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Non-conformistic pipe-scaling for a classical organ

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1. The Italian Renaissance organ :

The Italian Renaissance organ developed in a specific way from the common antique and medieval ancestors all subsequent organ types are supposed to have emerged from. Just like in all other art forms, Italian music is highly refined and expressive, in contrast with North European structuralism and restraint. Accordingly, the classical Italian organ which reached maturity when the polyphonic Josquin-Palestrina style acquired supreme recognition by the Council of Trent, was essentially designed to evoke this a capella performance practice. This in contrast with the North European (N.E.) organ, which stood apart from everything else and favored new sonorities and eventually new musical languages.

And so the goal was to reach utmost tonal unity throughout the voices constituting the polyphonic web, as it was performed in Italy's large Romance and Renaissance stone churches. All the essence of the Italian classical organ can be explained from this.
Tonal homogeneity is reached by the dominance of a fundamental pipe rank, the Principale. It is the heart of the organ around which everything else is built as means of creating subtle variations, and this is stressed in the prospect which shows the Principale from the longest pipe onwards, as illustrated in Figure 1 on the next page. On the contrary, in the N.E. organ, the principal ranks are mainly dedicated to and merge into the plenum sound. This Principale, as a representative of the singing voice, has a rich, yet profound character, obtained through relatively narrow scaling, low cut-up, low wind pressure through relatively wide foot bores and delicately adjusted flues.
Tonal homogeneity is further obtained by a very slender disposition besides the Principale: accents are given to its respective harmonics by means of principal ranks called after the musical interval they build with the fundamental: Ottava (8th), Quintadecima (15th), Decimanona (19th), and so on. These ranks are not clustered into some kind of mixture register. Indeed, this N.E. invention, with its complex breaks sometimes leading to pitch blurring and formant development, is entirely absent in the Italian 'ripieno': here, once a rank reaches a certain pitch (usually d8 at 1/4'), it simply breaks back an octave and tonal transparence is safeguarded. In general the aliquot principal ranks are conceived like the Principale, with an even somewhat smaller scale.
One of the elements that give the organ its grandeur, its ability to produce powerful low frequency tones, requires adequate collaboration of the surrounding space. The concept adopted by N.E. organ builders was to add more lower octaves to each note the larger the space, thus leading to 16' or even 32' based organs. In Italy however, lower notes were simply added the larger the space, thus extending the keyboard in the bass direction, a practice which actually corresponds to the ancient rule of thumb that the longest (open) pipe should fit about 16 times in the largest distance the sound can travel uninterrupted. Consistent with this is the 'suspended' pedal, which is essentially an aid to play the sometimes long held bass notes.

A very particular feature in Italian organ building is a tradition that existed in the classical period to use other materials than pipe metal for the pipes, specifically wood. Organs with all pipes made from cedar or cypres wood, having a smoother sound and being cheaper, were built for private mansions and palazzo's, but very little of them have survived today.

2. Building an Italian organ :

One of the goals of this building project is to see how acoustic principles can help to better understand the particular features of a style organ. The Italian Renaissance organ seems a good choice for this investigation for a number of reasons:

* Economic design with one dominant pipe rank characterizing the instrument.
* Through the use of spring chests leading to spacious placement of the pipes and shallow cases, and through absence of ranks of equal frequency, reduced mutual acoustical influence of pipes.
* Wooden pipes, with simpler geometry and greater internal damping than metal pipes, are better candidates for physical analysis.
* Through large footbores and low wind pressure, less complications from the pipefoot and, combined with low cut-up, less turbulent airjet-labium interaction.

Although many other capital problems remain the same as for any organ, it is felt that the limpidity of the overall character might be somehow reflected in the physical phenomena involved. The goal is to be able to somehow express the particular character of the instrument in acoustical terms.
Everything in the design of the organ depends on the pipe sizes, therefore this report will focus on determining mouth width scales, all pipes assumed to be square in internal cross-section. Based on these the windchest layout can be drawn, which in turn fixes the size of the instrument.

A final remark concerns the space where the future organ is projected, a large stone chapel with approximate length 25m, width 9m and height 12m, and large reverberating time T = 5 sec on average. A minimum sounding frequency for this room guaranteeing sufficient diffusivity can be found by considering the modal density using the Schroeder frequency: $f_m = 2000(T/Volume)^{1/2}$, giving 86 Hz. Applying the organ-builders rule of thumb would give 108 Hz, but this rule assumes a space more shaped like a church (that is, larger aspect ratio of the groundplan) and ignores absorption anyway.

