Sustainable Optimum acoustic Interior Design Solution For Renovation of Speech Closed Spaces.

Dr. Doaa Ismail Ismail Attia
Assistant professor of Interior Design and Furniture, Faculty of Applied Arts, Benha University

Abstract:
The speech closed interior spaces are distinguished from other closed interior spaces by almost the usual fixed positions of both the sound source and the listener (Ex; students classroom, conference room, lecture hall, etc). Thus, it is possible to acoustically help both the speaker and the listener through the usage of proper acoustic interior design for the space. The main acoustic defect which the listener in the speech closed interior space always complain of is that speech intelligibility is particularly poor. This is normally due to the noise, the uncontrolled sound direction and the reverberation time which is too long . As a result of factors these factors the speech intelligibility cannot often be met by all the seats. Also, in speech closed interior spaces, although the areas of acoustical treatment (reflective, absorptive and diffusive) were adequate, they might not be placed correctly in the ceiling, walls and floor and so not effective to reduce noise, control sound direction and addressing other acoustical issues arising in the interior space. Hence, speech closed spaces should be Architecturally designed according to the latest knowledge concerning the acoustical requirements. In the case of renovations, for various reasons, the acoustics of speech closed interior spaces often do not fulfill the acoustical requirements. A listener cannot be affected and convinced efficiently by what the speaker says if he/ she cannot hear the speaker clearly. So, the relationship between the speaker and the listener will be damaged. Acoustic interior design has a role concerning the proper management of such problem to improve such closed spaces. In this paper, to address this defect to improve intelligibility in speech closed interior spaces, the author considered new appropriate optimum acoustic interior design solution for the ceiling, walls and floor. **Problem:**- Difficult speech communication is considered a common issue in many speech closed spaces such as conference rooms, lecture halls, student's class rooms, etc. Numerous listeners are suffering from poor speech intelligibility .The listener cannot be affected and convinced efficiently by what the speaker says if he cannot hear the speaker clearly, thus, the relationship between the speaker and the listener will be damaged, also The areas of some acoustical treatments using reflective, absorptive and diffusive materials to reinforce sound and decrease noise may not be placed correctly on the ceiling, walls and floor of the speech closed interior space and so they are not effective. **Objective :** introduce an optimum acoustic interior design solution to improve speech intelligibility for speech closed spaces leading to a uniformly diffused strong sound field, free of any defects, arriving to all listeners, and thus a good acoustical environment and present a sustainable strategies to obtain efficient use of energy and efficient use of materials.

Keywords:
Acoustics Interior Design, Suspended Ceiling, Sound Reinforcement, Noise, Ceiling Reflector, Sound Absorber, Sound Diffuser, Sound Reflector, Intelligibility, Optimization.

Paper received 27th April 2017, Accepted 12th May 2017, Published 1st of July 2017

Introduction :
The speech closed interior spaces are distinguished from other closed interior spaces by almost the usual fixed positions of both the sound source and the listener (Ex; students classroom, conference room, lecture hall, etc). Thus, it is possible to acoustically help both the speaker and the listener through the usage of proper acoustic interior design for the space. The main acoustic defect which the listener in the speech closed interior space always complain of is that speech intelligibility is particularly poor. This is normally due to the noise, the uncontrolled sound direction and the reverberation time which is too long . As a result of factors these factors the speech intelligibility cannot often be met by all the seats. Also, in speech closed interior spaces, although the areas of acoustical treatment (reflective, absorptive and diffusive) were adequate, they might not be placed correctly in the ceiling, walls and floor and so not effective to reduce noise, control sound direction and addressing other acoustical issues arising in the interior space. Hence, speech closed spaces

should be Architecturally designed according to the latest knowledge concerning the acoustical requirements. In the case of renovations, for various reasons, the acoustics of speech closed interior spaces often do not fulfill the acoustical requirements. A listener cannot be affected and convinced efficiently by what the speaker says if he/ she cannot hear the speaker clearly. So, the relationship between the speaker and the listener will be damaged. Acoustic interior design has a role concerning the proper management of such problem to improve such closed spaces. In this paper, to address this defect to improve intelligibility in speech closed interior spaces, the author considered new appropriate optimum acoustic interior design solution for the ceiling, walls and floor. The optimum interior design solution is based on a combination of two different phases: the first ; is to reinforce sound using an optimum overhead suspended inclined ceiling reflector with optimum slope angle and optimum width that reflects the early sound waves towards the essential areas of speech closed space. The second ; is to optimize reducing noise without losing sound strength by covering the rest of the ceiling, rear sides and back wall with "absorber-diffuser" panels or "absorber-reflector" panels which partly absorb and partly diffuse or reflect early and late rays .The optimum interior design solution for the ceiling, walls and floor not only improve speech intelligibility but also helps to uniform and homogenate the sound field inside the speech closed space and so gives comfort and encourage the usability of the space. The optimum interior design solution also improves the sustainability since it increases the efficiencies of acoustical energy, also the materials used are recyclable, reusable and renewable materials.

Research problem:

- Difficult speech communication is considered a common issue in many speech closed spaces such as conference rooms, lecture halls, student's class rooms, etc. Numerous listeners are suffering from poor speech intelligibility .The listener cannot be affected and convinced efficiently by what the speaker says if he cannot hear the speaker clearly, thus, the relationship between the speaker and the listener will be damaged.
- The areas of some acoustical treatments using reflective, absorptive and diffusive materials to reinforce sound and decrease noise may not be placed correctly on the ceiling, walls and floor of the speech closed interior space and so they are not effective.

Research objective :

- Present and Shed light on optimum acoustic interior design solution to improve speech intelligibility for speech closed spaces leading to a uniformly diffused strong sound field, free of any defects, arriving to all listeners, and thus a good acoustical environment.
- The specialized acoustic interior designer, who is responsible for providing an interior acoustical environment that provides the listener's needs, must put sustainable strategies to obtain efficient use of energy and efficient use of materials.

Background:

In speech closed interior space, the influence of poor acoustics on the listeners and speakers was investigated in (1) and (2) .The interest and desire to improve speech intelligibility for speech closed interior spaces, such as educational spaces in general and student classrooms, lecture hall, discussion room, etc in particular has significantly increased where the intelligibility of speech is a vital factor that must exist(3). This improvement could help in improving the quality of listeners learning experiences. For speech closed interior space with large number of seats, the achievement of good speech acoustics is more complex. Actually low acoustic energy of early arriving rays, the uncontrolled for the sound direction, noise with echoes or flutter echoes and excessive reverberation time, are common defects in speech closed spaces (4). These defects impede the hearing process as the spoken words become unclear and incomprehensible (5).Hence, increasing sound force and decreasing noise without decreasing acoustic energy is usually required.(6)

Treating ceiling, walls and floor is an acoustical interior design concern in speech closed spaces. In the present work, it is shown how to install a suspended ceiling with optimum inclinated intelligent reflector with a height which is less than the actual height and how to cover the rest of the ceiling and rear sides and back wall with hybrid ; "absorber –diffuser" panels or "absorber – reflective" panels .

