Proceedings of the Institute of Acoustics

TOWARDS A DESIGN FOR PIPELESS ORGAN LOUDSPEAKERS.

L.K. Comerford and P.J. Comerford

Microcomputer Music Research Unit (Department of Computing), University of Bradford, UK

1. Introduction

This paper is written from the point of view of authors without technical expertise in the field of loudspeaker design, but with practical experience of voicing pipeless classical organs of a variety of sizes and styles installed in a wide range of buildings. This voicing work is centred upon use of a digital musical instrument simulator [1] developed by the Microcomputer Music Research Unit (MMRU) in the Department of Computing at the University of Bradford; the most recent generation of the simulator is known as BEST (Bradford Enhanced Synthesis Technology). BEST additively synthesises single cycle and multiple cycle waveforms, and both types of waveform can be "voiced" (that is, adjusted in spectral and frequency envelope in the transient and in the steady state) in real-time on a PC using specially developed graphical tools.

Loudspeakers are an essential part of this sound creation work, and the success or otherwise of pipeless organs depends not only on using a synthesis system of sufficient quality, and on expert on-site voicing, but also on the loudspeakers used (and their positioning in the building). This application places an interesting combination of demands upon a loudspeaker system, and for this reason, the MMRU is commencing an EC-funded research project which complements its work on synthesis systems by aiming to define the design characteristics of loudspeakers with suitable qualities for use in pipeless organs. A related study by the MMRU is examining the viability of producing practical guidelines for optimal placement for pipeless organ loudspeakers in a range of installations with varied acoustic environments.

As a necessary preliminary to defining loudspeaker design characteristics for this purpose, this paper considers the following questions:

- what features are special about organ sound?
- what are the qualities loudspeakers must have in order to produce these special features of organ sound?
- what is to be learned from past experience of loudspeakers used for pipeless organs?
- how is the success of loudspeaker designs for this purpose to be evaluated?

2. Features of organ sound

Each pipe organ is really a collection of musical instruments which produce sounds of different pitches and with different tonal characteristics, all under the control of one player and all able to sound simultaneously. In this way, an organ is perhaps more like an orchestra under the control of a conductor than it is like any other instrument played by a single musician. The variety of the characteristics of sound sources active together, with different tuning, amplitude and frequency envelopes, tonal spectra and so on, creates the **complex perceived ensemble** [2] characteristically associated the sound of an organ. Its sound can vary in power from the merest whisper to extremely forceful plenum, and can encompass fundamental frequencies ranging from 16Hz (very rarely, as low as 8Hz) to around 16.3Khz, with partials extending beyond the range of human hearing. This wide frequency range is an important musical feature in the construction of each organ chorus, which is based on the extension of tone up and down from unison pitch [3]. It is used in organ music to enhance crescendos by re-inforcing the upper harmonic structure of the chorus[4], and also has the effect of increasing perceived ensemble [2].

The features outlined above should be equally present in pipe organ sound and pipeless organ sound. One of the areas where these two types of organ will differ most markedly is that of spatial considerations. In a pipe organ, the unique location of each pipe, the perception of which is emphasised by transients [5], enhances the ability of the ear to perceive the presence of separate sound sources active simultaneously [6], and contributes to a complex spatial effect. In even the largest pipeless organ there is not a separate loudspeaker for each note of each stop sounded.

3. Considerations for pipeless organ loudspeaker design

Given the above characteristic features of organ sound, the following considerations are of importance for loudspeakers to be used for its production.

- **wide frequency range**
  A frequency range extending to 20KHz and above is not an unusual loudspeaker requirement, but the bottom notes of pipeless organ pedal stops necessitate loudspeakers capable of producing very low frequencies (16Hz and sometimes below) at a high level of power. Precise splitting off of very low frequencies in the synthesis system allows the design of loudspeakers to handle these frequencies to be optimised to cover only the required range.

- **good transient response**
  Attack (and decay) transients are an essential feature of all musical sounds, and in organ sound they affect not only tonal identification per se, but also the differentiation of the presence of each sound in a plenum. Good transient production, unblurred by boosted resonance at relevant frequencies [7], is therefore important.

