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4pMU4. Novel computer aided design of labial flue pipes

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A labial flue pipe is a well known tone generator, which is familiar and easily recognisable as the organ pipes seen in many concert halls and churches. However, the design and understanding of the sounding mechanism of such pipes is fraught with difficulty. Traditionally labial pipes are constructed from age-old lookup tables that are closely guarded intellectual secrets. This paper discusses a novel computer program that facilitates the design and construction of such labial flue pipes. The computer program allows almost all aspects of the labial flue pipes design to be varied, the resultant frequency is generated and in addition the Ising efficiency number is provided. Furthermore, a discussion is included related to the fact that even though an Ising number greater than 3 indicates that a pipe is overblown, the fundamental tone is still predominant. A comparison will also be made between a CFD simulation of the labial flue pipe jet mechanism and smoke trail plots typical of such analysis

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THE LABIAL FLUE PIPE

The labial flue pipe consists of three critically linked components, the Wind Sheet Thickness, the mouth and the cavity. These can all be seen in Figure 1. The Wind Sheet Thickness (WST) is a small slit through which a jet of air under pressure exits. This air jet travels across the mouth and impinges on the labium blade. The action of the air jet hitting the blade results in a standing wave being initiated in the pipe or cavity. This standing wave is the tone or voice of the pipe.

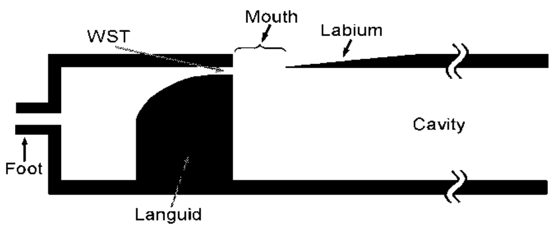

Figure 1 Elements of the Labial FLue Pipe

THE JET MECHANISM

Lord Rayleigh [1] (p. 376) said of the jet mechanism that it is of such importance "*...as to demand all the consideration that we can give*". Elder [2] says that it is of

"*....historic interest as one of the unsolved problems of classical physics*".

While it is not intended to undertake an investigation of the operation of the jet mechanism as it pertains to sound production in this document, a short review of some of the key investigators is probably in order. Investigators such as Elder [2], Rayleigh [1], Mercer [3], Jones [4], Außerlechner et al [5], Verge [6] amongst others provide a wealth of information on the operation of the jet mechanism.

One particular view on the operation of the sounding mechanism was that the cavity simply reinforces the sound generated by the friction caused by the jet '*playing*' with the lip of the labium, or as Elder [2] puts it the

"*coupling of edge-tone oscillation to a pipe resonator*".

Both Elder and Mercer [3] however advise caution in such a simple definition and quote the findings of Jones [4] who states that there are other effects at play than just edge tones.

However, regardless of the specifics of the tone generation, it cannot be denied that the operation of an air jet impinging on a blade edge coupled to a cavity results in a tone being produced. Using CFD simulation analysis of the jet mechanism the vortices that form as a result of the action of the jet impinging on the blade can be clearly seen. Figure 2 shows the simulated formation of these vortices with a counter clockwise rotation forming above the labium and a clockwise rotation below. These vortices replicate well with the typical smoke trails seen in works by Jeans [7] and Verge et al [6].

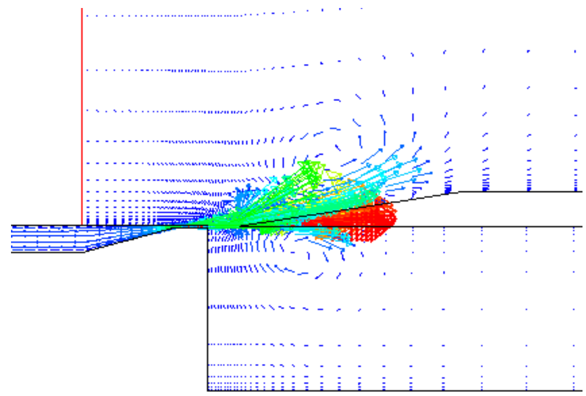

Figure 2 CFD simulation showing vortices forming

IDEAL PIPE RESONANT FREQUENCY

The main body of the labial flue pipe is a resonant cavity or pipe which is largely responsible in determining the resonant frequency of the system.

