A study on acoustics of conch shell

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The mechanism of generation of musical sound in conch shell excited by lip vibration is presented with reference to up-to-date literature on operation of wind instruments. The process of ‘mode-locking’ is indicated in the context of our observed spectrum. The spectrum of conch sound is explained with reference to the geometry of conch shell and its equivalence as a conical horn, where the nature of spectra fairly agrees with the theory.

**Keywords:** Conch shell, conical horn, mode-locking, sound spectrum.

The use of conch shell as a musical instrument has been in practice in various cultures on diverse occasions since ancient times. Particularly in India, it is used both as a ritual vessel and trumpet in social and religious solemnization functions. The conch shell (sankha) is an essential element in Buddhist custom. It was an important ritual instrument in pre-Columbian south and central America. It is used as a musical instrument in Japan and Fiji. But, in spite of its wide use for centuries the world over, its acoustics has received very little attention. Recently, Bhat and co-workers have reported the tomographic picture of sample spectrum analysis of the shell-sound and an approximate formula for its resonant frequency.

We had taken up an investigation on the shell acoustics and in the process, we were led to study the geometrical structure of the shell. It was interesting to note that the structure follows Fibonacci pattern. This paper is in continuation of an earlier report and here we present findings on working of a conch shell as a wind instrument. The mechanism of production of shell-sound has been understood to be due to external excitation in the form of lip-vibration which causes pressure difference between air columns in the shell-mouth and the cavity of the instrument, producing consequently, the resonant modes. The role of mouth of conch cavity has been explained and the interaction between the player's lips and the instrument has been depicted as a block diagram. An expression for the flow of air through the lips is presented in terms of the pressure difference and the lip opening amplitude.

It turns out that a coiled tunnel in structure, the conch shell cavity, effectively behaves as a straight conical horn and hence the theory of propagation of sound in conical horns has been applied to this case. The geometry of the shell reveals that the conch cavity coils as Archimedes spiral, which provides a clue to obtain the length of the spiral horn. As a result, we arrive at a formula for frequency of the fundamental note in standard form.

Further, analysis of spectrum of the conch shell sound through computer software is presented and it is pointed out that the shell sounds with lock-in frequency at higher odd multiple of the fundamental along with the overtones of all integral multiples of the lock-in frequency. The peculiarity of the behaviour of shell from its sound spectrum is pointed out and a plausible explanation is put forth by showing that the shell behaves simultaneously as a closed-open and open-open system.

**Conch-shell as a wind instrument**

The conch shell is one of the earliest wind instruments found in nature. Most of the wind instruments, whether found in nature or man-made, are either cylindrical or conical in shape. But the shape of conch shell cavity is rather unique. The X-ray tomographic picture of cavity is shown in Figure 1. It may be noticed that the cavity grows around a central pillar (columella) both in axial and transverse directions forming a spiral structure. Like other lip-driven musical instruments, the conch shell provided with an appropriate mouthpiece directs right amount of vibration to the cavity. Such a mouthpiece may be just an opening cut at the apex or may be an artificial attachment at suitable location on the shell body.

Mouthpiece, be it for a trumpet or horn, has similar design. Each pretends conical cup-like shape with a narrow passage to the resonator at the end position. However, in case of a conch shell, the shape is slightly different from others. The passage to conch shell cavity lies at the side of mouth piece. The difference in design of mouth piece is shown in Figure 2. Due to such departure in feature of shell mouthpiece, the player needs special skill to generate excitation. In all brass instruments, trumpet, trombone and the like, the source of excitation is the player’s lip-vibration. In conch shell too, such mechanism is operative.

**Lip vibration mechanism**

The study of lip-vibration was first initiated by Helmholz, who introduced inward and outward swing
mechanism of lips. Later Martin, Elliot, Browsher, Campbell, Yosikawa, Fletcher and Tornopolosky have investigated the mechanism more closely. The sound generation mechanism in a conch shell is initiated with the vibration of lips due to wind pressure. The source of wind is the player’s lungs, which generates a constant pressure \( p_m \) on lips where lips behave just as pressure-controlled valve. Campbell has presented a theoretical model of closed feedback loop. When a note is being generated on the instrument, the valve opens and closes periodically at a frequency which is close to the standing wave frequency of air column in the resonator. This allows a periodically fluctuating volume flow of air \( v \) into the resonator which supplies energy to sustain the oscillation in the air column. Consequently, a pressure antinode and velocity node is formed at the lips-reed end of the air column. Figure 3 shows the interaction between player’s mouth and instrument. In such a case, lips can be treated as a forced oscillator. The forcing term is proportional to the pressure difference \( P_m - p \), where \( p \) is a fluctuating pressure. If at any instant, volume flow of air is given by \( V + v \), then the rate of energy transfer to the air column turns out to be

\[
W = (P + p)(V + v) = PV + Pv + pV + pv,
\]