- **high power handling and high efficiency**
  Pipeless organ sound is often to be produced at high levels in large spaces and to be heard over a long distance. As well as the obvious requirement to produce distortion-free waveforms from affordable amplifiers in these circumstances, loudspeakers for pipeless organs need to be robust enough to withstand long exposure to such usage. This is the more important since they are often installed in inaccessible places thus making minimal maintenance and repair a necessary consideration.

- **wide dispersion**
  In relation to pipeless organ sound, this has two aspects: the directionality of the sound produced from each loudspeaker, and the spread of sound from the entire loudspeaker installation associated with each instrument.

In a pipe organ, even in an instrument of modest size, all the pipes together take up a considerable amount of space often bounded by chamber walls. Reflections off adjacent pipes and off the walls increase the effective dispersion of the sound of each pipe. Thus only a large obstacle can obscure more than a small proportion of such a dispersed sound source as an entire pipe organ. The sound from loudspeakers, on the other hand, being more directional from each loudspeaker, spread over a lesser physical area than an "equivalent" amount of pipes, and seldom set in a large chamber, is much more easily blocked by obstructions such as pillars, especially as organ loudspeakers are often required, for architectural rather than acoustic considerations, to be installed in the least conspicuous place possible. This has a particularly deleterious effect upon high frequencies.

- **low colouration**

  Colouration is really a product not just of the loudspeaker but of the loudspeaker and the location in which it is set; this makes it hard to be definitive about loudspeakers to be used for pipeless organs since they are to be sited in locations of such acoustic variety. Both local effects, such as the nearness of walls, and more general influences like building size, surface coating and the presence of padded seating, will alter the perceived colouration. Although it is possible, and indeed desirable, to voice an organ to suit its acoustic environment, this facility should not have to be used to compensate for unwanted colourations from the loudspeaker itself. Lower mid-range colouration is particularly to be avoided.

- **size**

  Pipeless classical organs are, by their nature, often to be installed in buildings where no architectural or acoustic provision has been made for their placement. This may be because of the antiquity of the building, or because musical and acoustical considerations have been held to be secondary in the planning of a new building. In practice this can place severe restrictions upon the available and permitted loudspeaker placement locations, with implications including the following:

  - *installation location*

    pipeless classical organ loudspeakers are often required to be located on high narrow inaccessible ledges or in shallow spaces behind decorative facades, where size is a limiting factor in the choice of loudspeaker.
  - *appearance*

    since locations which allow direct egress of sound are often also in direct line of sight, it can be important that the loudspeakers are either of suitable size and shape to be conveniently hidden or disguised by an acoustically transparent covering while still allowing sound egress, or that they are widely judged to be objects of beauty in themselves which blend appropriately with their surroundings.

  For these reasons, there are installations where it would be an advantage for the loudspeakers to be of the smallest size concomitant with fulfilling other requirements. Given the limited space often made available for pipeless organ loudspeaker installation, small size would also have the advantage that a large number of loudspeakers each carrying a separate signal could be more easily accommodated, with consequent beneficial effect on spatial perception.

- **moderate cost**
  To enhance spatial effect it is important that pipeless organs use multiple sound output channels, each with its own loudspeaker; an instrument built with Bradford synthesis technology has the potential for up to 64 sound output channels. Using separate sound channels produced from different locations is of importance for pipeless organs, since the human auditory system is sensitive to the direction of sound sources [8], using interaural distinctions in sound intensity, in spectrum, and to some extent in time [9]; it can therefore use multiple loudspeaker locations, each producing different signals, to enhance perception of spatial dimension and so be aware of simultaneous sound sources, which are a characteristic musical feature of organ ensemble. Thus it is important that the loudspeakers are producable at a cost which makes this use of multiple loudspeakers an economic proposition. As noted earlier, high efficiency, facilitating the use of less expensive amplification, is economically desirable.

4. Past experience of loudspeakers used for pipeless organ sound

When pipeless organs are sold commercially, each company tends to supply a different type of loudspeaker; the type of loudspeaker used may be influenced not only by acoustic considerations, but by constraints of cost and space, as outlined above. The MMRU, although not responsible for the loudspeakers used in commercial installations of Bradford organs, has experience of many different types of loudspeaker used in these situations.