For a pipe open at one end, as shown in Figure 3 the resonant frequency is given in equation (1).

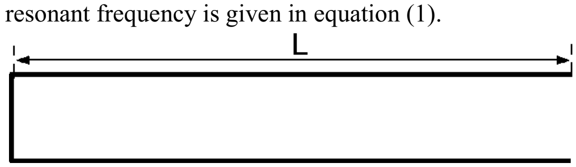

Figure 3 Open pipe

$$L_{eff} = \frac{a_0}{2 \cdot f} \qquad (1)$$

In the case where the pipe is closed or stopped at the end the resonant frequency is given by

$$L = \frac{a_0}{4 \cdot f} \qquad (2)$$

Equations (1) and (2) show an interesting difference, For the closed or stopped pipe the resonant frequency is given as being inversely proportional to the physical length, L of the cavity. However, in the case where the pipe is open, the resonant frequency is given as being inversely proportional to the acoustic or effective length, L_{eff} of the pipe.

This effective length, L_{eff} takes account of the fact that a pressure wave exiting the open pipe does not suddenly drop to ambient pressure at the exact end of the pipe. The pressure does indeed dissipate to ambient but not for some distance. This extra distance has the effect of making the pipe appear longer than its physical length. This extra length is termed 'End Correction'. This end-correction difference between physical length and effective length is shown in Figure 4.

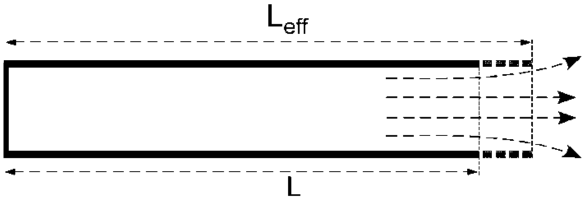

Figure 4 Open pipe effective or acoustic length

Rayleigh [1] credits Blaikley (1846 – 1936) with the experimental determination of the end correction of an unflanged pipe, which at the time was determined to be 0.576 times the radius of the pipe. Nowadays Kinsler [8] and others give the end correction for the cavity of an unflanged pipe as being

$$\Delta L_C = 0.6 \cdot r \tag{3}$$

Where r is the radius of the pipe cavity.
For more information on the end-correction phenomenon the reader is referred to the works of Kinsler [8], Fletcher et al [9], Rayleigh [1], Blackstock [10], and there are many others.

Returning to the labial flue pipe, unlike the plain pipe as shown in Figure 3 there are actually two openings… the mouth and the cavity, see Figure 1. This means that there are two end corrections to be accounted for.

Ising [11] gives end-correction equations for both the cavity (ΔL_C) and the mouth (ΔL_M) of a tubular pipe as:

$$\Delta L_C = 0.34\sqrt{S} \tag{4}$$

$$\Delta L_M = 0.73\frac{S}{\sqrt{S_M}} \tag{5}$$

Where S is the cross-sectional area of the pipe and S_M is the cross-sectional area of the mouth opening.
Equation (4) produces a similar result to Kinslers equation for the end correction given in equation (3).

Ising goes on the state that the overall effective or acoustic length of an open ended tubular labial flue pipe is:

$$L_{eff} = L + \Delta L_M + \Delta L_C \tag{6}$$

Obviously with a closed of stopped pipe there is only the end correction for the mouth, ΔL_M to be taken into account as ΔL_C ceases to exist.

However, for the experimental investigation at hand a square pipe was considered more usable because alterations and adjustments were considered to be easier to implement on a square pipe as opposed to a tubular one.