(1)

where \( P \) is the mean pressure, \( V \) the mean volume flow and \( v \) the fluctuating part. In the above equation, second and third terms average out to zero in a cycle and first term does not affect the energy balance. So the net energy transferred to the vibration mode is \( pv \), which is the product of two fluctuating quantities. So for different phases, of \( p \) and \( v \), the value of \( pv \) will change from maximum to minimum. This will be having maximum value when \( p \) and \( v \) are in the same phase. It will remain positive up to the phase difference \( \pi/2 \). In this stage, the air column will gain energy and in the next half cycle it starts to lose it.

To discuss the dynamics of conch player’s lip-vibration, it is appropriate to represent the lips by ‘double reeds’. Each of the two reeds may be treated as a ‘single reed’ and their combined effect comes into play. Helmholtz
first classified reeds into two types, i.e. ‘strike inward’ and ‘strike outward’. In such classification, conch player’s lips can be taken as ‘strike outwards’ type. The dynamics of lips-reed is a well-studied problem. Fletcher and Tornoplosky have described it as outward ‘swinging door’ (+, −)\(^15\). Figure 4 shows different phase of lip-vibration.

However, a number of experimental studies have been reported where the motion of lips has been observed photographically\(^13,16,17\). Among them, Martin has observed the displacement of lips very closely. Even in his study, all input phase angles between pressure and lips-vibration could not be deciphered. The prime findings of Martin’s observation are\(^15\): (i) lip motion is sinusoidal, and (ii) lips just close once in every cycle for all notes.

The flow equations for such model are setup and solved in the following to give the opening of reed per unit pressure in the mouthpiece as a function of frequency\(^15\). Primarily, there is a threshold blowing pressure to initiate the lip-vibration. This is determined by lip-tension and is independent of player’s mouth cavity. Similarly in conch shell vibration, there is threshold amplitude of sinusoidal pressure. The shell does not sound resonantly if blown with lips-pressure amplitude below that. Let \(P_{th}(f)\) be the threshold pressure required to produce a note of frequency \(f\). If the lips are initially closed, then they need pressure to open against their own tension \(T_{th}\). If \(m\) is the vibrating mass of the lips, then resonance frequency \(f\) would be proportional to \((T_{th}/m)^{1/2}\) as reported in the literature\(^18\). But the experimental result of Elliot and Brower proposed the relation \(m \propto 1/T_{th}\). So it is better to approximate\(^9,15\),

\[
P_{th}(f) = \gamma f,
\]

where \(\gamma\) is the proportionality constant. Hence, the lips are forced open once by a blowing pressure \(P\) greater than \(P_{th}\), then it oscillates in resonance with the instrument. So player has to adjust his lips tension to match the note to play.

To derive the flow equation, the impedance at the mouthpiece is taken as\(^15\)

\[
Z = \left(\frac{\sigma}{2}\right)\left(\frac{V}{\sigma^2}\right)
\]

where \(\sigma\) is the opening area of the lips, \(\sigma\) the density of air and \(V\) the volume flow. By the definition

\[
Z = \frac{P_m - P_i}{V}.
\]

And from eq. (3) we get

\[
\frac{P_m - P_i}{V^2} = \frac{\sigma}{2\alpha^2}.
\]

This leads to the flow through the lips to be given by

\[
V = \left(\frac{\sigma}{\sigma}\right)^{1/2}(P_m - P_i)^{1/2} a.
\]

The area of opening of lips \(a\) can be approximated as\(^15\)

\[
a \approx Cx^{3/2},
\]

where \(x\) is the vibrating amplitude or average lips opening and \(C\) is a constant. So eq. (5) turns out to be

\[
V = \left(\frac{\sigma}{\sigma}\right)^{1/2}(P_m - P_i)^{1/2} Cx^{3/2}.
\]

Further, \(x\) is an oscillatory function given by\(^16\)

\[
x = A(P_m - P_i)(1 + \cos 2\pi ft),
\]

where \(A\) is a constant.

