

SOUND OF THE ORGAN – ACOUSTICS OR ART?

Václav Syrový

*Musical Acoustics Research Centre (MARC) Prague
Sound Studio of Music Faculty, Academy of Performing Arts in Prague,
Malostranské. nám. 13, 11800 Praha 1, Czech Republic
syrový@hamu.cz www.hamu.cz/sound*

Abstract: The pipe organ represents a unique musical instrument in terms of technology, architectonic design and mainly sound. The source of the organ's sound is the flue pipe – the simplest wind musical instrument in terms of acoustics and construction, with fixed pitch, loudness, timbre and room localization of tone in the entire organ along with its sound correlation to the acoustic properties of the room.

1. Introduction

The organ is defined as a wind musical instrument consisting one or more scale-like rows of individual flue and reed pipes which are made to sound by air under pressure directed from a wind-raising device (soundboard or wind-chest) and admitted to the pipes by means of valves operated from a keyboard (manual, pedal).

The basic aspects of timbre of sound of the organs comes from the mechanism of production the tone in the flue pipe, and also from the philosophy of structure of organ sound, and finally from radiation of sound and its propagation within the real room. We can look upon these aspects in terms of both acoustics and of art. The whole of the pipes stands against the simple physical principle of flue and reed pipes as an artifact made to evoke emotions mainly through the sum of the elements of sound produced by these simple spatially-dislocated pipes.

The sound of the pipe organ is attributed to characteristic rationality due to the minimum participation of the musician, i.e. the organ player - organist, on the production of tone in the pipes, and due to the physically arranged structure of sound. In spite of this, it is this very rationality, together with the conditions for propagating sound in the given room, which effects the subjective perception of the listener many times more emotionally than in the case of sound of other musical instruments.

2. The production of tone in the pipe

The analytical model of the musical instrument forms a connection of the drive mechanism (exciter) as a source of energy with its own

vibrating mechanism (oscillator) and consequent resonator, which also normally enables radiation of the sound energy into the surrounding area. Limitation of individual parts in the majority of musical instruments does not cause special difficulties. If we take violins for example, it is the arrangement of bow, string and sound box. For the clarinet, it's the arrangement of airflow, the reed and the air column within the instrument, for the tympani it is the arrangement of the mallet, membrane and volume of wind within the drum chamber.

For the flue pipe, the oscillator is limited, actuated by wind flowing at the foot of the pipe, vibrating the air column within the body of the pipe. This is less obvious at first glance, and it is traditionally connected to the production of so-called friction tones, as described by Czech physicist Čeněk Strouhal in 1878. If the flow of wind is led through a narrow slit with sharp opening, the steady wind flow changes into turbulent, air vortex. A similar phenomenon also occurs when wind flows through a sharp edge. Along both sides of the slit or edges, there is formed a periodically repeating air vortex.

This periodicity gives production to friction tones, which clearly bring for example the rapid waving of a stick, but at normal speeds of the flow of air, these friction tones have very low intensity.

The arrangement of mouth in the flue pipe provides good conditions for the production of friction tones, which sometimes even deviate into so-called flue tones, i.e. tones originating by the throughput of wind along the space between the lower lip and the languid, and for edged tones, i.e. tones emanating from the wind bundle on the edge of the upper lip.

The mouth of the organ is directly connected with the air column, which is distinguished by strong

resonance qualities and which evidently predominates in terms of energy. The influence of the air column however is so great and so specific that it fundamentally influences the described mechanism of friction tones. If we prevent vibrating of the air column, we may set a regime of the production of friction tones and also associate the sound working point of individual pipes within one stop. The influence of the primary friction tones, to which acousticians and organ builders give credit for significant meaning upon creation of a tone in the flue pipe, actually regresses upon vibration of the air column.

That is, the methods of making the sound more visible were discovered by a true oscillator – an air reed in the mouth of the pipe, which differ greatly from the mechanism of friction tones, uninfluenced by the air column. The vibrating reed is relatively sharp-edged and does not have the character of wind vortex as friction tones. During this period, its effective length changes, which from the acoustic viewpoint represents an actually changed effective height of the mouth. The regime of oscillations of the reed can influence in part the position of the edge of the upper lip against the flue (windway), and in part by the design of the flue, i.e. its width, the languid bevel of the pipe and nicks on the languid.