As a result of subjective listening tests using different loudspeakers, field-tested with a pipeless organ at a church site in a variety of different positions and under a variety of conditions, the MMRU originally (in 1980) chose for its own use the *Wharfedale E90* loudspeaker (details in endnote[i]). This decision was made in the light of loudspeakers available for testing at the time and affordable on a university research budget, and was influenced by the high efficiency of these loudspeakers, their good high frequency response and the "cleanness" of their sound. The loudspeakers were judged to perform best, for a wide range of organ styles and in varied acoustics, with the low contour control set to -2 (this reduced frequencies in the range c. 200Hz to 1.5KHz by c. 2dB). Drawbacks for pipeless organ use were the lack of low bass frequencies, the large size and heavy weight of the loudspeakers, and the directional nature of the sound produced, especially the high frequency sound.

As a result of such tests, a pipeless organ manufacturer, J. Wood and Sons Ltd of Bradford, commissioned Wharfedale to produce 2 modified versions of the E90 for commercial use in the pipeless organ market; this work was undertaken by their engineer Mr. R. Lee. The models produced were:
E90 'O'

- The -2 setting on the low contour control was "built in" to the design and the contour controls were removed.
- The single treble driver was replaced by a separate crescent-shaped array of 6 tweeter units, mountable on top of the main enclosure, producing slightly less high frequency response than the original E90 on-axis, but increased high frequency response off-axis.
- The enclosure was constructed of less heavy, unpolished wood, with short legs instead of back wheels.

E90 'S'

This loudspeaker was designed to handle only low bass frequencies, down to 16Hz.

- It had 2 bass driver units (no midrange or treble)
- Contour controls were removed
- The oval front port of the original E90 was replaced by a circular port in the bass of the enclosure (the enclosure stood on short legs).
- The loudspeaker was used in conjunction with a specially designed external circuit for the boosting of resonance at 16Hz.

Although still bulky, and with mid-range frequencies still directional, this combination of loudspeakers was judged successful in producing powerful, distortion-free, clean-sounding organ tone over a very wide frequency range in a large variety of installation situations and different acoustic environments.

Unfortunately, when the original driver units used in the E90 'O' and E90 'S' became unavailable, the substitutes used were less successful for this application. There was particular difficulty in identifying a bass driver which would reproduce frequencies of 16Hz.

In an attempt to tackle the problem of directionality, an experimental loudspeaker called the *Toblerone* was used by J. Wood and Sons Ltd. As its name implies, this enclosure was triangular in cross section, each face being 440mm wide and 1200mm high. The enclosure had a circular 110mm diameter port in the top, and two 200mm (8") drivers were set one each into 2 of the faces, at different heights (about 1/3 and 2/3 of the height). High frequencies were produced from the same crescent-shaped array of 6 tweeters as was used with the E90 'O'. The Toblerone was used either standing up, with the same signal being produced from both left and right facing faces, or else lying on the undrivered face near a wall, with the same signal being both directed out into the room and bounced off the wall. The Toblerone did not have the power handling capability of the E90 'O', making it unsuitable for use in many organ installation situations, nor did it have a comparable low frequency response; it was also slightly more coloured by lower mid-range resonance. However, used in conjunction with the array of tweeters (and with the E90 'S' to produce the lowest frequencies), all frequencies were now well diffused, and it was judged to work well in close listening environments and in small buildings, used either alone or in addition to the E90 'O'.

In some small-scale domestic installations where space is at a premium, great compromises have had to be countenanced in the choice of loudspeakers. Almost any external loudspeaker is preferable to the practice of using internally fitted drivers speaking from beneath the key shelf into the organist's knees, although even this situation can be improved by the addition of upward-pointing tweeters to ensure that high frequencies are not attenuated. The most successful loudspeakers of bookshelf size experienced by MMRU, and evaluated in a wide variety of acoustic environments, were *B&O Beovox CX100*; it must be noted however that these were only suitable for installations not requiring high output power, and that supplementary loudspeakers were needed for any frequencies below c. 60Hz.

