ARCHIVES OF ACOUSTICS
2, 2, 105-113 (1977)

THE APPLICATION OF ORGAN SOUND IN REVERBERATION MEASUREMENT IN THE CONCERT HALL OF THE WARSAW ACADEMY OF MUSIC

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Reverberation in the concert hall at the Academy of Music, Warsaw, was determined in the range from 50 to 8000 Hz using the organ as a sound source. The results obtained for 100-4000 Hz do not differ significantly from those obtained from conventional method.

To explain the differences in the range of lowest frequencies, the control measurement of the sound decay in low register organ pipes was performed. It was found that the time of sound decay in these pipes may actually be comparable to the reverberation time of the hall.

In the range of highest frequencies the measurement was carried out using a specially selected organ chord to get the sufficient energy in the upper part of the spectrum. The results are in agreement with those obtained by conventional measurements.

1. Introduction

For some time the increased interest in possible application of musical instruments, as natural sound sources in measurements of the reverberation time in concert halls, has been observed. These measurements are based on recording of a music piece, ending with a strong, suddenly interrupted chord, or on recording of a single chord with special harmonic structure and instrumentation. The reverberation time is evaluated at various frequencies with the aid of band-pass filter.

Reverberation measurement using natural sound source has several advantages. Firstly, it may be expected that this method preserves the natural conditions of sound radiation in a hall. The kind of a sound source, the placement of instruments on the stage, their spectral and directional characteristics etc. are adequate to those usually occurring during the concert. Secondly, the use of natural sound sources enables the measurements with the audience being present in the hall, i.e. in the condition when routine measurements are not possible. The recording made for measuring purposes must satisfy some special

conditions of a microphone placement. Also the microphones used should not have directional characteristics. The artistic phonographic recording, often distorting the natural reverberation, is therefore not advisable.

Apart from the advantages mentioned above the measurement with natural sound sources presents also some disadvantages. One of the most serious is the relatively low acoustic power of musical instruments and difficulties in achieving immediate damping of their radiation which is indispensable for evaluating the reverberation correctly. The lack of power, necessary for building up the appropriate sound intensity in the hall, is most evident at the extremes of the auditory spectrum, thus making the evaluation of reverberation at very high and very low frequencies difficult or even impossible.

The distortion of measurement, caused by the low rate of sound decay at the source, may be of two kinds. First, it may result from inefficient additional damping or non-simultaneously applied disconnection of power supply in vibrators of musical instruments. This may concern either a single instrument (e.g. non-simultaneous release of keys) or a group of musicians or singers. Secondly, the distortion of measurement may be caused by the insufficient rate of sound decay in such cases where additional damping cannot be introduced. This factor eliminates some instruments from their possible application as natural sound sources in reverberation measurements [4].

Among many musical instruments that might be considered as suitable in reverberation time measurements, the organ seems to be particularly useful. This is because of several reasons. Firstly, the organ may produce high level of spectral energy in broad frequency range. Secondly, the vibrators of organ pipes have small inertia and their vibrations quickly disappear (this claim does not fully pertain to the lowest register which will be discussed later on). Thirdly, the organ is operated by one musician, which is very convenient for technical reasons in reverberation measurements. Another favourable fact in measuring reverberation using organ as a sound source is that this instrument can be found in most concert halls and churches. LOTTERMOSER [2] has described an interesting case of using the recording of the organ sound for measuring reverberation. It comprised the evaluation of acoustic conditions of the church "Frauenkirche" (Dresden), which was completely destroyed during the World War II, on the basis of old recordings of the organ. Thus additional clues to the reconstruction of the interior were obtained.

2. Reverberation measurement over full frequency range using single organ chord

The organ at Warsaw Academy of Music is equipped with four manuals, pedals and 60 flue and reed stops. Electropneumatic action is combined here with a mixed, slider- and ventil-wind-chest action (Great). The instrument is spaced at the two opposite side walls of the concert hall at the stage level. Total volume of the hall is 5.500 m^3.

For reverberation measurements two following chords were recorded:

– the final chord of J. S. Bach's organ toccata in D minor,

– the final chord of J. S. Bach's organ prelude in E flat major,

– a chord obtained by depressing all the twelve keys in lowest octave of the Great (tutti combination).

