SPACE AND AIR ECONOMY IN THE ORGAN LOW REGISTER

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ABSTRACT

The low register in an organ generally commands the space and air supply required. A number of classical and novel measures to economize with these are compared in terms of efficiency in sound level generation and a sideglance at musical usefulness. The comparison includes the source mechanisms of flue, beating and free reeds, pipe and cavity resonators. Designs are presented where a flue pipe is detuned by one semitone by an additional capacitance at its flow node.

1. INTRODUCTION

The acoustic power delivered by a monopole source is proportional to the squares of its frequency F and flow U. Assuming for reasoning that the sound power delivered from each pipe in a rank should be same this means that pipe flow will have to be inversely proportional to frequency, and at a given efficiency also the supply flow S. We may represent this with a proportionality $f \approx 2^{-n/12}$, where n is semitone number on a scale of rising frequency, e.g. like the MIDI note numbers. A simple verbal interpretation of this may be: *the lowest octave in a rank will use approximately the same supply flow as all its higher octaves combined*. E.g. a compass of five octaves will use air in the ratios 16 : 8 : 4 : 2 : 1.

The same applies to the lengths of the pipe resonators, while their cross dimensions vary according to mensuration practice. Using a ‘halving number’ M (the number of semitones you go along the tonal scale to reach a pipe with half the diameter, typically M=18), the pipe cross dimensions vary as $2^{-n/M}$. For the total volume of pipes we then have $V \approx 2^{-n/12-2n/M}$. Then similarly: *the spatial volume of the lowest octave in a rank will exceed the remaining octaves by 4 times using M = 18, or 3 times with M = 24*. This underlines the volume occupied by the bass pipes is a prime factor in the space economy.

Sparse piping is common in small secular organs, you omit several notes in the bass register, mostly sharp ones. This may be regarded as an illegal circumvention of the problem. Contrarily however, sparse pipes may be equipped with special devices, ‘detuners’, to enable one pipe to play more than one note, thus enabling a chromatic compass, but with restrictions on possible simultaneous notes.

An obvious means toward small volume is to select short pipe types. Counting length alone, minimum comes for a Helmholtz type cavity enhancing only the fundamental. For flue pipes you may use quarter wavelength stoppered ones rather than half wavelength open ones. A consequence is then that the harmonic spectrum is reduced to contain essentially only the odd harmonics. An efficient practice is to play the fundamental with such a pipe in combination with a one octave higher open flue pipe. The latter then fills in the missing odd harmonics of the lower pipe.

The same trick applies to cylindrical quarter wavelength reed pipes (clarinet type), although it is more common to use a conical resonator, about 0.35 wavelengths, resonating near all low harmonics of the exciter. Reed pipes offer a wide range for the voicer in terms of power and timbre, but in the bass the necessary boot volume is not negligible.

2. EFFICIENCY MEASUREMENTS

Basic timbral properties are given by the pipe type, but we focus here on a series of measurements to illustrate the efficiency of the pipes, in the physical meaning of acoustic power delivered, as fraction of the blowing power supplied. A disparate set of wooden pipes were measured at varied conditions. Some of these samples are of regular design, borrowed from an organ, others are experimental ones where flue thickness and cut up can be easily varied. Some cases use a reed excited Helmholtz resonator where the cavity is variable by different length frames, clamped together, and brackets for a continuously adjustable port area. The objects are enumerated in Tab. 1 and measured data and some following results pertaining to efficiency are graphically shown in Fig 1. Each measurement included:

- P_0, blowing (foot, boot) pressure in Pa.
- U_0, blowing airflow in liter/sec.
- F, fundamental frequency in Hz.
- L_a, sound pressure level in dB (unweighted) at 25 cm distance from the pipe opening(s).
- P_e, effective sound pressure in kPa at the pressure maximum for the fundamental, inside the resonator. In most cases this pressure waveform is nearly sinusoidal, exceptions are beating reed pipes (pulses) and the narrow flue pipe (square wave with some highpass droop).
- Q_0, low level quality factor for the resonator, from resonance bandwidth and external excitation. This was of less interest as is was found to be always moderately to much higher than the Q in operation.

