17. „Didgeridoo”

The ‘didgeridoo’ is a simple wind instrument traditionally made by the Australian aborigines from a hollowed-out log. It is, however, a remarkable instrument because of the wide variety of timbres that it produces. Investigate the nature of the sounds that can be produced and how they are formed.
What is a „didgeridoo”?

Scheme of didgeridoo:

- Instrument’s interior is chamfered by termites;
- Sometimes irregular shape of the pipe (twisted, conical);
- Beeswax mouthpiece

What is responsible for interesting and remarkable sound of didgeridoo?

- Air from lungs
- Vocal folds
- Lips
- Throat
- Didgeridoo
What is responsible for the sound of didgeridoo?

1st case: smooth interior, straight didj
- sound waves modified by the instrument
- sound waves created with player’s vocal folds and throat
- motion of player’s lips, tongue and cheeks – sounding mechanism
- lip valve – vibration analysis
- Changing the volume and shape of a resonant cavity (throat) by cheeks and tongue

2nd case: smooth interior, widened didj

3rd case: rough interior

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sound waves amplified by the instrument
Didgeridoo – pipe of an opened or closed end?

We can suppose, that didgeridoo is a tube closed on one end by lips – in that case standing wave will appear when we raise oscillations of frequencies defined by the equation:

\[ f = \frac{(2n + 1)c}{4(L + \Delta l)} \quad (n = 0, 1, 2, 3 \ldots), \]

After deeper analysis, we can say, that it is not completely sealed by mouth – other harmonic frequencies (of course they will be weaker resonated) will appear – they are defined by equation:

\[ f_{\lambda/2} = \frac{nc}{2(L + \Delta l)} \quad (n = 1, 2, 3 \ldots), \]

- \( c \) – sound velocity in air,
- \( \Delta l = \frac{8a}{3\pi} \) - entry correction
- \( L \) – resonator’s length,
- \( a \) – pipe radius

\[ \Delta l = \frac{8a}{3\pi} \]
White noise transmission through didgeridoo with smooth interior

Amplitude [dB] vs. Frequency [Hz] graph

1 : 3 : 5 : 7 ....
Long, straight PCV pipe:

\[ L = 1.7 \text{ m} \quad \text{d}_{\text{OUT}} = 4.4 \text{ cm} \quad \text{d}_{\text{IN}} = 5 \text{ cm} \]
Spectral view of sound

Irregular areas => effects of play (changes of cheeks shape, position of tongue etc.)

Horizontal lines => harmonic
Structure of sound

(x axis – time [s], y axis – freq. [Hz])
Frequency characteristic

Amplitude [dB] vs. Frequency [Hz] graph for PCV pipe

Linear scale

Logarithmic scale
Theoretical and experimental harmonic frequencies

Theoretical values calculated from equation:

\[ f_n = \frac{(2n+1)c}{4(L + \frac{8a}{3\pi})} \quad (n = 0, 1, 2, 3 \ldots) \]
Didgeridoo - experiments
Frequency characteristic - 1

Amplitude [dB] vs. Frequency [Hz] graph for 1st play

Linear scale

Base freq. 73,5 Hz

Logarithmic scale

1 : 3,1 : 5 : 7,1 : 8,9
What is responsible for the sound of didjeridu?

sound waves amplified by the instrument

2nd case: smooth interior, widened didj
Didgeridoo vs Bessel’s horn

A better assumption for didgeridoo, which sometimes widens on the end, will be a Bessel’s horn. In that horn resonant frequencies are equal:

\[
f = \frac{c}{4(L + \Delta l)} \left[ (2n - 1) + \beta \sqrt{\alpha(\alpha + 1)} \right] \quad (n = 0, 1, 2, 3, \ldots)
\]

\[\Delta a = bx^{-\alpha}\]

\(\alpha\) – enlargement coefficient,
\(x\) – distance from the beginning.
\(b\) – determines the radius of the instrument.
\(\beta\) – coefficient equal 0,6 for \(\alpha < 0,8\) and 0,7 for \(\alpha > 0,8\).
Didgeridoo vs Bessel’s horn

\[ f = \frac{c}{4(L + \Delta l)} \left[ (2n - 1) + \beta \sqrt{\alpha(\alpha + 1)} \right] \quad (n = 0, 1, 2, 3, \ldots) \]

In case of typical widening Bessel’s equation is much simpler:

\[ for \ \alpha = 1: \quad f \approx \frac{nc}{2(L + \Delta l)} \]

This theoretical model is working also for not widening didgeridoo:

\[ for \ \alpha = 0: \quad f = \frac{(2n + 1)c}{4(L + \Delta l)} \]
What is responsible for the sound of didjeridu?

