MODERN LOUDSPEAKER TECHNOLOGY MEETS THE MEDIEVAL CHURCH

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1 INTRODUCTION

The acoustics of medieval churches, particularly those of larger churches and cathedrals, had a direct and formative influence on the worship offered within them. Developments in patterns and styles of worship over the centuries and the recent exploitation of church buildings as venues for concerts and civic events have left many Cathedrals and Great Churches acoustically unfit-for-purpose. This paper seeks to review the acoustics of large medieval churches with special reference to Beverley Minster, the largest gothic parish church in Europe. It is further the purpose of this paper to illustrate how recent developments in DSP-controlled loudspeaker arrays offer a new option for reproducing high quality sound within the large, highly reverberant spaces which such buildings present.

2 HISTORICAL CONTEXT

Great Churches and Cathedrals in the English tradition are visually imposing structures. Whilst they were built to glorify God they also, to some extent, glorified the institution of the church, making a powerful statement of authority and influence. In creating these vast buildings the church created spaces, which are visually impressive and awe inspiring, but acoustically limiting.

The buildings were divided so as to reflect the divisions and hierarchies in ecclesial practice at the time they were built. An elite occupied a relatively intimate space, the chancel/choir and presbytery/sanctuary whilst large congregations could be accommodated in the vastness of the nave. In most instances a screen visually separated these two spaces, emphasising the de-coupling and division.

Within chancels, volumes of order $5000m^2$, worship followed monastic precedents; clergy said the daily offices of morning and evening prayer and the choir sang. The acoustics of the chancels were difficult – so much so as to shape the development of sounds that were produced within them. This evolutionary pressure influenced the development of sacred music and the clerical voice. Music succeeded by working with the difficult acoustics. Slowly changing passages, as in much choral music, worked with the long reverberation times. Alternatively, very quickly changing passages, as ultimately expressed in organ toccatas, “beat” the long reverberation times. Spoken voice in the chancel relied on the development of the slow, somewhat exaggerated liturgical voice and the proximity of all occupants of the space.

The naves, volumes of order 15000 m^3 with hard, reflective surfaces on their walls and floors, were space whose acoustics were seriously limiting. The occupants of these spaces could not hear intelligible speech from a voice more than a few metres distant and certainly not from voices of clergy at the high altar or in the chancel.

As example, the average of the reverberation times measured at a number of points in the nave and in the chancel (the “Quire”) at Beverley Minster are shown in Figure 1