**Geometry of conch shell**

The rigid bone cover of conch (\(Xancus pyrum\)) is used as conch shell, a sounding instrument. As conch is a living organism, it is difficult to fit an exact geometry for all species. Therefore, we have made an attempt to construct a generalized geometry for common conch shell cavity. Our measurements of the parameters in the structure satisfy the celebrated Fibonacci patterns found abundantly in nature. To study the interior cavity of conch shell, X-ray tomography was taken both for axial and transverse sections which is shown in Figure 1. Measurement of radius of curvature of the conch cavity is taken from the transverse section tomography. The values of radii satisfy the equation

\[
r = \alpha \theta,
\]

where \(r\) is the radius, \(\theta\) the angle and \(\alpha\) is a constant. This is the equation for Archimedes-spiral. In most of the
samples, the maximum value of $\theta$ growth is $8\pi$. The plot of our measurement of the spiral growth is presented in Figure 5. The flareness of the horn depends upon the factor $\alpha$. In some samples of shells after angle $8\pi$, the flare is appreciably large. But such flare does not directly contribute to the resonance in the cavity and hence skipped from our consideration. For a small angle of curvature growth $d\theta$, radius of curvature $r$ can be taken as constant. Then length element of arc is given by

$$dl = r d\theta$$

$$l = \int_{\theta_0}^{\theta} r d\theta = \int_{\theta_0}^{\theta} \alpha \theta d\theta = \frac{\alpha (\theta^2 - \theta_0^2)}{2}$$

(10)

$$l = \frac{R \theta}{2}$$

with $\theta_0 = 0$

where $R$ is the spiral radius at the open end. In the above calculation, the growth of shell in $z$ direction is not taken into consideration. When $\theta = 8\pi$, corresponding to four complete turns of the cavity coil in general,

$$L = 4\pi R.$$  

(11)

This implies that the value of $R$ at the maximum angle can provide the effective length of the conch cavity. The validity of eq. (11) is confirmed by physically measuring the effective length with thread tape.

**Analysis of conch shell sound**

Sound from some conch shells was received with microphone and analysed by computer using the sound technology FFT software (Spectra Plus). The software was tested with standard frequency from wave generator and tuning fork. Spectrum, spectrogram, 3D surface graph of spectrum, time series and phase graphs are presented in Figures 6–17. The software records, along with the primary plot parameters, i.e. peak frequency and amplitude, a few associated quantities like total harmonic distortion (THD), inter modular distortion (IMD), THD + noise and signal-to-noise ratio (SNR). THD is the ratio of harmonic power to fundamental power and IMD is the measure of distortion caused by mixing two tones.

**Spectrum**

Spectra of sound of five conch shell samples are shown in Figures 6 and 12–15. Detailed data including radius of
conch shell, fundamental frequency and lock-in frequency are presented in Table 2. From the data it is found that smaller the radius, higher the frequency. Lock-in frequency is one of the important aspects of lip-driven wind instruments. The spectra show sharp lock-in frequency having several harmonics up to 10 kHz. The second harmonic is exactly two times the lock-in frequency and subsequent harmonics are integral multiple of lock-in frequency. The harmonics exhibits gradual decrease in amplitude with increasing order. All spectra are sharp, having the band width between 1 and 2 Hz. Corresponding quality factor is above 150. Total harmonic distortion rises proportionately with the radius of conch shell and lies within 20. The inter modular distortion (IMD) for all samples of conch shells is within 4–6%.

**Spectrogram, 3D-display and time series graph**

The spectrogram view of conch shell displays the spectral data over time with amplitude in colour scale. They show only four prominent lines, all sharp and clear. The first one is with relatively high amplitude and other three are lesser than the first one. 3D views display spectral data over time. Here frequency is shown along x-axis and time along y-axis. Time series presents the raw audio data of amplitude over time (Figures 7–10).

