Flue organ pipe operating regimes and voicing practices

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A combination of certain pipe voicing parameters, including wind pressure, sets up a specific feedback cycle operating regime when the pipe is blown. It is the most important voicing adjustment. In most blowing conditions maximum energy is expected to be transferred to the acoustic field inside the pipe when the jet injects air in phase with the acoustic pressure, the phase delay on the jet then being about half a period and the pipe sounding at its fundamental passive resonance frequency. In this study the relationship between this optimum concept and voicing practices is investigated. A procedure to determine the operating regime of pipes from various registers and organs using data from in situ acoustic and flow measurements was developed. Correlations were sought with pipe scaling, pitch range and tonal architecture. Principal pipes turn out to usually operate at pressures above this theoretical optimum, and acoustic power is traded for spectral richness, leading to different voicing styles. As a general rule, voicers appear to intuitively attempt to put forth the distinctive acoustic features of the resonators. Erratic variations in operating points throughout pipe ranks were also observed, the resulting differences being more or less successfully compensated by other voicing parameters.

1   Introduction

The concept of the pipe organ results from the remarkable pitch stability of its pipes, without which its synthesized sounds coming from simultaneously sounding pipes and the player's control system over this process would be pointless. All types of organ pipes, and in particular the flue pipes which are the subject of this paper, are able to keep variations in their sounding frequency down to a few cents while wind supply pressures vary over the equivalent of many thousands of cents. However, this sensibility varies over the possible range of wind pressures where the pipes can be brought to speak. In this paper the acoustic mechanisms that enable this pitch stability will be recalled and serve as a basis to elaborate on the main topic: the choice of the pressure regime to operate the pipe, a choice which is also guided a dependence of the sound spectrum on the operating regime.

2   The regenerative feedback loop

Briefly, the exciting mechanism of a flue instrument is a non-linear self-generating and self-limiting flow amplifier. Under suitable conditions the roundabout propagation of disturbances in the feedback loop can regenerate itself and lead to stable oscillations whose amplitude and frequency depend on the various hydrodynamic and acoustic parts involved. For the purposes of this paper, in which frequency stability will be studied in particular, the main subject of interest will be the timing relationships governing this loop.

2.1   Phase relationships

2.1.1 The jet

The hydrodynamic interaction mechanism between the transverse acoustic flow and the jet is still under active investigation. Among the competing models have been, among others, the acoustic transverse current as the physical quantity directly controlling the jet [1], the acoustic displacement by simple back and forth entrainment of the jet [2], the acoustic pressure gradient across the jet accelerating it transversally [3], jet velocity profile skewing by the transverse pressure gradient [4]. The possibility remains that not one single flow parameter is involved as in those models and the interaction might be a far more subtle hydrodynamic process.

The displacement model has been most often used in simulation models and, as far as phase relations are concerned, is similar to the pressure gradient model [5]. Following this model, the transit phase over the jet is determined between the so-called negative acoustic displacement and the jet flow entering the resonator. The transit phase φ_{jet} is calculated by integration over the travelling distance, taken as the mouth height or cut-up, and assuming a turbulent jet with the maximum jet velocity decreasing inversely proportional to the square root of the distance [2]. Furthermore, the disturbance propagation velocity is assumed to be half the maximum jet velocity.

2.1.2 The jet drive

How the jet flow drives the acoustic pipe flow is equally a complex hydrodynamic process which is classically modelled by applying conservation of mass and momentum to a small control volume, the mixing region, situated between the pipe mouth and the resonator [2]. The jet drive adds a certain amount of phase delay φ_{drive} between the injected jet flow and the pipe pressure. In most organ pipes, it turns out that the jet mainly drives the resonator by injecting flow volume against the pipe pressure.

2.1.3 The resonator

The resonator moves its stored energy back and forth between kinetic and potential forms at a precisely controlled rate, given sufficiently low losses. Moreover it can strongly vary its reactance close to a resonance frequency. Both properties are important to stabilize the positive feedback loop it is part of while still allowing a range of operating regimes.

