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An Acoustic Diffraction Study of a Specifically Designed Auditorium Having a Corrugated Ceiling: Alvar Aalto's Lecture Room

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Summary
There is an auditorium operating as a discussion room and lecture room at the Municipal Library of Vyborg, Russia (built during Finnish rule when the city's name was Viipuri in Finnish), designed by Aalto and built in 1933–35, where the wave-shaped ceiling has been especially designed to enhance the acoustics and make every position within the room acoustically equivalent. No matter where a speaker is standing, he is supposed to be heard equally well all over the room. The corrugated ceiling has therefore been constructed to distribute sound optimally, at least from the point of view of a ray theoretical analysis. The numerical study presented here shows that the corrugation is such that the ray approach is not exactly valid due to diffraction effects that must be incorporated as well. A detailed description of the sound distribution as a function of the position of the sound source and the receiver is presented for different situations including the exact configuration of Aalto's auditorium. The used approach is constrained in terms of frequencies by the corrugation dimensions of the auditorium. Practically it means that the theory can predict correct results up to 800 Hz, which is 70% of the frequencies commonly of interest in speech or music. Additional effects caused by windows, pillars near the windows and downstand beams hidden above the ceiling are not considered. The acquired knowledge is important for future construction of similar rooms.

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1. Introduction

In contemporary architecture there exist several examples of the use of corrugated ceilings and walls, most often for esthetical reasons, sometimes also for acoustical purposes. One example is the early-modernistic discussion room (Figure 1) at the municipal library in Vyborg, Russia (built during Finnish rule when the city's name was *Viipuri* in Finnish), an internationally acclaimed design by the Finnish architect Alvar Aalto [1, 2, 3]. The library, built in 1933–1935 AD and widely considered the first manifestation of regional modernism, is famous for its wave-shaped ceiling in the auditorium. The ceiling consists of strips of wood attached to a corrugated ceiling. Aalto's purpose was to make every position within the room acoustically of equal value enabling the speaker to position himself anywhere in the room without changing the audibility to the audience.

Other examples of corrugated ceilings can be found at the 'Nederlands Danstheater' in The Hague, the Netherlands, designed by the Office for Metropolitan Architecture (1959 AD); the chamber concert room at the concert hall in Bruges, Belgium, designed by 'Robbrecht and Daem chartered architects'; the Bogcaffé in Copenhagen, Denmark; the 'Casa da Musica' in Porto, Portugal, designed by the Office for Metropolitan Architecture (2001 AD); …

A remarkable example of a corrugated ceiling used for esthetic reasons is the very beautiful Madrid Barajas Airport Terminal 4, in Spain, having a wooden corrugated ceiling (2000 AD). Another example, where a periodical structured ceiling appears as a natural consequence of a modular construction procedure is the historical Chapel Bridge in Luzern, Switzerland (1333 AD + later reconstructions). Perhaps currently the most widely known example is the ceiling of the Richmond Olympic Oval, constructed for the Olympic winter games in Vancouver (Canada, 2010 AD).

Diffraction by corrugated structures can also be found in architectural marvels such as the El Castillo Pyramid in Chichen Itza [4] (1000 AD–1300 AD), Mexico, or the Hellenistic Theater of Epidaurus [4, 5], Greece (300 BC).

By reducing the acoustic wavelength, therefore transferring from acoustics [6, 7] to ultrasonics [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21], diffraction effects on

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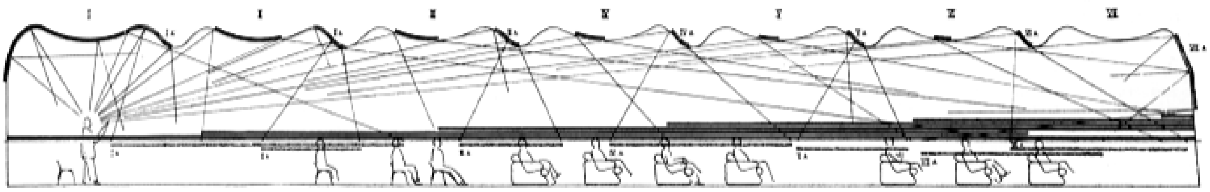
(a)

Figure 1. a) Aalto's discussion room (auditorium) at the Municipal Library in Vyborg, Russia (built during Finnish rule when the city's name was Viipuri in Finnish) is an internationally acclaimed design by the Finnish architect Alvar Aalto. The library, built in 1933–35 and "considered the first manifestation of regional modernism", used to be famous for its wave-shaped ceiling in the auditorium.
b) Long section sketch made by Aalto himself.