The listed voicing interventions are projected into both the character and the timbre of the tone of the pipe. The bias of oscillations of the reed inside the pipe leads to a stronger, but less timbreful tone, and deflection out from the pipe to a weaker, but more timbrefully rich tone. Nicks on the languid lead to limiting the production of rush and noise components upon initiating a tone and make voicing of the pipes easier.

The qualities of the organ tone are in a much greater measure determined by its own resonators – air column, which in the coupled system with air reed evidently dominate in terms of energy. The frequency of the tone of the flue pipe is given by the length of the air column and its type of ending. Every pipe has an open end in its mouth and an open, closed (stopped) or semi-closed (partially stopped) end at its upper opening. The functional length of the air column that determines the pitch of the pipe tone is larger than the corresponding mechanical dimension.

That is, the air column is burdened by the radiation impedance of the mouth or upper end, and this impedance is dependent not only on the shape and dimension of the opening, but also on the

frequency of the tone of the pipe. Therefore the diameter of the opening of the pipe influences not only the degree of non-harmonicity of the resonance modes of the air column, but also the intensity of higher harmonic components in the resulting tone. With the rising diameter or cross section, the content of the higher harmonic components in the tone drop, which becomes “rounder”, and vice versa. The dimensional relations of one pipe and between pipes mutually form so-called scaling, which in a significant manner influence the character of the tone, mainly then its timbre in both the sense of individual stops, and in the sense of dependence on the pitch of the tone during the course of every stop.

3. Structure of the organ sound

Back in antiquity, the pipe organ brought with it the basic philosophy of contrast of sound of one flue pipe and the sound of the entire ensemble of these pipes. On sacral ground, this inner contrast was gradually led to outer unity of the instrument sound in close relation to the acoustic properties of the room. Here, organs also came into contact for the first time with choir singing, and with its basic sound differentiation of male bass and female, or then more properly worded, boyish treble.

From imitating this vocal differentiation, a chorus principle developed of stop-list in the dialog of male voices – “core” principales and female voices “soft” flutes. The multi-voice likeness of choral singing (organum) stems from parallel-led voices towards the basic voice (vox principalis), has projected itself into the philosophy of pipe organ sound built on the basic stop – Principal.

Towards this came the necessity to handle the room in terms of energy, which would only be possible by way of rationally built structure of sound. That is, the sound power of the tone rises much more quickly, when the tone is enriched by higher harmonic components, than when this tone is only replicated in unison.

Therefore, the rationale of structure of the tone of one pipe brought over to the rationale of structure of sound of the ensemble of the pipes and arrangement of individual series of pipes in the sense of tonal pitch corresponded to the sequence of higher harmonic components of a single tone. This principle of structure of the so-called sound pyramid of the organ, which does not exist in any other musical instrument or ensemble of instruments, became typical and unique even in its

historical development and relation, mainly to sacral places.

The sound of the pipe organ in its dominant likeness is given by a “addition” of tones of various ranks of pipes – individual stops, which differentiate from one another in pitch, loudness and timbre (including the character of attack) of the tone, and in the competency towards the partial whole of the pipe organ – so-called *werk*, which is precisely defined along not only sound terms but also in terms of the localized space. The principle of the sound pyramid is projected into the offer of stop-list in the sense of additive sound synthesis and also the chorus and *werk* principles respectively.

The chorus principle is set upon basic scaling contrast of narrow pipes of *principales* and wide pipes of flutes, and is often augmented by a contrasting, most narrowing pipes of string stops, and functionally entirely different reed stops. The *werk* principle is founded on the contrast of originally independent instruments (grand organ, positive organ, portative organ, regal), which are assigned to individual manuals (keyboards) of a single instrument, and which together form a logical whole.

Consequently, the built sound pyramid of principal (*diapason*) stops, which follow their pitch position in position of harmonic tones, leads to the basic sound value of the pipe organ - towards the so-called plenum of specific volumen, pitch position and sound balance in relation to the room and appropriateness towards the selected organ *werk*.

The plenum also represents the boundary between the newly created sound whole and an entirely illogical sound emulsion of individual stops, i.e. the golden cut between sound unity and contrast, upon whose relation the philosophy of the sound of the pipe organ is founded. The structure of plenum reflects according to the most varied of empirical relations, mainly the size of the room, in which the pipe organ is located, and the number of listeners.

