FROM ‘KNOCKING GHOST’ TO EXCELLENT ACOUSTICS - THE NEW TONHALLE DÜSSELDORF: INNOVATIVE DESIGN OF A CONCERT HALL REFURBISHMENT

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1 INTRODUCTION

The Tonhalle Düsseldorf was rebuilt in 2005 - the ideal chance to solve acoustical problems. Main problems were huge echoes caused by the dome-shape. But how remove the echo respecting the architecture? Peutz proposed a creative solution referring to the former use as planetarium. The idea: a visually opaque, acoustically transparent dome. Behind, reflectors avoid sound focus points - the sound is redirected upwards as far as possible. Many scale model measurements evaluated a reflector-geometry optimally reducing the echo. Moreover, it was necessary to use a visually opaque material for the new inner dome that shows the needed acoustical transparency. Moreover, podium acoustics improved to optimise the contact of the musicians, and the chairs were optimised so that a higher reverberation time results. The acoustical design was realised together with HPP architects and the other engineering bureau’s - and all the renewed technical installations had to be integrated into a very complex geometry. The realisation of the project was a challenge, which had to be completed in record time. Result is an architectonic and an acoustical improvement: Besides the exorcism of the ‘knocking ghost’ the Tonhalle Düsseldorf now can compete with other concert halls with exceptional acoustical properties.[1]

Fig. 1: Inner view of the Tonhalle Düsseldorf before (left) and after (right) refurbishment

2 PROBLEM ANALYSIS AND STARTING POINTS

The acoustical problems of the former Tonhalle were caused by the shape of the hall: it was almost half a sphere of 15.000 m³ volume, 40 m diameter and a height of 24 m (see fig 1).
The main problem was the very strong echo effect on ear height in the main audience caused by the shape of the hall: by the concave geometry sound foci are formed as in a concave mirror. In these foci all reflections from all directions, i.e. all parts of the dome add up coincidentally with equal delay time (see fig. 2) – and form echoes, which were in the 250 and 500 Hz octave band up to 20 dB stronger than direct sound. Even worse, due to the nature of physics, for every source point on the stage a mirror focal point could be found, where the echo was that enormous!

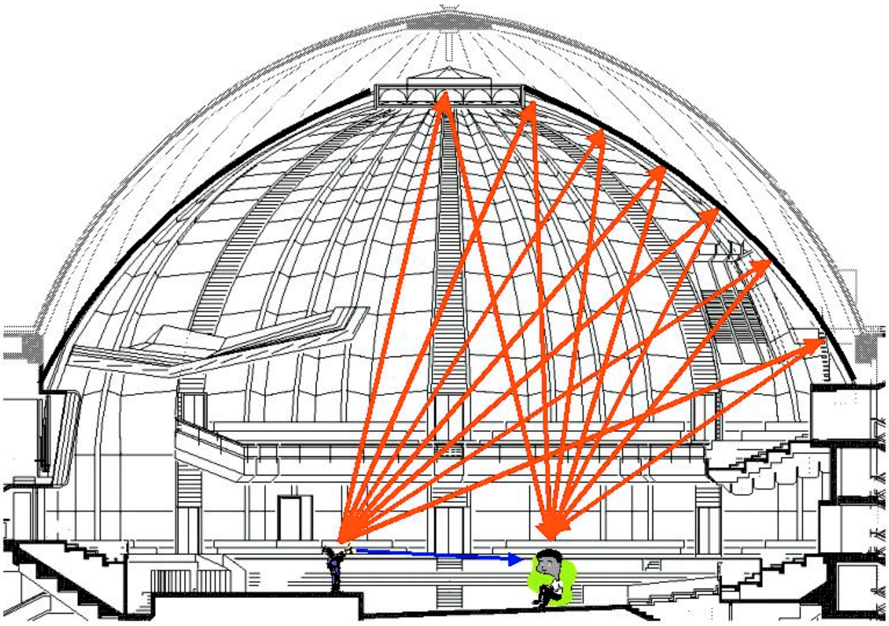


Fig. 2: Cause of the ‘knocking ghost’: coincidental reflections with equal delay time