(b)

corrugated surfaces become interesting for nondestructive investigations of materials. Periodic structures in general are also interesting for filters in the form of phononic crystals [22, 23, 24] and other wave guides [25]. The ability to rescale both the periodicity and the acoustic wavelength enables the use of similar techniques to study diffraction at any size.

2. Applied diffraction model

The model applied here is basically equal to the plane wave expansion model applied by Declercq and Dekeyser [4, 5] and will not be outlined in detail. It has also been used in ultrasonic diffraction studies as cited in the introduction. The model is essentially based on the early works by Lord Rayleigh and more in particular on optimizations to the theory for ultrasound diffraction gratings [8]–[21]. In essence the model describes the reflected and transmitted diffracted sound fields as a summation of plane waves each of an order 'p' and propagating in a direction determined by the grating equation and the dispersion properties. Each of the diffracted waves has amplitudes that are found by incorporation of continuity of stress and strain along the corrugated interface. Because of the periodicity of the corrugation, the equations themselves, which depend on one spatial coordinate x, are also periodical and therefore a Fourier transform (DFT) is applied transforming the spatially dependent equations into a discrete set of equations independent of x. The result is a discrete, but infinite, number of coupled equations and unknown variables (complex amplitude of the diffracted sound waves) that can be implemented into a computer program by reduction of the infinite number of equations and variables to 2N+1. The integer 'N' is called the number of diffraction orders and is here chosen as 7, to ensure sufficient numerical convergence, as in earlier works [5,6,9–22]. The applicability of the model is limited by the fact that internal scattering effects within the corrugation are ignored. This limitation reduces the appropriateness of the model to a constrained frequency range depending on the corrugation dimensions as outlined in previous works [4, 5]. Extensive studies have been performed in the past by Lipmann [20] and Wirgin [26] and the constraints have been experimentally confirmed in earlier works on diffraction of ultrasound on corrugated samples [9–22] . The 'Wirgin criteria' are somewhat tighter than the older 'Lipmann criteria'. We present results only in a frequency range where the theory is realistic, i.e. in a frequency range never significantly surpassing limits imposed by Wirgin and Lipmann. As long as one works within the limitations determined by Lipmann [20] and Wirgin [26] one should not worry about internal scattering effects within the corrugations themselves – making the Rayleigh decomposition (i.e. the plane wave expansion technique) a correct approach.

3. Geometrical aspects

The purpose is to study the consequences of diffraction of sound on a corrugated ceiling in a room consisting of two

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parallel walls: the corrugated ceiling and plane floor. The length of the room is D, the height is H and the corrugation is determined by a periodicity Λ and a peak-to-peak height h. A schematic of the room is shown in Figure 2. The origin of the Cartesian coordinate system is in the right upper corner. The coordinates of the sound source are given by (x_S, z_S), those of the listener are denoted by (x_L, z_L). Every position along the ceiling can be considered as a diffraction spot. A diffraction spot is the position where a sound ray interacts with the ceiling and is diffracted into different diffraction orders accordingly. One such spot is shown in Figure 2 and its coordinates are given by $(x_D, 0)$. The angle of incidence is then θ_{inc}.

3D effects are ignored and therefore the room is considered 2D. Accordingly the sound source is simplified as cylindrical whence an amplitude decay proportional to $1/\sqrt{R}$, R being the distance of sound propagation after emission by the source. Just as in [5] the cylindrical sound field is split into rays. The propagation, diffraction on the ceiling and possible interaction with the end walls and floor are considered consequently. There are three sound paths considered between the sound source and the ceiling. They are shown in Figure 2. The first path is a clear path between source and ceiling, the second path is after reflection upon an end wall, the third path is after reflection on the floor. Reflections are taken into account by means of mirror sources (as seen in Figure 2). Energy loss due to reflections on the smooth surfaces of end walls and floor is for simplicity approximated by a reflection coefficient given by

$$\rho = 1 - \alpha, \tag{1}$$

the energy reflection coefficient being ρ and the absorption coefficient α. Assumption (1) is to a great extent a good approach, often applied in building acoustics.

