflected wave that now interacts with the outgoing wave to produce standing waves. As a result acoustic impedance at beginning(x=0), the input impedance becomes:

$$\text{Zin} = \text{Zo}\frac{\text{ZL} + \text{iZo}\tan(\text{kL})}{\text{Zo} + \text{iZL}\tan(\text{kL})} \qquad (4)$$

ZL - Impedance at the end of the pipe(x=L)

Zo – Characteristic impedance of the pipe

$k = \frac{2\pi}{\lambda}$ – Wave number and i is the imaginary unit

The acoustic impedance plays a major role when it comes to describing the propagation in pipes of various shapes. Majority of modern instruments and many ancient ethnologically important instruments have internal bores that flare out towards their ends. In the case of Nadaswaram where each resonances of the air column within the bore of the instrument corresponds to a peak on the input impedance curve. For a narrow cylindrical bore wind instrument with end radius a ≈ 1 cm, the cut-off frequency (ka ≈ 1) is ≈ 5.5 kHz.[2] Below this frequency the instrument will support a number of relatively weakly damped resonant modes, which will radiate isotropically from the ends of the instrument or from open holes cut in its sides. In contrast for Nadaswaram the detail shape and size of flaring bell at the end determines the cut off frequency. The large size of the bell leads to an increase in intensity of the higher partials and hence brilliance of tone-color, especially when the bell is pointed directly towards the listener.

III.EFFECTS OF ANASU OR FLARING BELL

Mostly brass and wooden instrument have bores, which are cylindrical in addition to flared bell like structure for gradual impedance transition. In Nadaswaram, bell like structure is called as Anasu. One of the principle reasons for such flares is that they act as acoustic transformers, which help to match the high impedance at the mouthpiece to the much lower radiation impedance of the larger-area radiating output end. However, increasing the fraction of sound radiated decreases the amplitude of the reflected waves hence the height and sharpness of the natural resonances of the air is attenuated. In addition, the shape of the bore can strongly influence the frequencies of the resonating air column, which destroys the harmonicity of the modes. This is used for the same purpose and Fletcher and Rossing[1] define its resonant frequency as follows:

For perfect cone instruments resonant frequency is $fn = \frac{nc_0}{2L}$ this equation can be rewritten for Nadaswaram as follows

$$fn = \frac{nc_0}{2(L_1 + L_2)} \qquad (5)$$

For hybrid instruments like Nadaswaram where n is odd and even number. L_1 = Length of tube cone + Length of Anasu L_2 (Bell) – Fig.3

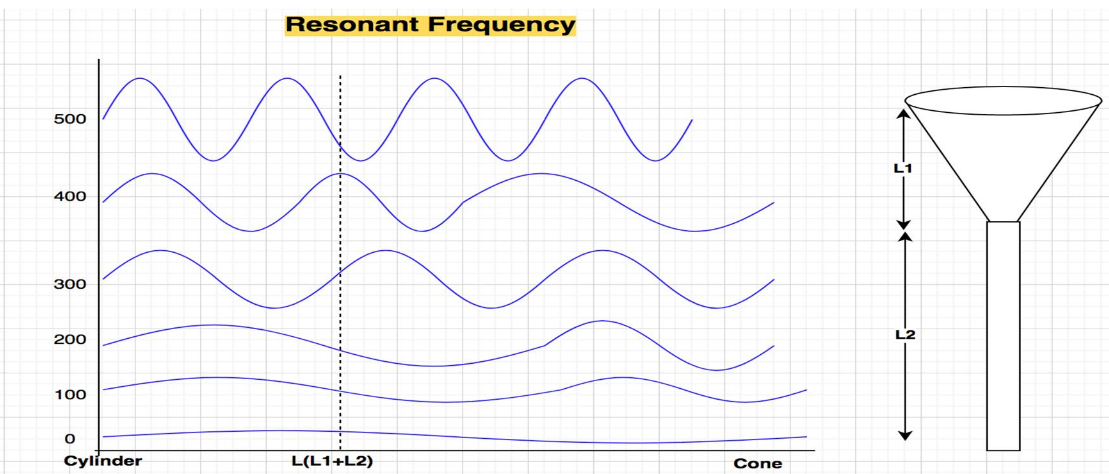

Fig.3 Resonant Frequency for Hybrid instruments like Nadaswaram

Thus from above equation we can assume resonant frequency is inversely proportional to twice fractional length of hybrid structure, while comparing it against pure cylindrical devices like clarinet or organ flute pipes. Horns attenuate frequency by increasing wave amplitude and reduce wavelength, thereby causing radiated sound to improve in these devices.

