ODEON - A DESIGN TOOL FOR AUDITORIUM ACOUSTICS, NOISE CONTROL AND LOUDSPEAKER SYSTEMS

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1. INTRODUCTION

The ODEON software was originally developed for prediction of auditorium acoustics. However current editions of the software are not limited to these fields, but also allow prediction in rooms such as churches and mosques, interior noise control, design of room acoustics and sound distribution systems in public rooms such as foyers, underground stations and airports. Some of the features in ODEON 5.0 Combined are; two methods for global estimation of reverberation time, various point response calculations providing decay curves, reflectograms, miscellaneous parameter graphs, 3D maps, multi-source calculations including point, line and surface sources, facilities for noise control calculations and multi-channel auralization using fully filtered BRIR's.

2. MODELLING

2.1 Modelling Rooms

Room geometries to be used in ODEON can be modelled in two ways, either the geometries can be modelled in a CAD program such as AutoCAD and imported into ODEON in the DXF format or the geometries can be scripted in ODEON's parametric modelling language. No matter the method of modelling, a surface is obtained by connecting points on surface's edge. Defining a sequence of points will automatically define both sides of the surface so there is no need to worry about drawing the sequence of points clock or counter-clock wise, even surfaces with concave shapes are allowed, see figure 1. ODEON being fairly insensitive as to how the user entered the model data is in particular an advantage when the geometry is supplied as a DXF file by third parties, who can not be assumed to be aware of any such rules.

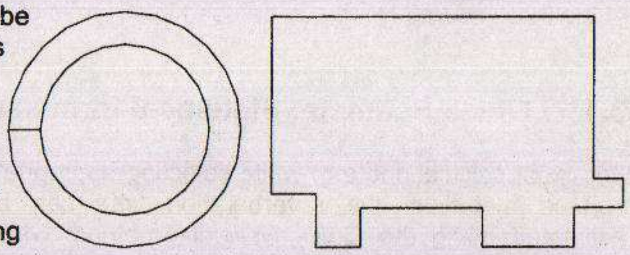

Figure 1 Example on complex surfaces. Left: A circular surface with a hole in the middle. Right: A surface with concavities on the edges.

2.2 Modelling In the Odeon Modelling Language

The modelling language available to the ODEON user for modelling geometries is a versatile scripting format [8]. The format can be used for simply entering geometries point by point and surface by surface. To support the advanced user however, it is also possible to use constants, variables, coordinate transformations and even programmatically scripts in order to create flexible room models at high speed.

2.3 Checking The Geometry Of A Room Model

Creating a suitable geometry for room acoustics calculations can be a lengthy process, which doesn't necessarily end when a nice looking model has been created. One of the common problems is that geometries should be watertight. Another problem, which may be less obvious, is that geometries should be consistent. ODEON has several tools for verification of geometries. To help finding leaks in geometries, ODEON can highlight free edges, display a rendered surface geometry of the room and indeed the ray-tracing process can be visualized in a 3D display in order to reveal leaks in the room or inappropriate source positions. To reveal surfaces, which are by accident duplicated, surfaces that are partly overlapping other surfaces or warped surfaces, ODEON provides a built in utility.

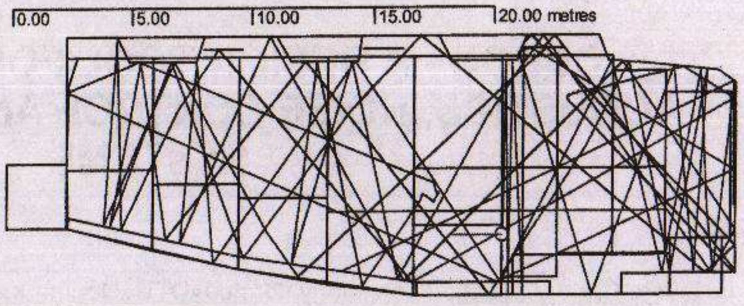

Figure 2 The *3DInvestigate Ray tracing* display is one of many tools that help the user to verify room geometries. Following the interactive ray-tracing on screen makes it easy so spot leaks in the geometry or inappropriate source positions.