The size of the room determines the scaling of the principal chorus, as well as the basis of the principal chorus, i.e. the lowest principal stop in terms of pitch, and the size of the sound crown as an opposite pole of the basis. The sound crown is the stop made up of several ranks of pipes (principal scaling) in relations to octaves and fifths - the so-called Mixture.

4. Radiation and propagation of the organ sound

From the standpoint of radiation of the sound, pipe organs represent an ensemble (in simplified terms) of acoustic sources of two types: stopped flue pipes with an radiation opening in the mouth, and reed pipes with radiation opening in the end resonator as a simple emitter, more frequently opened (also half-stopped) flue pipes with two radiation openings (in mouth and the end) similar to acoustic dipoles. It is generally the case that with the rising frequency (of basic tones and their higher harmonics), the radiation angles oriented to the axis of the radiation opening narrows.

The dipole character of mainly long open pipes complicates the radiation relations of the pipe organ luckily only close to the instrument, in greater distances they appear only in mutually vertical position, so-called main directions of radiation. The mouth on the majority of flue pipes is aimed horizontally into the room towards the listeners, the end of the open pipes and the sound of the reeds on the contrary are aligned vertically towards the ceiling of the room.

For increasing the sound effectiveness for listeners, certain reed stops are located in the horizontal position into the prospect of the pipe organ (i.e. Spanish trumpets). Propagation of the sound of the organ in the specific room influences location of the organ towards the listener, the sound perception of the listener is influenced by the distance from the organ, by the intensity and delay of the first reflections in the horizontal, vertical and medial plane, as well as the reverberation time and its frequency dependence.

The sound of every musical instrument, i.e. even the organ, is perceived by two subjects – the player (organist), who is found in relatively small distance from the pipes, and the listener, whose impression of the organ sound is strongly made by the acoustic qualities of the given room.

For organs however, there exists a third regular listening position, which is inside the instrument within immediate proximity to the pipes, in which the organ builder is found during tuning and voicing (adjusting the sound) of the instrument.

All three listening position are very important for the voicing of pipes and for an evaluation of objective and subjektive organ sound quality too.

5. Subjective reflex of problems of the pipe organ

The acoustic problems of organs in sacral rooms come from a series of causes, which can be generalized as acoustic qualities of the room, location of pipe organ with regard to the radiation and consequent propagation of the sound and stop-list (specification), scaling and voicing of the pipe organ.

The construction and mainly sound development of the organ is first correlated to sacral ground, upon which, after initial refusal as an instrument with a worldly feature, the pipe organ arrived in the 8th century. Pipe organs were beginning to be constructed on a regular basis within churches from the 10th century, and there they gradually obtained their contemporary likeness, which from the aspect of the relation of their sound and acoustic qualities of the room, obtained the optimum sound during the height of the Baroque Period.

The most important acoustic parameter of closed places, in which the sound of the pipe organ developed (and also the entire European musical thought), was the reverberation. This reverberation not only extended the information and thus enabled overcoming the chronological threshold of hearing, but also "amplified" it, and "filtered" it in the sense of its frequency dependence. Mutual oversounding of tones created a virtual, vertical sound structure, which conformed with the vertical structure of the sound pyramid for organs, and then gradually there was created an organic relationship between the organ and the room.

Monumentality of large instruments in large areas was born, as was *intimacy* of small instruments in small rooms. In a large room, the small instrument from the viewpoint of monumentality often appears as insufficient in terms of sound, but displays a purposeful intimacy, ex. in the likeness of choir organs. In the small room, the large instrument always appears as oversized, and the monumentality of the music actually seems to become aggressive.

From the purely psychoacoustic viewpoint, the organic harmony of instrument and space represented the monumental organ plenum (or tutti) by balanced dynamics and timbrefulness of the space leading up to the known feeling of "goose bumps", and this isn't even in any way the consequence of just the volume of sound or simply the existence of a reverberation. The subjective

causality of the monumentality of sound (mainly the pipe organ) is necessary to search for in the sound pre-image of the organ, what was the human voice in its vocally choral presentation.