The flue width D (nominal airband thickness) was grossly measured with feeler gauges, but a more reproducible effective value was obtained from the Bernoulli equation as $D = (U_0 / W)(2 P_0/\rho)^{-½}$, knowing the cut up width W. All flues are wedge shaped with about 10 degrees convergence angle, with sharp termination edges and no nicks.

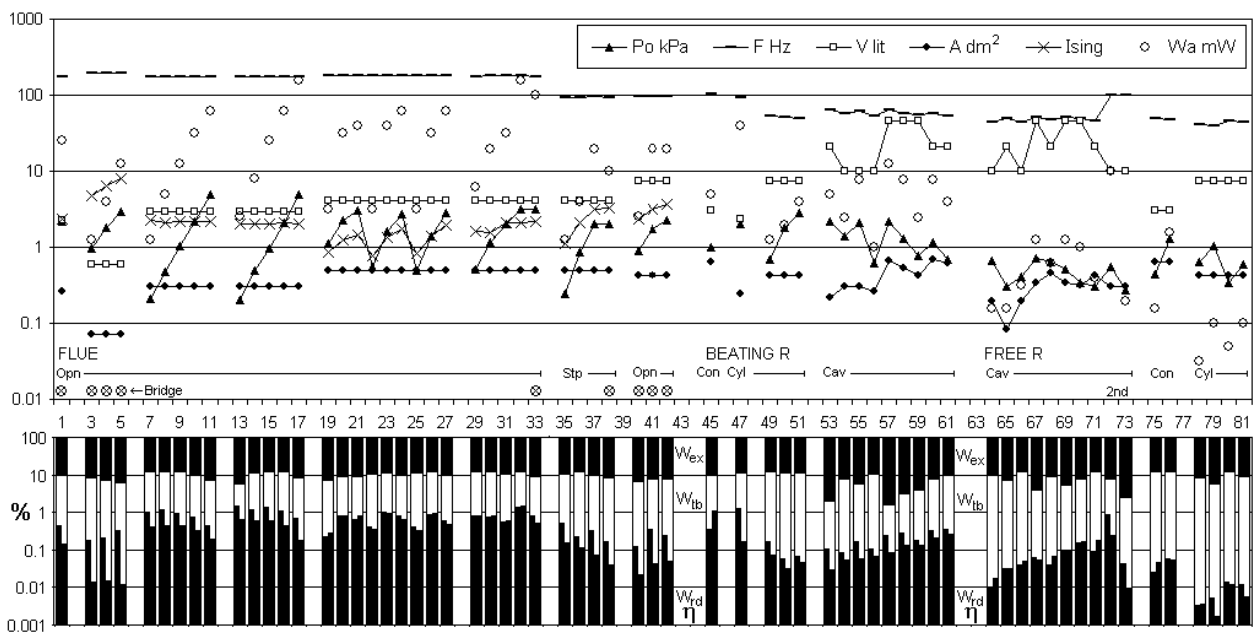

Figure 1: *Top: Some dimensional data and measurements for the pipe samples. Bottom: Computed cumulative percentage of input power developed in radiated sound W_{rd}, resonator loss W_{tb}, and the excitation mechanism W_{ex}. W_{rd} corresponds to efficiency η and is split into a left bar for the result found from external sound, and a right from internal sound pressure.*