3. CALCULATIONS AND ALGORITHMS

ODEON Combined allows simulation of point, line and surface sources. Point sources are intended for simulation of musical instruments, speakers, loudspeakers, small noise sources in industrial environments etc. Line and surface sources are intended for the simulation of large vibrating noise sources such as machinery in industrial environments. However, extended sources can also be useful for simulation of sound transmitted into the room through windows, ventilation noise etc. Any of the three source types can be used in all types of calculations available in ODEON.

3.1 Quick Estimate, Statistical formulas

For initial calculations e.g. while selecting appropriate surface materials, the reverberation time can be estimated using the *Quick Estimate* method, which provides prompt estimates of the reverberation times using statistical formulas. In order to estimate the volume, ODEON runs a small ray tracing calculation, from which the mean free path and thus the volume is obtained. Finally ODEON calculates the reverberation times using the Sabine, Eyring and Arau-Pachades formulas. The user may as an option provide the volume manually, if not satisfied with the estimate derived from the mean free path.

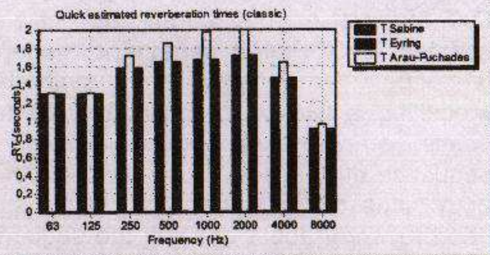

Figure 3 *Quick Estimate* provides fast estimates of reverberation time using different statistical formulas.

3.2 Global Estimate

To get a global estimate of reverberation time in a room, ODEON also offers another method, which is ray-tracing based. This method takes into account the shape of the room, location of the absorbing materials, scattering properties of the materials etc. To calculate the decay, ODEON emits rays from a source, and then calculates how the rays decay (on average) due to absorption at surfaces and due to air absorption. Unlike the statistical methods this method also has the advantage that it does not depend on an estimated volume, which may or may not be correct. For rooms such as concert halls and auditoria that are not dominated by strong decoupling, the reverberation time is a global measure and in this case the global decay method provides a good estimate on the decay time in the room.

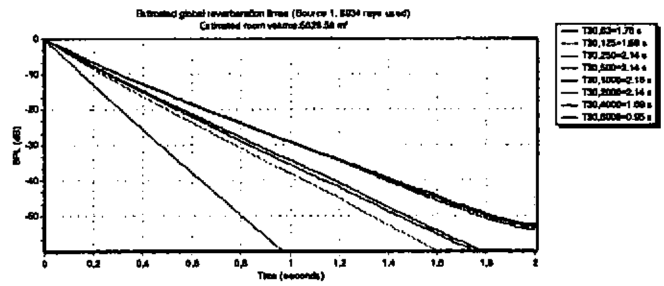

Figure 2 Global decay curves estimated using the *Global Estimate* method takes into account none diffuse conditions.

3.3 Point Responses

3.3.1 Point Responses From Line And Surface Sources

To calculate the point response from a line or surface source, ODEON applies a special ray tracing method [7]. Taking the surface source as the example this is how the calculation method works; ODEON distributes a number of secondary sources having a Lambert directivity over (one of the sides) of a selected surface in the room geometry, then a ray is radiated from each of these secondary sources and reflected at the surfaces of the room. The orientation of the reflected rays are calculated as a weighted direction between a random chosen direction (the random angles being distributed according to the Lambert distribution [4]) and the specular reflection direction, using the scattering coefficient of the reflecting surface as the weighing factor. Using the approach described each ray will generate a number of secondary sources corresponding to the number of times the ray was reflected plus one. The last part of the calculation is related to a specific receiver, at this point it is determined which of the secondary sources are visible at the receiver point and the contribution of the visible secondary sources are summed to the response of that receiver.