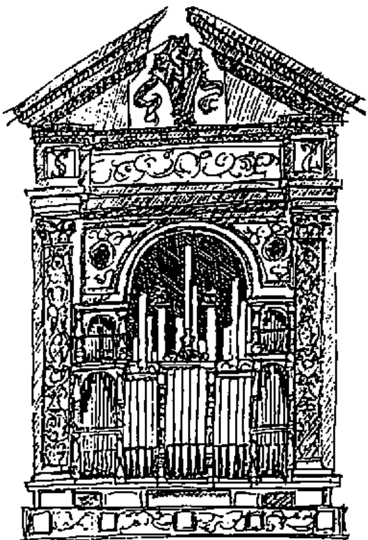

Figure 1 : Typical prospect of an Italian Renaissance organ : Firenze, Basilica della SS. Annunziata, D. di L. von Lucca, 1523.

3. Pipe scaling :

The organ-builder saw pipe scaling much from an economical side: attempting to use a little different mandrels and measuring-sticks as possible, reuse existing pipe-work, fitting pipes in given locations, respect certain prospect proportions, and, indeed, sheer economy of materials consumption. All this results in pipe scales many of which today look very puzzling or awkward although they can be found in great masterpieces which furthermore unmistakingly belong to a certain style. Fortunately the theorists were not completely unpractical, their predilection for simple fractions and geometric constructions was shared by the builders whose most important measuring tool was the proportional divider. But neither theorist nor craftsman is able to clearly characterize a particular style by simple and unequivocal parameters.

The qualitative characterization of the classical Italian organ given above is a background to a more specific description in terms of acoustical quantities of the Principale, the goal being to derive a scaling law for the rank. All pipes are assumed to have a square inner cross-section.
Many, especially 19th and early 20th century, organs exhibit a loudness peak in the middle to upper range, which is very suited for homophonic music, stressing melody and softening the accompaniment (see for example Harrison,1996). Poyphonic music requires a more balanced loudness progression, as confirmed by measurements on old Italian organs (Isabella,1996). Therefore the starting point will be the requirement of equal loudness levels throughout the rank. At this stage influence from the objects around the pipe and from the surrounding space will not be included here. Furthermore, attention will in the first place be given to loudness levels rather than the sound timbre produced by the pipes, the practical argument being that for square wooden pipes (with mouth width fixed by the diameter scaling) having a low cut-up adequate speech can be reached only in a limited loudness level range whereas the voicing can substantially change the timbre.

The method is to consider the energy going in and out of the pipe and using conservation of energy to make conclusions about the frequency dependence of the energy flows. A flexible and analytically simple dependence of pipe side (for square pipes) or diameter (for round pipes) on frequency is : $D = f^{-x}$, (1)
where f is the fundamental frequency of the pipe with side or diameter D and x defines the progression of D throughout the rank. To some $.5^x$ is a more familiar parameter as it indicates the size ratio of 2 pipes 1 octave apart; if x=.75, then this parameter equals the wellknown .595 or 3/5 of the normal scale.
Further assumptions as to the pipe geometry are:
* cut-up and flue width are proportional to D (2)
* supply pressure and, given the assumption of large foor bores, jet velocity constant. (3)

First the energy delivered to the pipe by the air from the flue will be considered. The air jet from the flue repeatedly blowing in the resonator and in the surrounding air more or less symmetrically, it can be considered as 2 equal and oppositely phased volume sources. one on the inner and one on the outer side of the labium. Their distance is assumed to be geometrically similar and thus also proportional to D. (4)
The magnitude of the sources can be assumed to scale like flue area multiplied by jet velocity. The power delivered by these sources can be estimated by first calculating the force exerted on the resonator air column. which is, by Newton's law, equal to displaced mass multiplied by the accelaration.
Displaced mass by the volume sources through the mouth, by (2) and (4), scales like: DD^2. (5)
Accelaration is the time derivative of flow velocity through the mouth of the volume sources, or, in steady state, the flow velocity multiplied by frequency. This flow velocity in turn is the flow rate of the sources divided by mouth area. Thus, using (2) and (3), the accelaration scales like: fD^2/D^2 . (6)
Finally, the power delivered is force multiplied by the acoustic velocity v of the resonator through the mouth, which, by (5) and (6), scales like : vfD^3 . (7)

Energy dissipates in various ways in flue pipes, through viscous and thermal losses near the walls, through radiation, and through turbulent air motion as a result of flow separation at the edges of the pipe. It has been

verified experimentally [Fabre et al, 1996] that, at least at the fundamental frequency, the turbulence loss mechanism is dominant. As a first approximation therefore, these losses only will be considered.
An air flow with density ρ, rate Q and flow velocity v through a pipe with cross surface D^2 carries with it a kinetic energy per unit volume of: $.5\rho(Q/D^2)^2$ or $.5\rho v^2$. (8)
If this flow discharges in free air, this energy is dissipated into heat by the flow separating from the outlet edges and becoming turbulent. The total power thus dissipated, and by (2), scales like : $v^2 vD^2$. (9)