Sound intensity levels, measured in the middle of the 8th row of the orchestra seats, were 92 dB for D minor chord, 93 dB for E flat major chord and 95 dB for the twelve-tone chord. The chords are presented in Fig. 1. The results of the spectral analysis of these chords, obtained with the use of B-K 1614 1/3 octave band analyzer, are presented in Fig. 2.

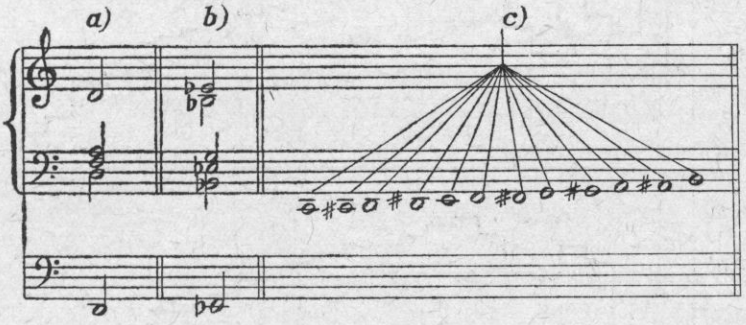

Fig. 1. Musical notation of three organ chords used in reverberation measurements a) D minor chord, b) E flat major chord, c) chromatic twelve-tone chord

The frequency analysis of D minor and E flat major chords displays the existence of partials in a considerably wide range. High intensity levels within the frequency bands, centered at 40 and 50 Hz, are produced in pedal register. It should be noted here that acoustic power distribution in the sound spectrum of organ chords may significantly change, depending on the specimen of the instrument. Differences are most significant for the lowest and highest frequencies [3].

The analysis of the twelve-tone chord as compared with the analyses of other chords shows the lack of the lowest partials in frequency bands 40 and 50 Hz. This is due to the fact that manual keyboards only were used in this case, connected by means of coupling mechanism. Manual keyboards of the organ in Warsaw Academy of Music have only two 16-foot stops, with the frequency of the lowest tone C – 32.7 Hz. These registers, Quintadena and Rankett, are characterized by weak fundamental tones. To secure the presence of strong low partials in the spectrum, it should be advisable to use the pedal keyboard. It appeared, however, impossible because of the difficulties in simultaneous release of 12 consecutive pedal keys without a special device.

Spectral analysis of the chords used leads to the preliminary conclusion that the measurement of reverberation by means of the organ sound may be