Another way to look at it through study of input impedance. Input impedance transition is more fatal for long wavelengths than short wavelengths. This is because for higher frequencies the bell is slowly changing impedance, thus the waves with high frequencies reflect less than low frequency waves. The primary purpose of the bell is the amplification of lower frequencies. The bell has also other effects on sound. It raises the frequencies of the lower modes because the flare makes the vibrating air column shorter at longer wavelengths. Thus, the air column is shorter for the lower modes, which will raise their frequencies. Physical insight into the influence of bore shape on the modes of typical brass instruments is given by the Webster's horn equation [7]:

$$\frac{1}{S}\frac{\partial}{\partial x}\left(S(x)\frac{\partial p}{\partial x}\right) = \frac{1}{c_0^2}\frac{\partial 2p}{\partial t2} \qquad (6)$$

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S(x) is a function defining variation in cross section area with x. This equation we get from wave equation with plane wave approximation. If we make simple substitution for p so that $p = \Psi S^{1/2}$ and looking at solutions varying at $\Psi(x)e^{i\omega t}$ above Webster equation can be rewritten as:

(7)

$$\frac{\partial^2\Psi}{\partial x^2} + \left[\left(\frac{\omega}{c0}\right) - 1/a\frac{\partial^2 a}{\partial x^2}\right]\Psi$$

which closely resembles Schrödinger wave equation in quantum mechanics. Here $1/a\frac{\partial^2 a}{\partial x^2}$ is analogous to potential energy and $\frac{\partial^2\Psi}{\partial x^2}$ corresponds to kinetic energy. Radius of the curve is also represented as R= $\frac{\partial^2 a}{\partial x^2}$

(8)

$$k^2 = \left(\frac{\omega}{c0}\right) - \frac{1}{aR}$$

Thus propagation of sound wave in a horn is directly analogous to the propagation of particle in spatially varying potential. If the curvature is sufficiently large sound waves will be reflected before they reach the end of the instrument. However, just like particle waves in a potential well, sound waves can still tunnel through the potential barrier and radiate into free space at the end of the flared section. For a horn with a rapidly increasing flare, the reflection point occurs when the wavelength $\lambda^2 \sim (2\pi)$Ra. The effective length of an instrument with a flared horn on its end is therefore shorter for low-frequency modes than for the higher-frequency modes. In other words rewriting wave equation we can say $\lambda_{reflected} > 2\pi(aR)^{1/2}$. Bell acts as a high pass filter, because above cut off frequency no sound is reflected back to the lip [4] For high frequency instrument like Nadaswaram, higher the cut off frequency we expect more rapidly flaring bell(Anasu) and these principles are kept in mind while designing this instrument.

IV. ADVANTAGES OF NADASWARAM REPRESENTING BESSEL HORN

Considering previously found solution for horn equation we can now apply it to different hybrid horns which are mainly classified based on its bell shape. Assuming Internal bore to be of cone, based on bell shape we can classify it as exponential horn, cosh horn and Bessel horn. Radii of exponential and cosh horn vary exponentially as Ae^{mx} and Acos(mx) respectively. We are not interested in other horn types but its useful to know its limitation while considering Bessel horn. It is also defined as:

$$a = bx^{-m} \qquad (9)$$

If m = 0 its cylindrical; m = -1 its conical. For Nadaswaram m is mostly positive in which case horn has a rapid flare at the origin x=0.