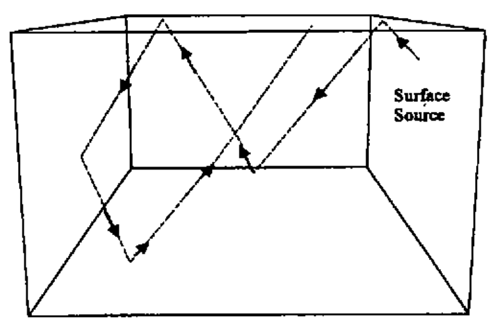

Figure 3 Illustration of one out of many rays radiated from a surface source and the first reflections of that ray. At each reflection point including the start point, a secondary source is generated.

3.3.2 Point Responses From A Point Source

To calculate the point response from a point source, ODEON can either use a hybrid calculation method (combining the image source method with special ray-tracing methods), which has been proven to work well in rooms such as auditoria [5] that are not dominated by curved surfaces, or a ray tracing method which yields better results in rooms such as churches or mosques [9], that are dominated by curved surfaces. No matter which method is being used, a point source is described by position, orientation, delay equalisation and a directivity pattern, allowing modelling of natural sound sources, noise sources as well as loudspeaker systems with multiple active sources.

The ray-tracing method applied for point source calculations are similar to the method used for surface and line sources except that the direct sound are emitted from one point (source) instead of a number of secondary source points.

It is possible to select whether Odeon should use the hybrid calculation method or a pure ray-tracing method, by adjusting a transition order, which determines the reflection order, at which the calculation method changes from a hybrid calculation method that includes generation of image sources to the pure ray-tracing method. The hybrid calculation method applied in ODEON is described in by Rindel & Naylor [1,2] except that the current version of ODEON also includes scattering for reflections below the transition order. In short the hybrid calculation method works as follows, rays are emitted from the point source and for low order reflections, below the transition order, rays are used indirectly in order to detect image sources while the program keeps track on the image sources detected in order only to get one contribution from each image source. Above the transition order the ray-tracing method, which is used for the line and surface sources, is used.

By nature the image source method does not include scattering so in order to include scattering in the early reflections, the early reflection calculations is in fact a hybrid method on its own. In short; Each time Odeon detects an image source, an inner loop of (scatter) rays are started, taking care of the scattered sound which is reflected from this image source /surface.
Example: If all scattering coefficients in a room are 0.5, then the specular energy of a first order image source is multiplied by (1-0.5) - and the specular energy of a second order IMS is multiplied by (1-0.5)*(1-0.5). The scattering rays handle the rest of the energy. The early scatter rays are handled in a way, which is indeed inspired by the way in which surface sources are simulated, actually each time an image source is detected, ODEON will simulate a surface source, which will emit a number of early scatter rays. The early scatter rays will be traced from the current reflection order and up to the transition order. At each reflection point of the early scattering rays, including the starting point, a secondary scattering source is created.

The last part of the point response calculation for a point source is, just as for the line and surface sources, to examine which of the generated image and secondary sources are visible at the receiver position. For the secondary sources generated by early scattering rays or by late rays, a contribution is added to the point response, if the source is visible from the receiver. For the image sources generated, a contribution is added to the point response if the entire reflection path from the source to the receiver is unobstructed. The contributions added to the point response takes into account:

- Directivity factor of the primary source in the relevant direction of radiation
- Reflection coefficients of the walls involved in generating the reflection (taking into account the angle of incidence for the reflection)
- Air absorption due to the reflection path of the reflection
- Distance damping
- Diffraction damping due to limited size of the surfaces generating the reflection

Three different point responses are available in ODEON 5.0 Combined; *Single Point*, *Multi Point* and *Grid* response. All three point response calculations share the calculation methods just described and offer a number of calculated room acoustic parameters in receiver point(s) for a given source configuration.

3.3.3 The Single Point Response Results

The *Single Point* response offers detailed results and auralization for a selected receiver point.