Equating power fed and dissipated in the pipe gives, by (7) and (9) : $vfD^3 \sim v^3D^2$,where the ~ sign means : scales like. Using (1), this gives : $v \sim f^{(1-x)/2}$. (10)
The sound pressure level is proportional to this acoustic velocity, to the area of the open ends and to frequency. Thus, by (1) and (10), the sound pressure level p scales like: $p \sim f^{1.5-2.5x}$. (11)

The final step to be performed is to express the frequency dependence of the loudness level. Different methods have been developed to establish the link between sound pressure level and the subjectively perceived loudness level. Using the method outlined in ISO Recommendation No.532 it is possible to calculate the subjective loudness level of complex musical tones (with at least 4 harmonic upper partials) for given sound pressure level and fundamental frequency. The following approximate relationships can be assumed from the graphs (which are essentially based on the Fletcher-Munson curves), assuming a loudness level of ±75 dB:
Lowest octave (between 62.5 Hz and 125 Hz) : 4 dB/octave or $l \sim f^{2/3}p$
Second octave (between 125 Hz and 250 Hz) : 3 dB/octave or $l \sim f^{1/2}p$
Third octave (between 250 Hz and 500 Hz) : 2 dB/octave or $l \sim f^{1/3}p$
Fourth octave (between 500 Hz and 1000 Hz) : 1 dB/octave or $l \sim f^{1/6}p$.
For the pipe rank to have a constant loudness level l throughout, x should, by (11) have the following values the respective octaves: x = .87, .8, .73, .67 .

Viscous and thermal losses are proportional to wall area, acoustic flow velocity and the gradient of this velocity across the boundary layer (Batchelor,1974). The thickness of this boundary layer scales as $f^{-1/2}$ so that the velocity gradient roughly scales as: $v\,f^{1/2}$. Viscous and thermal losses thus, because pipe length scales as f^{-1} , for scale like : $D\,f^{-1}\,vvf^{1/2}$. (12)
Assuming for the moment these losses to be dominant, a power balance equating (7) and (12), gives: $vfD^3 \sim v^2Df^{-3}$, or, using (1): $v \sim f^{1.5-2x}$. (13)
The associated sound pressure level scales like : $p \sim f^{2.5-4x}$. (14)
From (10) and (13) it can be seen that for the normal values of x between .6 and .85, v has a very similar, and weak, frequency dependency. Or, put it another way, considering both friction and turbulance losses together: both terms have a similar frequency dependence around x = 2/3 at which value v scales like $f^{1/6}$ in both cases.
This means that viscous and thermal losses and turbulence losses will influence the loudness in much the same way throughout the rank, as illustrated by x values, calculated with (13) with the same data as before, of: x = .8,.75,.7,.67 .

Radiation losses are proportional to the square of the open ends surface areas, the square of acoustic velocity of the pipe and the square of frequency, thus scaling like $D^4v^2f^2$. (15)
Comparing (12) and (15), using (1), it can be seen that for values of x below 5/6 the viscous and thermal losses will dominate at low frequencies and radiation losses at high frequencies, and vice versa for x values above 5/6. This conclusion will be used to assume that radiation losses do not significantly influence the loudness level of the rank, especially in the case of wooden pipes with their higher wall losses, although they certainly strongly determine the progression of the timbre throughout the rank.
The scaling rule thus obtained is now compared to scales from extant Italian organs. Figure 2 shows the deviation of a number of scales with respect to the normal scale with x = 3/4. The deviations are expressed in half-tones, that is, the number of pipes more to the right or the left of the corresponding note of the normal scale one has to shift to find a pipe of equal size.

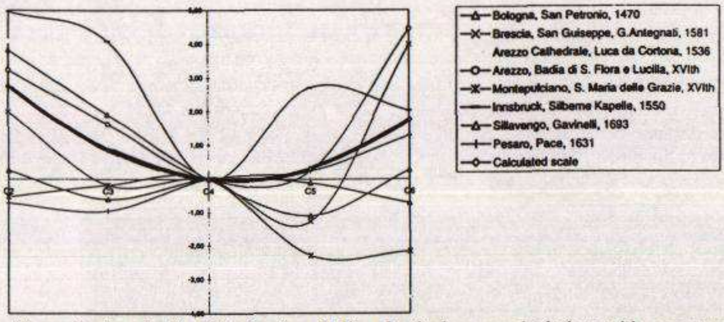

Figure 2 : Normalized scales (to C4) of various Italian classical organs, deviations with respect to normal scale x = 3/4