Bessel horn has radius varying at a rate of $1/x^m$ from their open end. Here m is ratio of input to output diameter at a range from 1 to 10. If we take mouth of horn located at x_0 giving the relation with bore radius A and the distance x from mouth of the horn as:

$$B = \frac{A}{(x+x_0)^m} \qquad (10)$$

or $$A = B(x_0 + x)^{-m} \qquad (11)$$

If we substitute varying diameter in horn function previously defined horn function can be rewritten as

(12)

$$\frac{\partial^2\Psi}{\partial x^2} + \left[\left(\frac{\omega}{c0}\right) - \frac{m(m+1)}{x^2}\right]\Psi = 0$$

Increasing the value of m increases the rapidity with which the flare opens out at the end. Here m which defines rate of flare (Fig. 4)

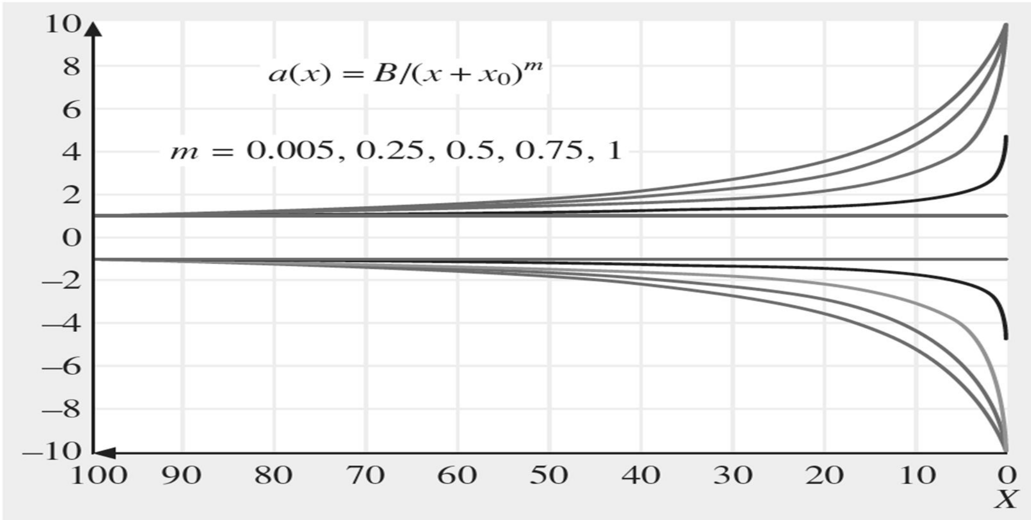


Fig.4 – Rate of flare. For Nadaswaram m is defined between 0.5 - 0.7

Here the important point to note is the way that the flare pushes the effective node of the incident sine wave(extended into flare section with dashed curve) away from end of instrument. Here effective length(of wave) is shortened and resonance frequency is increased(refer: eq.7) this effect is largest for lower frequency. From [Fig.5]. Pitch can be lowered by around a semitone by moving supporting hand up into the bell of the instrument which is referred as hand stopping. The pitch can be lowered by around a semitone, by placing the downwardly cupped hand and wrist against the top of the flared bell, effectively reducing the flare and increasing the effective length of the instrument. Alternatively, the pitch can be raised by a similar amount when the hand almost completely closes the inner bore.