![Spectrogram view of spectrum of conch sound (sample 1).](image)

![Spectrogram view of spectrum of conch sound (sample 2).](image)

![Spectrogram view of spectrum of conch sound (sample 3).](image)

![Spectrogram view of spectrum of conch sound (sample 4).](image)

Although the spectrum graphs are of prime relevance for our study of conch acoustics, the other allied graphs
Table 1. Calculated and observed lock-in frequency

<table>
<thead>
<tr>
<th>Calculated fundamental frequency (Hz)</th>
<th>Lock-in frequency at 3rd harmonic</th>
<th>Lock-in frequency at 5th harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated</td>
<td>Observed</td>
</tr>
<tr>
<td>Conch-1</td>
<td>124.85</td>
<td>374.55</td>
</tr>
<tr>
<td>Conch-2</td>
<td>152.05</td>
<td>396.175</td>
</tr>
<tr>
<td>Conch-3</td>
<td>152.6</td>
<td>457.8</td>
</tr>
</tbody>
</table>

Table 2. Calculated and observed frequency with bandwidth and quality factor of different samples of conch shell

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>Bandwidth (Hz)</th>
<th>Quality factor</th>
<th>Fundamental frequency (Hz)</th>
<th>Observed frequency (Hz)</th>
<th>Calculated frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conch-1</td>
<td>5.5</td>
<td>2.3</td>
<td>162.074</td>
<td>124.85</td>
<td>372.79</td>
</tr>
<tr>
<td>Conch-2</td>
<td>5.2</td>
<td>2.3</td>
<td>174.947</td>
<td>132.05</td>
<td>402.4</td>
</tr>
<tr>
<td>Conch-3</td>
<td>4.5</td>
<td>2.7</td>
<td>169.464</td>
<td>152.6</td>
<td>457.58</td>
</tr>
<tr>
<td>Conch-4</td>
<td>4</td>
<td>2.199</td>
<td>236.189</td>
<td>171.59</td>
<td>519.49</td>
</tr>
<tr>
<td>Conch-5</td>
<td>3.6</td>
<td>2.699</td>
<td>217.379</td>
<td>190.66</td>
<td>586.78</td>
</tr>
</tbody>
</table>

Figure 14. Spectrum view of conch sound (sample 5).

Figure 15. Spectrum view of conch sound (sample 1), with high blowing pressure.

However, the fundamental frequency is computed by using the frequency formula to be given in the next section. Table 1 shows the observed lock-in frequencies for three conch samples corresponding to different blowing pressures with the computed frequency for each case.

Generation of notes in conch shell

When uncoiled and straightened in imagination, the conch cavity spiral approximates to a conical horn. As regular curvature hardly affects the mechanism of generation of notes in wind instruments, we visualize the sound production mechanism in conch shells in light of that in conical horn. The musical acoustics of conical horn has been dealt in detail by Ayer and co-authors\textsuperscript{19}. The relevant geometry is depicted in Figure 18.

The linear wave equation for acoustic pressure $p$ is given by

$$\nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0. \quad (12)$$

For a system with spherical symmetry, which the cone conforms to, the first term involving the Laplacian operator assumes the radial form,

$$\nabla^2 p = \frac{1}{\rho^2} \frac{\partial}{\partial \rho} \left( \rho^2 \frac{\partial p}{\partial \rho} \right) = \frac{1}{\rho} \frac{\partial^2}{\partial \rho^2} (\rho p).$$

Since $\rho$ and $t$ are independent variables, the wave equation turns out to be,

$$\frac{\partial^2}{\partial \rho^2} (\rho p) - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} (\rho p) = 0.$$
of the solution in the form, $e^{i\omega t}$, the final wave equation settles to read,

$$\frac{\partial^2 p}{\partial \rho^2} - \frac{\partial^2 p}{c^2 \partial t^2} = 0,$$

(15)

which allows the general solution,

$$p = \frac{e^{i k \rho}}{\rho},$$

(16)

where $k = \omega/c$. These are the well-known spherical Hankel functions or spherical Bessel functions of third kind and zero order. Applying the boundary condition that there exists a pressure node at the wider open end of the cone, the solution comes to be

$$p(\rho) = [\sin k(\rho - \rho_3)]/\rho.$$  

(17)

Of course, for an open–open frustum, position of nodes at both ends $\rho = \rho_1$ and $\rho = \rho_2$, leads to the frequency relation

$$f_n = \frac{nc}{2l},$$

(18)

where the length of cone $l = \rho_2 - \rho_3$. This case is similar to the formation of standing waves in an open–open pipe.