Sample #	*Type*	*Resonator dim. (mm)*	*Frequency*	*Comments*
1	Flue, open, roll	855*51*51, H26, D0.85	196	Principal
3-5	Flue, open, bridge	820*27*27, H11, D0.7	196	Cello
7-17	Flue, open	892*55*55	175	Experimental, H and D varied
19-33	Flue, open	845*70*70, H31,	175	Regular, D varied
35-38	Flue, stoppered	825*70*70, H31, D0.73	93	Regular. Same body as #19
40-42	Flue, open, roll	1752*65*65, H30, D0.8	98	Principal
45	Beating reed	Conical 1430*80*80	98	Trombone, tongue 65*12*0.7 mm
47	Beating reed	983*49*49	92	Clarinet, tongue #45
49-51	Beating reed	1745*65*65	49	Clarinet, tongue 130*17*1.5 mm
53-61	Beating reed	Cavity 10/21/46 liter	49	Helmholtz res., port area tuned.
64-73	Free reed	Cavity 10/21/46 liter	49	Helmh. res., tongue 130*10*1.5 mm
75-76	Free reed	Conical 1430*80*80,	49	Trombone. Body #45, tongue #64
78-79	Half free reed	1745*65*65	49	Clarinet. Body #49, tongue #64
80-81	Free reed	1745*65*65	49	Clarinet. Body #49, tongue #64

Table 1: *Measurement sample numbers of Fig. 1 and some further characteristics.*

The acoustic output power from the pipes can be estimated two ways from these data. An obvious one is to multiply the external intensity (in W/m^2, derived from L_a) by the area of a 25 cm radius sphere around the pipe opening(s). However the sound level varied somewhat with direction, even at the small distance used, which indicates that standing waves in the room interfered to partly disvalidate the measurement. – An alternative way is to use the resonator internal pressure. This pressure applied to the cavity compliance results in a volume flow, essentially all of which passes the pipe opening(s) and exerts the output power in the radiation resistance. When we neglect the fraction of this flow consumed in internal loss mechanisms like viscosity and wall heating, then for a cavity resonator of volume V these operations amount to the power

$$W = \omega^4 P_e^2 V^2 / (4 \pi \rho c^5). \quad (1)$$

A complication rises from the ω^4 factor which means a 12 dB/oct slope when converting internal pressure into delivered power. Experimentally, this could be implemented as a double differentiation of the P_e signal. This was not done in the present study where in most cases the P_e signal was essentially sinusoidal. In a few cases (conical reed horn and very narrow 'cello' pipe) this was not true, causing a fairly big under-estimation of their power, as apparent from Fig. 2, which compares the output power estimations for all samples, obtained with these two methods.

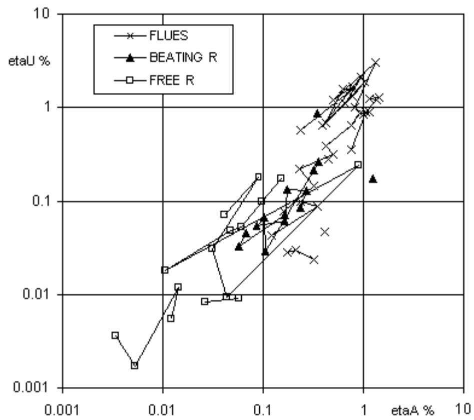

Figure 2: *Efficiency estimated from internal pressure vs. that from external SPL.*

The second method suggests a speculative extended interpretation, modeling the resonator as in Fig. 3. Assuming a reasonable Q and neglecting detail refinements, at resonance we can dismiss the reactive elements to have only a resistive divider. This device has R_a for the useful sound radiation in parallel with R_t for resonator losses. From resonator volume V and ω we can compute R_a as the parallel equivalent to the radiation resistance(s) for the opening(s) of the resonator.

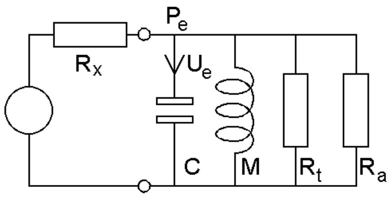

Figure 3: *A resonator modeled as a single RMC parallel circuit, with resonance angular frequency $\omega=(MC)^{-1/2}$ and quality factor $Q=R/(\omega M)=\omega C/R$, where R is the parallel combination of exciter, turbulence and acoustic components.*

The resonator is fed through a symbolic resistor R_x. This represents the exciter, but is only a computational vehicle that is not simply related to the pipe physical dimensions. With a constriction like a reed, part of it can however be interpreted: Differentiating the Bernoulli equation with respect to U, we find a differential resistance

$$R_x = dP/dU = \rho U/A^2 = 2P/U, \qquad (2)$$

simply twice the 'DC flow resistance'.