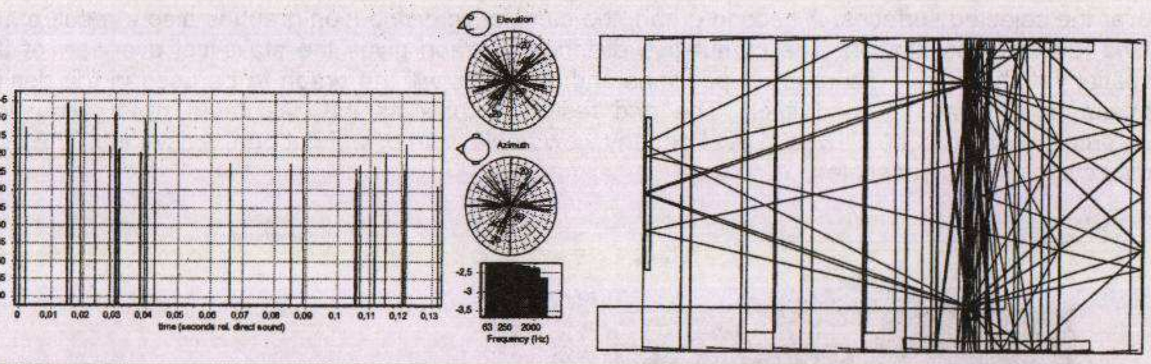

Figure 3 A few examples of the *Single Point* results. Early reflection paths displayed along with its associated refectogram in a situation where a flutter echo is present. Individual reflections or groups of refelctions can be examined in depth. ODEON is capable of predicting as well auralizing echo problems even for high order reflections.

The *Single Point* Results are:

- Room acoustics parameters: EDT, T_{30}, SPL, C_{80}, D_{50}, Ts, LF_{80}, STI, A-Weighted Late Lateral SPL(A), SPL(A), ST_{early}, ST_{late} and ST_{total}.
- Decay curves.
- Reflectogram showing the early reflections, the strength per octave band, time of arrival, azimuth and elevation angle. The reflectogram is directly coupled to the *3DReflection path* display.
- *3D Reflection paths* display allows tracking down early reflections, which are calculated using the image source method in a 3D display of the room geometry.
- A zoom able graph displaying the calculated BRIR (Binaural Room Impulse Response).

3.3.4 The Multi point response result

The *Multi point* response calculation calculates point responses for a number of discrete receivers. Apart from offering room acoustic parameters for these receivers, the *Multi point* response also provides a number of graphs and tools making it useful in particular for environmental acoustics:

- A noise control display, where the influence of the different active sources can be assessed simultaneously at the different receiver positions.
- A graph showing the simulated spatial decay curves which are useful for evaluation of the acoustics in workrooms [10].
- Graph showing parameter versus distance for a selected parameter.
- A graph showing a selected parameter for all receiver positions and frequency bands.

3.3.5 The Grid Response result

The *Grid* response is the calculated point responses for a grid of receivers. The receiver grid is specified from a number of surfaces in the room geometry, a receiver distance and a receiver height over the selected surfaces. A second graph, the cumulative distribution graph is also a result of the *Grid* response calculation. The cumulative distribution graph gives the statistical overview of the spatial variations over the receiver positions and often this will the graph to be used in the design phase rather than the grid itself. The grid result contains all the calculated room acoustical parameters and can be viewed in 3D from any view angle, with or without perspective etc. The user may customize colour scales.