The program of demands for the refurbishment contained as most important aim, to reduce the noticeable and as disturbing perceptible echoes as far as possible.
Starting point for acoustically consulting of the modernisation of the Tonhalle was to develop a concept to suppress the dome echo effectively.
Moreover, the definition of the character of events planned in the new Tonhalle was crucial: about 65% of the events should contain symphonic music, chamber music and choir music. Thus the reverberation time of the occupied hall had to be increased from formerly 1,35 sec. to the ideal for symphonic music of 2,0 sec.

3 DEVELOPMENT OF THE SOLUTION

3.1 Conception to remove the echo

The room acoustical consultant Peutz proposed an innovative concept to solve the echo problem: *a visually opaque, but acoustically transparent new inner dome*.
Behind this a new shell of carefully directed reflectors breaks up the hemispherical shape and avoids coincidental energy summation (see fig. 3).

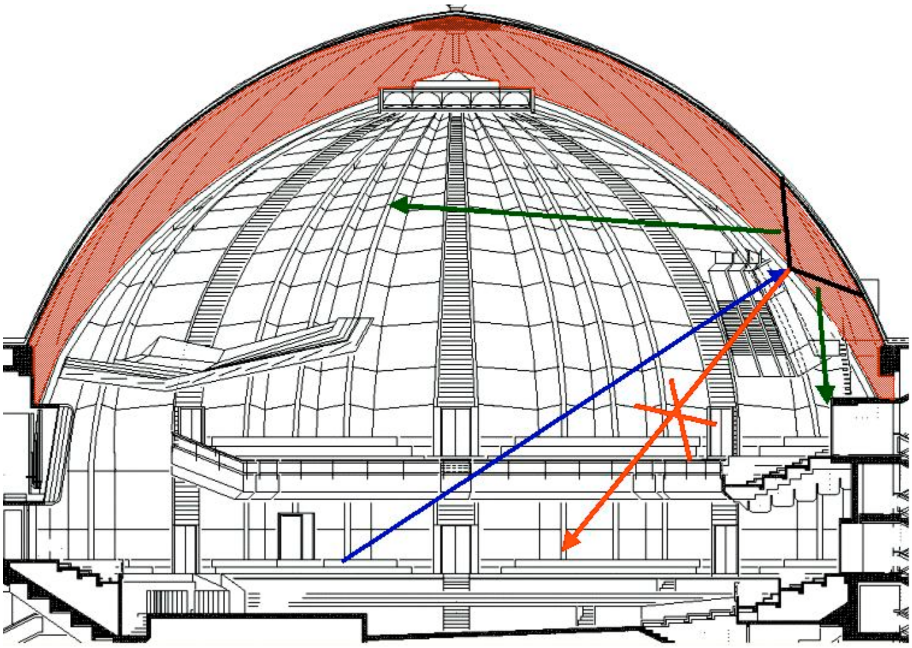


Fig. 3: Principle of the solution: sound-transparent inner dome with reflectors behind

3.2 Scale model measurements

Because of the fact, that focusing properties of concave surfaces in low frequencies cannot modelled accurately in computer simulations, it was plausible and necessary to perform measurements in a scale model of the auditorium. Therefore of the formerly existing auditorium an acoustical scale model was built in 1:12 scale (see fig. 4) to be able to evaluate and auralize frequency bands from below 100 Hz to 4 kHz (1200 Hz to 48 kHz in model frequency range).