Loosely conjecturing a driving signal P_0, fed trough the 'pressure divider' R_x and R, we can now also compute a dissipated power in R_t. From P and U we may additionally estimate an effective average open area A through the reed. It must be noted that the power in all three resistors is still far below the supplied blowing power, remarkably almost constantly around 10% of it, whether flue or reed samples. Of the oscillating energy a small and highly variant fraction goes into R_a to produce useful sound while the rest is lost by turbulence etc. in R_t. We might call the remaining 90% an exciter loss, partly in R_x, partly unexplained other input losses. With flues one may see them as converters from static into kinetic energy, inside the resonator converted back and manifested in P_e.

2.1 Flue pipes

For flue pipes the present samples give little tangible hints to any specific dimensional relations connecting to efficiency, notably not even the low level Q, non-trivial correlations are small. An outstanding exception is however the intonation number, defined by Ising [1] as

$$I = V^*(D/H^3)^{1/2} / F, \qquad (3)$$

where V is the initial speed of the air jet, estimable from foot pressure P_0, D its thickness, H is cut up height, and F is frequency. Optimal for the flue drive mechanism is said to occur at I near 2, which appears supported by fig 4. 'Higher' voicing (higher V, P, D, lower H) normally causes overblowing when I>3, here prevented with bridges, extremely so with the very slim pipe #3-5. This renders very prominent higher harmonics, but a weak fundamental. For efficiency in the fundamental, not surprising, normal mensuration appears as broadly optimal. Significantly narrower pipes, or special devices like bridges or freins may still keep up loudness by virtue of the higher harmonics.

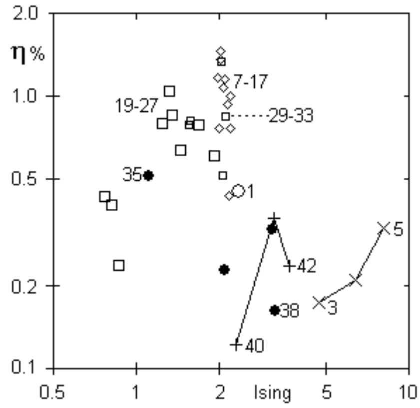

Figure 4: *Flue pipe efficiency (external sound) vs. Ising intonation number.*

2.2 Reed pipes

With beating reed pipes the length and thickness of the tongue are essentially dictated by pitch, pressure, and tongue material, [2]. Remaining parameters, available to control power level and timbre are tongue width and the area of the shallot opening which can be made considerably smaller than the tongue to increase R_x. With a large R_x the resonator will operate at a high Q but with a low pressure and efficiency, and weak harmonics. When instead R_x is small, then the resonator is heavily damped, higher harmonics from the reed are much transmitted and would render a brutal timbre, and air consumption would be high. - Shallot leathering is an additional option to soften timbre.

Free reeds like in an harmonium are ultimate to conserve space, prominently because they keep pitch without any resonator. Their main drawback is very low efficiency, slow tonal onset, and that the fundamental is weak relative to the second harmonic. The low sound level can be appreciably incremented using resonators. Since their waveform is two slightly grouped pulses per period tuning the resonator to the second harmonic is particularly effective (samples #72-3). #78-79 tested a shallot with a deep fitting trough rather than a thin plate, blocking the flow during half the cycle, but was a failure in improving the fundamental.

3. VOLUME CONSERVATION

There is a continuum of possible resonator designs from a cavity with an opening area A, varying the neck length L from a small value up to a quarter wavelength pipe of same cross section, see Fig. 5. For a given resonance, as L is increased the required volume V decreases, estimable from the Helmholtz resonance formula.