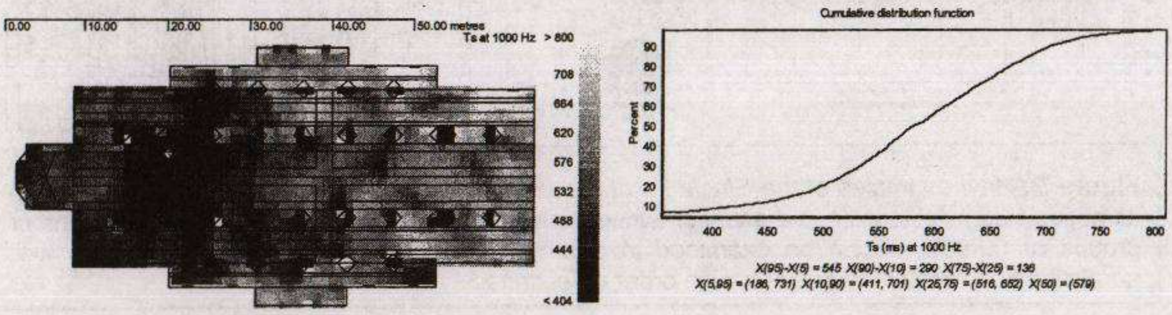

Figure 4 A *Grid* response result. The receiver grid and its corresponding cumulative distribution graph for a selected parameter.

4. AURALIZATION

As a part of the point response calculations, ODEON is capable of creating BRIR's (Binaural Room Impulse Responses). The BRIR's can be used for auralization either by listening directly to the generated BRIR or by convolving an anechoic signal with the BRIR and listening to this result – as a last option a number of such simulations can be combined together in order to form multi channel auralization.

The typical point response calculated by ODEON includes more than 100000 reflections per source. The calculation time needed to create a BRIR (Binaural Room Impulse Response), which is the key to the auralization is typically less than 30 seconds on a 600 MHz Pentium III. The calculation carried out during the creation of the BRIR's includes full filtering of each reflection in nine octave bands (the 16 kHz band being extrapolated) and applying a set of HRTF's (Head Related Transfer Functions) for each reflection. Using the complete filtering scheme has several advantages apart from sounding natural. Not only does the auralization output allow evaluation of the reverberation time, level, speech intelligibility and clarity. It also allows an evaluation of:

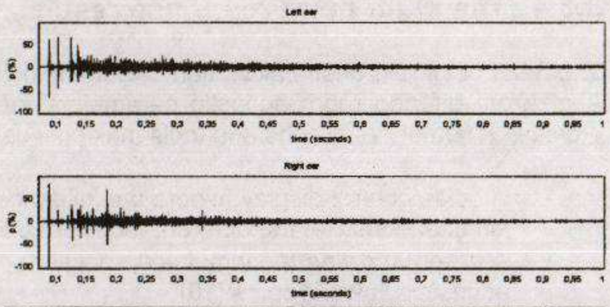

Figure 5 Example on a calculated BRIR. The first 1.0 seconds of the BRIR at a receiver position some 13 metres from the source in a hall for chamber music are shown.

- High order echoes e.g. flutter echoes.
- Directivity and frequency response of sources.
- Envelopment (the experience of being surrounded by sound, very much relies on the lateral reflections arriving *later* than 80 ms after the direct sound).
- Frequency dependent reverberation time. Frequency dependent reverberation is not a question of a simple equalisation of the reverberation, the equalisation is time variant - usually the sound will get darker as the sound decays - a very dominant feature of rooms with extreme reverberation times (cathedrals, mosques etc.).
- Modulated decay. Long decays in rooms such as cathedrals often has ripples on the late decay rather than a smooth decay.

4.1 Verifying the auralization filters

A question that appears when using an auralization system is whether the system is actually capable of auralizing the acoustic properties, which has been predicted by the room acoustic program. A simple way of testing this issue is to simply measure the room acoustics parameters on the impulse response filters created by the room acoustics program, using a room acoustics measuring program capable of analysing an impulse response in the Windows wave format and then compare the room acoustic parameters predicted by the prediction program with those measured on the auralization filters.

Below is a comparison of room acoustics parameters predicted by ODEON, and those measured on the auralization filters[1] using the Dirac [11] measuring program. Models of two very different rooms were used for the comparison; a model of the Elmia multi purpose, which were used in the 2nd Round Robin on Room Acoustical Computer Simulation [6] as well as a model of a very reverberant church (the Grundtvigs church, Copenhagen, Denmark). For each of the rooms two receiver positions are shown, one close and another far from the source. As can be seen from the results, the predicted and measured parameters are very close; eventually the average error is far below one subjective limen [6] even though the filters tested are for very different room acoustic conditions. It should be remembered that the test is really a cross test of the ODEON auralization filters as well as the measuring program.