1- The acoustical performance in speech closed interior spaces:

1-1Ways to obtain good speech intelligibility in speech closed spaces:

Good speech intelligibility results mainly from attenuating noise and reinforcing sound before it reaches the listener. These can be achieved by: (7)

- The speech closed space should be designed in a way that the audience is as close to the sound source as possible. This requirement can be achieved by either maintaining a sense of roundness in the speech closed interior spaces, for example by using the circular or the van shape to the space, or by using a round balcony, hence bringing more seats closer to the sound source.

- The sound source should be raised as much as it is feasible, to secure a free flow of direct sound to every listener. Also the sound source should stand high enough to be seen by the listener.
- A good sight line helps effectively in the good acoustical perception, where the ability of reading lips helps in achieving part of speech intelligibility. This requires a minimum floor slope of at least 7° (8).
- The sound source should be closely and abundantly surrounded by large sound reflective surfaces to increase the sound energy received by the listener. The dimensions of the reflecting surfaces must be comparable with the sound waves to be reflected. The reflectors should be placed in such a way that the time-delay between the direct and reflected sound is as short as possible.
- The volume of the speech closed interior space should be kept at a reasonable minimum, thus shortening the sound paths.
- Placing the opposite reflectors parallel to each other, particularly those close to the source, should be avoided, in order to eliminate undesirable flutter echo.
- The listener should be placed in areas which are advantageous to both viewing and listening. Excessively wide seating areas should be avoided. Aisles are preferably located at the sides of the speech closed space where viewing is restricted, not in the centre where viewing and listening is favorable.

1-2 Outlines of good acoustical requirements in closed speech interior space: (7)

- There should be adequate loudness in every part of the speech closed space, especially in remote seats.
- Sound energy should be uniformly distributed within the speech closed space.
- Optimum reverberation characteristics should be provided in the speech closed spaces to facilitate whatever function required.
- The closed speech interior space should be free from acoustical noise defects .
- Background noise and vibration should be sufficiently excluded in order not to interfere with the function of the enclosure.

1-3 Acoustical surfaces that treat acoustical defect´s in speech closed spaces:

There are acoustical surfaces that could be added to the interior boundaries (ceiling, walls and floor) to correct the acoustical defects in the speech closed space.

These are reflective, absorptive and diffusive surfaces(Figure 1-1). Although the acoustical design of speech closed spaces relied on absorption yet, it should be considered that an optimal acoustical design can only be achieved using an appropriate combination of each ingredient(7)

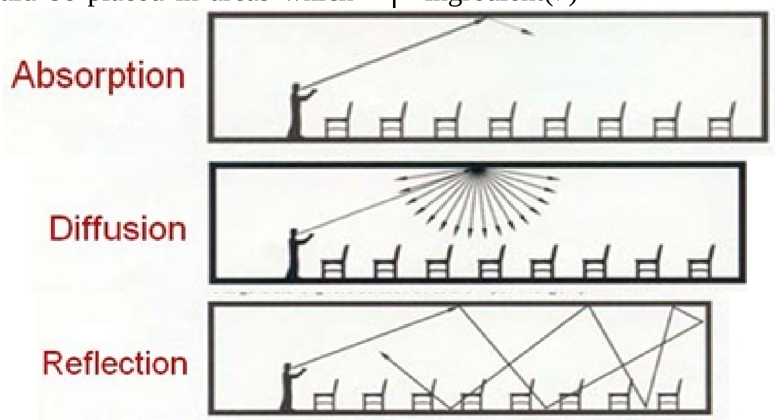
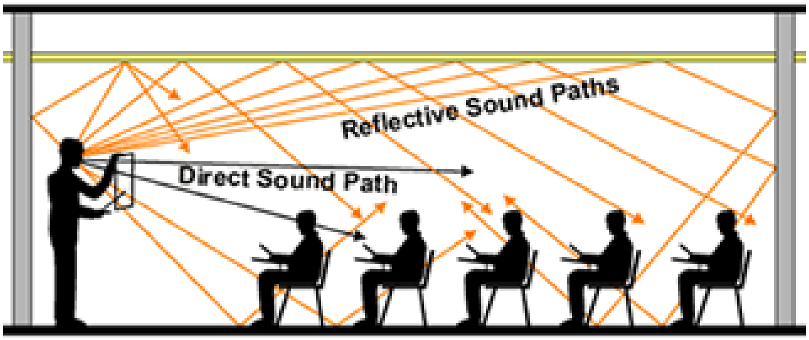


Figure (1-1). Illustration showing how absorption removes the beneficial early reflections from the ceiling; reflection redirects them and diffusion uniformly distributes them for greater coverage and intelligibility.

1-3-1 Sound wave reflection surfaces:

The Sound wave traveling in a medium strikes a reflective surface separating two media. The direct incident sound wave is reflected back into the initial medium obeying the ordinary laws of reflection where the angle of incidence equals the angle of reflection, and the incident, reflected waves and the normal all lie in the same plane. The reflective surface redirects sound (7) (Figure 1-2).



(Figure 1-2) direct sound path and reflective (indirect) sound path

1-3-2 Sound wave absorptive surfaces:

The absorptive surface attenuates sound by dominating the sound reflections thus reducing noise (improve speech intelligibility), but it also reduces the sound energy. The types of materials used in the absorption surfaces are divided according to mid and high or low sound frequencies.

- **Surfaces absorbing mid and high frequencies**:

The sound in bands by mid and high frequencies can be absorbed by porous materials (such as carpets, acoustic tiles, curtains, fiberglass and fiber cotton, fiber wool).These materials are characterized by its high performance at high frequencies and its less impressive performance at low frequencies, because of their relatively high absorption coefficient in the frequency bands. This system is usually installed on the ceiling and the floor such as acoustical ceiling tile and carpets. (7), (8)

- **Surfaces absorbing low frequencies:**

The Sounds in low frequency bands can be absorbed by resonant absorber systems such as thin MDF panels on air gap behind the panels. The utilization of this system adds an important advantage: while it absorbs the unwanted low frequency and it acts too as a reflector for the mid and high frequencies that is essential for the intelligibility of speech. This system was installed on the front walls and on one –third of the side walls in addition to the walls of the stage due to its location in the front near the sound source. It reflects effectively and early the high sound energy always required for the intelligibility of speech .(7), (8), (9)

- **Single Plane Absorptive Syndrome**

In many speech closed interior spaces, absorption is typically the only treatment used and it is often concentrated on the ceiling and floor, with high frequency absorbing material like acoustical ceiling tile and carpeting. This is called the Single Plane Absorption Syndrome (SPAS). All of the absorption is concentrated in the vertical plane, which actually accentuates the potential flutter reflections in the horizontal plane which is purely reflective. This causes the echoes and flutter echoes be more audible and problematic, which should be avoided.(9), (10)(Figure 1-3)

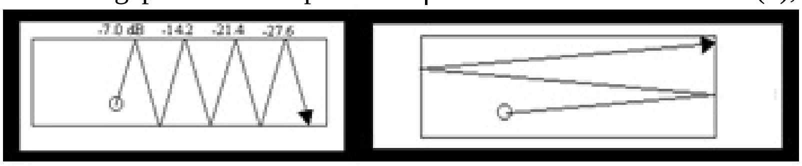


Figure (1-3) Single Plane Absorptive Syndrome. Sound in the vertical plane is attenuated by an absorptive ceiling and floor but hardly at all in the horizontal plane from reflective walls.