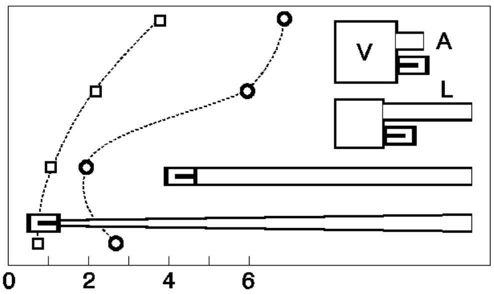

Figure 5: *Relative interior (squares) and circumscribed (circles) resonator volume, varying neck length L at constant frequency and mouth area A.*

The total volume of cavity and neck is however smallest at the extreme where L is a quarter wavelength. For volume conservation at given sound and supply level this indicates a pipe resonator is always preferred over a Helmholtz resonator. A Helmholtz can be smaller than a pipe only when its opening A is appreciably less than the pipe area, and this means a correspondingly smaller power handling capacity. An historical circumvention is a 'Wick's cube', one common volume shared by a set of different length ports connected with individual pallets, operable up to almost half an octave.

3.1 Pipe detuners

A conventional work around with sparse piping is to augment some pipes with tone holes, the same principle as used in orchestral woodwinds, such that you can raise them by one semitone.

One dual method proposed here is to connect an additional closed cavity at the flow node. This will instead detune the pipe lower. To lower a pipe one semitone corresponds to making it about 6% longer, so the required extra volume is estimated to be this fraction times the pipe area. Fig. 6 shows a practical implementation. The merit of this method is that the 'tone hole' and its operating mechanism are comparatively small, there is little flow but high pressure at this node. However, the additional device forms a cavity resonator where it is imperative its resonance is higher than the pipe fundamental. Otherwise the pipe interior will not feel it as a compliance and pipe function will be severely disturbed, in the first place by overblowing.

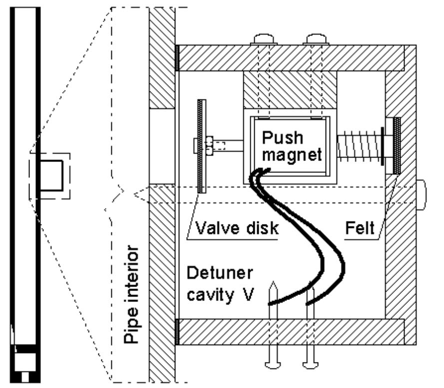

Figure 6: *Cavity detuner at a flow node.*

A variant method is to use a tube, closed with a valve at one end. The open end impedance of this has a first (resistive) minimum at resonance where the tube is a quarter wavelength. Just below that resonance it is capacitive, with a greater compliance than for the tube volume alone. So placing its open end at the flow node of a regular pipe will detune it lower. Since this detuner tube is shorter than a quarter pipe wavelength, when the valve is opened the detuner tube will have no action (other than a slight damping) and the pipe returns to its normal pitch.

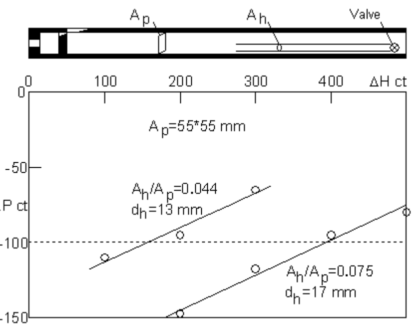

Figure 7: *Narrow tube detuner and measured effect.*

The graph of Fig. 7 shows measured results. The horizontal axis is how many cents ΔH above the basic pipe frequency the auxiliary tube is tuned. The vertical axis ΔP shows how many cents the pipe fundamental lowered as consequence. The target of lowering by one semitone is shown with the dotted line and measured points are indicated with circles. The trajectories can not be extended toward smaller ΔH. When the detuner resonance becomes too close to the pipe pitch, it will destroy the pressure maximum and the pipe will overblow (cf. action of the middle hole in a harmonic pipe).

4. REFERENCES

[1] Ising, H.: Erforschung und Planung des Orgelklanges. Walcker Hausmitteilung Nr 42, Juni 1971, pp 38-57.

[2] Liljencrants, J.: Design dimensions for a reed pipe tongue. http://mmd.foxtail.com/Tech/reedPipeDimensions.html, 2001.