- Sound waves amplified by the instrument
- 3rd case: rough interior
Didgeridoo - experiments

Museum of Asia and Pacific Ocean in Warsaw
The chamfered interior is rough. There are even some 1,5 cm posts.
Rough interior – Termites problem

Amplitude [dB] vs. Frequency [Hz] graph

ROUGH

Irregular part caused by rough interior

SMOOTH

the same as in didji with smooth interior
Rough interior – Termites problem

Base freq.: 90 Hz

Amplitude [dB] vs. Frequency [Hz] graph

1 : 3 : 5, 2 : 7 : 8, 8
What is responsible for the sound of didjeridu?

- Motion of player’s lips, tongue, and cheeks – sounding mechanism
- Lip valve – vibration analysis
- Changing the volume and shape of a resonant cavity (throat) by cheeks and tongue
Sounding mechanism

Because, the lip valve operates at very nearly its resonance frequency, the motion of the player's lips is nearly sinusoidal:

\[ x = a_0 + a \cdot \sin 2\pi f \]

\[ U = \gamma x(p_0 - p)^2 \]

\( a, a_0 \) – determines the amplitude
\( p_0 \) – steady blowing pressure
\( p \) – pressure inside the instrument
\( x \) – the lip opening.
\( f \) – frequency of the oscillations.
\( U \) – volume flow though the lip valve

Referring to: *The Didjeridu*, Neville Fletcher, Acoustics Australia, Vol 24
After solving these equations we obtain:

\[ U \approx \frac{p_0}{R} - \frac{p_0^2}{R^3 \left( a_0 + a \cdot \sin 2\pi ft \right)^2} \]

R - acoustic resistance of the instrument tube

The volume flow graphs vs. time for different amplitudes of lips vibration:
Sounding mechanism

The resonance frequency of this resonator can be estimated by whistle frequency analysis (the whistle frequency is the resonance frequency of the Helmholtz resonator).

Achieved range – differs from about 500 Hz to about 3 kHz (because of changing the mouth volume with the tongue and cheeks)
What is responsible for the sound of didgeridoo?

- **sound waves modified by the instrument**
  - **1st case:** smooth interior, straight didj

- **motion of player’s lips, tongue and cheeks – sounding mechanism**
  - **lip valve – vibration analysis**
  - **sound waves created with player’s vocal folds and throat**
  - **Changing the volume and shape of a resonant cavity (throat) by cheeks and tongue**

- **2nd case:** smooth interior, widened didj

- **3rd case:** rough interior
Overall explanation of frequency characteristic
Conclusions

- The best assumption is to treat Didgeridoo as a Bessel’s horn type of resonator.

- A big variety of sounds produced is caused by composition of resonating properties of didjeridu and mouth, cavity and vocal folds usage.

The didjeridu’s sound is affected by:

- Length of the instrument;
- Thickness of the instrument;
- Its interior roughness;
- Shape;
- medium properties;
Literature

N.H. Fletcher, T.D. Rossing  The Physics of musical instruments
http://www.didjshop.com/physicsDidj.html

Used software
Cool Edit 2000
Audio Analyzer 2000
Realtime Analyzer Light 2.0.0.1
Easy Video Capture
‘Ligawka’ / ‘Trombita’ – Polish ‘didgeridoo’
Formation of sound in a didgeridoo

\( \lambda = 4L \quad f_0 = \frac{v}{\lambda} = \frac{v}{4L} \)

\( \lambda = \frac{4}{3}L \quad f = \frac{3v}{4L} = 3f_0 \)

\( \lambda = \frac{4}{5}L \quad f = \frac{5v}{4L} = 5f_0 \)

\( \lambda \) – wavelength, 
\( f \) – resonance frequency

\( v \) – sound velocity

Antinode of pressure

Node of pressure
Overall explanation of frequency characteristic

Fundamental frequency:

0.445 kHz

And now, the frequency analysis is understandable for us
### Harmonic components

<table>
<thead>
<tr>
<th>Harmonic components</th>
<th>Measured value of frequency</th>
<th>Theoretical value of frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>54 Hz</td>
<td>49.9 Hz</td>
</tr>
<tr>
<td>1st harmonic</td>
<td>148 Hz</td>
<td>143.7 Hz</td>
</tr>
<tr>
<td>2nd harmonic</td>
<td>255 Hz</td>
<td>239.5 Hz</td>
</tr>
<tr>
<td>3rd harmonic</td>
<td>340 Hz</td>
<td>335.2 Hz</td>
</tr>
<tr>
<td>4th harmonic</td>
<td>435 Hz</td>
<td>431.2 Hz</td>
</tr>
</tbody>
</table>