Each of the sound rays reaching the ceiling is diffracted by the corrugation into a number of diffraction orders. Similar to [5] the number of rays constituting the cylindrical sound source is dependent on the frequency and a ray density is chosen corresponding to three rays incident on the ceiling per wavelength. Each incident ray results in a number of diffracted rays that may or may not reach a considered listener.

The numerical decision whether or not a sound ray reaches a listener is based on the geometrical distance between the listener and the ray. One may argue about the numerous possible imposed criteria but for this paper the criterion is chosen to ignore a ray when its distance to the listener is more than 30 cm and to register a ray as detected if the distance is less. All rays are added up in complex space in order to incorporate amplitude and phase.

In addition to reflections before reaching the ceiling, sound rays may also be reflected along their path from the ceiling to the listener. A clear path from ceiling to listener is depicted in Figure 2 (top), reflection on the end wall before reaching the listener is depicted in Figure 3; reflection on the floor before reaching the listener is depicted in Figure 4.

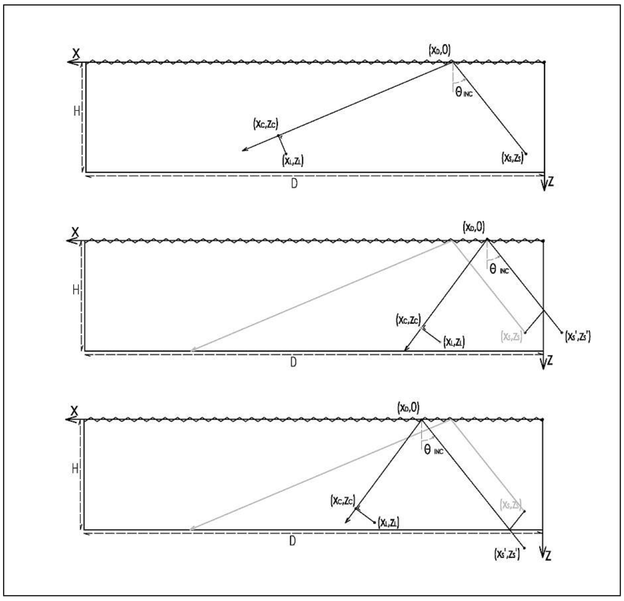

Figure 2. Cross-section schematic of geometry of the room with sound source (top), wall mirror source (middle), and floor mirror source (bottom). The position (x_C, z_C) is the position closest to the listener, along the considered. Its distance to the listener is used to decide whether the ray is detected or not. The first path is a clear path between source and ceiling, the second path is after reflection upon an end wall, the third path is after reflection on the floor.

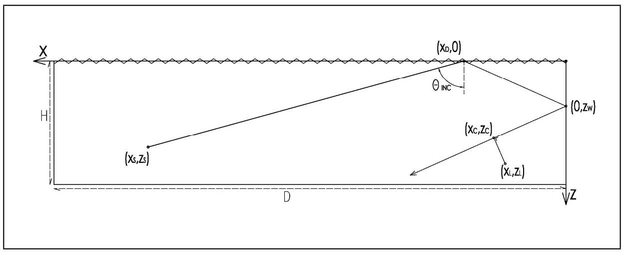

Figure 3. Sound reaches the listener after being reflected on the wall.

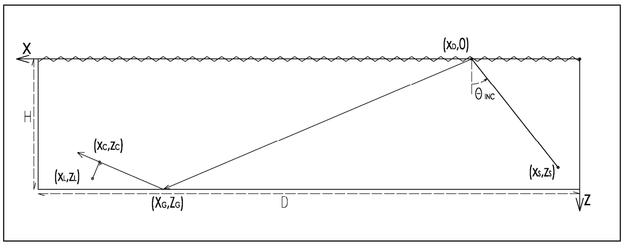

Figure 4. Sound reaches the listener after being reflected on the floor.