To this end Liljencrants [12] provides equation (7) that incorporates both cavity and mouth end corrections for a square pipe

$$L_{eff} = L + 0.3H + 0.8\frac{A}{\sqrt{B}} \tag{7}$$

Where A and B are is the cross-sectional areas of the pipe cavity and mouth opening respectively. These regions are clearly seen in Figure 5

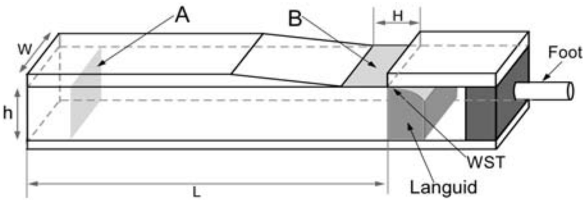

Figure 5 Square Labial Flue Pipe

EFFICIENCY OR ISING NUMBER

Before proceeding with the software design there is one important concept that needs to be addressed: Pipe efficiency. Pipe efficiency in this case means the purity of the tone produced by a particular pipe, in other words how many overtones are being produced for a specific set of conditions.

Ising [11], in a relatively obscure pipe manufacturers in-house magazine produced an equation describing the effects of the jet mechanism on the tone produced by the pipe. Isings equation was taken by Rioux [13] and adapted it to be more recognisable, although both equations produce the same result.
Riouxs' version of Isings equation incorporates Bernoulli and is given in equation (8),

$$I = \sqrt{\frac{2 \cdot \Delta P \cdot WST}{f^2 \cdot \rho \cdot H^3}} \tag{8}$$

Where WST (Wind Sheet Thickness) is the thickness of the jet, H is the length of the mouth, f is the frequency of interest in Hertz, ΔP is the difference in pressure in pascals between the foot and ambient, essentially the blowing pressure. ρ is the density of the medium (usually air). I is the efficiency or Ising number and ideally should be between 2 and 3, with 2 being most efficient and 3 being overblown.

SOFTWARE

The fundamentals are now in place to proceed with the development of a software based design system for the labial flue pipe.
Concentrating on the square pipe for the reasons already given, combining equation (1) and (7) yields the ideal oscillation frequency.

Unfortunately the calculation will produce a result regardless of whether such a result is physically possible. It is at this point that equation (8) becomes important as it indicates the efficiency or purity of the resultant tone. This will be revisited in a later section.

Figure 6 shows the front panel of the software suite with the theoretical analysis displayed for a 4cm long by 1cm square Labial Flue Pipe with a mouth and WST of 5mm and 0.3mm respectively under a differential pressure of 0.1 bar. Both the Ising and Reynolds numbers are clear visible.

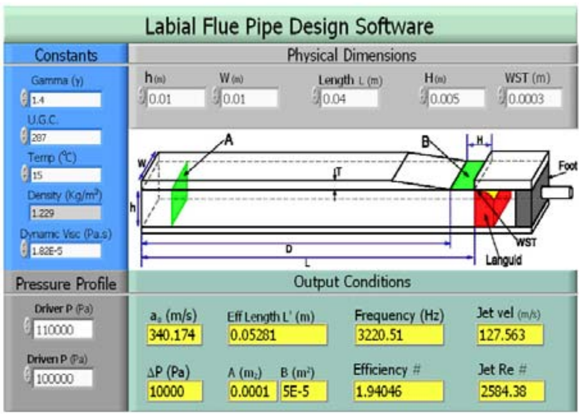

Figure 6 Design Software Front Panel

Figure 7 shows the labial flue pipe designed using the software and parameters displayed in Figure 6.

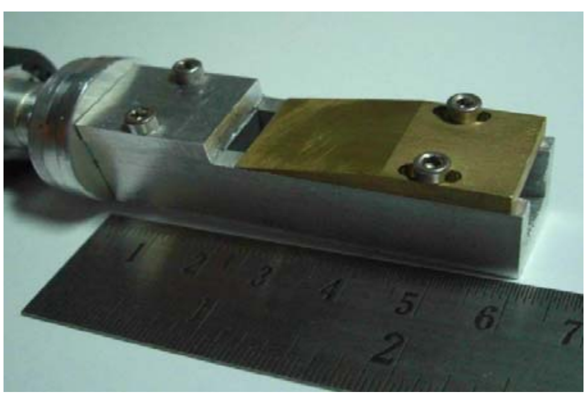

Figure 7 Labial Flue Pipe from Design Software

It is obvious from equation (8) and also from using the software shown in Figure 6 that with all else being equal, as ΔP increases the Ising value, I, will increase. It also appears that resonant frequency is independent of pressure differential. However Bhargava [14] reported that as driving pressure increased so too did the frequency response of the labial flue pipe such that with a approximately a 5x increase in driving pressure

"…the octave is clearly heard with the fundamental."