Pipe organs in their initial development on sacral ground stemmed from the choral presentation not only from the viewpoint of timbre differentiation of sound, ex. in the sense of separating the spatial arrangement from "male" and "female" stops – "voices", but also along lines of volume of sound, have conformed with limited dynamics of the human voice. The monumentality of choir singing is not and has never been about a pathological scream, but rather in complicated interferences stemming from intonation, modulation and spectral deviations of the physiological position of the voice of individual singers. Further interference enters, stemming from the real area as a consequence of the "addition" of direct and reflected sound in the room where the listener is located.

Monumentality of sound generally depends on:

- *the psycho-physiological phenomenon in the human ear*, then mainly the increased non-linearity of the transfer in consequence of incorporating adapting mechanisms at the levels of acoustic pressure above 80dB/A, which in terms of the pipe organ depends on the recommended level of volume of the stop Principal 8' approximately 80 Ph, and together with leveling curves of the same loudness and thereby with leveling of the timbre sensation.

Upon registration of the plenum (approximately 90 Ph) or tutti (approximately 100 Ph), the influence of differential tones (1st order) must, in non-linear transfer, constantly exceed sum combination tones, whose impression is now accompanied by the entrance of aggressiveness of the sound.

- *the sounding of the sound in the real space*, as a cause of amplifying and lengthening of sound information and in psychological consequence also confirmation of this information. Dependent upon this is also the influence of virtual sound structure arising as oversounding of individual tones of the original single-voice melody. The natural filtration of sound information through frequency dependence of the reverberation time has a relatively smaller influence on monumentality in this case.

- *interference* between naturally tuned vertical structure of the sound pyramid of the pipe organs and equally tempered tuning of keyboards and with

interference occurring as a consequence of deviations from such tuning. Similar interference occurs at the location of the listener as a consequence of various time delays of various rays of sound. The commercial practice names the listed interference as “chorus” or “choral” or “cathedral” effect.

It's not possible to understand the intimacy of the sound as the opposite of monumentality, but rather as a qualitative anti-field leading to total unison of sound information. The intimacy of monumental-sounding pipe organs comes mainly from the available possibilities of the instrument and from registration fantasy of the organist.

For the intimacy of the sound, the previously mentioned dynamic and timbrefulness and balance of the new virtual space in immediate proximity of the listener, where the influence of the real area retreats, and detail begins to become dominant in the sound, even from the viewpoint of the various types of interference mentioned.

If the boundary between monumentality and intimacy should express only the parameter of reverberation, then its length would measure around 2 seconds. Roughly 3.5 seconds is considered the optimum duration of reverberation for organ music of a solo character, and for that of a chamber character, it is closer to 2 seconds. In rooms with the reverberation time under 2 seconds, sound intimacy should be dominant, stemming from the size of the stop-list, scaling and voicing of the pipes, even in the case of formal resizing of the instrument.

The monumentality and intimacy of the sound of the pipe organs do not only represent their differentiating incorporation into the room, but also one of the contrasts leading to sound unity of the instrument as a whole.

A typical example of this contrast could be, for example, the dialog of the great organ and positive organ, originally entirely separated independent keyboard instruments within the confines of a church. Closely related to the monumentality of the sound of the pipe organ is the spaciousness, defined as the sound overlap by the sight of perceived dimensions or outlines of the pipe organ or organ case.

Wide and narrow rooms analyze in the listening axis a small impression of spaciousness, the sound of the organ is locally limited to the location of the organ case, and the listener does not have the feeling of “surrounded by music”, which is also

strongly related to monumentality. Similarly, rooms also appear with a strongly attenuated ceiling.

Even other criteria of acoustic quality of the space contribute to monumentality of the sound in varied measure, such as brightness, balance, volume, etc. These criteria are defined and quantified ex. in the measure of bright, the measure of volume, etc. Their optimum mutual ratios are widely changing in relation to the intended aim of the room, and the lecture hall, other concert hall for chamber music, and a different hall for orchestral music will all indicate different relations.

The autonomous area for pipe organ music has always been inside a place of worship – sacral, where the organs first fulfilled the function of a wedding instrument and subordinate to appropriate liturgy. It's from this subordinate position that even certain classic forms of organ music developed, such as choral prelude.

