# CHARACTERISTICS OF AIR-JETS IN FLUE ORGAN PIPES

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## 1. INTRODUCTION

During the course of constructing a pipe organ it is necessary to make small adjustments to each pipe individually to obtain the required tone and blend. This process of voicing the pipes essentially consists of altering the air flow, alignment and working length of the air-jet to give the required tone quality. The adjustments are critical and affect both the initial transient and the harmonic structure of the steady tone [1]. In order to study this process it is necessary to have an adequate description of the behaviour of the air-jet.

This paper presents a self-consistent set of measurements of the steady-state characteristics of a single acoustically perturbed air-jet. The results are compared with existing theoretical models and the various constants in these models calculated for the air-jet measured here. As far as possible the results are expressed in a concise form suitable for use in a calculation of the harmonic structure of the pipe tone.

## 2. MEASUREMENT PROCEDURE

### 2.1 Action of Air-jet

The steady tone of a flue organ pipe is sustained by the coupling of the air-jet to the resonating air-column in the pipe. The standing wave in the pipe sets up transverse waves on the air-jet which propagate along the jet, growing in amplitude until they reach the top of the pipe mouth. Here the jet swings alternately into and out of the pipe. Each time the jet swings into the pipe it imparts a pulse of volume velocity and momentum to the air inside, sustaining the standing wave and therefore the steady tone of the pipe [2].

### 2.2 Test Method

Figure 1 shows the air-jet rig. The supply pressure was 680 Pa (68 mm wg) except where stated, giving a mean inlet velocity of 24.9 m/s. The flue width was 1.2 mm for all the measurements and the excitation frequency was 118 Hz except for the measurements in Sect 3.4. A loudspeaker was used to perturb the jet rather than the jet being perturbed by the standing wave as in a real organ pipe. In place of the pipe resonator an anechoic duct was used to prevent a standing wave from forming. This arrangement decoupled the jet and so made it possible to vary the jet parameters (eg jet velocity) without changing the acoustic excitation.

A hot-wire anemometer was used to measure the speed of the air-jet at a given point. The sensitive part of the probe was a 2 mm strand of 5 μm tungsten ware. The bandwidth of the anemometer was in excess of 2kHz so the probe effectively measured instantaneous air speed at the chosen point. The anemometer signal indicated that the jet was turbulent over the whole range of measurement conditions.

## 3. AIR-JET MEASUREMENTS

### 3.1 Jet Centre Velocity

The equation for mean velocity at a point in a turbulent plane air-jet is developed in [3] and is given by:

$$V(x,y) = \alpha_1 V_i[\Delta y/x]^{1/2}\text{sech}^2(y/b(x))$$

where:

- x is — distance along jet from flue
- $y$ — distance across the plane of the jet (origin at flue)
- $V_i$ — jet inlet velocity (at flue), assumed uniform
- $\Delta y$ — flue width
- $b(x)$ — jet half-width, which is predicted to vary linearly with x ($b = \alpha_2 x$)
- $\alpha_1, \alpha_2$ — constants

The $\text{sech}^2(y/b(x))$ term gives the jet a bell-shaped profile which spreads out as b increases with distance from the flue.

Figure 2 shows measurements of $V(x,0)$ for a range of supply pressures and at various distances along the jet. The inlet velocity $V_i$ is obtained from measurements of volume flow divided by flue area. For this jet the value $\alpha_1 = 2.9$ gives a reasonable fit to the data.

### 3.2 Jet Profile

The velocity profile of the unperturbed jet was measured at various distances along the jet using the hot-wire anemometer. Figure 3 shows the profile at six positions along the jet for an inlet pressure of 715 Pa. Measurements were also made at other pressures.

The theoretical jet profile is $\text{sech}^2(y/b)$ where $b(x)$ is the jet half-width. For the measured profiles $b(x)$ is identified as half the width of the jet when the velocity is 0.42 of its peak value (since $y=b$ when $\text{sech}^2(y/b) = 0.42$). The resulting values of $b(x)$ for various x fall close to a straight line through the origin and a good fit to these results is given by

$$b(x) = 0.129x$$

This result compares with $b \sim 0.11x$ identified in [4] from measurements on a smaller jet. As noted in [4] the jet width shows no dependence on blowing pressure.

In Figure 4 three of the measured jet profiles have been normalised in peak value and plotted against $(y/b)$. The result shows that the measured jet profiles correspond closely in shape to the theoretical profile.

### 3.3 Phase Speed of Disturbances

Thwaites and Fletcher [3] found that the phase speed $u(x)$ of disturbances on a turbulent jet in a viscous fluid was proportional to the jet centre velocity $V(x,0)$ and that this linear relationship can be predicted from the theory. Thus

$$u = \alpha_3 V(x,0)$$

where $\alpha_3$ is a constant for a particular jet.