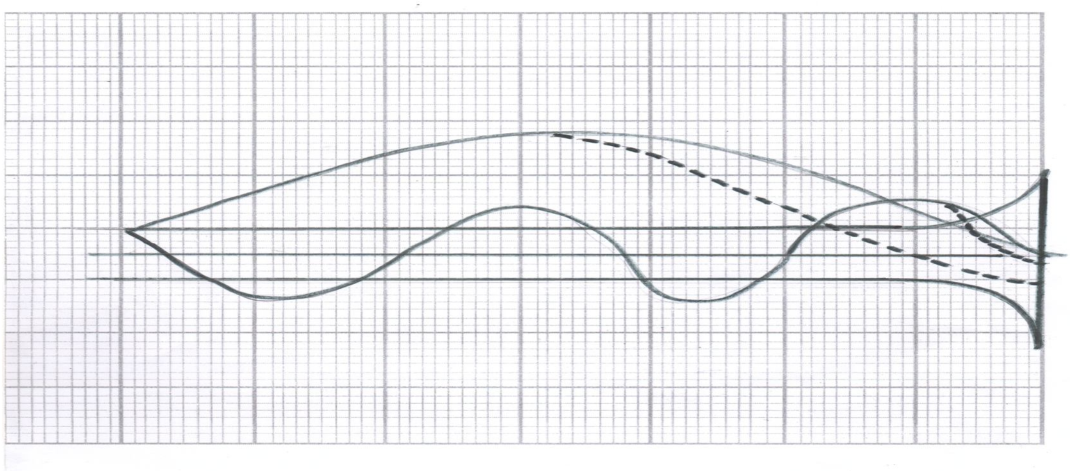


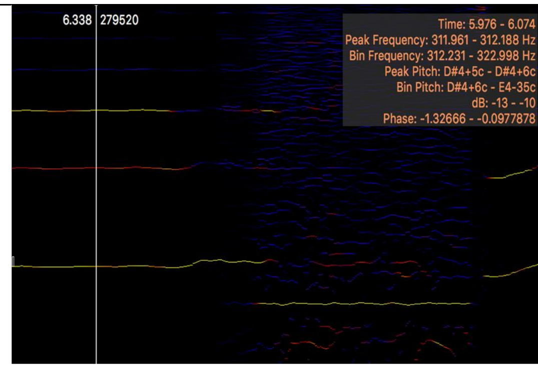
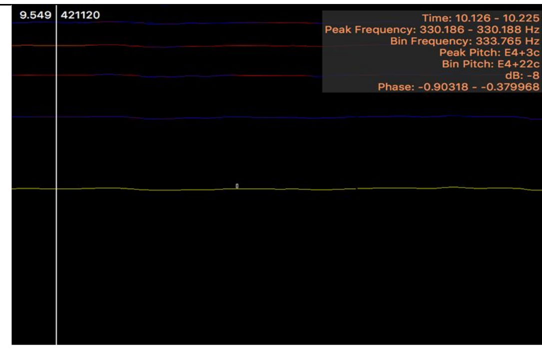
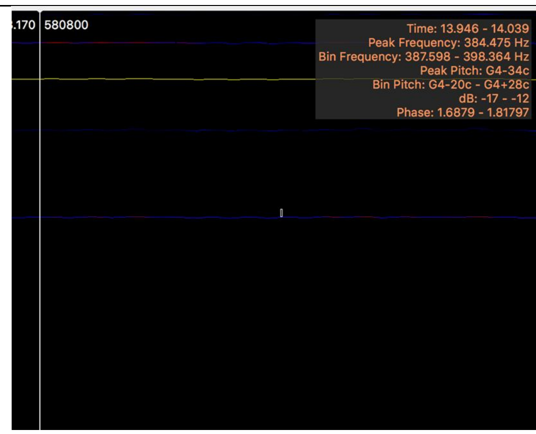
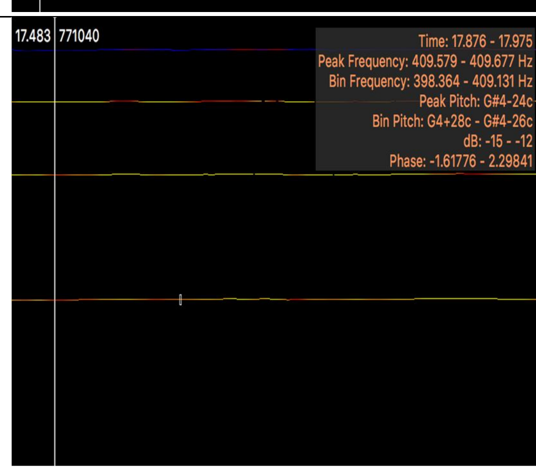
Fig 5. m=1/2 or 0.5 Increase in wavelength and resulting shift inwards of effective nodal postion.

V. RESULTS USING SONIC VISUALIZER:

TABLE I
Showing Variation OF Amplitude with Frequency for Nadaswaram [7]

Frequency Hz	129.1	172.2	215.3	301.4	387.5	430.6	473.73	517.8	732.1	818.2
Amplitude(db)	-83.9	-83.9	-85.93	-82.44	-81.66	-81.30	-79.90	-78.74	-70.2	-56.2

Table II
Showing Pitch And Corresponding Peak Frequency For Pari Nadaswaram

Pitch	Peak Frequency (HZ)	Visualizer
D#	312.998	
E4	330.118	
G4	384.475	
G#	409.677	