It can be seen that the calculated scale behaves as some kind of mean value, although the individual scales show considerable variation. In fact, two distinct ways of scaling can be identified. The first is some kind of 'fixed scale' method, with constant x value, usually obtained by some grafical method, and consequently appearing more or less as a straight line. The second method adds a constant value (though not necessarily constant throughout the whole rank) to this fixed scale, which then has value x=1/2 for ease of graphical construction. The resulting scale shows the characteristic enlarging towards bass and treble with respect to the normal scale. The overall picture seems to suggest that the Italian classical organ favors wider bass pipes compared to the normal scale, which, referring to the calculated scale, might correspond to a more even loudness progression. As an illustration the figure 3 shows scales of some N.E. baroque organs, of more recent date than the Italians because in N.E. original pipework from before 1650 is extremely scarce. It can be noticed that bass and treble scales are placed more symmetrically around the normal scale. The appearence of the two scaling methods is clearly visible.

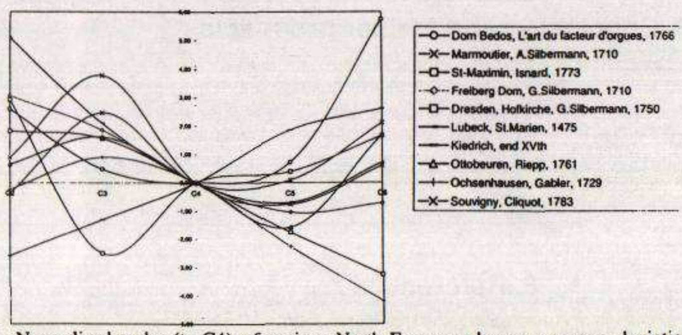

Figure 3 : Normalized scales (to C4) of various North European baroque organs, deviations with respect to normal scale x = 3/4

4. Windchest layout :

Just as in the other parts of the Italian classical organ, windchest design shows straightforward logic. The Principale always fills the prospect, with the largest pipe right in the middle, immediately showing the real size of the instrument. Notes are layed out in thirds, connected to the mean-tuning practice and giving the typical appearance of the Italian prospect as shown in figure 1.

Using the pipe scales and the sequence of the notes in the chest, closely associated to the prospect layout, the dimensions of the bar frame are calculated using software developed for that purpose. First the bar and channel widths are calculated taking into account restraints like minimum distances between pipes, minimum required widths of bars (with their pipeholes) and channels, ... Next pipe locations are calculated considering furthermore minimum distance between pipes behind one another, passage of the register spring slides, positioning with respect to the pipe supporting structures, ... An example of this layout is shown in figure 4 for a design with 5 ½ registers, showing the pipe footprints with pipeholes and the bar frame:

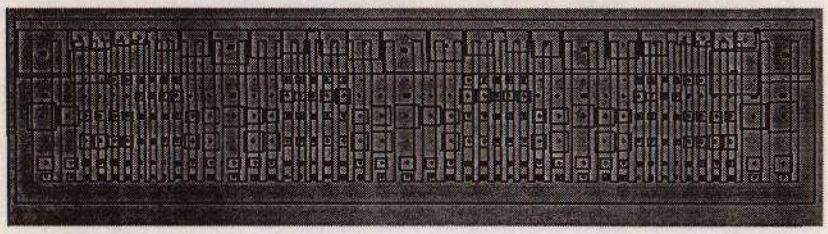

Figure 4 : Layout of a springchest showing bars and channels, footprints of pipes and pipefoots. Front upwards

This layout is plotted in real size on transfer-paper and can be directly used in the workshop instead of measuring-sticks and the traditional pipe stencils. For reasons of sheer size, the lowest 3 pipes are closed pipes, a usual practice in smaller organs, and they are placed on the left and right of the chest, behind the apparent columns of the prospect. One more large pipe was also placed out of sight for reasons of prospect proportion: the 3 pipefields in the middle of the prospect thus each have a large central pipe extending high above the adjacent ones. Most of the front pipes stand on groove blocks.

5. Conclusion and further prospects :

An attempt was done to characterize the pipe diameter scaling of the Italian classical organ in terms of measurable acoustic parameters. The often observed widening in the bass with respect to the normal scale is also observed in a calculated scale assuming constant loudness level throughout the rank. In an instrument so economically designed as the Italian organ, pipe scales determine the whole layout,starting with the windchest. Further work on this organ building project will include pipe mouth design, particularly important for an instrument like this which needs delicate voicing, wind transport throughout the instrument using bellows as feeders, and instrument-auditorium interaction.

6. References :

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