So therefore it would appear that somehow resonant frequency is being affected as driving pressure increases.

Using the labial pipe shown in Figure 7 the differential pressure across the pipe was varied with the resultant tone monitored by a professional class audio microphone that was sampled directly by a labview based data acquisition system.
Table 1 shows harmonic frequency and magnitude results for varying differential pressures. For clarity the table is limited to a differential pressure of 0.4bar.

Table 1 Harmonic Frequency, Magnitude and Ising # variations with changes in ΔP on a pipe with H=5mm, WST=0.3mm and L=4cm.

ΔP	0.1b	0.2b	0.3b	0.4b
Harmonic #	Measured Frequency (Hz)			
Fundamental	3270	3405	3420	3480
1st	5640	6800	6835	6955
2nd	9805	10200	10255	10435
3rd	13070	13600	13680	13910
Harmonic #	Measured Magnitude			
Fundamental	0.215	0.223	0.224	0.234
1st	0.010	0.039	0.095	0.105
2nd	0.010	0.015	0.021	0.075
3rd	0.004	0.010	0.002	0.009
	Ising #			
	1.9	2.7	3.4	3.9

What is interesting to note from Table 1 is that as the differential pressure increases the magnitude of the first harmonic increases. However, for the same change in pressure the magnitude of the fundamental frequency remains relatively constant. Also of note is the Ising or pipe efficiency number. Ideally the Ising number should be between 2 and 3, so from this data the optimum pressure range for this pipe would appear to be from just greater than 0.1bar to approximately 0.25bar.

Increasing the differential pressure beyond 1.45bar caused the pipe as given to choke, with the result that the tone produced by the pipe ceased.

Figure 8, Figure 9, Figure 10 and Figure 11 show time domain and frequency response plots from which the data in Table 1 was obtained.