2.1.4 The pipe mouth

The air mass flowing coherently in and out of the pipe mouth is determined by the mouth geometry and controlled by the acoustic pipe pressure. In turn this mass disturbs the air jet flowing across the mouth, thus closing the feedback loop. Assuming the radiation losses to be small compared to the inertance of this mass it can be assumed that the phase difference between the acoustic pipe pressure and the negative jet displacement (or transverse jet pressure gradient) is always half a period.

2.2   The closed feedback loop

Following this discussion, when the feedback loop is closed and $\varphi_{jet} + \varphi_{drive}$ equals an uneven number of half periods of the oscillating frequency, the jet flow inside the pipe is in phase with the acoustic pipe pressure. The jet

flow thus sees a resistive pipe, that is, the feedback cycle and the pipe must be oscillating at the passive resonance frequency of the pipe (loaded by the open end flows). If φ_{jet} is slightly decreased, for instance by increasing the blowing pressure, the jet flow starts to lead over the acoustic pressure. The resulting "blind" flow is compensated by the pipe turning more susceptant, invoked by a small increase in the oscillating frequency of the loop. If φ_{jet} is further decreased, the jet flow gradually loses its capacity to deliver power to the pipe and this oscillation will cease. However, roughly assuming $\varphi_{jet} + \varphi_{drive}$ to have a range of half a period (from leading to lagging in quadrature to the pipe pressure), by the time $\varphi_{jet} + \varphi_{drive}$ comes down to ¼ period, the $\varphi_{jet} + \varphi_{drive}$ range for the next pipe resonance, which by the same argument goes up to 3/8 of the original period, will have taken over and the feedback loop will stabilize around this new frequency. Similar considerations hold for φ_{jet} increasing, except that now mode switching can also take place in the hydrodynamic jet modes and the $\varphi_{jet} + \varphi_{drive}$ ranges, for instance from first to second hydrodynamic mode, corresponding with first and third pipe harmonic, do not all overlap, so that there may be pressure ranges giving silence here.

2.3 Parameters determining the operating regime

φ_{jet} depends essentially on the cut-up, the wind supply pressure and the flue width, but apart from their direct impact on the feedback cycle timing, they influence the sound spectrum in different ways.

2.3.1 Cut-up

Increasing the cut-up brings the resonance frequencies closer to the harmonics because the mouth correction decreases and the oscillation frequency is lowered through an increased φ_{jet}. Furthermore, the jet velocity profile near the upper labium is flatter so that lower harmonics are favored. The pipe sounds rich, complete and lively up to a certain level where the sound looses presence and becomes breathy. On the other hand, decreasing cut-up excites the higher harmonics through the sharper jet velocity profile but the corresponding resonances get more out of tune. Thus only the lower range of the higher harmonics is favored, leading to a incisive, formant-like sound texture. The small φ_{jet} value increases regime settling time during attack, giving edge-tone like transient feedback phenomena the time to develop. Too small a cut-up evidently makes the pipe overblow.

2.3.2 Wind supply pressure

Decreasing wind pressure, compared to increasing cut-up, increases φ_{jet}, but without the change in mouth correction and the jet velocity profile turning flatter the sound becomes darker and duller.

2.3.3 Flue width

Changes in flue width modify the jet geometry in a complex way. On one extreme, if the jet has a small aspect ratio ("thick" jet), it has hardly spread and changed its velocity profile when it reaches the upper labium. Decreasing the flue width essentially reduces the pipe drive

flow but does not influence the feedback cycle nor the velocity profile [6]. On the other extreme, more applicable to most organ pipes, if the jet has a large aspect ratio, decreasing the flue width reduces the jet velocity and further spreads the velocity profile at the upper labium. φ_{jet} thus increases and the pipe excitation becomes weak. In practice the resulting sound becomes meager.

2.3.4 Operating regime characterization

From the discussion above it becomes clear that a useful dimensionless parameter to characterize the feedback cycle regime should at least include the cut-up, the wind supply pressure and the flue width. Obviously, an additional operative parameter associated with time is required to match the time dimension in the pressure: frequency.

Following the definition of the usual Strouhal number, the ratio of the jet disturbance transit time to oscillation period will be calculated by extending the integration outlined before to the flue exit. The result will not be very different in values but will yield a formula similar in simplicity to the Strouhal number.