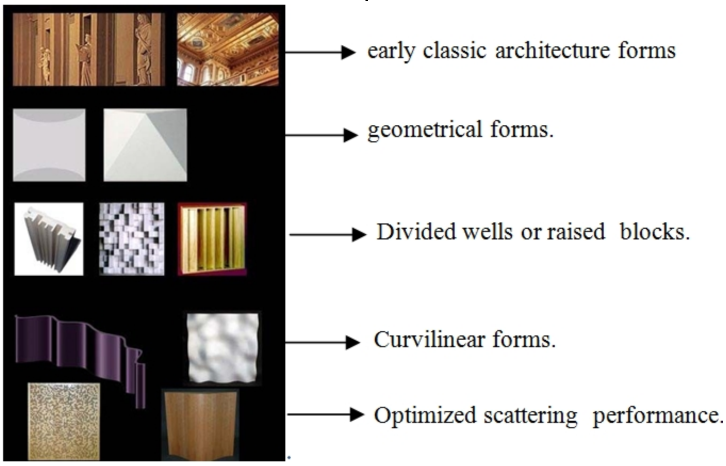
1-3-3 Sound wave Diffuser surfaces:

Diffusion is a process by which incident sound energy is uniformly scattered, (Fig1-1). Sound diffuser uniformly distributes sound in a closed space to remove acoustical glare caused by strong specular reflections. Diffusers are used to treat sound aberrations in rooms such as echoes. They are an excellent alternative or complement to sound absorption because, they do not remove sound energy but it become uniformly scattered. so the diffuser are used to effectively reduce distinct echoes and reflections while still preserving the sound in the space.

Compared to a reflective surface, which will cause most of the energy to be reflected an angle equal to the angle of incidence, a diffuser will cause the sound energy to be radiated in many directions, hence leading to a more diffusive acoustic space.

Diffusers can aid sound diffusion; they are more often used to remove echoes. These devices reduce the intensity of sound by scattering it

over an expanded area, rather than eliminating the sound reflections as an absorber would.
The earliest forms of diffusion consisted of classic architectural columns, statuary, relief ornamentation, etc. As these classic forms disappeared, geometrical forms were used to provide useful scattering and classic beauty. These are followed by the first periodic grating diffusers, based on mathematical number theory. These periodic surfaces consisted of either divided wells or raised blocks, whose relative depths or heights were specified by a mathematical sequence, like the quadratic or primitive root sequence. These gratings were optimized and moved from rectilinear to curvilinear forms, then the surfaces go from a design motif to optimized scattering performance. All of these surfaces are shown in Figure (1-4) (9), (10), (11), (12)
.



(fig1-4) different kinds of diffuser surfaces.

1-3-4 Couple closed space :
A couple closed space can be defined as a main volume connected through one or more openings to a second space with a lower volume. when a sound source is placed in the main volume, the sound energy trapped in the coupled room, returns with a delay. The delay in the arrival of the sound energy coming from the coupled space produces double sloped energy decay, not typical in conventional volumes. This phenomena can be treated using insulating material .(13)

2- Optimum acoustic interior design solution to improve speech intelligibility in speech closed spaces:
The sound strength inside a speech closed space depends on : the nature of the speaker's sound, the position of the listener with respect to the speaker, as well as the shape of the speech closed space and its dimensions. This means that the interior designer must consider that the sounds which actually reach the listener´ s ears will vary from one position to another, from the speaker to the listener, from the subject of the speech to another …etc.
In this section, a new optimum acoustic interior design solution is considered to address and improve poor speech intelligibility in speech closed space. This interior design solution represents a combination of two main acoustical interior design phases ; the first is to reinforce sound using an optimum overhead suspended inclinated ceiling reflector that reflects the early sound waves towards the essential areas in speech closed space. The second is to absorb noise and preserve the acoustic energy in the closed space using "absorber-diffuser" panels or "absorber-reflector " panels which partly absorb and partly diffuse or reflect early and late acoustic rays. These panels cover the rest areas of the ceiling, rear sides and back wall.

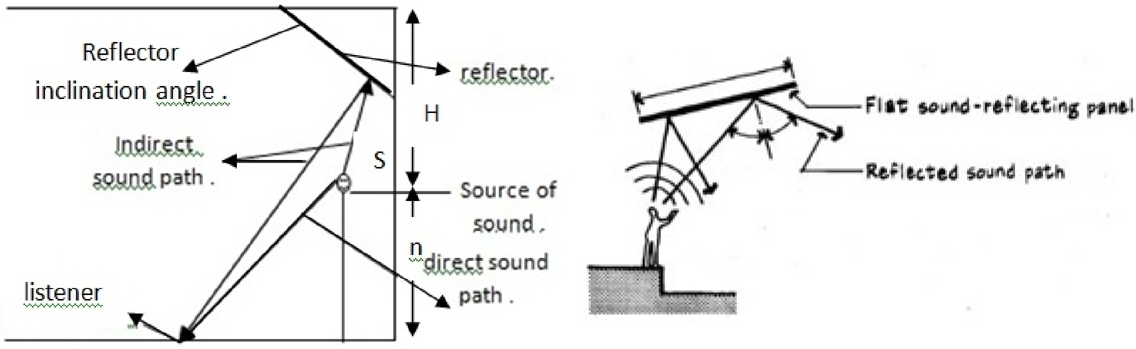
2-1 First phase: Optimum solution for sound reinforcement:
Researchers have revealed the importance of early acoustic rays reflections to intelligibility. When early reflections arrive between roughly 20-50ms after the direct sound there is a process called temporal fusion, in which the direct sound is fused with the early reflections making it louder and more intelligible(9). In case of speech closed interior spaces, one of the interior design criteria used to address speech intelligibility is providing early reflections and not absorbing them .

Optimum inclinated ceiling reflector:
An overhead inclinated optimum ceiling reflector is considered to improve the sound force for the unamplified voice thus helping to improve the quality of understanding where high speech intelligibility is required, . So this reflector provides as much natural reinforcement.
In what follows using mathematic, geometry and optimization, we explained exactly where and how the acoustical rays hit the ceiling reflector surface and studied the propagation of sound throughout the speech closed space, then the

optimum possible solution to reinforce sound was considered .