Such practical experience of the performance of loudspeakers used in the past for pipeless organ sound endorses the considerations noted above, the need for power and efficiency and the benefits of wide dispersion. With regard to frequency range and colouration, it has been noted that lack of satisfactory high frequency distribution is the most detrimental to satisfactory organ sound, closely followed by the effects of mid-range boom. It is also apparent that in practice, before being adjudged suitable for pipeless organ applications, a loudspeaker design must be evaluated in a number of different building acoustics and, unfortunately, in installation locations which may not accord with those specified by the manufacturer. It has been the experience of the authors across a wide variety of installations and acoustic environments that, given loudspeakers capable of producing the wide frequency range required, and with a sufficient number of separate signal channels, a critical factor in the successful location of pipeless organ loudspeakers seems to be having hard flat parallel surfaces quite near to the sound source, so that a high degree of indirect sound can be produced without excessive spectral modification, especially with minimal attenuation of high frequencies. A local environment such as this can create a high degree of perceived spaciousness while retaining clarity. A pipe chamber can often produce a local acoustic of this type with wide-spectrum indirect sound reflected from other pipes and from the chamber walls. This appears to the authors to be one reason why the change in overall building acoustic caused by the arrival of an audience or congregation is, in general, less detrimental to pipe organ sound than to a pipeless organ, which seldom has the benefit of such an ambient chamber.

5. Evaluation

The aim of the study is to identify or produce loudspeakers which will allow the synthesis system to be used to the full and to have the best chance of performing with the same musicality as pipes. Once a set of performance criteria has been defined which will fulfil this aim, in the light of the considerations discussed above, it will be possible to identify whether these criteria can be met with an "off the shelf" solution or combination of solutions, or whether custom designs are required. Then begins the task of design evaluation, and of comparing alternative solutions. This evaluation should have two aspects. Firstly, loudspeaker performance must be measured against the specified *performance criteria* (power handling capability, efficiency, frequency response, dispersion and so on), with consideration for the different kinds of acoustic environment in which the loudspeakers will be sited; further discussion of performance criteria is beyond the scope of the present paper. Then using *perceptual tests*, the loudspeaker performance must be assessed, individually and comparatively, against the sound of pipes heard in the same acoustic environments.

A number of considerations inform the definition of these perceptual tests, including musical context, audio memory, acoustic environment, subject selection and experimental method. **Musical context** has a profound effect upon perception [10], so it is important for the evaluation to use "real music" rather than experimental sounds [11], including a variety of organ tone, stops of different volume, and a range of ensemble sizes and playing styles. Another important consideration is the shortness of **audio memory**. It is undoubtedly possible to retain entire "auditory images" over a long period of time, enabling familiar voices and sounds to be recognised even in unexpected contexts. However the authors have experienced, personally and by observing other critical listeners to organ sound, that it can be very difficult to retain accurate details of one sound in memory for qualitative perceptual comparison with another, subtly different, sound, if the sounds are separated by more than a few seconds. More "informed" comparison is possible if the contrast is repeated a number of times - presumably because the brain is able to "recognise" and retain more detail in the compared sounds on successive auditions. Thus the evaluation method should permit speedy alternation of sounds for comparison, and repeated presentations. As noted above, evaluation should take place in a variety of acoustic environments at different realistic installation sites, in order to discover how loudspeakers perform "across the board" not just in optimal conditions. On the question of subject selection for the result evaluation,

> "Acquired knowledge interacts with current sensory data to interpret the auditory stimulation." [12]

This is true in all listening situations, musical and non-musical, where interpretation of sounds reaching the ear is informed by experience. "Specialist" listeners may have experience which enables them to distinguish or interpret more from a sound stimulus than can non-specialist listeners. Well-known non-musical examples are the "Golden Ears of the French Navy", who

> "have been trained in sonar detection to listen to what most of us would hear as a noisy underwater sound field and to perceptually segregate and identify a multitude of underwater sources such as clicking shrimp, whales, porpoises, schools of fish, and ocean-going vessels. They even succeed in classifying such vessels as commercial or military, as surface or submarine, as diesel or nuclear, as Russian, American or French." [12]

