Sound Generation, Amplification and Absorption by Air Flow Through Waveguide With Periodically Corrugated Boundary

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The results of extensive experiments on the generation, amplification and absorption of sound in a corrugated waveguide with a flow are presented. In the presence of air flow in the corrugated pipe the tone or multitone noise is generated. This sound looks like the flute one and at first sight it is not connected with the pipe size - the pipe length could be a few meters or a half-meter, but the main frequency of pipe noise is located in the same region. The measured spectrum show that the noise is a collection of closely located peaks distributed in a narrow band region with central frequency \( f_j \propto (0.45 \pm 0.6) \frac{U}{l} \) (\( U \) - flow velocity, \( l \) - period of corrugation). The regions of closely located frequencies are repeated in high frequency domain and the mean frequency of the next domains are approximately \( f_n \propto n \cdot f_j \) (\( n \) - integer). The noise mechanism is very stable and acoustic output at the duct outlet is very high. When external sound field is introduced to the corrugated tube with flow, the strong sound decay by flow is observed at frequencies below \( 0.4 \frac{U}{l} \). Transition from decay through amplification to generation of sound is investigated quantitatively. Some theoretical models of described phenomena will be present. The comparison theoretical and experimental results will be done.

In the presence of air flow in the corrugated pipe the tone or multitone sound is generated [1-4]. The sound mechanism is very stable and acoustic output at the duct outlet is very high. When passing the air flow through the tube with smooth wall the sound spectrum does not change, i.e. for the smooth tube the absorption sound by flow and generation is not observed. In spite of the fact that many researchers have investigated the effect of sound generation in the corrugated tube due to flow the mechanism of this phenomenon is not clear until now.

We carried out new experimental researches of air-acoustical interactions in the corrugated tubes. The dependence of sound generation on the tube geometry and the investigation of the coefficient of sound amplification under forced oscillations were general directions of our researches.

The experimental set-up is shown in the Figure 1. The corrugated tube 3 is connected with the compressor 1 through the plenum 2. The flow velocity is regulated by change of voltage across the compressor 1 using laboratory autotransformer 8. Mean flow velocity is estimated by means of Bernoulli’s formula \( U = \sqrt{2\delta P / \rho} \) (\( \rho \) - air density), the pressure \( \delta P \) at the outlet of corrugated tube is measured by Pitot tube 5. The loud speaker 6 is placed inside the receiver 2. The sound signal of the loud speaker 6 is given by the audio output of PC 7. The microphone 4 is placed at the distance of 0.3m from tube outlet. The signal from the microphone 4 is passed to the sound input of PC 7. For detailed research of sound absorption due to air flow the horn 9 (spatial angle is equal to 0.4) was joined to outlet of corrugated tube. The horn was absent at other measurements.

Figure 1: 1 - compressor, 2 - plenum, 3 – corrugated tube, 4 - microphone, 5 – Pitot tube, 6 – loud speaker, 7 - PC, 8 - LATR, 9 - horn
Tubes with periodical irregularities on the walls have been made in the following way. The wire (diameter 1.4mm) was wined with constant pitch on the cylinder (diameter 7.2mm). A few of paper layers were glued on top of the wire and after that the inner cylinder was taken out. Five tubes with different pitch of winding and one control tube have been made (see Table 1). The research of tubes with different corrugated pitch shows the natural frequency increases when pitch of corrugated increases. The stable sound generation is observed only with tubes I.3, I.4 and I.5 (the tube I.6 “sings” in small region around its $U_{\text{min}}$). Therefore the sound generation exists in small region of the corrugation pitch. The sound generation is absent when corrugation pitch is too short or too big. Minimum flow velocity at which auto generation is beginning is presented in the Table 1. Furthermore the decrease of the corrugation pitch results in the simplification of the frequency conversion, the state when two or more frequencies are generated becomes unstable.

Strouhal number of tubes I.3, I.4 and I.5 is approximately the same. Its mean values equal respectively 0.52, 0.56, 0.58 (Figure2). The sound generation is observed at different frequencies for tubes with different corrugation pitch under the same velocity (Figure3). For example, when flow velocity is equal to 12mps the spectrum of the tubes II.3 has one peak at the frequency 1976Hz, the spectrum of the tubes II.4 – at the frequency 1620Hz, but we see two peaks (1264Hz and 1566Hz) in the spectrum of the tube II.5.