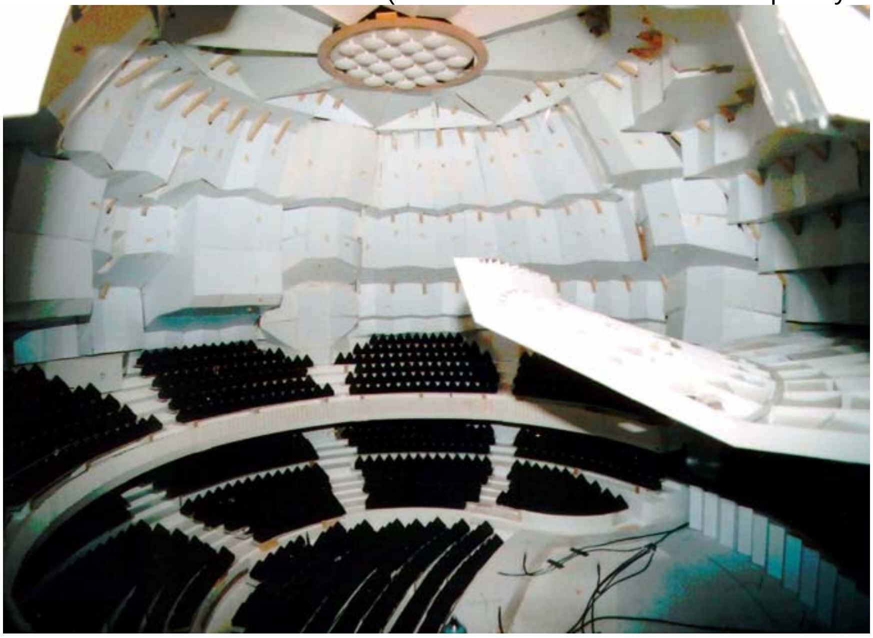


Fig. 4: View of the scale model in the final, echo-suppressing geometry

Especially for scale measurements model sources were developed which are able to radiate sound as omni-directional as possible in the relevant, frequency-transformed transmission range. The miniature microphones also are specially selected to meet the specifications of linear frequency response and omni-directionality in model frequency range.
In every model variant by means of a maximum length sequence analyzer[2,3] (WINMLS) impulse responses were measured at 14 constant microphone positions and 3 source positions (29 transmission paths).

From the impulse responses the (with a time constant of τ = 20 ms) smoothed ETC was calculated for the five octave bands from 125 Hz to 2 kHz. At first the existing situation of the hall was verified and then subsequently 182 different variants were examined. Every new variant was only a little changed in comparison to the variant before. The ETC's and the parameters calculated out of it were compared concerning the echo suppression.
By this way of testing the effect on the echo of small geometry changes the echo forming mechanism was identified and the effect on the echo of any constructional measure was tested in the model before changing anything in the real hall. Even more, the main structure of the new hall was ready before start of the refurbishment. Nevertheless, the model was helpful also during the refurbishment, when small details in the reality differed from the conceptional geometry, the effect was be tested and optimised.
Most important in order to remove the echo was the finding, that placing of even ideal diffusors cannot solve the echo problem of a hemispherical shape in general: diffusers still reflect a certain amount of energy in mirror direction (following the law of Snellius) and therefore also into the focus. But this was to avoid – no energy was allowed to add up at the same delay time in the foci. This cannot be achieved with diffusing, but only with carefully directed reflecting surfaces.

3.3 Experiments with diffusors and reflector geometries

In order to develop geometry's, that scatter as much sound energy out of the mirror direction and as little as possible into the foci, the directional scattering characteristics, many different diffusers and reflector geometry's were examined in form of 1m x 1m panels in a (for high frequencies) anechoic chamber. In a specialised measurement setup[4-7] the from the samples reflected impulse responses were measured by a MLS system using 19, each by 10° turned microphone positions radially distributed in the half-circle round the sample (see fig. 5).