If for every diffracted wave of order m the wave vector is denoted by $k^m = (k_x^m, k_z^m)$, then we define C as

$$C = \Re e \left\{ \frac{k_z^m}{k_x^m} \right\}. \tag{2}$$

The position along the acoustic ray that is closest to the listener is given by (x_C, z_C), and can be found by solving

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the following equations for a clear path between the ceiling and the listener,

$$\left\{ \begin{array}{c} z_c = C(x_c - x_d) \\ z_c - z_l = -\dfrac{x_c - x_l}{C} \end{array} \right\}. \tag{3}$$

For a ray that is first reflected on the right end wall ($x = 0$) before reaching the listener,

$$\left\{ \begin{array}{c} z_c = -C(x_c + x_d) \\ z_c - z_l = \dfrac{x_c - x_l}{C} \end{array} \right\}. \tag{4}$$

For a ray that is first reflected on the left end wall (x=D) before reaching the listener,

$$\left\{ \begin{array}{c} z_c = C(D - x_d - x_c) \\ z_c - z_l = \dfrac{x_c - x_l}{C} \end{array} \right\}. \tag{5}$$

For a ray that is first reflected on the floor before reaching the listener,

$$\left\{ \begin{array}{c} z_c = -C(x_c - x_d - H/C) + H \\ z_c - z_l = \dfrac{x_c - x_l}{C} \end{array} \right\}. \tag{6}$$

As soon as the position (x_C, z_C) is calculated, the distance from the listener is then

$$\sqrt{(x_l - x_c)^2 + (z_l - z_c)^2}. \tag{7}$$

4. Discussion of mumerical results

When the sound field is studied in a room, 'scattered and diffracted sound' are distinguished on the one hand and 'direct sound' (from source to receiver) on the other hand. Because the direct sound is independent of diffraction and scattering phenomena and because it is always the same no matter what geometrical configuration for the room is considered, we omit it in our results. Therefore the results highlight better the effects of diffraction and scattering. Furthermore sound that is merely reflected and does not interact with the corrugated ceiling is also neglected. Results presented in this paper therefore show only the influence of the diffraction effect on the acoustic field inside the room and will in reality combine with the direct sound field. When, for instance, in this report results show a very low acoustic level for a given frequency and at a certain position, it therefore means that at that position and for that particular frequency, a listener would only hear direct sound, and no sound added by the diffraction effect. Note that in this paper we assume side wall reflections be ignored and floor reflections be negligible. In reality there would also be contributions possible, depending on the geometry of the sound source by side wall reflections and, in the case of a floor that is less absorptive than assumed in this paper, also by floor reflections.

The developed numerical procedure is rather time consuming and this depends further on the exact corrugation shape. Therefore we limit ourselves to a description of results for a sinusoidal corrugated surface because for such a surface the calculations turn out to be the fastest; and resemble the ceiling of Aalto's discussion room quite well. In addition we have performed a number of test calculations for other corrugations (sawtooth shape, steel deck shape, ...) and found reasonably similar results.

According to Aalto himself, a corrugated ceiling is responsible for a better distribution of sound throughout the discussion room and presumably makes every position throughout the room acoustically equivalent. Alvar Aalto made this assumption based on ray considerations without considering diffraction effects caused by amplitude and phase transformations upon interaction with the corrugated ceiling, therefore ignoring the generation of acoustic diffraction orders. The current section must provide decisive answers to Alvar Aalto's statements based on an exact acoustic simulation, in the frequency interval under consideration.

Aalto's discussion room is characterized by: length D = 32 m, height $H = 4.2$ m, corrugation period $\Lambda = 2.25$ m and corrugation peak-to-peak height $h = 0.5$ m. Because of limitations to the validity of the applied theory [5], as outlined earlier, the calculations for Aalto's discussion room are limited to 800 Hz, which is 70% of the frequencies commonly of interest in speech or music. For higher frequencies the numerical analysis still works, but may not correspond to physical reality since, as far as we know, experimental validation of the model outside the frequency interval as imposed by Lippmann [20] and Meecham [21] has never been reported. If results were to be obtained for frequencies beyond 800 Hz, a finite element or related approach could be followed. A geometrical approach as considered by Aalto himself becomes naturally justifiable for very high frequencies.