From today's viewpoint, historic sacral rooms fulfill the criteria of acoustic quality first and foremost for organ music (liturgical and concert character), and the vast majority of the organs in these environs displays the corresponding psycho-acoustic effect.

In certain criteria, such as in the frequency dependence of the reverberation time it is even possible to differentiate “Gothic” character with a continuous drop in the reverberation time in relation to the rising frequency, and the “Baroque” character with its typical maximum reverberation time in the middle frequencies.

The modern sacral rooms, if they are not on the level of architectonic replicas, differ from Gothic body and Baroque dome differ greatly, even of course along acoustic lines. From this viewpoint however, the modern pipe organ differs from the Baroque ones in only entirely meaningless aspects, and therefore come into conflict with the subjective notion and the reality of the organ sound in modern sacral rooms.

The subjective notion of monumental, grand organ tones as a consequence of a non-organic relationship of instrument and space become in conflict with reality of the oversized to aggressive sound, or the opposite with an “undelivered” sound spreading from somewhere in the back or from above.

6. General procedure of sound design of pipe organs

There exists no universal guide for how to simply attain the required organic unit of sound of pipe organs and room, since this unity isn't easily defined. The pipe organs were always designed and constructed (still today) in existing spaces. It could therefore seem that it is the pipe organ, or mainly its acoustic qualities, must adjust in all aspects.

The impression of this feature of formal unity may however, in the case of non-typical rooms, lead to abandonment of the principles of construction of the pipe organ sound, and to violation of its typical subjective effect. In the past, organ builders built their instruments in sacral rooms only on the basis of their experience and feel for sound, as they had with them no knowledge or means of today's musical, psychological and room acoustics. Currently, organ builders are satisfied with these open experiences only during construction of instruments in classic, in the majority of cases problem-free organ rooms, and in the event of already existing modern sacral rooms, they may base their design proposal for an instrument only on their acoustic documentation.

In the case of a project of a new sacral room, the design of the organ should be created at the same time in confrontation not only with the design of the acoustic qualities of this room, but also with the impression of their realization. Specific location of the instrument, incorporation of individual organ divisions and design of the organ case and prospect may attain (or worsen) in a fundamental way the required "filling" of the room with sound, emphasize (or suppress) monumentality or on the contrary, the intimacy of the sound of the organ.

Location of the organs must take into account in psychoacoustic terms the more advantageous distribution of sound from the instrument to the listener from above and from the small room to the large one. The main direction of radiation of sound (in the horizontal direction of the pipe mouths and in the vertical direction of the pipe openings) must be in accordance either with the direction of the required concentration of sound, or on the contrary with the required dispersion of the sound. These requirements shall influence location of the instrument either at the wall or even better, in the corner of the room, or opposite in sufficient distance from the wall.

Due to the fact that the radiation qualities of the organ are not omni-directional, it is possible to consider location of the organ for example in the middle of the auditorium as an exception to the rule in order to serve the purpose.

In the event of locating a larger instrument at the level of the auditorium, it is necessary to use reverberation from the ceiling of the room, which means incorporating the organ divisions, or their soundboards (wind-chests) and construct the organ case in such a way, so that the fundamental part of the sound of the organs used these reflections.

Radiation of the instrument may also influence the orientation of soundboards towards the room and specific locations of the pipes on it. In justifiable cases, it is possible to simply limit the disturbing specificity of "pronunciation or articulation" of the pipes including radiation of high frequencies by turning or half-turning the particular pipe within the pipe racks.

The acoustic qualities of the room and the design of localization of the instrument are firmly influenced by the architecture of the room, and in the vast majority of cases, preempt the actual design of the organ stop-list. The stop-list does not only include a formal enumeration of stops and aiding equipment, but also scaling of the pipes (i.e. dimensional design including material), choice of soundboards, action and wind system, and the design of further construction and technical details. The basic question appears to be the size of the instrument – number of stops, limited from the side of the user, and also mainly the purchase price and room, which has been determined for location of the instrument.

The organist's wish is always the largest, and universally conceived stop-list, which fulfills the requirements of liturgy and also enables concert usage of the instrument. Upon the first decision, the acoustic qualities of the room are generally not taken into consideration, and the design of the stop-list only follows formal criteria, mainly the relation of the number of stops to the size of the room or number of listeners.