Mathematical Geometry studies to obtain optimum acoustic solution :

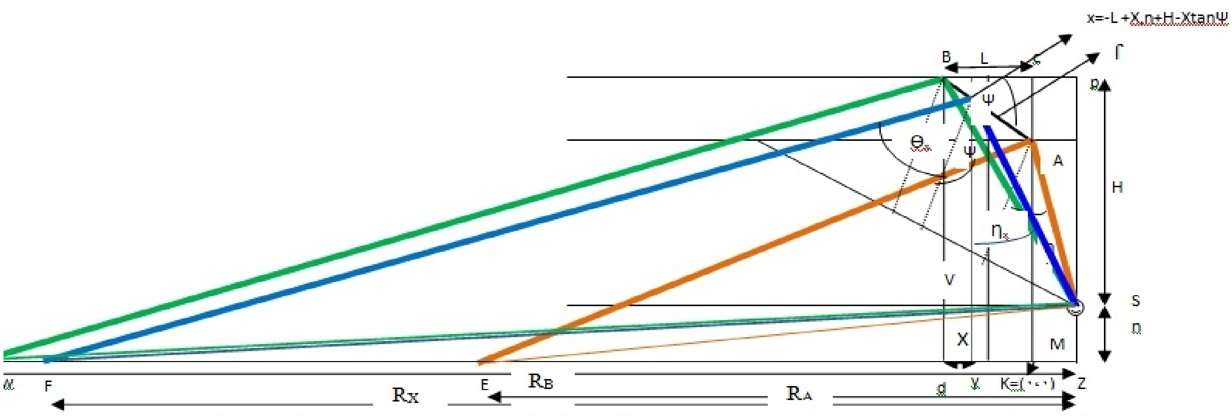
The sound that we hear in a closed interior space is determined by direct sound rays from the sound source and the reflected indirect sound rays from the closed space boundaries and interior contents .To cause the sound to be louder and more intelligible, the direct sound rays need to be fused with the early indirect reflected sound rays. This requirement exists when the difference in length taken between direct and indirect sound pathes is optimum (minimum) (fig2-1). In what follows, for a given height the author used this requirement to obtain the optimum values for the reflector inclination angle and the reflector width that makes the difference in length between direct and indirect sound paths is minimum.



(fig 2-1) inclinated reflector, direct sound path and indirect sound path directed from sound source to listener.

Reflection pattern studies with ray tracing ;

The Sound rays are drawn assuming specular reflection which is the angle of incidence equal to the angle of reflection. The following pattern studies will answer the requirements we are looking for which is achieving : optimal values for both the slope angle, and reflector width with fixed reflector´s height, i-e optimizing (minimizing) the difference in length between direct and indirect acoustical ray pathes from the sound source to the listener place.



(Fig2-2)Ray diagram shows how and where the acoustical rays hit the reflector surface and study the propagation of direct and indirect sound rays through out the speech closed space.

Symbolic definition

Point Z is the intersection of vertical line ZP passing through sound source S and horizontal axis ZW passing through the listener ears.

C K and Z W are vertical and horizontal axises, where K≡(0, 0).

H, n are vertical lengths between S and points P, Z respectively.

$\overline{AB}$ is the reflector with slope angle Ψ =CBA and width ʃ =L/cos Ψ where, L =BC.

E, F, W on ZW are respectively positions of reflected rays from A, x, B on reflector AB.

M is horizontal length from point K≡(0, 0) to point Z≡ (M, 0).

$0 \le X \le L$ is variable horizontal length between the two vertical lines dB and yx with minimum value X=0 on dB and maximum value X=L on KA.

x =(-L+X, n+ H – X tan Ψ) is a variable point on the reflector AB where B ≡(-L, n+H) and A ≡ (0, n+H-Ltan Ψ).

Θ_X, Θ_B, Θ_A are respectively incident angles at points x, B, A .

η_X, η_B, η_A are respectively angles between yx, dB, kA and Sx, SB, SA.

$R_X \equiv R_X$ (Ψ, L, M, H, n)=ZF, $R_B=R_B$(Ψ, L, M, H, n)≡ZW, RA≡ RA (Ψ, L, M, H, n) = ZE.

FX ≡ FX (Ψ, L, M, H, n)=(Sx+xF –SF), FB= FB (Ψ, L, M, H, n)= (SB+BW –WS), FA= FA (Ψ, L, M, H, n)= (SA +AE – ES) are respectively the distances between indirect and direct sound ray pathes from S to points F, W, E.

CA=ZE and CB =ZW are given numerical positive values chosen by the designer according to the volume of the speech closed space.

Ψ*, L* and ʆ* are the optimum values of Ψ, L and ʆ.

Computational evaluation of Ψ * and ʆ*

Lemma(1)

For e(M, L, X)= L-X +M , 0≤X≤L, -L≤M≤L and 0< Ψ<π/4.

(i) RX =e(M, L, X)+(n+H-Xtan Ψ) [e(M, L, X)+(H-Xtan Ψ) tan2 Ψ] / [(H-Xtan Ψ)-e(M, L, X)tan2 Ψ] .

RA=M+ (n+ H-LtanΨ) [M+(H-L tanΨ) tan2Ψ]/[H-LtanΨ–M tan2Ψ].

RB= (M+L)+ (n+ H) [(L+M)+ Htan2Ψ]/[H-(L+M)tan2Ψ]

(ii) FX= √{(M+L-X)2+(H-Xtan Ψ)2}+ √{(H+n-XtanΨ)2+(RX-(M+L-X)2}-√{n2+RX2}.

FA= √{M2+(H-LtanΨ)2 +√(H+n-LtanΨ)2+(RA - M) 2}-√{n2+RA2 }.

FB = √{(M+L)2+H2 }+ √{(H+n)2 +(RB-(M+L))2 }-√{n2+RB2}.

Proof: From (fig2-2):

(i) [R_x -(M+L-X)]/ [H+n-Xtan Ψ] =tan (ϴx + Ψ) =(tan ϴx + tan Ψ)/(1-tan ϴx tan Ψ); where tan ϴx= tan(Ψ+ ηx)= (tan Ψ +tan ηx)/(1-tan Ψ tan ηx) and tan ηx= (M+L-X)/(H-Xtan Ψ); we achieve RX. For X=L, 0, we achieved RA, RB respectively.

(ii) FX= Sx+xF-SF, Apply pythagoras theorem on triangles SxV & YxF & S Z F we achieve Sx=√{(M+L-X)2+(H- Xtan Ψ)2}, xF=√ {(RX-(M+L-X))2 +(H+n-Xtan Ψ)2}, SF=√{(n2+RX2)}, For X=L, 0 we achieve FA, FB respectively.

Procedure 1: numerical evaluation of Ψ* and ʆ*

Formulation of the problem;

For certain values of H, M, and n, minimize{λ1FA(Ψ, L) +(1- λ1)FB(Ψ, L) with three constrains RA(Ψ, L)=CA, RB(Ψ, L)=CB and Ψ< π/4 to evaluate Ψ* and L* then ʆ*.Using lagrange optimization method (14) with lagrange function ʌ(Ψ, L)= λ1FA(Ψ, L) + (1- λ1)FB(Ψ, L)+λ2(RA(Ψ, L)-CA)+λ3(RB(Ψ, L)-CB). The partial derivatives of the function ʌ: δ ʌ / δL = δ ʌ / δ Ψ = δʌ / δ λ1= δʌ / δ λ2= δʌ / δ λ3 =0, leads to nonlinear system of five equations in five unknowns L*, Ψ*, λ_1, λ_2, λ_3.