Unless otherwise stated, we consider the following material properties: mass density of air: 1.1466 kg/m^3, sound velocity in air: 343 m/s, mass density of the wooden ceiling: 700 kg/m^3, bulk longitudinal and shear sound velocity in the wooden ceiling: 3600 m/s respectively 2000 m/s. For the absorption coefficient of the wooden end walls, see α in (1), we take these values: 0.02 below 375 Hz, 0.03 below 1.5 kHz.

The developed procedure works perfectly for a reflective floor. Nevertheless, for Aalto's discussion room we assume that the audience, and the absorbing seats, absorb most of the sound; therefore a limitation of the presented results to the situation where the floor is a perfectly absorbing surface is obvious.

4.1. Eccentrically positioned sound source

First, a source is considered situated off the center, at 1 m from the right end wall of the room at 1.7 m height. The listeners are positioned at different positions throughout the room at a height of 1.2 m.

We first consider the case of omitted end walls. The acoustic level distribution (in dB) as a function of the distance of the listener to the origin (right end wall of the

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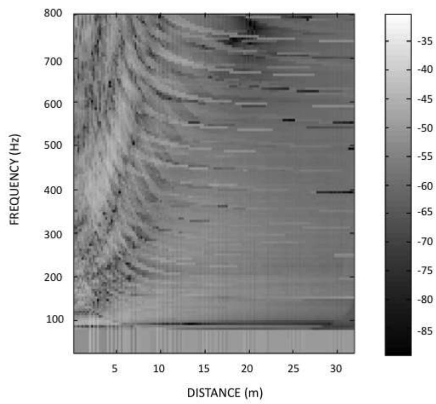

Figure 5. Sound level distribution in dB as a function of the distance from the origin and as function of the frequency, neglecting reflections from the end walls. For comparison with later figures, this figure corresponds to the configuration of Aalto's discussion room with removed end walls; furthermore the periodicity Λ of the corrugated ceiling is 2.25 m and the peak-to-peak height of the corrugation is 0.5 m. The height of the room is $H = 4.2$ m. The right hand side column is the grayscale for the levels in the diagram.

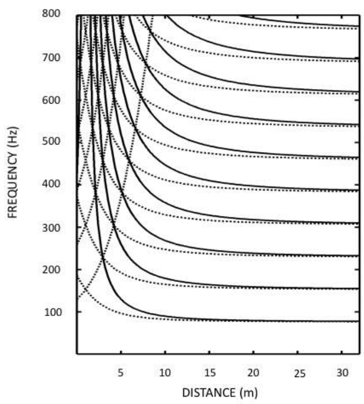

Figure 6. Frequency patterns caused by the presence of the critical frequencies and caused by the Bragg scattering effects. The lines are a graphical representation of formulas (8) and (9) in the text.

room) and as a function of the frequency is given in Figure 5. Note that the acoustic level, here and elsewhere throughout the paper, is a relative value with respect to the arbitrary reference level near the sound source.

There are patterns visible that are mainly resulting from the complicated diffraction phenomenon caused by different diffraction orders originating from the corrugated ceiling.

Two effects result in special formations in the sound pattern. They are both generated by the corrugated ceiling. The first phenomenon is caused by so-called critical frequencies where sound transforms from evanescent to bulk [5,6, 9–22, 28]. The critical frequency usually has a significant impact on the amplitude of all the accompanied diffraction orders. The second phenomenon is due to Bragg diffraction and results in back-reflected sound generating a standing wave pattern between sound source and ceiling. The two conditions are calculated as follows.
Bragg condition:

$$k_x^m = -k_x^{\text{inc}} \rightarrow -k_x^{\text{inc}} = k_x^{\text{inc}} + m\frac{2\pi}{\Lambda} \rightarrow |f| = \left|\frac{mv}{2\Lambda\sin\theta^{\text{ray}}}\right|. \tag{8}$$

Critical frequency:

$$k_x^m = \frac{2\pi f}{v} \rightarrow \frac{2\pi f}{v} = \frac{2\pi f}{v}\sin\theta^{\text{ray}} + m\frac{2\pi}{\Lambda} \rightarrow |f| = \left|\frac{v}{\Lambda(1-\sin\theta^{\text{ray}})}\right|. \tag{9}$$

In formulas (8) and (9) the angle is defined positive for rays propagating towards the side corresponding to negative diffraction orders and is defined negative in the opposite direction. It is clear that the two conditions asymptotically tend towards the same minimum frequency for changing negative ray angle, i.e. for rays propagating towards the positive x-direction. This frequency is given by

$$|f| = \frac{mv}{2\Lambda} \tag{10}$$

and is equal to $f = m76.222$ Hz for Aalto's discussion room. Below 76 Hz there are no diffraction phenomena and the sound waves perceive the ceiling as if it were a smooth surface.