Parameter/room	Grundvigs church $d_{s\text{-}r}$ = 5.6 metres		Grundvigs church $d_{s\text{-}r}$= 44 metres		Elmia $d_{s\text{-}r}$ = 5.3 metres		Elmia $d_{s\text{-}r}$ = 30.7 metres	
	Odeon	Dirac	Odeon	Dirac	Odeon	Dirac	Odeon	Dirac
EDT	6.20	7.68	9.06	9.59	1.43	1.44	1.85	1.74
T30	7.61	7.94	7.32	7.85	1.97	1.98	1.83	1.85
C80	-1.2	-0.66	-10.3	-10.3	3.3	4.65	-2.2	-2.18
D50	0.39	0.39	0.06	0.07	0.58	0.66	0.19	0.20
Ts	362	353	670	711.9	79	64.3	137	139

Table 1 Room acoustic parameters at 1000 Hz predicted by ODEON and measured from the simulated impulse responses using the Dirac program.

[1] A special set of head related transfer functions (HRTF's) were used in order to simulate an omni directional measuring probe rather than a dummy head. Also reflections were added to the impulse response using random phase in order to simulate a simple DC filter. The DC filtering would normally be included in the HRTF filters.

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Proceedings of the Institute of Acoustics

APPLICATIONS OF PAFEC VIBROACOUSTICS TO THE AUDIO INDUSTRY

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1. PROGRAM HISTORY

The company PAFEC Ltd was born out of the mechanical engineering department at Nottingham University in 1976. The program, also named PAFEC (Program for Automatic Finite Element Calculations), was developed, used for consultancy and sold into industry. Originally the capability was for stress, vibration and thermal analysis. The current author joined in 1982, being employed originally to write programs for underwater shock analysis, using the doubly asymptotic approximation. This work was extended to include steady state harmonic analysis. Further functionality was added, extending the application areas, and user base, to sonar, audio, automotive and other areas.

2. MODELLING METHODS

In PAFEC VibroAcoustics the fluid medium is modelled with acoustic finite elements, wave envelope elements and boundary elements. It is often important to include the interaction with a structure, which may be the source, receiver, or may be an important boundary condition for the acoustic region. This can be modelled with a wide range of structural finite elements. The structural and acoustic models can be uncoupled or fully coupled. In the uncoupled case the structural response is assumed to be unaffected by the pressure distribution in the surrounding acoustic medium. This would be appropriate for an engine block vibrating in air. In a fully coupled analysis there is continuity of normal velocity and pressure/(-ve normal stress) on the fluid structure interface. This is almost always required for underwater acoustics, as water is a dense medium. In loudspeaker design, the air has low density, but also the cone and dustcap are light. To get accurate results a fully coupled analysis is necessary, see ref [1].

Finite and boundary element analyses are applicable to 'low frequency' problems, where the system being modelled is a small number of wavelengths in extent, and is complimentary to ray tracing approaches. To analyse the acoustics of a concert hall, a finite or boundary element model would be unmanageably large. Finite and boundary element analysis solve the wave equation more precisely and thus naturally copy with phenomena such as diffraction, which ray tracing cannot cope with satisfactorarily. FE and BE can be used to analyse cone breakup, domes (ref [2]), radiation from a drive unit (ref [1], [3] and [4]), diffraction by edges, placement of speakers in a small room (ref [5]), horn design (ref [6]), diffuser design (ref [7])...

3. EXAMPLES

3.1 ANALYSIS OF SMALL ROOM

Figure 1 shows a model of a simple room, with the ceiling removed. It is based on a 6m X 4m X 2.5m cuboid, with the extra features of a rounded corner, a closet, a fireplace and a window. Two idealised sources, assumed to be in phase, are positioned either side of the fireplace. A listening position is located in line with the centre of the fireplace, on the opposite side of the room. The boundaries are assumed to be rigid, apart from a window made of glass. The air is modelled with an acoustic boundary element mesh, composed of quadratic patches. The window was modelled with some structural shell elements, in a fully coupled analysis. Frequencies from 10Hz to 150Hz in steps of 0.5Hz were analysed.