Using matlab computer language and subroutine fsolve to solve iteratively the system of equations to obtain the optimum values of L*, Ψ* then evaluate ʆ* =L*/cosΨ * (table 1).

In put data :

For H=1→4 m and n=1/2 m, M= L, L/2, 0, - L/2, - L also, C_A=5m, C_B=10m.

Table 1

	M=L			M=L/2			M=0			M=-L/2			M=-L		
H	L*	Ψ*	ʆ*	L*	Ψ*	ʆ*	L*	Ψ*	ʆ*	L	Ψ	ʆ*	L*	Ψ*	ʆ*
1	0.15	32.2	0.18	0.14	34.9	0.17	0.12	37.2	0.16	0.12	39.1	0.15	0.11	40.7	0.14
1.5	0.31	27.9	0.35	0.26	32, 0	0.30	0.23	34.9	0.28	0.21	37.3	0.26	0.19	39.3	0.25
2	0.52	23.6	0.56	0.40	29.2	0.46	0.35	32.8	0.41	0.31	35.6	0.38	0.29	38	0.36
2.5	0.76	19.6	0.80	0.56	26.6	0.63	0.48	30.9	0.56	0.42	34.1	0.51	0.39	36.6	0.48
3	0.96	16.9	1.00	0.73	24.3	0.80	0.61	29.0	0.69	0.54	32.6	0.64	0.49	35.3	0.60
3.5	1.10	15.2	1.13	0.87	22.3	0.94	0.73	27.4	0.83	0.64	31.1	0.75	0.58	34.1	0.71
4	1.18	14.2	1.21	1, 00	20.7	1.07	0, 85	25.9	0.94	0.75	29.8	0.86	0.68	32.9	0.81

Lemma (2):

let ʆ (α, μ) is part of the reflector width, where M=α L, -1≤α≤1 and X=μ L, 0≤ μ≤1, Then ʆ (α, μ) =K(α, μ).H, with K(α, μ)≤ tan Ψ/ {cos Ψ(μ tan2 Ψ-α)}.

ʆ (α, 1)is the total width of the reflector for different M=αL.

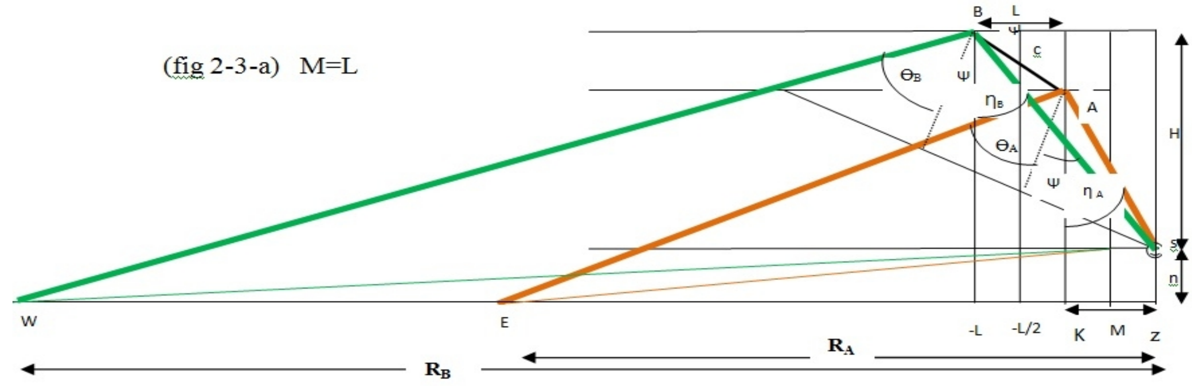
Proof: From (fig 2-2), tan ϴX ≡ (tan Ψ +tan ηX)/(1-tan Ψtan ηX) where tan ηX = (M+L-X) /(H-XtanΨ) since ϴX> 0, tan ϴX>0, tan Ψ. (H-XtanΨ)+M+L-X ≥ 0. Since L-X ≥ 0, so tan Ψ.(H-XtanΨ) +M≥0 which leads to result .

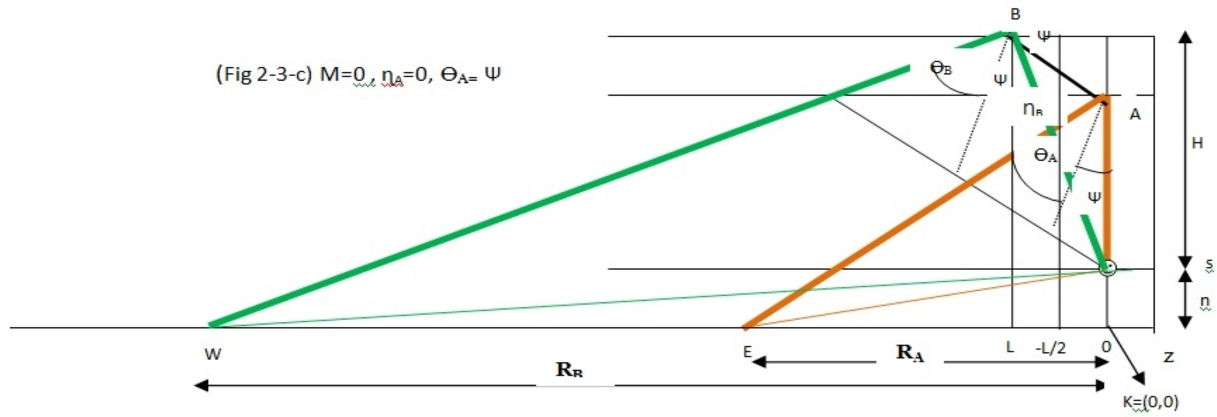
One of the requirement to obtain good speech intelligibility in speech closed space is that the listener´s seats must be the closer to the sound source. In what follows we prove that the best choice to satisfy this requirement is to choose M=-L.

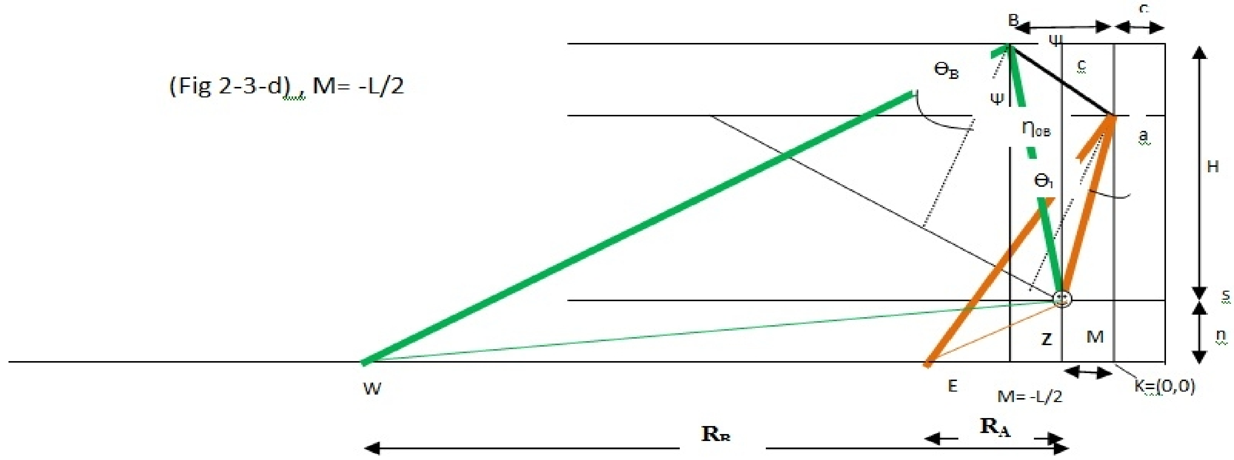
Lemma (3) : x is a point lies on the reflector AB, for, o≤ Ψ ≤π/4, o≤X≤L, Rx (M)≡ Rx(Ψ, L, M, H, n), then for -L≤M≤L, Rx(-L) takes the smaller value.