In such a case, a group of specialist listeners could, by virtue of their specialism, give rise to statistically significant results, despite the small size of the group in comparison with the general population [13]. In this case, the specialist knowledge would be of organ sound, including specifically pipe organ sound. The challenge for the experimenter would be to identify such specialist listeners who would nevertheless approach synthetic organ sound in a non-biased fashion, and who would also not have any preconceptions about the suitability of particular types of loudspeaker. For comparisons between pipe sound and pipeless sound, or between identically constructed pipeless sounds produced through different loudspeakers, it is suggested that paired comparisons would be a suitable experimental method. Despite being numerically cumbersome in producing statistical results, this approach is successful in enabling very similar sounds are to be compared perceptually without recourse to longer term audio memory; such direct comparison of two stimuli is more reliable than if more than one comparison is to be made at once. This method has been proven useful and effective in the case of distinguishing subtle differences in organ sound [2].

To date, the choice of loudspeakers for use with pipeless organs has been made largely on a heuristic basis. By examining special features of organ sound and their implications for loudspeaker requirements, reviewing past practice, and suggesting considerations to be taken into account during evaluation, it is hoped that this paper will have opened the way to a more formal approach which will produce more satisfactory results.

6. References

[1] COMERFORD, P.J. Simulating an organ with additive synthesis. Computer Music Journal, Vol. 17, No. 2, Summer 1993, pp55-65

[2] COMERFORD, L.K. The perception of ensemble in organ sound. PhD Thesis, University of Bradford, 1996

[3] MERCER, D.M.A. The physics of the organ flue pipe. American Journal of Physics, 1953 pp376-386.

[4] PADGHAM, C. The scaling of the timbre of the pipe organs. Acustica, Vol. 60, (3), 1986, pp189-204

[5] VERCOE, B. Perceptually-based music pattern recognition and response. Proceedings, 3rd. International Conference on Music Perception and Cognition, Liege, 1994, pp59-60

[6] HANDEL, S. Listening : an introduction to the perception of auditory events. MIT Press 1989

[7] WATKINSON, J. The art of monitors. Studio Sound and Broadcast Engineering, Vol. 37, No. 9, September 1995, pp61-64

[8] ASKILL, J. Physics of musical sounds. Van Nostrand 1979

[9] BUTLER, D. The musician's guide to perception and cognition. Schirmer, New York 1992

[10] McADAMS, S. and BREGMAN, A. Hearing musical streams. (Chapter 36) in ROADS, C. and STRAWN, J. ed. Foundations of Computer Music MIT Press 1985

[11] KRUMHANSL, C.L. Perceptual structures for tonal music. Music Perception, Vol. 1, Fall 1983, pp28-62

[12] McADAMS, S. and BIGAND, E. Introduction to auditory cognition. Chapter 1 in McADAMS, S. and BIGAND, E. ed Thinking in sound : the cognitive psychology of human audition 1993 Clarendon Oxford

[13] SWAIN, J.P. Musical perception and musical communities. Music Perception, Vol. 11, No. 3, Spring 1994, pp307-320.

Acknowledgements

The authors are grateful to Mr. Richard Wood, M.A., of J. Wood and Sons Ltd, for permission to reference experimental work on loudspeaker design.

---

[1] *Wharfedale E90 loudspeakers (published data)*

Typical frequency response:	*43Hz to 18Khz +/- 3dB*
Bass loading:	*maximally flat fourth-order Butterworth*
Contour controls:	*4-position low contour control for lower midband response 100Hz to 2khz (maximum attenuation -5dB); 4-position high contour control - operates progressively over 2khz to 10KHz (maximum attenuation -5dB)*
Sensitivity:	*1 watt produce 95dB SPL at 1 metre*
	1.2 watts produce 96dB SPL at 1 metre
Nominal impedance:	*8 ohms*
Drive unit complement	*2 x 250mm (10") moving coil bass drivers*
	2 x 100mm (4") moving coil midrange drivers
	1 x 25mm (1") compression drive horn-loaded treble driver
Dimensions:	*Height 1130mm; Width 380mm; Depth 371mm*
Nominal enclosure volume:	*110 litres*

Suitable for amplifiers from 15 to 200 watts (RMS per channel)