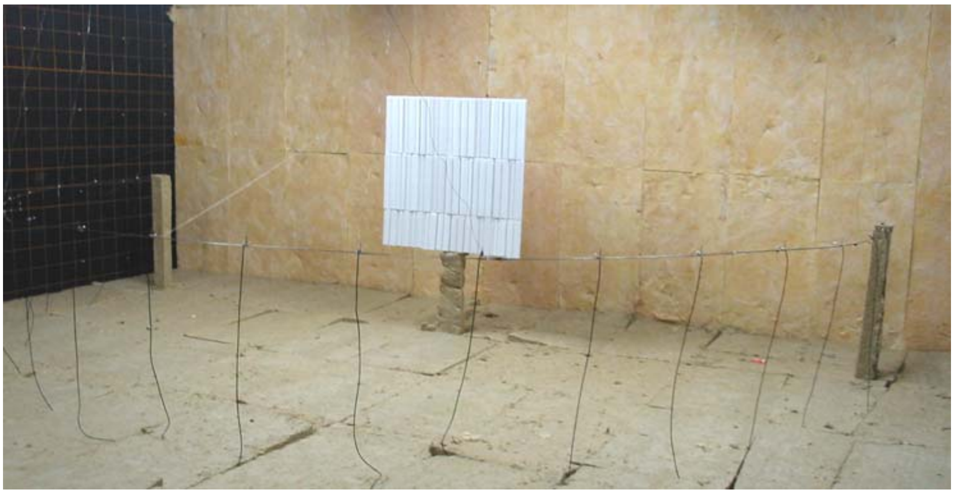


Fig. 5: Setup for the reflection measurements in an anechoic chamber

From the measurement results was derived, that the dimensions of the reflecting surfaces have to be at least 3,5 m to be effective at 200 Hz, where the echo level was highest. As optimum angle relative to the tangent of the cupola 30° was estimated, resulting in a constructional depth (variation) of 1,5 m and more. A geometry, which meets these specifications, is periodically repeating prisms.

By means of the acoustical scale model these findings were used to develop in numerous variants a very specialised and complex geometry. This new shell forms the new acoustical enclosure of the concert hall and avoids with its optimal formed, directed and folded reflectors, that the sound can sum up in foci. Instead, the reflectors direct the sound coming from the podium upward into the cupola, where the sound waves are reflected as often as possible before reaching the audience.