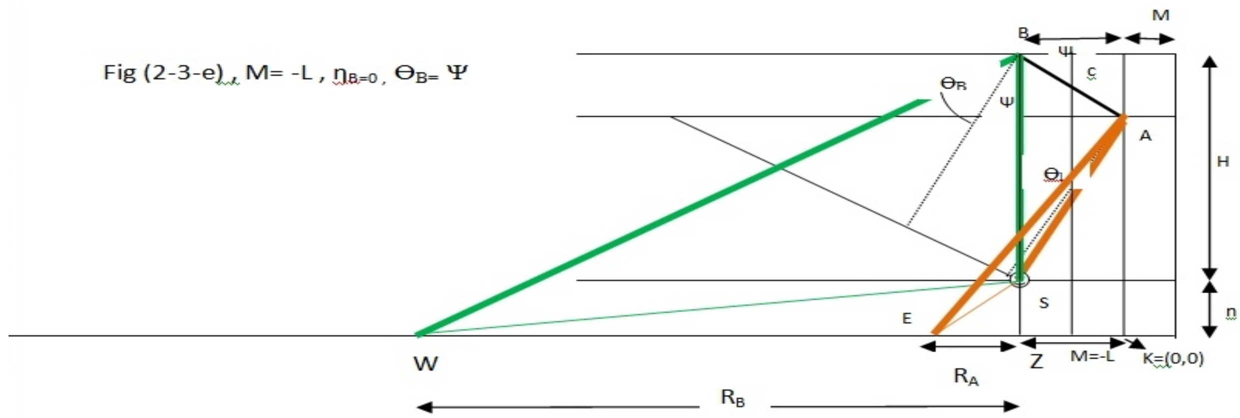
Proof : For -L≤M≤L, o≤X≤L, (L –X+M) ≥ M , so e(L, M, X)decreases as M decreases, then from lemma 1, Rx(M) decreases as M decreases. i-e Rx (L) > R x (L/2) > R_x (0) > R_x (-L/2) > R $_x$ (-L) (Fig2-3).

Reflection pattern studies with ray tracing to lemma3









Lemma 4 : For M= -L, the optimum width of the reflector is $\int^*=H.K^*$, where $o<K^*<\sin\Psi^*<1/\sqrt{2}$ where $0<\Psi^*<\pi/4$ and $L^*=\int^*.\cos\Psi$.

Proof : For $M=\alpha L$, where $\alpha=-1$ i-e M=-L and $\mu=1$, for $\int$ is the total width of the reflector and according to lemma 2, and lemma 3 we get result.

Procedure 2: numerical evaluation of Ψ^* and $\int^*$

Formulation of the problem:

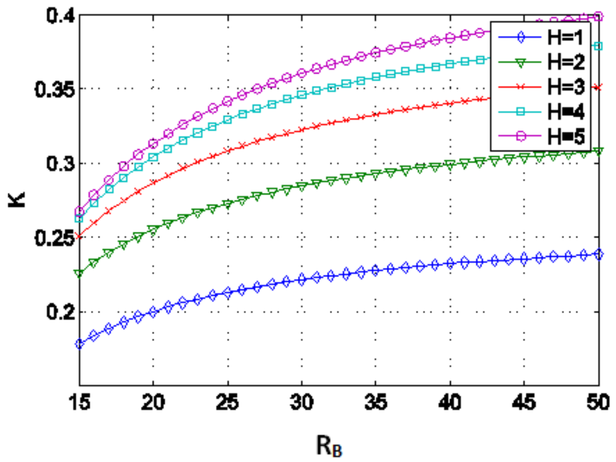
For M= -L, from lemma 1, 2 we evaluate $R_B(\Psi^*) =(H+n)\tan 2\Psi^*$ and $R_A(K^*, \Psi^*)=-L^*+ (H+n-L^*\tan\Psi)(-L^*+(H-L^*\tan\Psi^*)\tan2\Psi^*) /(H-L^*\tan\Psi^* +L\tan2\Psi^*)$ then from lemma 4, $\int^*= H.K^*$.

Ψ^* and $\int^*$ can be evaluated directly using matlab language and iterative subroutine fsolve to solve the non linear system of two equations $C_B= R_B(\Psi)$and, $C_A=. R_A(K, \Psi)$ and $\Psi <\pi/4$ to obtain the optimum values of Ψ^*, K^*, then evaluate $\int^*$.

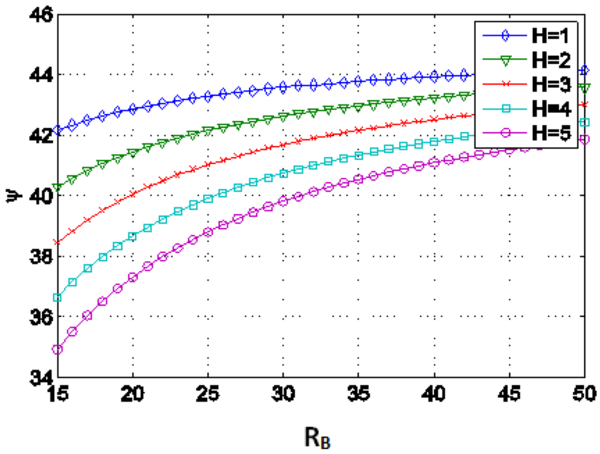
In put data : For H= 1→4m, and n=1/2m, C_A=5, C_B=15, 20, 25, 30.