Both frequency patterns, for any diffraction order of importance within the given configuration, are plotted in Figure 6 as a function of the distance from the origin measured along the x-axis. For this purpose formulas (8) and (9) have been implemented by means of formula (11).

$$\theta^{\text{ray}} = \frac{\arctan(x-1)}{2H - z_s - z_l}. \tag{11}$$

The convergence towards $f = m76.222$ Hz is clearly visible in Figure 6. What is even more important is that the patterns visible in Figure 6 are very much alike the patterns of Figure 5. It means that the phenomena just described form the core of what determines the outcome.

Whereas Figure 5 is very interesting to understand the diffraction phenomenon, it does only partly correspond to the discussion room of Aalto because the reflective end walls have been ignored. If reflections from the end walls (or also side walls) are taken into account, then Figure 7 is obtained. As a matter of fact Figure 7 shows the acoustic level distribution (in dB) as a function of the distance of the listener to the origin (right end wall of the room) and as a function of the frequency. There is a tendency visible, at distances from the source larger than around 10 m, of a considerable level drop for certain frequency bands. This tendency is so strong that again an explanation is desired. Actually the presence of a reflective end wall corresponds to a mirror source at a symmetrical position behind the end

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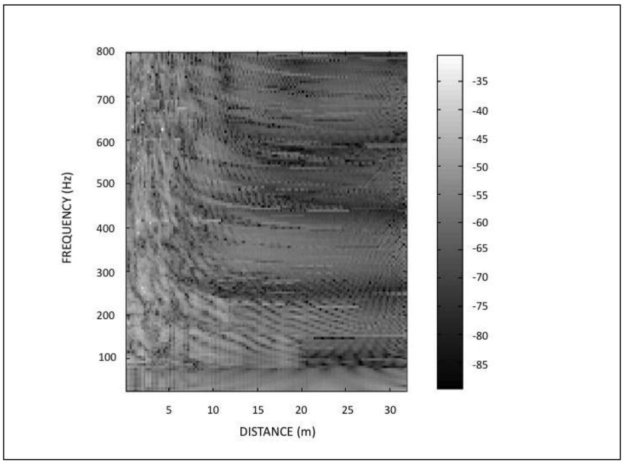

Figure 7. Sound level distribution in dB as a function of the distance from the origin and as function of the frequency, incorporating all the considered sound paths, including those resulting from reflections on the end walls. This configuration corresponds to Aalto's discussion room. The height of the room is $H = 4.2$ m, the length is $D = 32$ m. The right hand side column is the grayscale for the levels in the diagram.

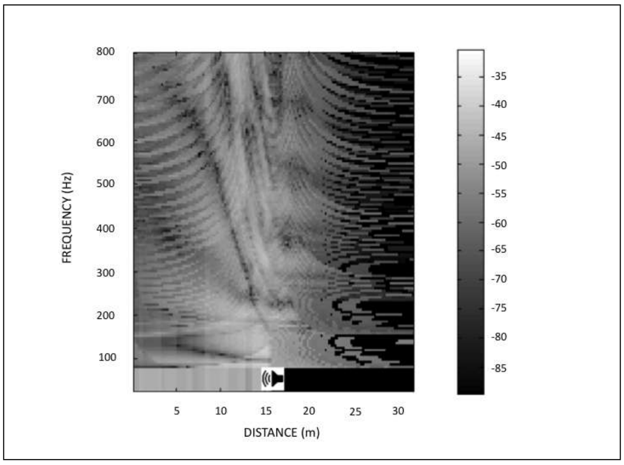

Figure 8. Comparable to Figure 5, except that the sound source is located at 16 m from the origin and emits sound only in the direction of the origin (semi-cylindrical source), i.e. in the direction of distances smaller than 16 m. Diffraction caused by the ceiling enables sound to be back diffracted and is therefore observable at distances larger than 16 m. The height of the room is $H = 4.2$ m. A 'speaker symbol' is added at the position of the speaker and showing the direction of the speaker. The right hand side column is the grayscale for the levels in the diagram.