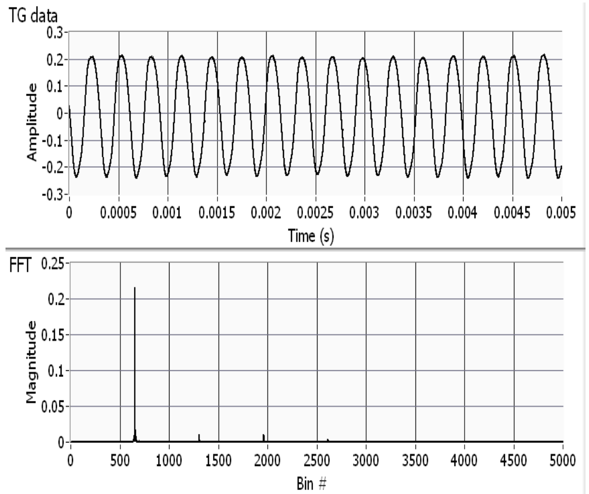

Figure 8 Time domain & FFT response to 0.1bar ΔP

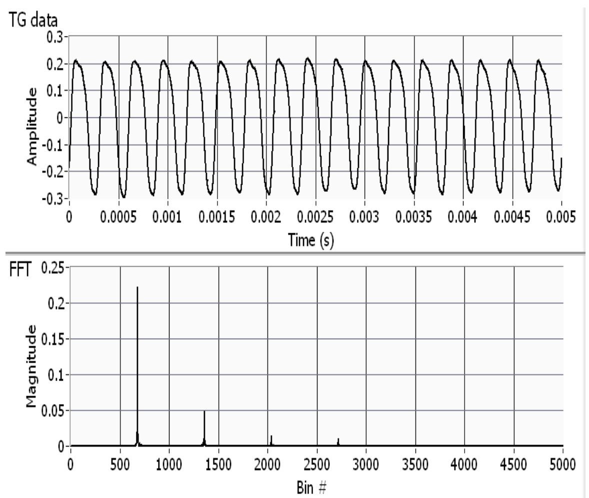

Figure 9 Time domain & FFT response to 0.2bar ΔP

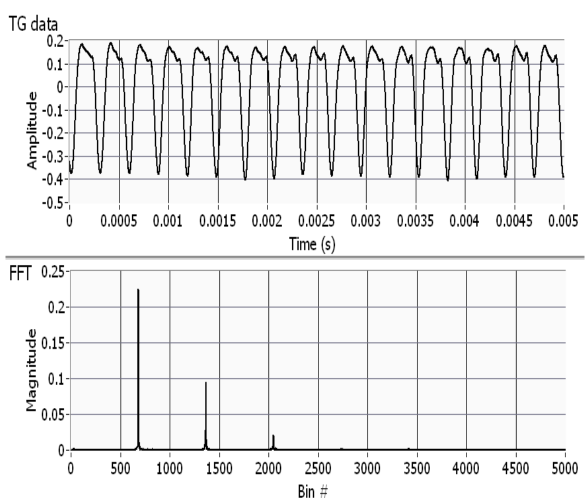

Figure 10 Time domain & FFT response to 0.3bar ΔP

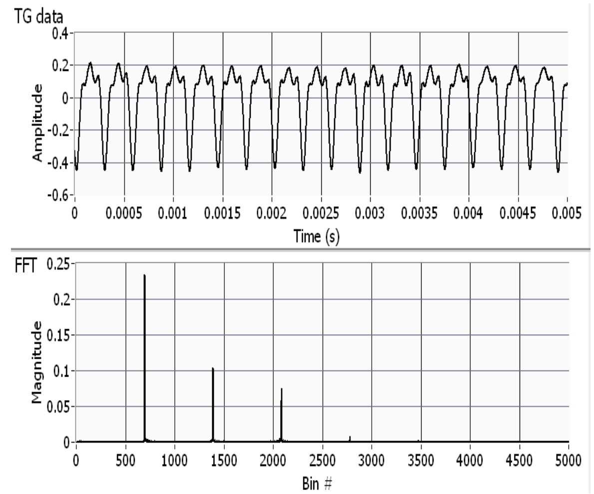

Figure 11 Time domain & FFT response to 0.4bar ΔP

Figure 8, Figure 9, Figure 10 and Figure 11 clearly show that the magnitude of the fundamental tone remains relatively static as pressure is varied but that the magnitude of the first harmonic increases substantially for the same pressure variation.

IDEAL V ACTUAL FREQUENCY

At the "design-for" pressure differential (0.1bar) the theoretical frequency is calculated to be 3320.5Hz. See Figure 6. During the experiment at 0.1bar differential the oscillation frequency was measured at 3270Hz, a difference of approximately 50Hz. Putting this into perspective in terms of 'cents', it is just over a quarter of a chromatic semitone difference.

$$1200 \cdot \frac{Log_{10}\left(\frac{3270}{3220.5}\right)}{Log_{10} 2} = 26.4¢ \qquad (9)$$

It should be noted that the change in frequency as differential pressure increased was not especially noticeable especially as the intensity of the oscillation for the given pipe measured at over 100dB.

Figure 12 Measured SPL for the given pipe

REYNOLDS VERSUS ISING

There is one parameter that has so far been ignored in the analysis: the WST air jet and its associated Reynolds number.
The Reynolds number, adjusted to incorporate Bernoulli is given in equation (10) and indicates whether a flow is considered laminar (<3600) or turbulent (>3600).

$$\mathrm{Re} = \frac{\sqrt{2 \cdot \rho \cdot \Delta P} \cdot WST}{\mu} \qquad (10)$$

Where μ is the dynamic viscosity of the medium.