Table 2

	RB=15			RB=20			RB=25			RB=30		
H	**Ψ***	**K***	**ʃ***	**Ψ***	**K***	**ʃ***	**Ψ***	**K***	**ʃ***	**Ψ***	**K***	**ʃ***
1.0	42.1	0.18	0.18	42.8	0.20	0.20	43. 3	0.21	0.21	43.6	0.22	0.22
1.5	41.2	0.21	0.31	42.1	0.23	0.35	42.7	0.25	0.37	43.1	0.26	0.39
2.0	40.3	0.23	0.45	41.4	0.26	0.51	42.1	0.27	0.55	42.6	0.29	0.57
2.5	39.3	0.24	0.60	40.7	0.27	0.68	41.6	0.29	0.73	42.1	0.31	0.76
3.0	38.4	0.25	0.75	40.0	0.29	0.86	41.0	0.31	0.92	41.7	0.32	0.97
3.5	37.5	0.26	0.90	39.3	0.30	1.04	40.5	0.32	1.12	41.2	0.34	1.17
4.0	36.7	0.26	1.05	38.7	0.30	1.22	39.9	0.31	1.32	40.7	0.35	1.38



Graph 1



Graph 2

Comments on numerical results for table 1, 2 and graph 1, 2:

- In table 1when M decreases $\int^*$ decreases and Ψ^* increases (horizontal)
- In table 1 and 2 as H increase, $\int^*$increases and Ψ^* decreases .(vertically)
- In graph 1 and 2 : as R_B increases both values of K^* and Ψ^* increases with bounds$1/\sqrt{2}$ and 45° respectively.
- numerical results insured the theoretical results of lemma 1, 2, 3and 4.
- computational works in procedure 1, 2 show that the results with M=-L in procedure 1 and procedure 2are equivalent, but procedure 2is preferable than procedure1, as it is more easier in numerical application and save both the computer time and effort.

2-2Second phase : Optimum solution for noise reduction :

To reduce noise and control sound in speech closed spaces, it is required to use the appropriate acoustic absorbing, reflecting and diffusing materials: with specific acoustic conditions to fulfill the acoustical activity inside the speech closed space. Absorption materials remove noise, but also remove acoustic energy leading to reduction of the loudness of the sound in the speech closed space. Also, absorption areas are often concentrated on the ceiling and the floor with high frequency absorbing material like acoustical ceiling tile and carpeting and so the space suffer from single plane absorptive syndrome. This is not a good solution since the resulting improvement is not net(Fig2-4). To treat this problem and to obtain optimal noise reduction solution, also preserving sound energy in space, it is necessary to replace the absorber surface by hybrid “absorber –diffuser” or“absorber –reflector ” surface .

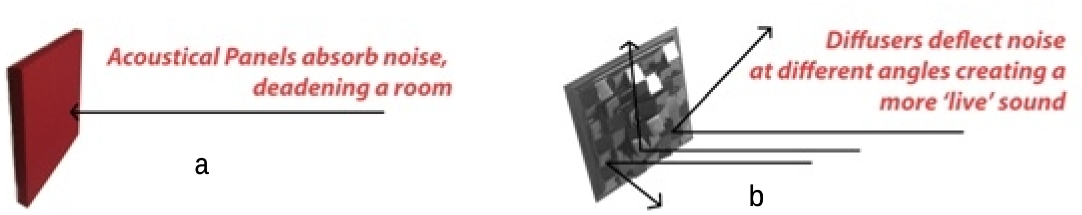


Fig2-4

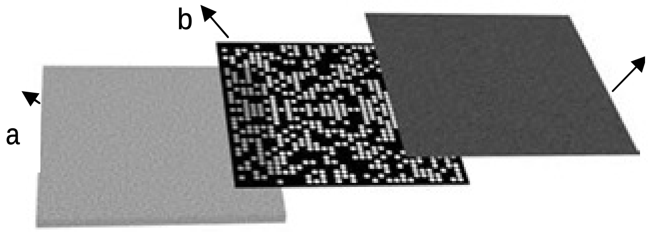
“Absorber –diffuser” panels :

The idea of “absorber- diffuser” panel is to form a surface which partially absorbs and partially diffuse sound energy(fig 2-5). The “absorber –diffuser” panel consists of a piece of absorber covered with a perforated diffuser then covered with a thin acoustically transparent cloth to protect the hybrid shape. If the sound ray pass through the holes in the covering diffuser; the absorption material absorbs noise and acoustic energy, while when the sound ray strikes the solid part of the diffuser, diffuse rays occurs and so the sound energy is diffused. “Absorber– diffuser” panel needs thin diffuser panel. Now a days, there exists a new classes of ultra-thin diffusers which is a lot more thinner than the conventional one, to be used (15) (fig2-5).

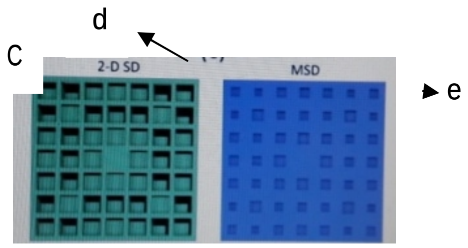
“Absorber –reflector” panel;

It has the same description as “ absorber-diffuser” panels, where diffuser material is replaced by reflector material and so partially absorb and partially reflect sound energy.

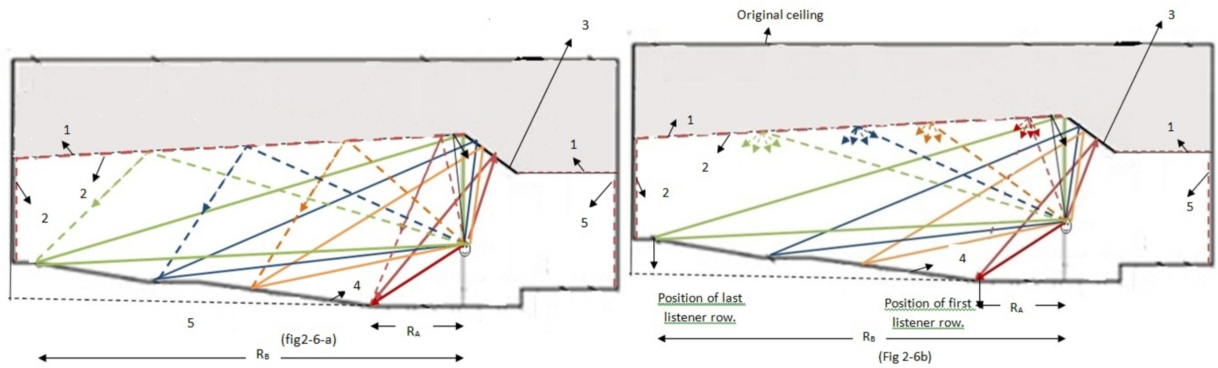
The key to achieve an optimum hybrid surface depends on choosing the parts, the more or less absorbed or reflect energy, also depends on the number and arrangement of the diffuser or reflector holes. These “hybrid “ panels on the ceiling and walls not only absorbe and diffuse or reflect acoustic rays but also protect and improve the aesthetic ceiling and walls shape.



(fig2-5) a) absorber material, b) diffuser material c) acoustic transparent cloth.



(Figure 2-5) d) diffuser, e) ultra –thin diffuser.



1-isolater material 2-” absorber- reflector” panels in (a)” absorber- diffuser” panels in (b). 3-optimum ceiling reflector 4- absorber stepped floor 5- Resonance system

(Figure 2-6): cross section shows the shape of the optimal suspended ceiling and the distribution of the “absorber-diffuser” material and “absorber-reflector ” material.

3-Application study:

We choose a lecture hall to demonstrate a general strategic approach using the given interior design solution (Figure 2-6) .