Tubes with different lengths but equal corrugation have been studied as well (Table 2). Mean value of Strouhal number is equal 0.5 for all tubes. It should be noted decrease of Strouhal number when flow velocity increases. For example, for tube II.4 when flow velocity is equal to 4.8mps Strouhal number is 0.49 but when flow velocity is equal to 28mps Strouhal number is 0.38. When a tube length is larger sound is generated easier. When a tube length is very small the sound generation disappears (for example, for the tube II.6 the sound generation is observed only at one velocity, and when the tube length is smaller the sound generation is absent).

Self-oscillations described above come under condition that flow induced sound amplification exceeds viscous and thermal absorption on the tube walls and outlet radiation losses. More detailed research of the flow induced sound amplification has been carried out under the condition of forced oscillations. The external sound source was the loud speaker 6 (Figure1). To prevent

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**Table 1: Different corrugated pitch tubes: internal diameter - 7,2mm, wire diameter – 1,4mm**

<table>
<thead>
<tr>
<th>Number</th>
<th>I.1</th>
<th>I.2</th>
<th>I.3</th>
<th>I.4</th>
<th>I.5</th>
<th>I.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length , sm</td>
<td>37,8</td>
<td>38,4</td>
<td>37,9</td>
<td>38</td>
<td>38</td>
<td>37,9</td>
</tr>
<tr>
<td>Pitch, mm</td>
<td>No corr.</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Nature freq., Hz</td>
<td>431</td>
<td>385</td>
<td>395</td>
<td>395</td>
<td>398</td>
<td>401</td>
</tr>
<tr>
<td>$U_{\text{min}}$, mps</td>
<td>-</td>
<td>-</td>
<td>5,5</td>
<td>4,8</td>
<td>5,5</td>
<td>10,3</td>
</tr>
<tr>
<td>$f$, Hz</td>
<td>-</td>
<td>-</td>
<td>1159</td>
<td>766</td>
<td>766</td>
<td>1212</td>
</tr>
<tr>
<td>Mode</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

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**Table 2: Different length tubes: inner diameter – 1,7sm, corrugation pitch – 3mm, width of flute – 1,65mm, depth of flute – 1,5mm.**

<table>
<thead>
<tr>
<th>Number</th>
<th>II.1</th>
<th>II.2</th>
<th>II.3</th>
<th>II.4</th>
<th>II.5</th>
<th>II.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, m</td>
<td>2,5</td>
<td>1,25</td>
<td>0,83</td>
<td>0,42</td>
<td>0,21</td>
<td>0,1</td>
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<tr>
<td>Nature Freq., Hz</td>
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<td>196</td>
<td>387</td>
<td>734</td>
<td>1408</td>
</tr>
<tr>
<td>$U_{\text{min}}$, mps</td>
<td>6,2</td>
<td>4,8</td>
<td>3,9</td>
<td>4,8</td>
<td>4,8</td>
<td>7,8</td>
</tr>
<tr>
<td>$f$, Hz</td>
<td>862</td>
<td>795</td>
<td>789</td>
<td>778</td>
<td>739</td>
<td>1409</td>
</tr>
<tr>
<td>Mode</td>
<td>13</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
self-oscillations the horn 9 was joined to the tube outlet. The horn increases radiation losses. It turns out that self-oscillations were excluded at all. The radiated sound was detected by microphone 4 placed inside the horn at the distance 0.5m from the tube outlet.

The change of the sound spectrum generated by loud speaker, when increasing the flow velocity, is presented in the figure 4. When the flow is absent the spectrum 1 has typical view with the peaks on fundamental frequencies of the investigated tube. When the flow velocity is small, for instance 3.9 mps, only a little change in the area of low frequencies is observed. When the flow velocity is 7.8 mps (the curve 2) and 12.8 mps (the curve 3) peaks at high frequencies increase (figure 4b, without horn generation of sound would present at these frequencies), but at low frequencies height of peaks decrease more than 2 times (figure 4a). When increasing flow velocity to 17 mps (the curve 4), the range where the resonance peaks are increased moves to more high frequencies, but the decrease (i.d. absorption of sound) takes place now not only on low frequencies (figure 4b).

Efficiency of sound absorption can be labelled by ratio of maximum of resonance peak to adjacent minimum (in case of perfect absorption there are no standing waves, so ratio mentioned above is equal to 1). These ratios are presented on the Figure 5. Typical dependency on flow velocity is as followed: at low flow velocities the ratio remains the constant, then it increases, reaches maximum (in the range of velocities where the process of generation would be), and then it decreases and tends to the constant value.

Let’s consider a possible theoretical model of described phenomena. The flow about the cavity generates the great shear of longitudinal velocity, in the limit – tangential discontinuity (Figure 6).