Figure 2 is a plot of SPL at the listening position against frequency. The resonance at 17Hz is due to the window vibration. (The breathing mode of the window in vacuo is 17.6Hz). Higher order modes of the window are less important because the contributions from different parts of the vibrating surface to the pressure at the listening position tend to cancel out. The remaining resonances in figure 2 are from room modes. The first one, at 30Hz, is however very small because the listening position is near to a nodal surface for the first room mode. As frequency increases the room modes become dense.

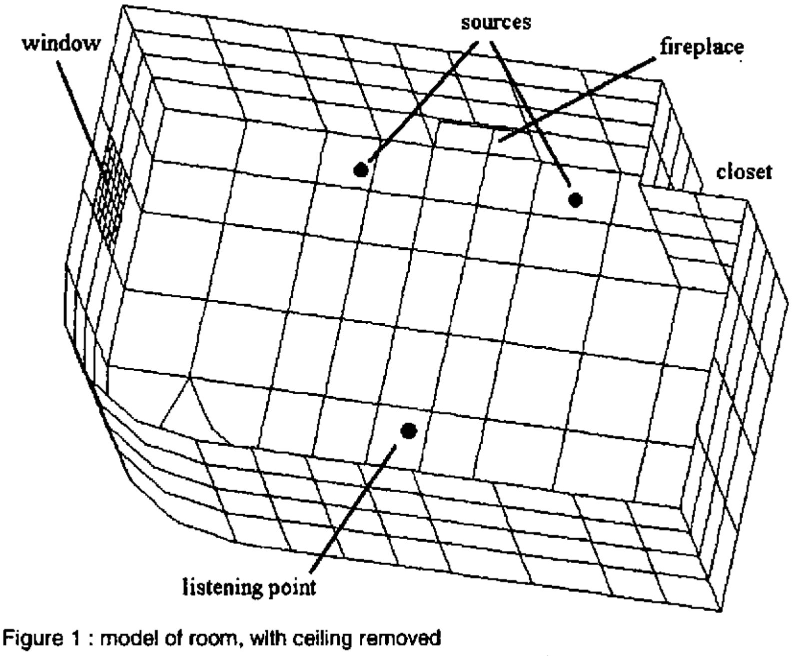

Figure 1 : model of room, with ceiling removed

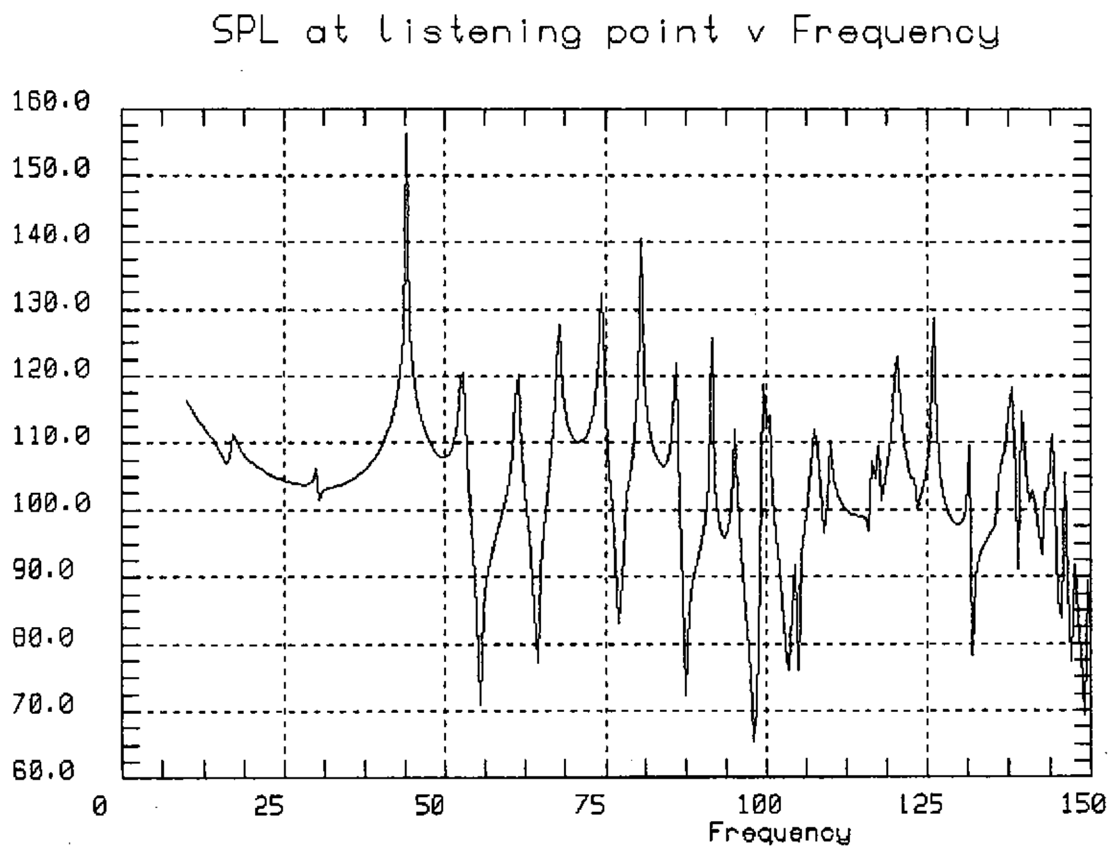

Figure 2 : SPL at listening position

3.2 RADIATION FROM A LOUDSPEAKER