Assuming a turbulent jet whose center velocity varies as $x^{-1/2}$, where x is the direction parallel to the pipe axis, balance of jet momentum is expressed as:

$$V_0 \sqrt{b_0} = V(x) \sqrt{b(x)} \qquad (1)$$

where:
b_0 is the flue width
$b(x)$ is the jet width in the x direction
V_0 is a center jet velocity close to the flue, stemming from the initial top-hat velocity profile
$V(x)$ is the center jet velocity along the jet, given by:

$$V(x) = V_0 \sqrt{\left(\frac{h_0}{x}\right)} \qquad (2)$$

where h_0 is the location in the x direction where V has velocity V_0.

The transit time to oscillation period ratio is then calculated as, using the assumptions made before:

$$D_{jet} = f \frac{2}{V_0} \left(\int_0^H \sqrt{\left(\frac{x}{h_0}\right)} dx \right) \qquad (3)$$

where:
f isthe fundamental feedback cycle oscillation frequency
h_0 is 3 times the flue width
H is the mouth height or cut-up
V_0 is the maximum jet velocity at the flue, where the jet is assumed to have a top-hat profile up to a distance h_0.

Assuming h_0 to be about 5 or 6 times b_0, corresponding to a jet spreading angle of around 10º, this gives:

$$D_{jet} \approx \frac{fH}{2V_0} \sqrt{\frac{H}{b_0}} \qquad (4)$$

This value differs with a factor 2 from the reciprocal of the so-called "Voicing Number" [9], which is defined as (original notation):

$$I = \frac{v_0 \sqrt{h_0}}{f e \sqrt{e}} \qquad (5)$$

where v_0 is the jet velocity, h_0 is the flue width ('jet thickness at the flue'), e is the cut-up, f is the frequency

This parameter seems to have been obtained by considering momentum conservation in the jet flow and a purely dimensional argument combining the quantities involved.

In view of the measurements on different pipe ranks, to be presented in the next section, it is useful to get some preliminary ideas of what value ranges of D_{jet} can be expected to be associated with various types of pipes. Principal pipes are intended to produce strong and bright sounds, therefore they should not be cut too high. As an additional result they will have a noticeable (but not too striking) attack transient, thus promoting melodic clarity. D_{jet} starting at 1/2 and less can be expected. Towards the bass range this becomes all the more important in order to provide sufficient harmonic content, but care must be taken not to obtain exaggerated attack times (an illustration of some of the basic voicing rules and dilemma's [7]). Flute pipes will have their D_{jet} closer to 1/2, providing quick attack and limiting harmonic content in the jet drive, which is usually matched by those pipes having larger scales and thus reduced and rather stretched higher resonances. D_{jet} values above 1/2 are not expected to occur as this would correspond to very dull and weakly sounding pipes with again long attack transients.

The measurements to be presented next serve to evaluate the D_{jet} values in complete pipe ranks. Given that various voicing manipulations can give results that more or less serve the same purpose, it's interesting to analyze the degree of coherence reached in the voicing process, which is traditionally guided exclusively by aural control, without any measuring device. Results will be presented using D_{jet} or an inverse Strouhal-like number Str_H^{-1} based on the cut-up as this is often used in the literature. D_{jet} and Str_H^{-1} are related by:

$$Str_H^{-1} = 2\, D_{jet}^{-1} \qquad\qquad (6)$$

3   Measurements

3.1   Procedure

The measurement procedure used can be performed on pipes in situ, that is, receiving the wind supply their were voiced on.

First the passive resonance frequencies are measured on the silent pipe by exciting the resonator with a white noise sound source. The source, a compact high quality speaker connected to a noise generator and amplifier, is placed 1 pipe diameter in front of the pipe mouth. The resulting acoustic pressure inside the pipe is measured at the edge of the open end at the top using a sub-miniature condenser microphone cell, suspended in the pipe axis. The pressure spectrum is analyzed with a resolution of 1/24 octave. All other measurements are performed on speaking pipes.