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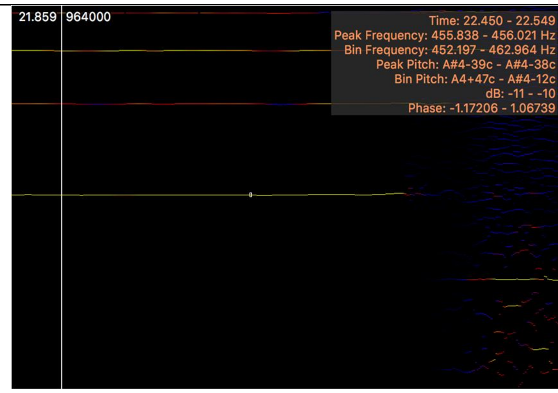
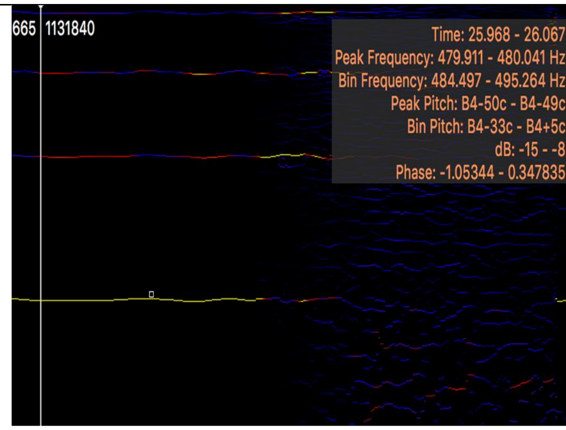
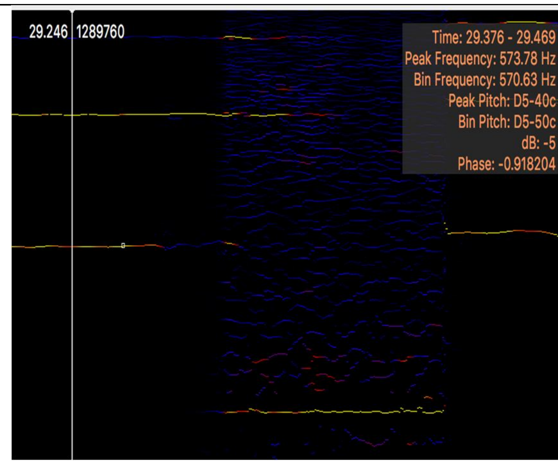
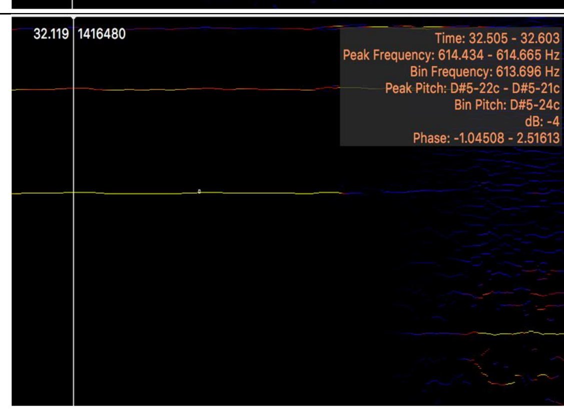
A4	456.021	
B4	480.041	
D5	573.78	
D#	614.225	

VI. CONCLUSION

Music instrument, like any other scientific invention goes through the same process of trial and error before getting standardized for general use. Instruments with strong adherence to scientific and acoustic principles gain prominence among the rest, as they undergo minimal structural changes. Nadaswaram is one such instrument, which was passed on to us for generations. This instrument readily complies with acoustic principles such as sound impedance, Helmholtz resonance, wave theory etc. to get the characteristic of a loudest non-brass wind instrument. The spectrum of the Nadaswaram contains a complete range of harmonics and octaves, which makes it as one of the most versatile instrument. While comparing with other wind instruments such as Oboe, flute, Basoon etc. Nadaswaram emerges to be the loudest instruments which fully attributes to its design of conical internal bore ,flaring bell(Bessel horn) and nature of reed. We also investigated the influence of the bell and other properties of the Nadaswaram which makes it necessary to introduce the acoustic impedance, Webster horn equation and Oslon equation. Later results using sonic visualizer confirmed the very nature of Nadaswaram and its performance among other wooden instruments.

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