The example below is considered in more detail in ref [1] and [3]. A model of cone/surround/dustcap fully coupled to the surrounding air was analysed. A half model, exploiting the plane of symmetry was use, as shown in figure 3. A unit amplitude force excitation was applied to the voice coil over the entire frequency range. Figure 4 shows the response on axis, both 1m in front of and 1m behind the front board. The main drive unit resonance occurs at 111Hz. At low frequencies there is a high level of response behind the box. As frequency increases, and the influence of diffraction diminishes, the pressure behind the box decreases and the device becomes more directional.

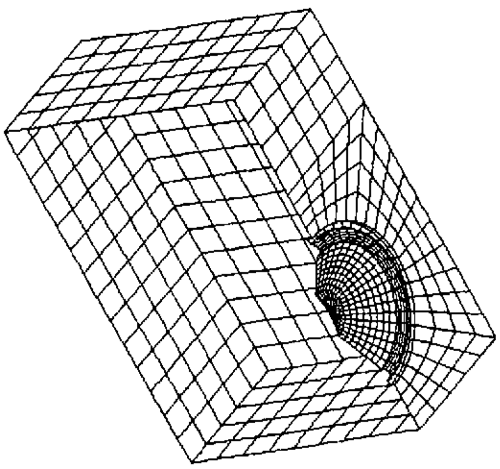

Figure 3 : boundary element model for radiation From loudspeaker

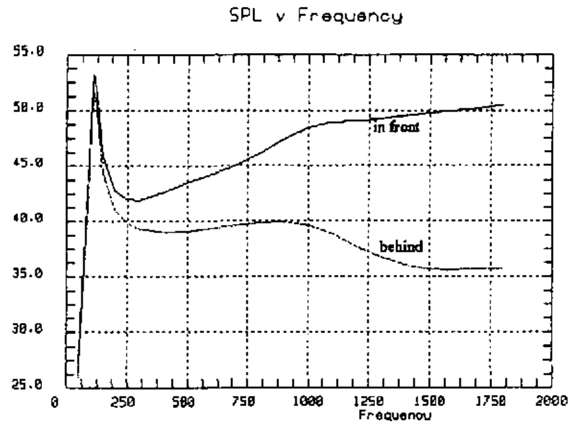

Figure 4 : analysis results from FE/BE analysis

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