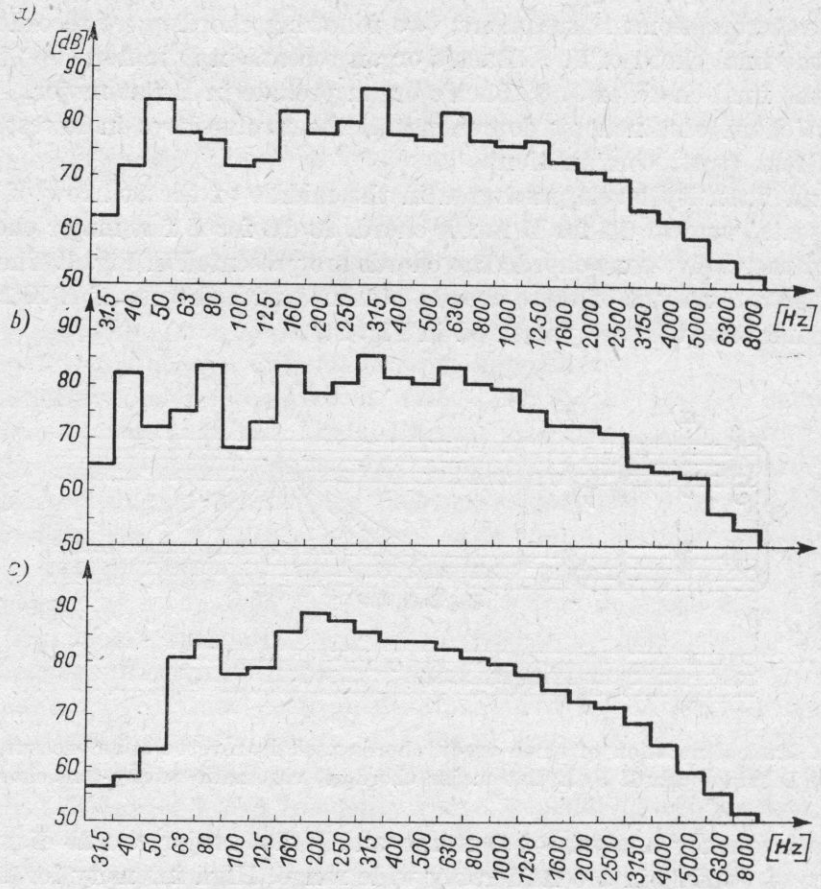

Fig. 2. The analysis of triadic organ chords used in reverberation measurements a) D minor chord, b) E flat major chord, c) chromatic twelve-tone chord. On the abscissa the mean values of 1/3 octave bands are given in Hz

difficult to accomplish at very low and very high frequencies because of the lack of sufficiently strong spectral components. This conclusion has been confirmed in further investigations.

The recording of the organ sound (stationary sound and the decay) was made by means of 4 condenser microphones with nondirectional characteristics and a 4-track tape recorder.

The placement of microphones was following:

1. in the middle of the 8th row of seats (height 1.5 m),
2. in the middle of the first row of the circle (height 1.5 m),
3. over the conductor's stand (height 3 m),
4. over the 8th row of seats, height 8 m (the so-called reverberation microphone)

A signal from each of the microphones was recorded separately.

Each of the four recordings of the three chords used were analysed by successive filtering through 23 1/3 octave filters with central frequencies from 50 Hz to 8 kHz. Values of the reverberation time were found from the rate of level decay in consecutive frequency bands in which signal to noise ratio was high enough. The reverberation time values, obtained in this way from four different microphone recordings, have been averaged for each frequency band. The characteristics of reverberation time, obtained by using three different organ chords and averaging microphone positions, are presented in Fig. 3 (a, b, c).

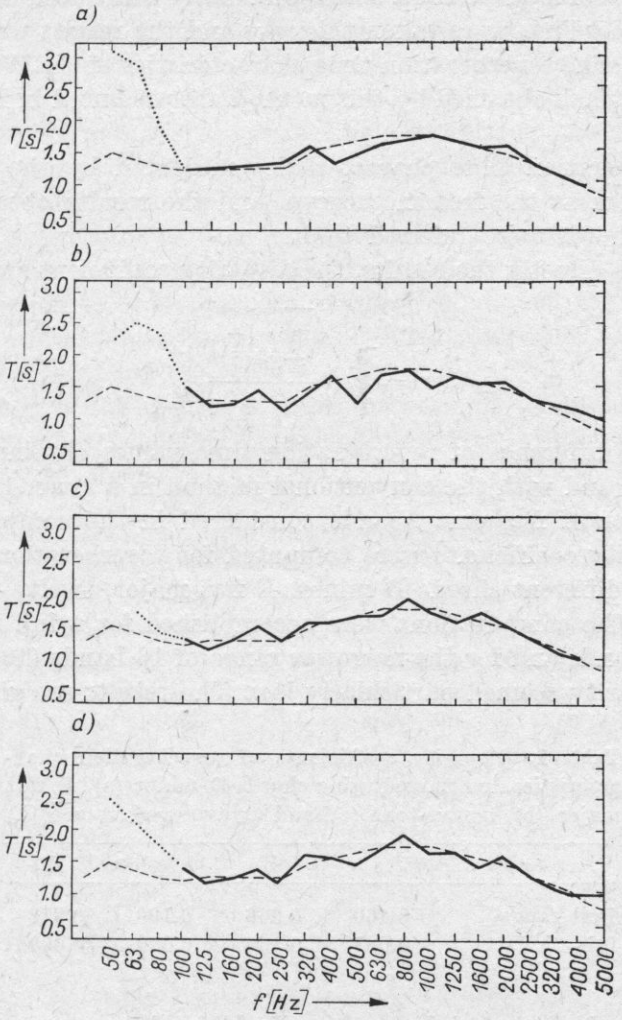

Fig. 3. The frequency characteristics of reverberation at the Concert Hall of Warsaw Academy of Music, taken with the use of the organ as a sound source. Broken line represents the reference characteristic obtained by conventional method (data of the Film Research Centre). Dotted line – results distorted due to long extinction time of the pipes
a) D minor chord, b) E flat major chord, c) twelve-tone chord, d) mean value

The curve in Fig. 3d presents the result of averaging the previously showed values.