Jet velocity measurements use a Dantec type 55P16 hot wire, with the wire placed parallel to the flue. The wire support is attached to a miniature X-Z motor-controlled traverse mechanism with which the jet can be probed in a plane perpendicular to the flue exit. Data from the hot wire

bridge DISA type 55M10 are acquired by a monitoring digital oscilloscope. A PC controls both the traverse mechanism and the oscilloscope, importing the measurement data from the latter, thus allowing to automatically perform and store a complete flow field measurement. The pipe pressure using the above mentioned microphone is also permanently captured and serves as a phase reference. The end-detection sensor in the traverse mechanism allows easy calibration andthe resolution is 5μm.

The following measurements are done:

The maximum jet velocity at the flue exit is determined by traversing the jet perpendicular to the mouth at a distance from the flue exit equal to twice the flue width and taking the central velocity.

The phase of the jet flow is determined by traversing the jet perpendicular to the mouth at the upper labium. Using the velocity readings the jet phase is determined by 2 alternative methods. The first involves determining the maximum inward phase of the jet with respect to the pipe pressure by detecting the minimum between inward and outward passages of the jet through the hot wire. For the second method temporal data are converted to spatial data, giving jet velocity profile snapshots. The inward flowing fraction of the velocity profile is isolated by detecting the location of the upper labium as a point of decreased velocity. Finally a measure of the inward flow is obtained by integrating the velocity profile. From this the inward jet flow as a function of time is derived, allowing the phase to be determined. It is assumed that the integration step will reduce errors introduced by the insensitivity of the measurements to velocity direction. Both methods essentially yielded the same phase information.

For each pipe rank more extensive measurements were done on a limited number of pipes, with the intention to explore the range of possible regimes. To this end the wind supply pressure was first measured using a special piece placed between the pipe's wind chest hole and the pipe foot, to which an electronic manometer type HMGD1 could be connected. This allowed to measure the supply pressure, with the pipe speaking. Then the pipe was removed and installed on a separate chest with variable supply pressure, thus allowing to operate the pipe in different regimes. For each regime the flow measurements described above were repeated, knowledge of the supply pressure on the original wind chest serving as a control reference to make sure that this situation could also be identically reproduced on the alternate chest. The various wind supply pressures allowed to operate the pipes from the onset of a stable acoustic mode on the resonator fundamental, up to well above the organ wind pressures the pipes were normally used with. The pressure were the pipes overblow could not be produced with this setup and accordingly no velocity measurements have been performed at these high pressures. Nevertheless, overblowing pressures could be measured by alternative means.

The results reported here stem from pipes of medium length as found in a 4' pipe rank of a Verschueren organ op.628 with sliderchest, pipework made by Fa. Stinkens. Mainly open pipes were investigated, and also some closed pipes in the same frequency range. The c pipes, some data of which are given in the next table for reference, were studied more extensively:

all measures in m, frequencies in Hz, pressures in Pa

	PC3	PC4	PC5	PC6	PC7	BC4
Cut-up	0.0135	0.0065	0.0052	0.0031	0.0016	0.0120
Foot diameter	0.0070	0.0060	0.0042	0.0032	0.0027	0.0054
Flue width	0.0006	0.0003	0.0002	0.0002	0.0002	0.0004
Length	1.0560	0.5460	0.2740	0.1320	0.0660	0.0275
Diameter	0.0710	0.0420	0.0260	0.0155	0.0100	0.0465
Overblow press	2800	1800	1500	1500	1400	2500
Passive res freq	134.5	250	508	1009	1930	258
Operating freq	137.3	258.4	514.1	1020.1	2037.6	261
Operating press	450	510	490	515	505	495