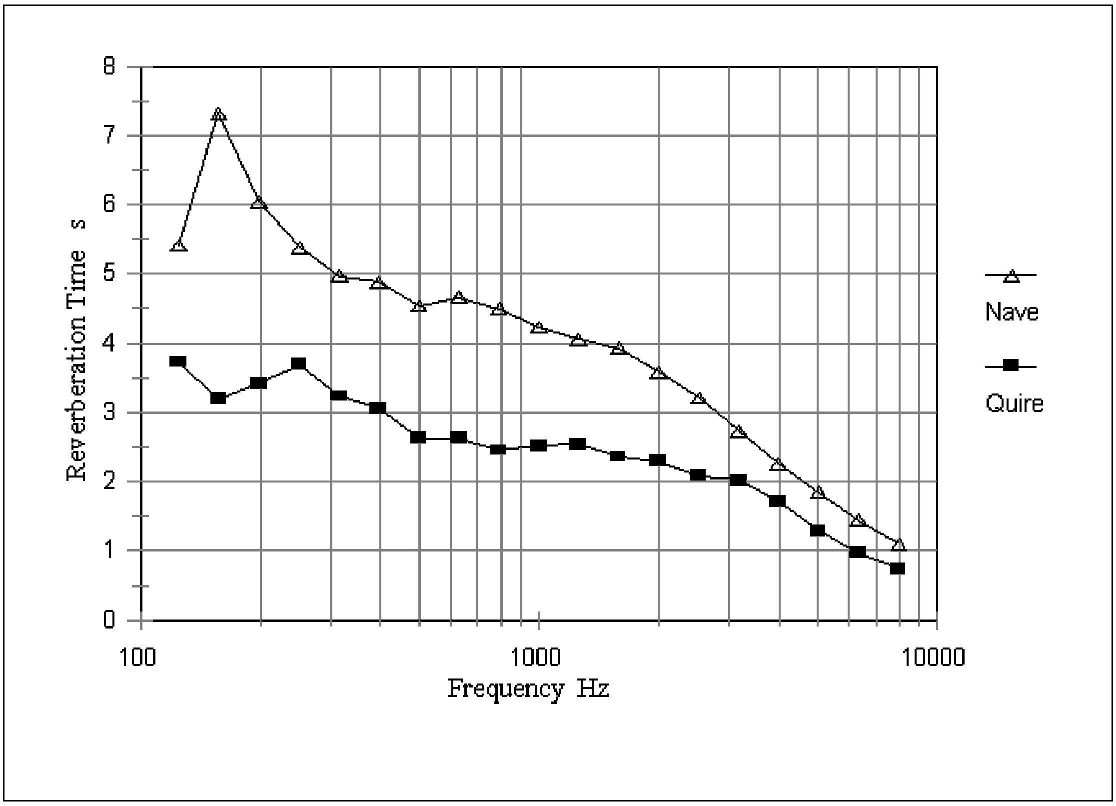

Figure 1 Reverberation Times in Beverley Minster

The relative volumes of the two spaces yield surprisingly similar critical distances (/reverberation radii) for a spoken voice (Q ≈ 2.5) of order 4 metres between 500 Hz and 2 kHz. Given the smaller linear dimensions of a chancel, many of its occupants are seated within this critical distance from the speaker. In a full nave the vast majority of occupants are outside the critical distance. The audible experiences of Church for those few seated in the chancel were clearly very different than those of the masses in the nave.

3 LITURGICAL DEVELOPMENT AND INNOVATION

Patterns and practice of worship are continually developing and the last 500 years have seen revolutionary change in English liturgical practice. Distant voices from the chancel of an English church in the 16th century would have been unintelligible to the common man even in perfect acoustics as the greater part of the service was in Latin. It was not until 1539 and the publication of the Great Bible that the scriptures were available to be read aloud in English churches *in English*. Faced with such potential for public access to the word of God, read aloud in the native tongue, the acoustics of the nave were suddenly revealed as a serious problem!

Innovation in the last century overcame the visual and acoustical remoteness of the high altar in Cathedrals and Great Churches by introducing a nave altar. From this altar located at the east of the nave, priestly actions of consecration during the mass became visible to all, opening the door to a change in engagement with this central pillar of Christian worship. Once priestly *action* became visible, it became clear that *words* should be audible. Prayers at the altar could be proclaimed aloud rather than mumbled – once again the limitations of the nave acoustics stood in the way!

A further important innovation in liturgical practice has occurred in the last 50 years, which sits very uncomfortably with the acoustics of medieval churches. Modern secular musical genres have been incorporated into sacred music and songs for worship. These developments are typified by the appearance of “music groups”, including percussion instruments and electric and electronic instruments. The temporal patterns of the music group’s repertoire and, in some cases, the spectral content of their output, interact with the reverberant field of old churches in an unsatisfactory manner. The large congregations in the nave, some of whom were drawn to participation in worship by the new musical styles, are unable to hear due to the acoustics of the nave.

Each of these developments and changes in the use of spaces available within Great Churches and Cathedrals have implied that more of those people occupying the nave should be able to hear and understand more of the spoken word and music used in worship. This was supported initially by the appearance of greater “vocal strength” and even more exaggerated diction – the “pulpit voice” - in the clergy. Latterly, the developments have only been sustainable in the presence of reinforced sound systems.

4 REINFORCED SOUND SYSTEMS IN GREAT CHURCHES AND CATHEDRALS

To improve audibility and intelligibility in the nave of large churches, sound reinforcement systems are now a necessary feature. The same acoustics that make unaided speech and certain aspects of music unintelligible within the nave also complicate the design of a sound reinforcement system. As example, a system with a single conventional loudspeaker (or pair of loudspeakers) at the east end of the nave will be unacceptable because the direct sound will be uneven over the sittings.

This natural consequence of the radiation will result in a hot area near the loudspeaker and increasing attenuation as distance from the loudspeaker increases. The reverberant field will be approximately equal over the entire nave, with the consequence that direct to reverberant ratio will change at different positions. Those seats within the reverberation radius of the loudspeaker will, by definition, experience positive direct to reverberant ratio, whilst those without will experience negative D/R ratio and associated poor intelligibility.

This phenomenon is illustrated by figure 2, which shows the RASTI at different positions along the centre line of the nave of Beverley Minster, associated with a single conventional loudspeaker at the east end of the nave. The loudspeaker had an eight-inch low frequency unit and a compression driver coupled to a CD horn, giving Q’s of approximately 4 and 5 at 500 Hz and 2 kHz, respectively.