All curves representing measured (a, b, c), Fig. 3, and averaged (d) values of reverberation time were compared with the reverberation characteristics obtained by the Acoustical Laboratory of the Film Research Center in Warsaw using conventional method. In these comparative measurements frequency modulated tones and bands of noise were used for each frequency 1/3 octave apart. Every measurement was taken with 10 different placements of the microphone and 2 placements of loudspeakers. The sound decay was traced by level recorder. 920 separate recordings were taken this way and the results were averaged for each frequency. The reverberation time characteristics of the Warsaw Academy of Music concert hall obtained by this method are presented in Fig. 3 as broken lines.

The reverberation time characteristics measured by the Film Research Center was taken as the freerence curve, and the results obtained by means of the organ chords were referred to it.

To compare directly the results, the disparity coefficient r was used,

$$r = \sqrt{\frac{\sum_{i=1}^{n} (\Delta T_i)^2}{n}},$$

where ΔT_i is a difference of reverberation time values obtained with the use of organ chords and with the conventional method in a given 1/3 octave band, and n – number of frequency bands considered in the comparison.

The disparity coefficients were computed for reverberation characteristics obtained using different chords D minor, E flat major, twelve-tone, and mean characteristic. The computations were accomplished for a full accessible range of 1/3 octave bands and for the narrower range of 16 bands (100 Hz to 4 kHz), where the disparity seemed particularly low. The results are given in Table 1.

Table 1. Disparity coefficients of reverberation characteristics determined using chords D minor (a), E flat major (b), twelve-tone (c), and at averaged values (d)

r	a	b	c	d
Full range	0.460	0.366	0.190	0.312
0.1-4 kHz	0.087	0.165	0.079	0.099

3. Discussion of the results and additional measurements

On the basis of the results presented, it may be claimed that reverberation measurements with the organ as a sound source led to the results very close to those obtained from conventional measurements. The disparity coef-

ficient was lowest in measurements with the use of the twelve-tone chord. As may be seen from Fig. 3, a particularly good agreement with the results from the conventional measurements was obtained in the range 100-4000 Hz. Also in this range the disparity coefficient obtained with the twelve-tone chord was the lowest. At frequencies above 4 kHz the spectral density was in most cases not sufficient and the signal to noise ratio was too small for quantitative assessments of the decay rate.

At frequencies below 100 Hz the reverberation values obtained were systematically higher than the ones measured by means of a loudspeaker. This could suggest that apart from the lower accuracy of measurements, due to insufficient acoustic energy, there occurred a systematic distortion caused by the high rate of sound decay in the organ itself.

To verify this hypothesis, tones of single pipes from the lowest registers were recorded, using a microphone with unidirectional characteristics, placed 10 cm from the mouth of the pipe. The time of sound decay of the pipe was estimated from the records as a hypothetical time necessary for the decrease of the acoustic pressure level by 60 dB. Per analogy to the conditions used in the determination of the reverberation time in rooms, the time of decay of vibrations in musical instruments thus defined was called *self reverberation time* [4] or *normalized decay time*.

Table 2 presents the results of measurements of normalized decay time for flue and reed pipes belonging to various organ stops in the Concert Hall of Warsaw Academy of Music.