Figure 13 shows a comparison between the Reynolds number and the Ising number for the pipe shown in Figure 7 but with various H and WST geometries (Length and cavity cross-sectional areas held constant). Each of the data points on the trend lines correspond to a different measured differential pressure for that particular geometry. In each case the differential pressure was increased until oscillation ceased.
For the condition where the mouth width, H was set to 9mm, regardless of the WST size, the pipe ceased oscillating before the minimum ideal Ising number, 2 could be achieved. For the case with H=3mm and WST = 0.3mm the pipe didn't start oscillating until after the maximum optimum Ising number, 3 had been exceeded.
It would appear from the data that in order to achieve an oscillation with the theoretical Ising number held between 2 and 3, the Reynolds number for the jet (WST) should not exceed approximately 7000.

In all cases the Reynolds number used is a theoretical one based on the dimensions of and conditions across the WST. Measurement of the actual Reynolds number of the jet was not undertaken.

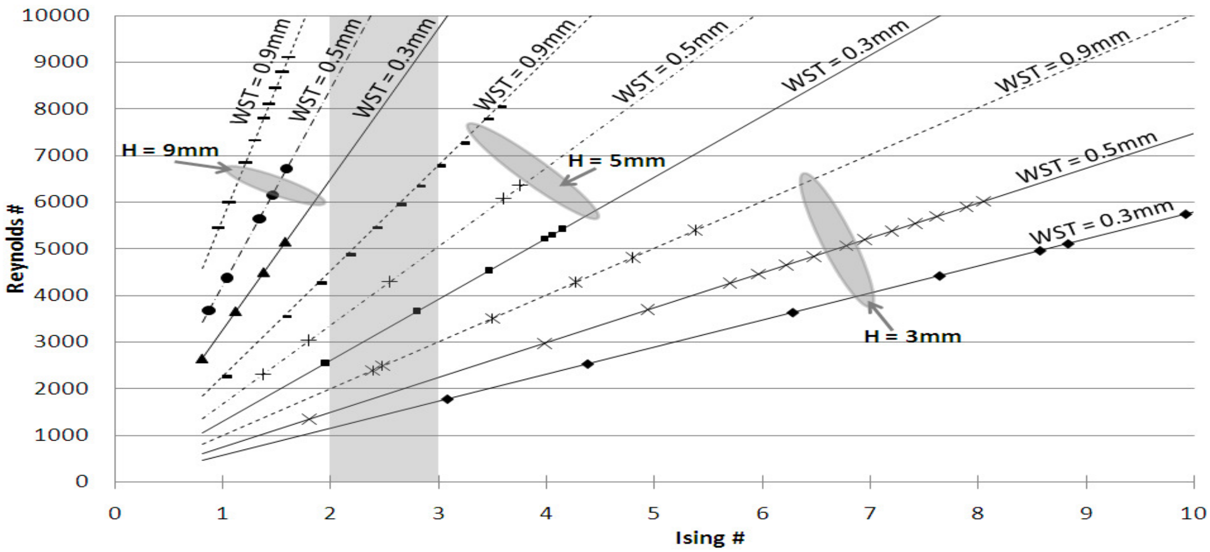

Figure 13 Reynolds versus Ising for different pipe geometries and varying differential pressures

CONCLUSION

The software as designed operates very well and provides a clear indication of the potential oscillation frequency and efficiency of, in this case a square labial flue pipe.
What is interesting is the apparent tie up between Ising and Reynolds for a given set of geometries: In some cases, as seen in Figure 13, even though the pipe oscillated in practice, the software for those conditions (ΔP, H, WST, L etc) indicated that the efficiency was outside the optimum Ising range of 2 to 3. Table 1 and Figures 8 – 11 show the effect of such a condition.
As a lower limit, from the data in Figure 13, the Reynolds number should be limited to approximately 1500.

From the data in Figure 13, for an optimal design with best efficiency (Ising ≈ 2), the calculated Reynolds number should be limited to less than 4000. If some efficiency can be sacrificed, i.e. Ising → 3, then the Reynolds number can be extended to approximately 6500.

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