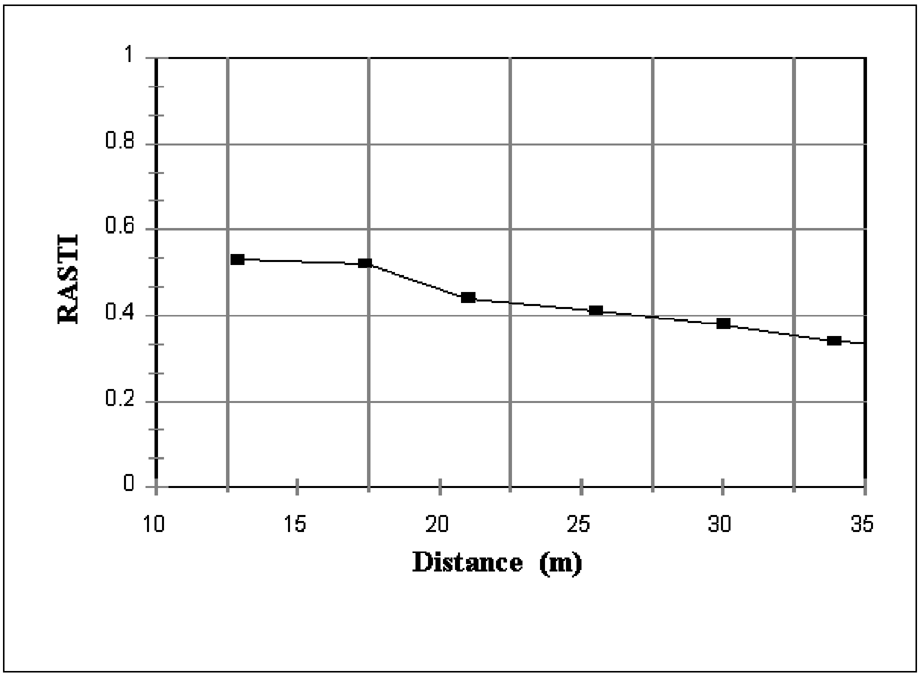

Figure 2 RASTI values in Beverley Minster;

Single Conventional Full-range Speaker System

The single loudspeaker achieves (surprisingly) good performance over distances *exceeding* the reverberation radius, but quickly deteriorates thereafter.

The variation of direct sound level over the sittings in the nave conventionally has been addressed using multi-speaker systems in which a number of loudspeakers are distributed through the length of the nave. These multi-speaker installations typically are time-aligned to match propagation delays of sound down the length of the nave. Whilst such an approach can avoid some of the problems that make a single conventional loudspeaker installation impossible, there remain some technical drawbacks.

The loudspeakers specified in multi-source installations are small. Their small size carries a penalty in a tendency towards omni-directional radiation, meaning that the reverberation radius is reduced, relative to a larger single unit. The large number, N, of small speakers required in a multi-source system also carries a penalty in direct to reverberant ratio relative to the operation of one loudspeaker, again reducing the effective reverberation radius. This penalty on D/R ratio amounts to 10log(1/N), which, in combination with the inherently low directivity of small sources, limits the potential performance of a distributed multi-source system in the nave of a large medieval church.

Recent advances [1,2] in the application of Digital Signal Processing technology to loudspeaker systems have opened new possibilities in implementing multi-source systems. Rather than distributing many sources throughout the nave, these systems cluster the multiple sources as an array. Each array element is driven by a signal designed such that the directivity of the total array can be precisely controlled.

The elements of a linear array, arranged as a vertical column loudspeaker, can be driven by inputs designed to generate a radiation pattern that is tightly controlled in elevation and usefully wide in azimuth. Such a digitally controlled column loudspeaker (or a pair) could be positioned at the east end of a large, reverberant nave and configured so as to produce uniform direct sound over all the sittings.

This concept is demonstrated by example in figure 3, which shows the early energy at seated and standing ear height, measured at different distances from a single AXYS Intellivox 6c digitally controlled column speaker at the east end of the nave of Beverley Minster. Here the early energy is defined as the integral of the squared impulse response over fifty milliseconds from the direct sound arrival time, t_d, i.e.:

$$EarlyEnergy = 10\log_{10}\left[\frac{\int_{t_d}^{t_d+.05} h^2(t)dt}{E_0}\right]$$