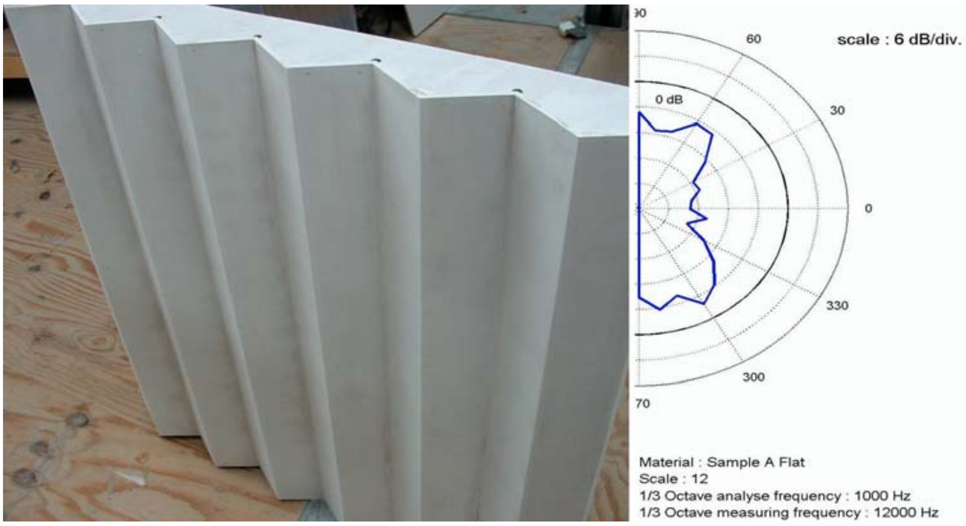


Fig. 6: View of the geometry of 30°-prisms with scattering plot at 1 kHz

3.4 Experiments with sound transparent materials

By means of laboratory measurements an appropriate acoustically transparent version of the formerly closed inner dome had to be developed. The wooden, echo causing panels of the existing inner dome had to be replaced by a material, which is transparent enough for sound to allow the reflectors of the new shell behind to be effective. After some preliminary consideration the material class of woven metals. To find out, what kind of woven metal could be transparent enough, in the Peutz laboratory comprehensive measurements were performed in the anechoic chamber.[8] These measurements turned out to be not of trivial nature, for a sound transparency near zero had to be measured. This meant, that the time response of the room and measurement setup had to be subtracted from the measured impulse responses in time domain to identify the reflections of sample and sample frame, which are already low in comparison to direct sound.

With help of this method a material of woven metal was identified to meet our specifications of the reflection in mirror direction to be – 20 dB relative to a 100% reflective plate (below 8 kHz).

3.5 Realisation of the concept

The new folded reflector shell developed in the scale model forms the new acoustical enclosure of the hall and was built out of duple gypsum board between outer and inner dome. Therefore the acoustically effective volume was increased by 10 %.

After the reflector geometry and the sound transparent material for the new inner dome was known, an architectural concept was developed by the architects HPP in record time. All technical installations had to be renewed also and to be integrated into the already complex geometry of the building. By intensive consulting and close team work with HPP and the other consultants the whole refurbishment, which was rather a daring exploit, succeeded and was done in a record time of only 6 months.

The folded reflectors behind the acoustically transparent woven metal changed the reflection structure in the echograms dramatically in almost all examined measuring paths. In figure 8 the typical improvement of the ETC is given in the 500 Hz octave: whereas the old hall showed an enormous dome echo, the new hall does not show a disturbing echo any more.

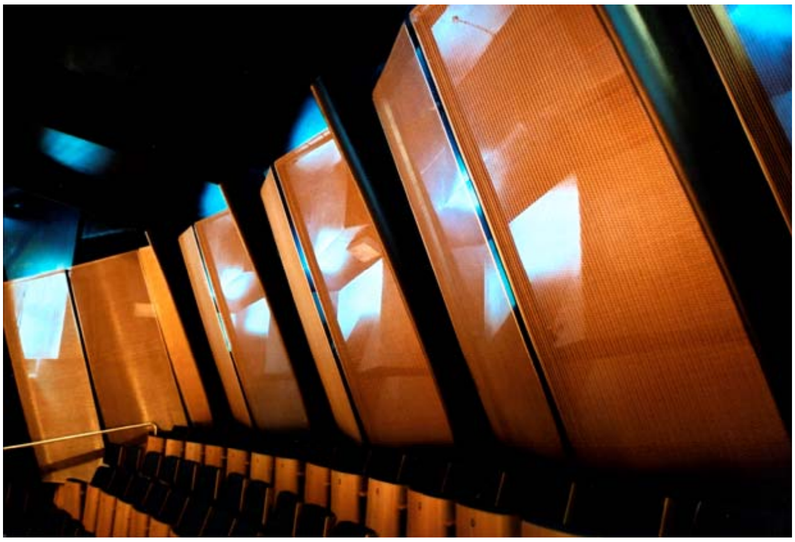


Fig. 7: View of the acoustical reflectors behind the sound-transparent inner dome