Theoretical values calculated from equation:

\[
f_n = \frac{(2n + 1)c}{4(L + \frac{8a}{3\pi})} \quad (n = 0, 1, 2, 3 \ldots)
\]
Waveform analysis

Amplitude [dB] vs time [s] graph for PCV pipe

norm
Waveform analysis

Amplitude [dB] vs time [s] graph for PCV pipe
Wavedorm analysis

Amplitude [dB] vs time [s] graph for PE pipe
Frequency characteristic

Amplitude [dB] vs. Frequency [Hz] graph for PE pipe
Frequency characteristic - 2

Amplitude [dB] vs. Frequency [Hz] graph for 2nd play

Linear scale

Base freq. 72 Hz

Logarithmic scale

1 : 3 : 5.05 : 7.05 : 9
Spectral view of sound

(x axis – time [s], y axis – freq. [Hz])
Teoretical model of didgeridoo

To simplify the initial analyse of the problem let’s consider a nonconical didgeridoo: a pipe of length $l$ and radius $r$

In that case we can describe formation of sounds in a pipe closed on one end
<table>
<thead>
<tr>
<th>PE/PCV pipe</th>
<th>Didgeridoo</th>
</tr>
</thead>
<tbody>
<tr>
<td>✨ little bit different timbre of produced sound (syntetic materials resonates slightly different than eucalyptus wood);</td>
<td>✨ instrument’s interir is chamfered by white ants (must be considered separately);</td>
</tr>
<tr>
<td>✨ smooth interior of the tube;</td>
<td>✨ nonregular shape of the pipe (twisted, conical);</td>
</tr>
<tr>
<td>✨ no mouthpiece</td>
<td>✨ beeswax mouthpiece</td>
</tr>
</tbody>
</table>
PE/PCV pipes - experiments

Short, curved PE pipe:

L = 0.85 m
\[ d_{wew} = 3.2 \text{ cm} \]
\[ d_{zew} = 4 \text{ cm} \]

Long, straight PCV pipe:

L = 1.7 m
\[ d_{wew} = 4.4 \text{ cm} \]
\[ d_{zew} = 5 \text{ cm} \]
Temperature influence on didgeridoo’s sound

All our calculations contained the sound velocity in dry air of temp. 20 degrees. Let’s see what will happen in other temperatures:

- The main influence on the sound velocity have the temperature, so we can neglect the humidity influence;

- for given temperature we can estimate sound velocity from equation:

\[ c = 331.6 + 0.6 \times t \]

\( c = \) sound velocity [m/s]
\( t = \) temperature [°C]

That means, that in case of temperature difference 20 °C frequency of the 1.3 m length instrument increase about 3.4%, (quarter of the musical key)
PE pipe – experiment results

Theoretical values calculated from equation:

\[ f_n = \frac{(2n + 1)c}{4(L + \frac{8a}{3\pi})} \quad (n = 0, 1, 2, 3 \ldots) \]

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</thead>
<tbody>
<tr>
<td>Base</td>
<td>96 Hz</td>
<td>94,9 Hz</td>
</tr>
<tr>
<td>1st harmonic</td>
<td>287 Hz</td>
<td>284,7 Hz</td>
</tr>
<tr>
<td>2nd harmonic</td>
<td>477 Hz</td>
<td>474,5 Hz</td>
</tr>
<tr>
<td>3rd harmonic</td>
<td>670 Hz</td>
<td>664,3 Hz</td>
</tr>
<tr>
<td>4th harmonic</td>
<td>862 Hz</td>
<td>854,2 Hz</td>
</tr>
</tbody>
</table>
This expression cannot be taken too literally in the limit as a $\mathcal{O}_a0$, but the shape of the flow waveform is essentially as shown in Fig. 3. Clearly such a waveform has many harmonics, and this accounts for the rich sound of the didjeridu, and of lip-excited instruments in general. The relative strengths of the upper harmonics are not well predicted by this simple flow waveform, however, for several reasons. The flow waveform gives a spectral envelope which is initially nearly constant and then declines at about 12 dB/octave. The assumption that $R$ is constant, however, is not very good, and this resistance is less for the upper harmonics than for the resonant fundamental, except for accidental near-coincidences with higher horn resonances. Finally, the transfer function between flow spectrum and acoustic radiation rises at 6 dB/octave at low frequencies and is then flat above about 3 kHz for the didjeridu horn. Despite these reservations, however, this simple treatment does give a fair idea of spectral behaviour.