$$t_d = \frac{d}{c}$$

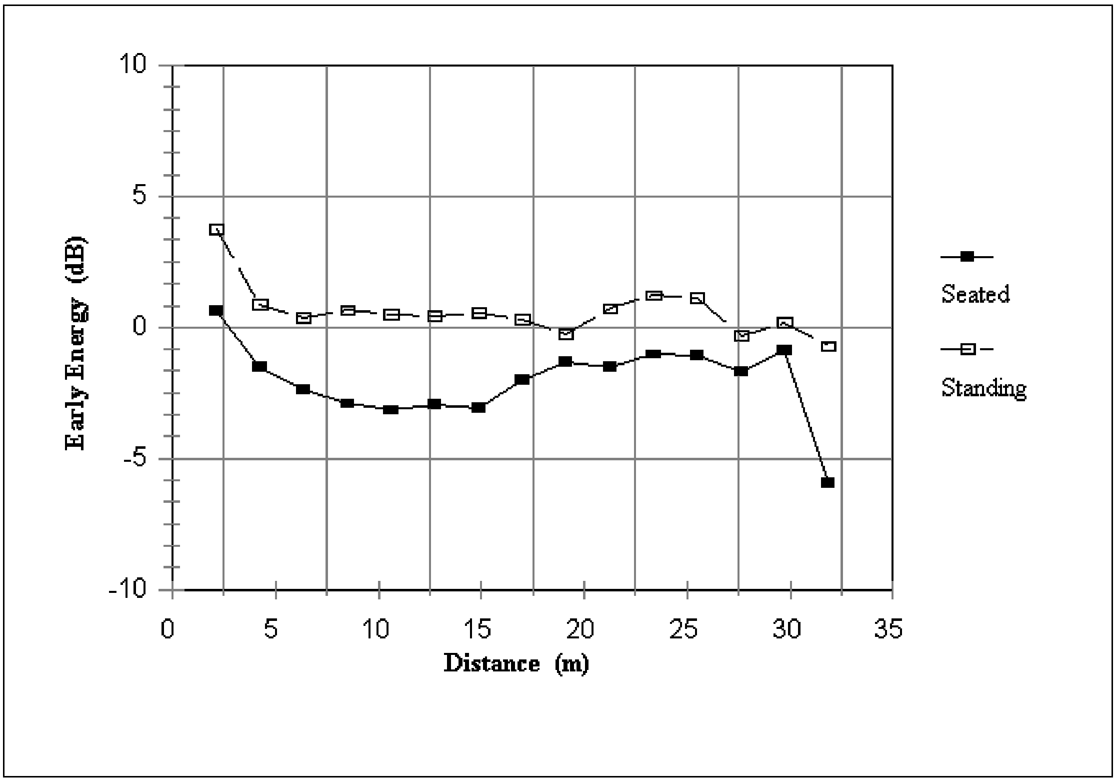

Figure 3 Early Energy at ear plane of nave in Beverley Minster;

AXYS Intellivox 6c Loudspeaker

Note that the early energy from the loudspeaker is effectively independent of distance, giving constant direct sound levels at all the sittings in the nave. The radiation pattern shown in figure 4, which was sampled on a vertical plane on the axis of the loudspeaker, achieves this. *(The effect seen at 20 m distance is an artefact of the interpolation procedure used to produce the contour plot from the data gathered at the 48 measurement points.)*

Notice that the ear plane, seated or standing, is below the main lobe and that the main lobe tilts downwards towards the ear plane to compensate for the sound attenuation over distance, leaving the effectively constant early energy at ear level reported as figure 3.

Figure 4 Vertical Slice through radiation pattern in nave of Beverley Minster;

AXYS Intellivox 6c Loudspeaker

Since the loudspeaker system was programmed to operate into a very tight "beam" (4 degrees included angle of elevation), the Q is high and the power going straight to the reverberant field is minimised. Given the constant direct sound arriving at all the nave sittings, measures of energy fractions such as clarity and deutlichkeit are very constant over the whole nave area. Similarly, the RASTI values do not fall with increasing distance (as in figure 1). Rather RASTI is constant, as shown in figure 5.

Figure 5 RASTI in nave of Beverley Minster;

AXYS Intellivox 6c Loudspeaker

5 CONCLUSIONS

The acoustics of large medieval churches have limited the sounds that can be used in worship since the time the buildings were erected. Subsequent changes in patterns of use have required that intelligible sound is audible over the entire nave, rather than in smaller areas of the building. This requirement is impossible to achieve using single loudspeakers of conventional design and difficult to achieve with a distributed multi-source system.

A DSP-controlled column loudspeaker has been shown to be capable of providing

- remarkably even direct sound coverage
- minimum excitation of the reverberant field and, consequently,
- good intelligibility

at all sittings within the nave of a very large English Minster church.

This installation is believed to be the first of its kind in Great Britain. It proves that the attractive performance of Digitally Controlled Loudspeaker arrays, widely reported in simulations and free-field measurements, also can be achieved within a highly reverberant space. Such evidence shows this modern loudspeaker technology to be a highly effective means of providing intelligible, high quality sound in large church buildings, making them spaces which are fit for the acoustical purposes which modern worship presents.

REFERENCES

1. E W Start & G W J van Beuningen, "Analysis of DDS-Controlled Loudspeaker Arrays by 'Near Field Acoustic Holography'", Proceedings of the Institute of Acoustics (Reproduced Sound) Vol 23, Pt 8, pp 95-109 (2001)

2. "DDC Digital Directivity Control" Paper available at Duran website : http://www.duran-audio.com/