But a conical horn or any wind instrument blown by attaching mouth to one of its open ends is no more an open–open system. It is a matter of common experience and dealt by LoPresto\textsuperscript{20}, that in such case the player’s lips cause a pressure antinode at the end to which the player blows, and as a consequence, that end may be considered closed. Therefore, one may expect only odd harmonics of quarter wavelength of sound to be present in the resonant system. Ayers\textit{ et al.}\textsuperscript{19} came to the same conclusion, on pictorial demonstration of standing wave formation in complete cones and the effect of consequent truncations at the nearest antinode to the apex. Of course, the same conclusion may be easily drawn by considering the pressure antinode at the closed end, for which $\sin(k(\rho_1 - \rho_2)) = \pm 1$, which demands

$$k(\rho_1 - \rho_2) = (2n + 1)\frac{\pi}{2} \text{ or } f_n = (2n + 1)\frac{c}{4l}.$$  

(19)

However, the case of conch shell, as a conical horn has the effective length $l = 4\pi R$, so

$$f_n = (2n + 1)\frac{c}{16\pi R}.$$  

(20)

Our observation of the fundamental frequency and lock-in frequencies along with complete values of the funda-
ments according to eq. (20) have been presented in Table 2. It may be noted that the agreement of the theory with experiment is good. Here the velocity of sound in air has been assumed: \( c = 345 \text{ m/s} \).

It is worth pointing out here that Bhat\(^{4,5,7}\) has mentioned correctly that the conch shell cavity is closed at the blowing end and opens at the mouth. But he states that the system can support the standing waves having 1/2, 3/2, 5/2, 7/2 wavelengths, which is not true as per conch sound spectrum and basic theory of organ pipes. Further, it may be noticed from the spectra that the integral multiple harmonics of the locked-in mode appear prominently and maintain an exponentially decreasing pattern. This is contradictory to the observation of Bhat, who noted that the odd harmonics of the first fundamental exhibit exponential decreasing pattern, whereas the even harmonics do show no definite pattern.

To confirm such behaviour of the shell, we studied the sound spectra due to lip-driven cylindrical pipes blown by human mouth. An exactly analogous behaviour in the spectra has been noted, with all distinct features of locking at odd integral harmonics of the fundamental and presence of all integral harmonics of the locked-in frequency. Now an explanation of such behaviour of the conch shell and the tube is in order. The only possible explanation is that the lip-driven mouth blown wind instruments do simultaneously behave as closed-open and open-open system, after the locking-in, because the lip closes and opens with sinusoidal vibration\(^{10,13,15}\). This gives rise to sinusoidal pressure variation at the blowing end and the tube closes and opens sinusoidally with frequency of lip-vibration. Such frequency being high enough, the modes build themselves in both options as persistent modes appear in recording.

**Conclusion**

In this paper, we have presented some results of our study on acoustic behaviour of conch shell. Usually the shell is blown by lip-vibration on attaching the mouth to the cut at the apex of the conch cavity. We have presented here the mechanism of sounding in the shell in light of familiar understanding of wind instruments. The sound spectra from five conch samples are presented and the skipping of fundamental resonant frequency to higher modes with higher blowing amplitude is pointed out. The phenomenon well known in acoustics as ‘mode-locking’ is indicated and it is emphasized that the sound spectrum shows the presence of all integral harmonics of the locked-in odd multiple frequency of first fundamental. The theory of generation of note in the shell is realized in light of that of conical horn, where the effective length of the cavity is derived on basis of conch geometry, which is pointed out to be an Archimedes’ spiral. It is to be noted that the frequency relation so obtained agrees fairly well with the observed spectra.

The results of the phenomenon of mode locking are being presented in a separate publication. Similarly, a more realistic theory of conch shell sound is being prepared for a subsequent publication.

It will not be out of place to mention here that the conch shell as a musical instrument and a trumpet has been in use, in different lands and civilizations throughout the ages. It is closely connected with human culture. So, the understanding of its acoustics has socio-cultural relevance, apart from being purely scientific.

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1. Clark, M., Some basic of conch shell trumpets and some very basics on how to make them, 1996; [www.furious.com](http://www.furious.com)
2. Encyclopedia Encarta.

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**Acknowledgements.** We thank P. S. Naik of the University of Hong Kong for generous help in providing information, literature and technical know-how wherever needed during the course of this work.