3.2 Results

### 3.2.1 Frequency dependence on pressure

As a reminder of the frequency behaviour of flue pipes, the next graph shows how the operating frequency dependence on wind supply pressure gradually flattens with rising pressure:
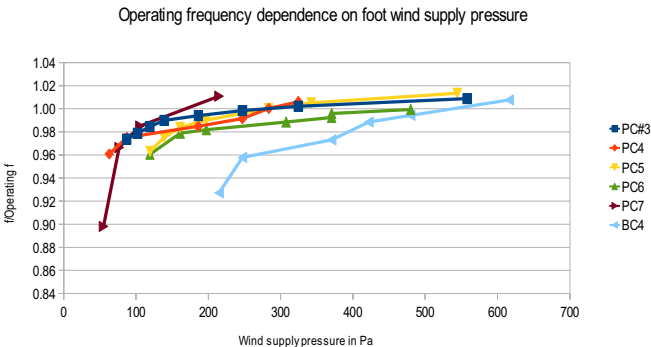
This illustrates one of the primary considerations made in establishing the operating point of the pipe: the higher the wind pressure the lesser the frequency varies with relative variations in the former. For most pipes this is well established when the intended operating frequency is reached. The highest pipe in pitch is seen to be the least stable, it explains why wind variations in the organ not only influence the global pitch but also threaten the relative tuning of the pipes. Therefore, pipes can only be voiced for a limited wind pressure range. From the discussion above, this poses lower limits to the jet disturbance transit time and thus to the wind pressure, as well as upper limits to the cut-up.

3.2.2 Overblowing limit

An upper limit of wind pressure to a given voicing configuration, including flue width and cut-up, is set by the minimum jet disturbance transit time for oscillations to be possible. The next figure shows the operating to overblowing wind supply pressure for the c-pipes:
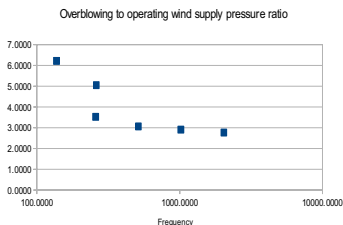
The jet velocity measurements for these pipes show that the foot wind pressure is roughly 50 to 30% of the wind supply pressure as the latter increases, so that a threefold increase might implies a doubling of the former and a decrease of the jet disturbance transit time with some 30%. This brings the total transit phase from about 30%, at the operating pressure, to 20%, which is somewhat less than the expected transition phase of 25%, following the discussion above. The sixfold increase for overblowing observed in the first pipe then is probably due to the relatively very small foot hole, even more limiting the foot wind pressure.

3.2.3 Disturbance transit phase

The jet disturbance transit phase was calculated using Eq. (4) for all the examined pipes including, for the pipes from the table, all the operating regimes they were examined in. The next figure shows the global results, showing all $1/Str_H$ values as a function of f:
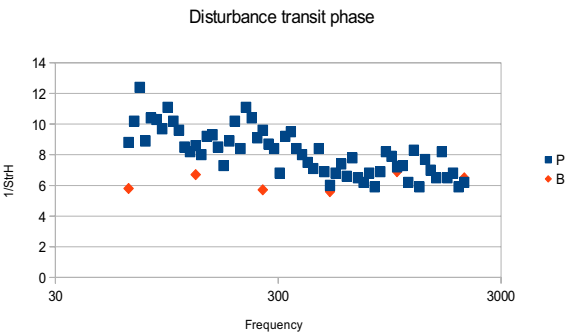

First of all, there is a significant variability in going from one pipe to the neighbouring one in pitch. It clearly shows the voicing process to be an aurally based rather then a geometrically based activity. As each operating regime casts a specific tonal signature on the sound spectrum, and the onset of each tone, partial equalization is obtained by adjusting other voicing parameters, such as languid height, upper labium shape or various kinds of mouth correction devices. This compensating process is the main subject of a subsequent paper, suffice it here to observe that imperfect equalization of the operating regimes is not necessarily a voicing deficiency. The liveliness and clarity in the musical language many a pipe rank can display is in many cases well served by those irregularities. Together with a well-managed, not necessarily rigidly stable, wind supply, they bring an organic, 'breathing' dimension in the sound. Together with the resonances offered by old dry wood, they are the main ingredients that unequivocally characterize old historic pipe organs.

From the figure, open pipes tend to be stronger blown than semi-closed pipes, which can be interpreted as an illustration of the principle that voicing serves to corroborate the properties of the resonator. Open pipes offers the potential for richer tonal spectra and should accordingly be voiced to have the jet provide energy in a large frequency range. Semi-closed pipes rather benefit from efficient energy coupling, thus providing support, and quick attack. These properties are favored by a feedback loop were the resonator is close to its passive resonance frequencies.

Among the open pipes, blowing is generally somewhat stronger in the bass in order to produce a richer sound.