The loudspeaker provided the acoustic disturbance to set up transverse waves on the jet. The air speed and acoustic pressure were presented together on a dual-beam oscilloscope. To measure the phase speed of waves on the jet the hot-wire probe was positioned at the outermost extreme of jet movement . The delay between a peak in acoustic pressure and the velocity peak could then be measured directly from the oscilloscope. This delay was not of interest by itself, but a comparison of the delays for different heights up the jet was used to estimate the phase speed of disturbances on the jet.

The phase delay of waves on the jet is given by:

$$T(x) = \int_0^x (1/u)dx + T_0$$

where $T_0$ is a constant for given frequency and pipe geometry. Substitution for u gives:

$$T(x) = \frac{1}{\alpha_3 \alpha_1 V_j (\Delta y)^{1/2}} \int_0^x x^{1/2}\, dx + T_0$$

using the above result for jet centre velocity. The integral can be evaluated analytically to give

$$T(x) = (1/\alpha_3)\left[\frac{2x^{3/2}}{3\alpha_1 V_j (\Delta y)^{1/2}}\right] + T_0$$

Figure 5 shows a plot of phase delay against the term in square brackets for all the measurements. A reasonably good fit to all the results is given by a straight line as shown, with $\alpha_3 = 0.33$.

Previous work at higher frequencies [3] gave higher values of $\alpha_3$, up to 0.5. The excitation frequency for the measurements reported here was 118Hz compared with 200-1100 Hz for those in [3] and this may explain the discrepancy.

### 3.4 Growth of Disturbances

When the jet was perturbed by an acoustic field in the pipe, transverse waves propagated up the jet and could be identified using the hot-wire anemometer. The indicated air speed showed two peaks per cycle of acoustic pressure as the jet swept twice across the stationary probe, moving into and out of the pipe. The two peaks per cycle coalesced into one as the probe was positioned at the outermost extreme of jet movement.

The amplitude of the jet wave at a given height was found by moving the probe to identify the innermost and outermost extremes of the jet movement. The difference in probe positions gave the peak-to-peak amplitude in millimetres.

To be consistent with [4] the measurements have been used to infer growth rate $\mu$ and wavenumber k ($=\omega/u$). It is then possible to express $\mu b$ in terms of kb, both dimensionless quantities.

Wave amplitude A(x) is related to growth rate $\mu(x)$ by:

$$A(x) = A_0 \exp \int_0^x \mu dx$$

where $A_0$ is constant. This can be expressed in the form:

$$\mu = (1/A(x))(dA(x)/dx)$$

The phase speed u and the jet half-width b were obtained using the equations developed in Sections 3.2 and 3.3. The results are presented in Figure 6.

No simple expression has been found to describe the growth rate of large amplitude waves on turbulent jets for organ-pipe conditions. However there is a clear trend despite the wide range of conditions, so a smooth curve has been drawn as shown through the results.

## 4. CONCLUSION

Measurements have been presented which describe the behaviour of an acoustically-perturbed air-jet over a range of conditions relavent to organ pipes. The results have been compared with theoretical predictions and form a consistent data base on a single air-jet which can be incorporated into a model of steady-state tone production in organ-pipes.

## 5. REFERENCES

[1] H J NORMAN 'The Organ Today' David &Charles (1980)
[2] N H FLETCHER 'Air flow and sound generation in musical wind instruments' Ann Rev Fluid Mech 11 p 123-146 (1979)
[3] S THWAITES & N H FLETCHER 'Wave propagation on turbulent jets' Acustica 45 p175-179 (1980)
[4] S THWAITES & N H FLETCHER 'Wave propagation on turbulent jets II, Growth' Acustica 51 p44-49 (1982)

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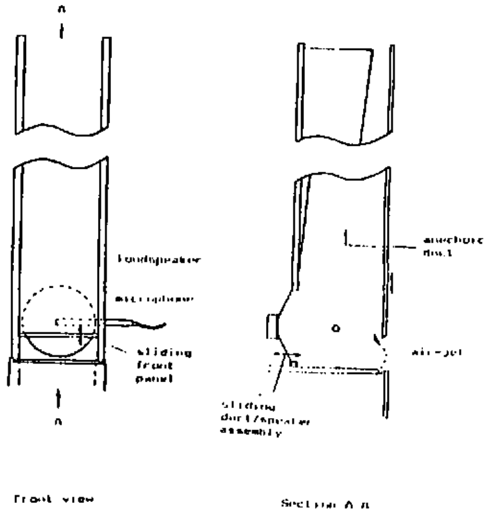