This relationship expressed by a series of historic and currently revised empirical formulas however is in itself misleading, and may serve only to compare various large instruments in various sizes or rooms, where there occurs no fundamental clash between the size of the room and the subjective impression of the reverberation time.

The proposal of the stop-list as a simple enumeration of stops depends on the geometric and also the acoustic properties of the room only immediately and in terms of stops and in indications of their pitch positions, provides the first impression of the logic of the construction of the sound pyramid, mainly of the principle choir, character of the plenum and variability of registration possibilities. In this likeness, the very same design of the spatial arrangement may be validated in various, completely different rooms in terms of acoustics, because it is incomplete and nonfunctioning.

The true relationship of the stop-list to the room represents to the proposal of scaling of the pipes, which stems from physical and acoustic relationships between the average or cross-section or volume of the pipe and corresponding loudness or sound power of the tone, corresponding timbre of the tone and corresponding carrying power and capability of mixing the tone.

It is generally the case that the larger the scale (diameter) of the pipe, the greater the loudness of the tone, and therefore a lower content of harmonic components, or “weaker” tonal timbre and higher capability for mixing and power carrying of the tone.

The larger room requires a larger scale for maintaining the subjective impression of the corresponding loudness of the tone. The scale of the pipe is however first dependent on the pitch of the tone, because the diameter of the pipe must decrease with the pitch of the tone, so that the character of the tone timbre is firstly maintained in the entire extent of the stop, normally four to five octaves in keyboard.

The scaling proposal is comprised of a choice of absolute scale (Principal 8') and in the choice of relative scaling, which establishes the dependence of absolute scale on the pitch of the tone, and also in the choice of relations of measure between individual registries in the vertical and horizontal sense of sound. While the absolute scale reflects first the size of the room, then the relative scale reflects the frequency “characteristic” of the room, i.e. the dependence of the reverberation time at the frequency.

Without regard to specific course of this dependence, if the listener does not perceive the overage or underage of low or high frequencies (given space “does not rumble” or “hiss”), or possibly unnaturally emphasized area of middle

frequencies, then the choice of relative scaling depends on the acoustic qualities of the room only through an individual approach and the feel of the organ builder.

If however the frequency dependence on the reverberation time mainly along subjective lines shows a certain anomaly or non-standard course, then the course of scaling may help the compensation of such deficiencies. Put simply, if the space shows for example a non-standard decrease in deep frequencies, expanded thus by scaling of the pipes in the low position, it is possible to compensate subjectively for this decrease.

The capability of mixing tones together so that the connection of two “timbres” creates a third “timbre”, is the quality of mainly widely scaled flutelike voices (stops), and then the already narrow scaled principals of even narrower strings.

The capability of mixing with the specific room connected only implicitly, through the selection of absolute scaling, but the power carrying of the tone with the properties of the room is directly related. Carrying is defined as the “resistance” of the tone against loss of its sound power in relation to the distance from the instrument.

A small carrying stop may sound very strong directly beside the organ, but its loudness will quickly weaken as it gets farther from the source. Aside from this the weaker, but still bearing tone is capable of filling the entire room. Therefore, losses decide on power carrying, i.e. frequency dependence of absorption or the reverberation time in the considered room.

This dependence is mostly unfavorable mainly for concert halls and modern sacral rooms against the transfer of high frequencies, and therefore the sound power of tones with a not too high a content of basic i.e. 1st harmonic component with the growing distance from the organ quickly drops. The pipe emits an energetically developed basic tone by a wide scale.

The loudness, just like the timbre of the tone, however, isn't only dependent on diameter scale, but also on other parameters of the pipe., i.e. on the scale (dimensions) of the mouth, wind pressure and overall voicing of the pipe. The choice of these parameters can significantly influence the character of the tone; a wide pipe may also issue a weak and sharp tone, and a narrow one may issue a strong and dull tone.

7. Conclusion

Three basic aspects determine the sound of the pipe organ: the mechanism of production of the tone in the flue pipe, the philosophy of the structure of sound and its radiation from the organ and propagation in the given room.

While for the first aspect the dominant factor is the acoustic interpretation, the second aspect is mainly represented by artistic experience. The third aspect then combines objective physical causality and art as an individual subjective approach to generally valid and objectively substantiated experiences.

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