3.2.4 Operating frequency versus Str$_H$

The next figure more specifically compares the operating regimes of the pipes of Table 1 as a function of $1/Str_H$:

Operating regimes of various pipes
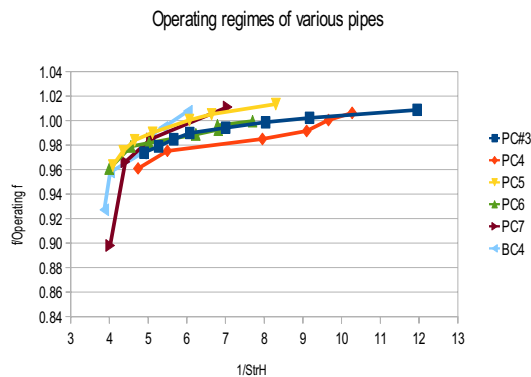
3.2.5 Passive resonance frequencies versus Str$_H$

The next figure shows the same as in 3.2.4. but plotted to highlight the relationship between Str$_H$ and the passive resonance frequencies:

Operating regimes of various pipes
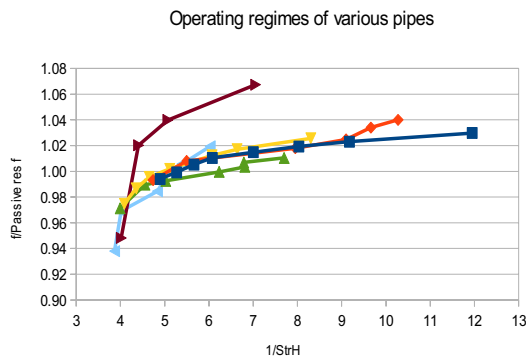
Except for the smallest pipe (probably due to measurement inaccuracy), the Str$_H$ are almost equal (1/5, 1/6 for the second smallest pipe) for all pipes when operating at their passive resonance frequency. So for sufficiently weak blowing the dependencies of operating frequency on Str$_H$ show the same behavior, corresponding to the resonator admittance becoming proportional to frequency.

3.2.6 Total jet transit phase

In order to validate the transit times calculated above, further measurements were done in order to verify whether the phases found were able to close the feedback loop. Using the method described above the phase difference between the jet flow and the pipe pressure was measured in the open c-pipes listed in the table above for a range of wind supply pressures which includes the passive resonance and operating frequencies. This phase difference was added to the transit phase of the jet disturbance between flue and upper labium calculated above. The resulting total phase, which is supposed to be the phase difference between initial jet disturbance displacement at the flue and the pipe pressure, is plotted in the next figure as a function of $1/Str_H$:

With the exception of the smallest pipe, were size reduction decreases measurement accuracy, all values fall

within +/- 20% of ½, which is the expected value according to the discussion above.

Total transit phase from jet exit to pipe pressure
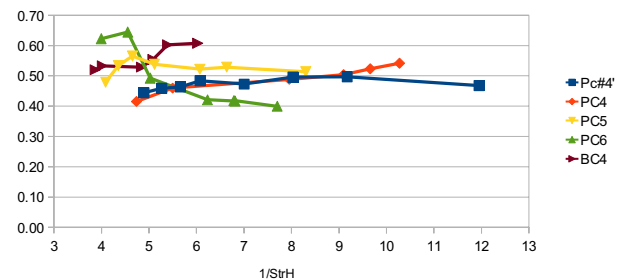
4   Voicing practices

Many of the effects of choosing an appropriate operating regime are incorporated in an excerpt of a presentation given by the organbuilder C. Fisk [8]:

"Let me try to explain what I mean by underblowing: If you first agree that the windway must be kept open (...), then classical voicing becomes a matter of balancing the toe hole opening and the cutup (...). If we choose a wide open toe hole, then underblowing will be achieved if we raise the cutup *just beyond* the point at which the pipe appears to be giving out its maximum volume of sound. Thus the classically voiced organ pipe is one in which the cutup is "a little too high." With the cutup on the high side, the tone becomes fuller and gentler; more important, the pipe is not quite as stable as it would be with a lower cutup, and this makes it *much* more easily influenced by pulses or irregularities in the flow of air coming through its toe hole."

5   References

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