Figure 1: Schematic Diagram of Air-jet Rig

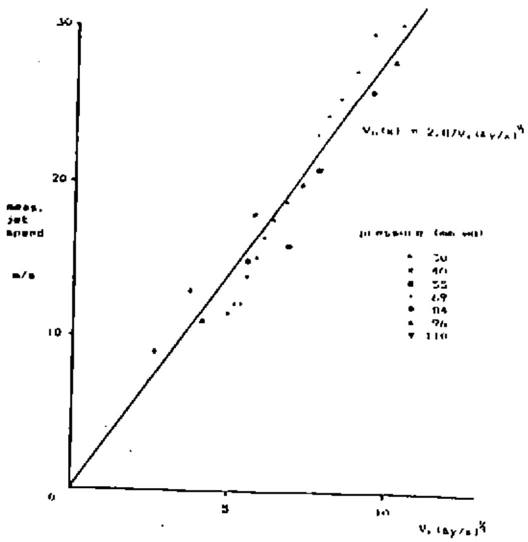
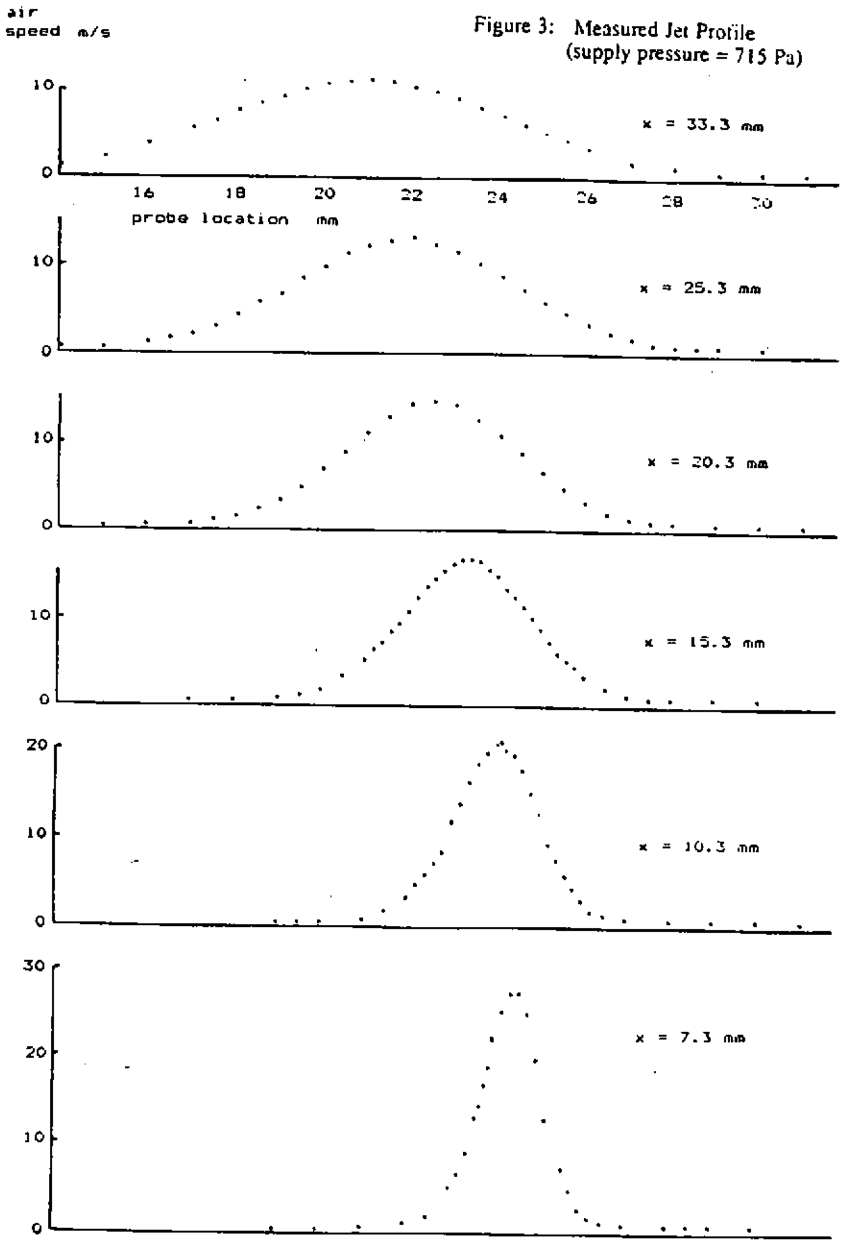



Figure 2: Measured Jet Centre Velocity

Figure 3: Measured Jet Profile
(supply pressure = 715 Pa)