wall. Along the line connecting both sources, i.e. along the x-direction at the height of the sound source, there is sound annihilation (or at least strong destructive interference) when the distance between real source and mirror source is an odd number times half of the wavelength of sound. In other words there is annihilation whenever the frequency is

$$f = \frac{(2n-1)v}{4x_s}. \qquad (12)$$

For the configuration corresponding to Figure 7, formula (12) results in

$$f\,[\mathrm{Hz}] = \{85.75, 257.25, 428.75, 600.25, 771.75\}. \qquad (13)$$

Still, in the configuration corresponding to Figure 7 the listener is always at a lower height than the sound source. This means that the annihilation will not be observed for small x-values, but will be noticeable for larger x-values. Indeed if Figure 7 is examined one can see that the pattern is dominated by diffraction effects as seen in Figure 5 for small distances x. For larger distances the patterns due to annihilation become more apparent. The frequencies listed in formula (13) are especially clearly visible at distances exceeding 10 m from the sound source.

4.2. Centrally positioned sound source

In the previous section it is found that diffraction effects in combination with reflections on the end walls result in distinctive level patterns throughout the discussion room. Such patterns are not beneficial because they prevent a smooth distribution of sound throughout the room. In the current section an examination is performed on the possibility of backward scattering effects due to the corrugated ceiling. If, as Aalto presumed, the ceiling makes every position throughout the discussion room acoustically equal, then there must be sound scattered to the space behind the speaker as well.

For that purpose a sound source is considered positioned at the center of the room (i.e. at 16 m from the origin). To highlight possible back reflection effects a semi-cylindrical source is considered that emits only into the half space containing the origin. It is clear that for a smooth ceiling sound will not reach the other half space unless sound is reflected by the end walls; these results, which are trivial, have been omitted in the report.

Under the assumption that speech is easier perceived without the presence of considerable echoes, relying on end wall reflection for sound distribution is considered less beneficial than relying on diffraction effects closer to the sound source and caused by the corrugated ceiling.

In the absence of reflective end walls, results shown in Figure 8 are obtained. Note that backward diffraction effects would not have appeared for a smooth ceiling. A 'speaker symbol' is added at the position of the speaker and showing the direction of the speaker in Figure 8.

Therefore Figure 8 shows that a corrugated ceiling distributes the sound better in space, certainly 'behind' the sound source through backscatter effects.

4.3. Study of effects caused by the geometry

Important to the acoustics of the discussion room is the peak-to-peak height of the corrugation and the periodicity. We repeat that Figure 5 presents the sound level distribution, ignoring reflections from the end walls and with corrugation properties corresponding to Aalto's discussion

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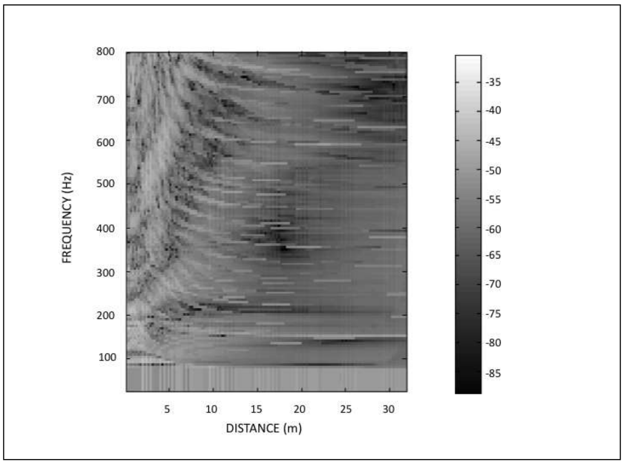

Figure 9. Sound level distribution in dB as a function of the distance from the origin and as function of the frequency, neglecting reflections from the end walls, for Λ is 2.25 m and the peak-to-peak height of the corrugation is 0.75 m. Only the height is different compared to Figure 5, still the result is significantly different. The height of the room is $H = 4.2$ m. The right hand side column is the grayscale for the levels in the diagram.