Table 2. Normalized sound decay time of some organ pipes in the Concert Hall of the Academy of Music, Warsaw

Stop	Pipe	Pitch	T [s]
Diapason 16′ Ped.	open flue	C_1	3.25
Diapason 8′ II Man.	open flue	C_2	0.80
Octave 4′ II Man.	open flue	C_3	0.41
Diapason 8′ II Man.	open flue	C_3	0.44
Octave 4′ II Man.	open flue	C_4	0.42
Subbas 16′ Ped.	stopped flue	C_1	2.60
Trombone 16′ Ped.	reed	C_1	1.00
Trumpet 8′ II Man.	reed	C_2	0.50
Trumpet 8′ II Man.	reed	C_3	0.40
Trumpet 8′ II Man.	reed	C_4	0.42
Rankett 16′ IV Man.	reed	C_1	0.47

It seems that the decay time of the organ sound is directly connected with the size of a resonator. This is confirmed by the fact that the pipe C_1 Rankett 16′ with a short resonator has a relatively short time of decay (0.47 s). Besides, flue pipes have longer time of decay than reed pipes of the same length. Thus one may conclude that reed-stop combinations are most appropriate in

measuring reverberation time because of the short time of decay and rich spectrum.

Evaluating the sound decay time of organ pipes is not very reliable due to the possible influence of the reverberation of the hall. To decrease this effect, the microphone was placed very close to the pipe under investigation. The positive factor influencing hypothetical accuracy of the measurement is that the reverberation time of the Concert Hall of Warsaw Academy of Music in the range from 50 do 100 Hz, measured by conventional method, is 1.50 to 1.35 s, respectively.

The evaluation of the sound decay time of organ pipes leads to the conclusion that at frequencies smaller than 100 Hz this time is comparable to the reverberation time of the hall itself. Application of the organ as a sound source in measuring reverberation at low frequencies is not possible in halls like the Concert Hall in Warsaw Academy of Music with short reverberation time in low frequency range. In halls, where reverberation time at frequencies below 100 Hz is much longer (as it usually happens in churches), the measurements of reverberation with the use of organ sound may be accomplished also at low frequencies. This possibility allowed LOTTERMOSER [2], as already mentioned, to reconstruct the reverberation conditions of the Frauenkirche church in Dresden, where reverberation at lowest frequencies exceeded 4 s.

Above 4 kHz reverberation measurements using previously described organ chords were practically impossible, due to insufficient acoustic energy of the organ chords used.

To complete the results, an additional measurement of reverberation time at frequencies 4 kHz, 5 kHz, 6.3 kHz and 8 kHz was accomplished, applying identical measuring technique as in the main experiment. The sound source in this case was a group of pipes with greater acoustic energy at high frequencies. The twelve-tone chord C_6-B_6 natural was used, with all stops drawn. The value of reverberation obtained in 1/3 octave bands at medium frequencies 4 kHz, 5 kHz, 6.3 kHz and 8 kHz were: 1.05, 0.80, 0.65 and 0.60 s, respectively. The respective values obtained with conventional method are: 1.00, 0.80, 0.70 and 0.50 s, so there is a high coincidence of the results also in this case.

4. Conclusions

The measurements of the reverberation time at the Concert Hall of Warsaw Academy of Music lead to the conclusion that the application of the organ in reverberation measurements gave the results very close (within definite frequency range) to the ones obtained by a conventional method. This agreement might have resulted partly from the fact that the organ pipes at the Concert Hall of the Academy are situated over two opposite walls and the sound produced is well diffused. To measure the reverberation in the frequency range

from 100 to 4000 Hz, a recording of the chords ending a musical phrase can be used. The measurement may be accomplished on the conventional recording of a concert, provided an adequate microphone technique was used, as specified earlier. Evaluating reverberation with the use of an organ chord at frequencies below 100 Hz is possible only in such halls in which the reverberation at these frequencies is considerably long, e.g. in some churches. The measurement at frequencies higher than 4 kHz is possible by means of specially matched organ chords with appropriate level of acoustic energy within this frequency range.

In the above-described investigations two tradic chords, D minor and E flat major, in "tutti" registration have been used. These chords were endings of well-known music pieces. The agreement of the results obtained with conventional measurements has not been much worse than in the case of a specially matched twelve-tone chord. Surely, a similar result may be obtained applying other chords completing phrases of various music pieces, provided the appropriate registration has been secured.

The registration of the organ chords, applicable to reverberation measurements, should give possibly high intensity level and equal distribution of energy in wide frequency range. Suggested here is the "tutti" combination, including reed stops rich in higher partials, or "pleno" registration with the usual choice of foundation and mixture stops. Highly unsuitable are chords played on flute stops which lack full overtone series.

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Received on 26th August 1976