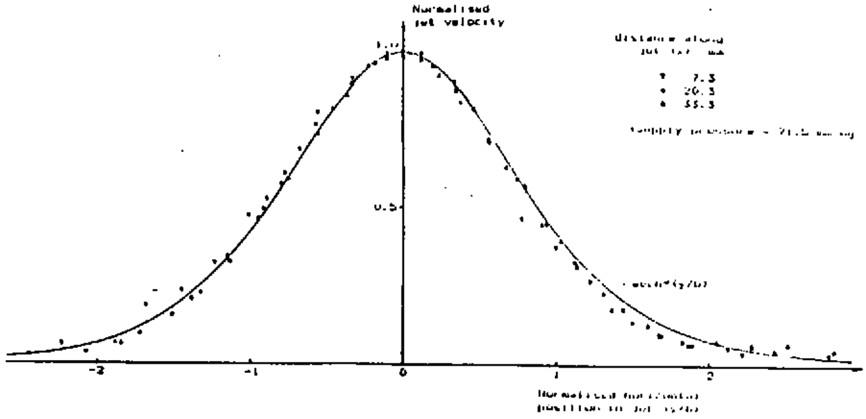



Figure 4: Comparison of Measured Jet Profiles with $\mathrm{sech}^2(y/b)$


Figure 5: Measured Phase Delay of Jet Waves

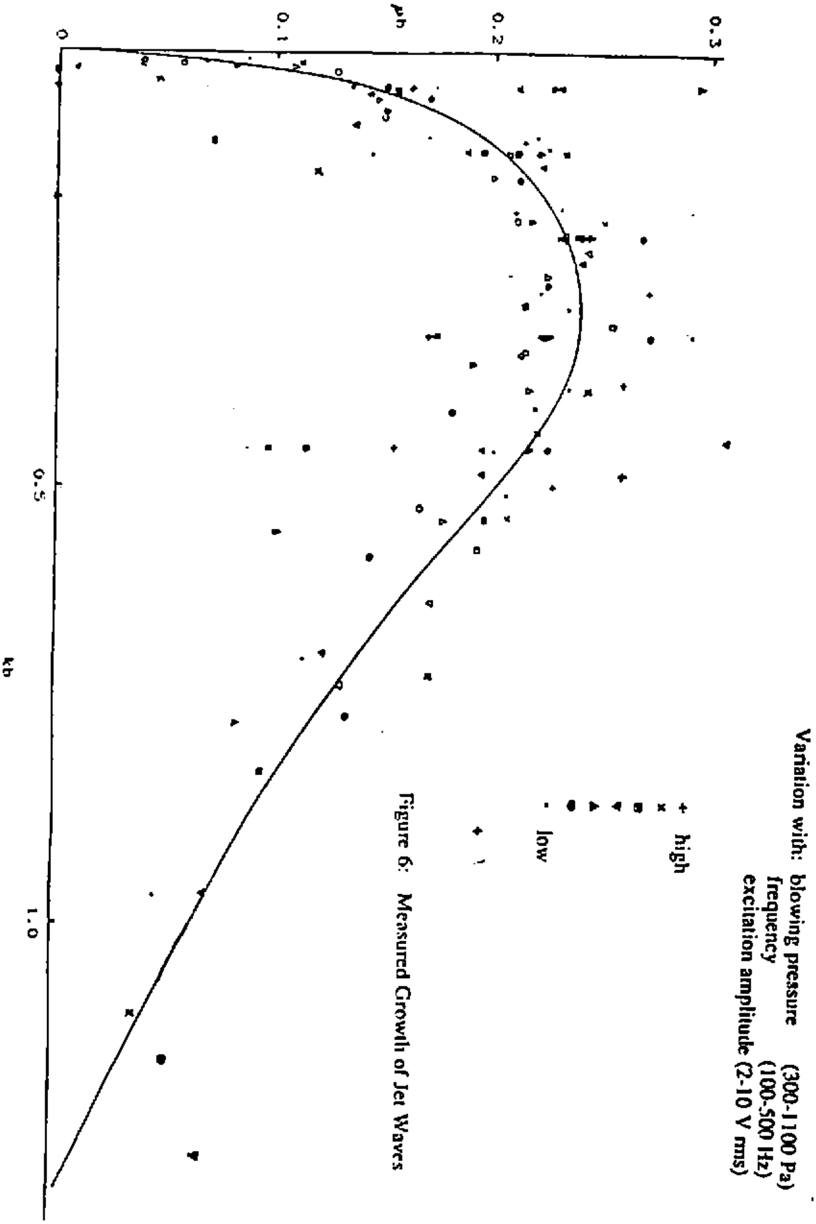



Figure 6: Measured Growth of Jet Waves