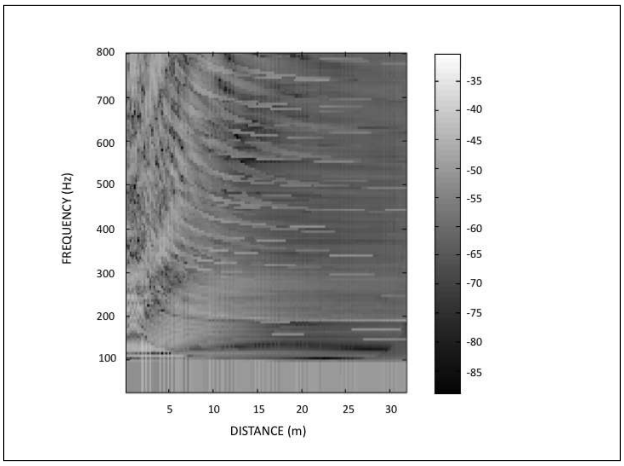

Figure 10. Sound level distribution in dB as a function of the distance from the origin and as function of the frequency, neglecting reflections from the end walls, for Λ is 1.8 m and the peak-to-peak height of the corrugation is 0.5 m. Only the periodicity is different compared to Figure 5, still the result is significantly different. The height of the room is $H = 4.2$ m. The right hand side column is the grayscale for the levels in the diagram.

room, i.e. the periodicity Λ is 2.25 m and the peak-to-peak height of the corrugation is 0.5 m.

If this is compared to Figure 9, where the results are shown for a similar configuration except that the peak-to-peak height of the corrugation is 0.75 m, it's clear that there is a significant dependence of the acoustics on the corrugation. In addition it is found that the sound pattern evolves slowly as the height is altered, but it is not possible to predict the results without fully calculating the acoustics because the patterns do not change linearly with changing height.

In addition to the height, it is also possible to change the periodicity. Figure 10 is again comparable to Figure 5, except that the periodicity Λ is now 1.8 m instead of 2.25 m. Yet again a significant influence is visible.

5. Concluding remarks

The acoustics is clearly influenced by the presence of a corrugated ceiling. This influence is rather complex and is a combination of positive and negative outcome. Still, it has been found that the use of a corrugated ceiling enhances the overall distribution of sound throughout the auditorium mainly because the corrugation causes sound to be back reflected, making a person better understandable even if he does not face the audience, see for example Figure 8. If a smooth ceiling was used instead, the same effect could only be caused by the end walls or perhaps to some extend by pillars near the windows or the side walls. The latter two cause time delays resulting in echoes, something which is much less outspoken for a corrugated ceiling as the reflections (diffractions) there occur much closer to the speaker. Effects caused by the vertical pillars near the windows are not considered in this paper due to constraints imposed by the used model and because it is out of the scope of this study.

However, the distribution is not perfect due to the existence of critical diffraction angles and Bragg scattering angles and also end wall effects; hence Aalto's statement that each position would be acoustically equivalent is false. Nevertheless the improvement with respect to a smooth ceiling is significant enough to give Aalto the credit he disserves for designing a corrugated ceiling not just for esthetics but also for acoustics.

It is also important to point out that, as can be seen in Figure 1, Aalto constructed rounded end walls consisting of a smooth transition from ceiling to end wall. This must have had a positive impact on the acoustics especially for an audience or a speaker situated near a wall. This effect has not been considered in our research because we were mainly interested in the effect on positions far off the end wall and because the applied model is not suitable to tackle such transitions between ceiling and end wall.

Because the presented study is a frequency analysis the effects caused by reverberation time has only been mentioned qualitatively and not quantitatively. Further research on the specific influence of reverberation times is a possibility for the future, but is beyond the scope of the here presented diffraction study.

For historical reasons we must also mention, as pointed out by the anonymous referee of our paper, that it is indeed possible that Aalto took the downstand beams into account when he configured his room. He could for instance have imposed a periodicity constrained by the present donwstands. We cannot look into his brains. However it is clear that Aalto could have chosen for a flat ceiling instead to cover the downstand beams, but he did not. He has chosen a corrugation for reasons of redistributing sound in a better way than a flat ceiling would. Whether the corrugation follows the downstand beams or the downstand beams were placed in order to correspond to the corrugation he intended is absolutely unknown to us.

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