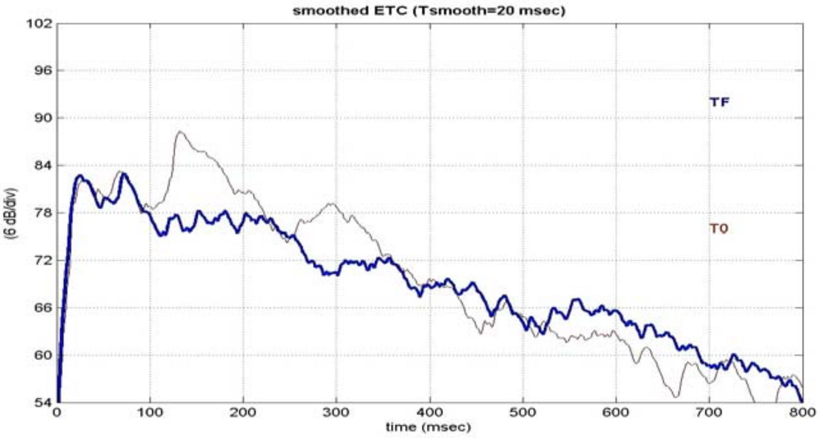


Fig. 8: Reflection structure of a typical echo path (500 Hz) before and after refurbishment

Peutz monitored the realisation process with laboratory, model and control measurements to ensure the correct execution of all measures even with testing the newly built surface parts of the new shell every second day on location.

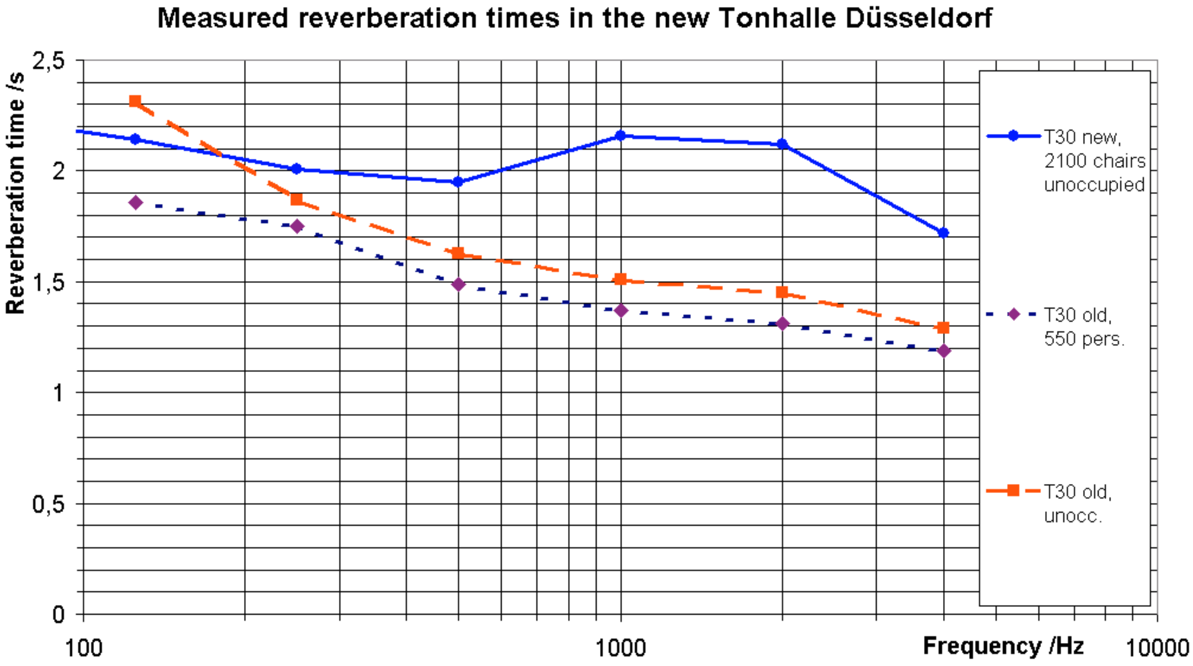
3.6 Increasing the reverberation time

A very important task of the consulting the refurbishment was to increase the reverberation time of the auditorium in occupied and unoccupied state: one more problem of the existing hall was a reverberation time much too low for symphonic music. The low values resulted from a too low specific volume and from the mechanism, that the dome geometry all the sound with the first reflection directed into the absorbing audience. By adding a large part of the volume behind the inner dome, which was formerly separated from the auditorium by the wooden panels. An increase of the specific volume was reached from approx. 7 m^3/ person up to approx. 8 m^3/ person. The new shell is built out of double gypsum board with a surface weight of 20 kg/m2 sealed by non-porous varnish, what led to a significant reduction of the absorption of the hall above 200 Hz.