(i)ceiling design

- For suspended ceiling with new height we calculate numerically both the optimum inclination angle Ψ* and width ʃ*to construct the ceiling reflector part .

- The rest of the ceiling area is covered by "absorber-diffuser" panels or "absorber-reflector" panels.
- To prevent the coupling effect phenomena between the main ceiling and the suspended ceiling we need to completely cover the boundaries of the space above the suspended ceiling by insulating material. (cladding for the upper parts and ceiling of the stage house.)

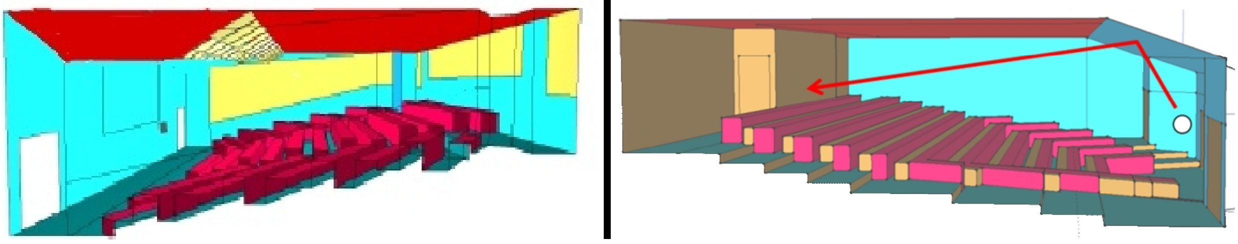
(ii)wall design:

- The front wall (low frequency):

A resonance system is installed on the front third of the side walls in addition to the stage walls .

-Rear Sides and back wall(mid and high frequencies);

Covered by "absorber- diffuser" panels or"absorber-reflector" panels.



(Figure 3-1) lecture hall with optimum acoustic interior design solution.

(iii) floor design :

The floor should be designed satisfying the following requirement :

- The acoustic interior design solution should consider the sight line and the angles that enables the listener, at any position in the space, to see the speaker and his actions without any obstruction. For this purpose, stepped benches with slopes at least 7° of the speech space floor are compatible with the requirement of a good sight line which helps effectively in the good acoustical perception where the ability of reading lips helps in achieving part of speech intelligibility. (Figure 3-1)

-The result of using "absorber-diffuser" panels or"absorber-reflector" panels for the ceiling, rear sides and back wall imposed on the design to use absorber finishing material on the floor.

(v) Furniture position

The arrangement of the listener seats is as close to the sound source as possible, so all listeners can hear with the same degree of sound strength and noise reduction, i-e uniform the sound field inside the space. This requirement can be satisfied by arranging successively the audience's seats in semicircular rows with common centre. The first and last rows have radius R_A and R_B, respectively.(Figure 3-2).The center of the circle is the point of intersection between the vertical line passing through the speaker, and the horizontal floor.

(Figure 3-2)

Sustainability in the interior design solution:

- The optimum interior design solution increase the efficiency of the acoustical energy, so improves the comfort and usability of this speech closed space.
- The materials used should be recyclable, reused and renewable materials.

4-Conclusion:

This research paper presents an optimum acoustic interior design solution to improve speech intelligibility for the speech closed space. The optimum solution redesign the ceiling, walls and floor. Redesigning the ceiling implies defining its new position, shape and function. The position of the new ceiling is achieved by installing a suspended ceiling on a height less than the actual space height ; part of the suspended ceiling is the inclinated optimal reflector with optimal slopping angle and optimal width which direct early acoustical rays towards the essential part of the closed space to reinforce sound. The rest of the ceiling area and the rear sides and the back wall are covered by "absorber- reflector" panels or "absorber- diffuser" panels to absorb part and reflect or diffuse another part of the early and the late reflections thus reducing the noise without losing acoustic energy. The research did not answer about the ratio that should be applied between: absorptive and diffusive or reflective materials in the hybrid panels, also the number of holes used in the diffusive or reflective materials to achieve the required acoustic force.

The vision of acoustic interior design solution includes the use of stepped benches with slopes at least 7º of the floor to be compatible with the good sight line.

The audience's seats maintain a sense of roundness inside the space by arranging them in successive semicircular rows to be as near as possible to the sound source and so all the listener can uniformly hear sound..

Results:

1- The optimum interior design solution for the ceiling, walls and floor improve speech intelligibility and so helps to uniform and homogenate the sound field inside the speech closed space and so gives comfort and encourage the usability of the space.

2- The optimum interior design solution also improves the sustainability since it increases the efficiency of acoustical energy, also the materials used are recyclable, reusable and renewable materials.

<u>Reference:</u>

(1) Mackenzie D., S.Airey, 1999, "classroom Acoustics. A research project. summary report "Heriot-watt University, Edinburgh)

(2) Saidely J. L.weber, P.leislnev, 2005" acoustic proper class rooms and their effect on the cognitive performance of primary school pupils "forum Acusticum, Budapest.

(3) Bradley JS.(2002) optimizing sound quality for classrooms. Sandiego.

(4) Schwiler Kurt Eggen, 2005, lecture halls-room acoustics and sound reinforcement Budapest:Forum acusticum .

(5) Eggen K. schwiler, V.Desarnaulds, Th.Imhof, w.koller, D.Norman, (2004), "Installations de sonorisation pour la parole. Recommendations pour les architects et les Maitres d'ouvrage", Swiss Acoustical society SGA-SSA, http:"www.sga-ssa.ch.

(6) ANSI/ASA(2010), American national acoustical performance criteria, design requirements and guidelines for schools, part I: permanent schools, USA, acoustical society of American .

(7) Okah Theophilus NwankwEgv, (2013), A study on acoustics control, M.S.C thesis, faculty of environmental, department of architecture university of Nigeria Enugu, campus, school of post graduate studies.

(8) El Khateeb A., 2003, Architectural acoustic theory and application.1st, 2ed. the Anglo Egyptian library.

(9) Antonio, P.D. (2003), "Acoustical Design of speech rooms using the complete acoustical palette ; Absorption, reflection, Diffusion and isolation" .

(10) Farren, J., 2003, acoustic design – rooms for speech, marshall day acoustics pty Ltd, Auck land .

(11) EL Wekili. E, 2015, "Optimizing class room acoustic performance to promote children education and well being, "Master thesis submitted to the faculty of the school of architecture", the university of Arizona.

(12) "Crutchfield's steve kindig" Room acoustics for home audio how to find and treat your room's trouble spots by.

(13) Sound Decay in Acoustically Coupled Spaces, acousthink .com, 25 february 2011, > blog> sound-decay.

(14) Lagrange –Multiplier –wikipedia, https:// en.wikipedia.org.

(15) Cox Trevor J., P.D'antonio (2003), Engineering art ; the science of concert hall acoustics, interior. Sciplinary science reviews, vol 28 no 2 .)

(16) Yifan Zhu, Xudong Fan, Bin Liang, Jianchun cheng, and yun, Jing, (2017), Ultra-thin Acoustic meta surface – based Schroeder.