The external sound pressure acts upon tangential discontinuity and excites hydrodynamic waves of displacement \( \xi(x,t) \). The propagation velocity of these waves is proportional to the flow velocity. These hydrodynamic waves can increase exponentially (like in the case of free tangential discontinuity). Hydrodynamic waves affect on the sound field due to two sources. Firstly, they produce volume velocity

\[
Q = \int (-i\omega)\xi(x)dx + \frac{1}{2} \xi(h)U^2 .
\]

The first term is excited by lateral displacement of the discontinuity. The second term describes medium penetration into the cavity at the end of tangential discontinuity. Secondly, hydrodynamic waves produce additional force acting from trailing cavity wall by means of alternate Bernoulli pressure along the axis of tube

\[
F = \frac{1}{2} \rho U^2 \xi(h) .
\]

These additional sources are introduced to the Euler’s equation and equation of continuity:

\[
\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} + \frac{\Pi \cdot h}{S \cdot (l + h)} - \frac{1}{\rho} F,
\]
\[
\frac{1}{c^2} \frac{\partial p}{\partial t} = -\rho \frac{\partial u}{\partial x} + \rho \frac{\Pi \cdot h}{S \cdot (l + h)} Q,
\]

\(u\) - oscillation velocity, \(p\) - sound pressure, \(\Pi\) - perimeter of the tube section, \(S\) - area of the tube section, \(h\) - width of the cavity. The wave equation for the sound pressure is:

\[
\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = \frac{\partial^2 p}{\partial x^2} + \rho \frac{\Pi}{S \cdot l} \frac{\partial Q}{\partial t} - \rho \frac{\Pi}{S \cdot l} \frac{\partial F}{\partial x} = 0,
\]

where third and fourth terms are some linear functional of the pressure. We can find for harmonic field with frequency \(\omega\):

\[
p'' + \left(\frac{\omega}{c}\right)^2 p + D_Q(-i\omega)p + D_F p'' = 0,
\]

where \(D_Q\) and \(D_F\) are some definite functions of the frequency, flow velocity and corrugation pitch. Their particular form is defined by a low of the tangential discontinuity oscillation \(\xi(x, \omega)\) under each cavity. An analytical method of finding \(\xi(x, \omega)\) for rectangular cavity has been given in [5]. After addition viscous and thermal absorption on the tube walls in the latest equation the approximate expression for the wave number may be obtained:

\[
k(\omega, U) = \frac{\omega}{c} + i \cdot D(\omega, l, U) + i \cdot \gamma(\omega),
\]

where \(\gamma(\omega)\) is viscous and thermal losses, \(D\) is a linear combination of \(D_Q\) and \(D_F\).

The searching of the function \(D(\omega, l, U)\) is the most important problem. This function is responsible for phenomena concerned with tube corrugation and flow presence.

We can note following regularity for \(D(\omega, l, U)\) from our experimental data. First, when flow velocity is small and frequency is rather high nothing changes. Therefore \(D(\omega, l, U) \rightarrow 0\) when \(U \rightarrow 0\) and \(\omega \rightarrow \infty\). Second, if the frequency is fixed when flow velocity increases the level of the resonance peak rises too (the increase is big for high frequency and small for low frequency). When flow velocity increases the level of the resonance peak decreases and it does not change when flow velocity increases more and more. Therefore \(D(\omega, l, U) \rightarrow \text{const}\) when \(U \rightarrow \infty\) and the frequency is fixed. Strouhal number \(\omega l/U\) knows to be the important non-dimensional parameter. Therefore the function \(D(\omega, l, U)\) ought to have evident dependence on Strouhal number.

As an example, we have sought this function in the form:

\[
D(\omega, l, U) = \frac{\rho U^2 \Pi}{S l} \cdot P_0 \cdot A \left(\frac{\omega l}{U}\right)^2 \times \left[\exp\left(\frac{B - \omega l}{U} - C \cdot \frac{\omega l}{U} + \Phi\right)\right],
\]

where \(P_0\) is pressure, \(A, B, C\) and \(\Phi\) are parameters. Results calculated by the last formula with \(A = 1, B = 1, C = 0.5\) and \(\Phi = 1.65\pi\) and experimental data is presented in the Figure 6.

![Figure 6: Comparison results calculated by theoretical equation and experimental data](image)

In spite of good correlation of theoretical estimations and experimental data more deep physical thought on the phenomenon should be necessary.

This research was partly supported by RFFR under grant 05-02-16086a, the scientific school of Prof. S.A. Rybak (NSH-1176.2003.2) and INTAS Ref. Nr. 04-80-7043.

**References**