All 1950 chairs of the hall had to be renewed either and was object of our consulting in order to minimise the absorption of the occupied state of the hall. Therefore the new design of the chairs was optimised in any detail. In laboratory experiments in our reverberation chamber the absorption properties of different chair variants were examined and optimised, so the chairs in the new Tonhalle have minimum absorption with seated person on it.

By the many reflecting and scattering surfaces and objects in the dome of the new auditorium and the enlarged volume, the reverberation times of the new Tonhalle is increased above 200 Hz significantly: the hall has now a very well-balanced timbre as the measurements on location reveal.

Fig. 9: Comparison of the measured reverberation times before and after refurbishment



4 RESULTS

The whole refurbishment of the Tonhalle Düsseldorf was rather a daring exploit, done in a record time of only 6 months.

The different states of the planning and realisation of the modernised were room-acoustically consulted. The result is very successful in acoustical point of view.

The room-acoustical scale model was an extremely valuable tool to develop the measures to improve the acoustical conditions in the new hall: the suppression of the former echo by the new geometry of reflectors was qualitatively precisely predicted in the scale model.

Repeated measurements in the auditorium before and after refurbishment verify the model measurement results: The new Tonhalle acts not any more as a concave mirror, but uses the new folded geometry as resonator to create a regular, homogeneous reverberation tail.

The minimised absorption of the seating supports the gain in reverberation time.

Listeners, critics and artists perceived all concerts with classical music since the re-opening on November 4th 2005 very positively.

Even more important than the exorcism of the “knocking ghost”-echo is the realisation of a remarkable improvement of the acoustics. Now the Tonhalle Düsseldorf is able to compete with other concert halls with first-class acoustics.

The result of acoustical consulting the modernisation is an architectonic and acoustical regeneration of the hall, but also an enrichment of the state capital Düsseldorf.

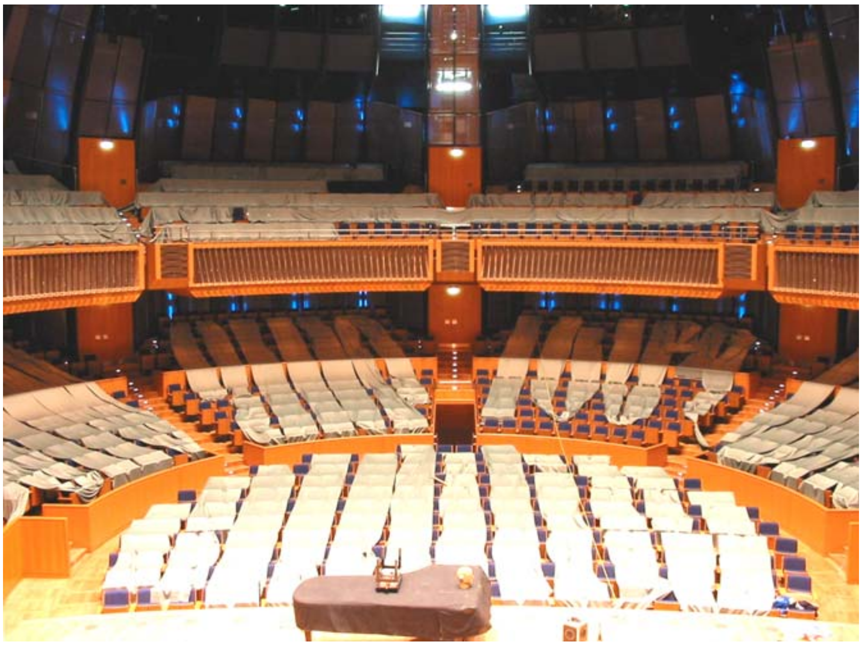


Fig. 10: View of the completed new hall during measurements with audience simulation

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