Full-Wave Modeling of the Transmission of Sound over Theater Seats: Near Field Investigation.

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The full-wave theory [Ezekiel Bahar, J. Acoust. Soc. Am. 89,19-26, (1991)] is applied to a computer simulation of sound transmission across a simplified model of theater seats. The acoustic response is derived for observation points above the seats for a range of incident angles and receiver heights . The results obtained from the model study are in good agreement with the experimental data recently obtained by J. S. Bradley, [J. Acoust. Soc. Am. 90, 324-333, (1991)]. The full-wave solution accounts for the acoustic pressure diffusely scattered by the chairs as well as the zero-order field scattered by the finite floor and the direct wave from the source. It suggests that the "seat dip effect" is mostly due to an interference phenomenon at the observation point between the direct field and the scattered field reflected off the floor. The model allows for a detailed analysis of the effect of scattered field by the chairs, both in front of, and behind the receiver. These results suggest the need for the use of high directionality microphones that can distinguish between the forward and backward scattered acoustic pressure during future experiments.

Suggested session: "New auditorium acoustics measurements - results and comparisons".

Technical Area: Architectural Acoustics

(PACS) Subject Classification number(s): 43.55.Ev, 43.55.Ka

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This is only a preprint. Not for citation.

Introduction

The seat dip effect has been the object of various experimental and theoretical investigations for the past 30 years [Beranek, 1960], [Sessler & West, 1964], [Shultz & Watters,1964], [Ando, & Tada, 1982], [Bradley, 1991]. We presented the results of our far field work using the *full-wave theory* [Bahar, 1991] at the 124th meeting of the A.S.A. last October in New Orleans and provided a rationale for the effect that parameters such as the seat spacing and the seat height have on the response at a point far away from the surface [Chéenne *et al*, 1992]. We also suggested the need for the use of highly directional microphones in future experiment so that the forward and backward contributions to the scattered pressure at the receiver from surfaces in front of (forward scatter) and behind (backward scatter) the receiver can be isolated from each another.

We have since used analytical results to account for observation points in the vicinity of the chairs in order to model the actual experimental setup. Thus we are concurrently developing computer programs based on the analytical forms of the full-wave solutions to evaluate the pressure at a short distance (a few wavelengths) from the interface. The basic theory and the current state of our efforts are summarized in the next paragraphs.

Statement of the hypothesis

The analytical results contain the following contributions to the acoustic pressure at the receiver: 1) the direct wave from the source, 2) the reflected wave from the floor surface, (a) in front of, and (b) behind the receiver, and 3) a scattered pressure due to the seat, (a) in front of, and (b) behind the receiver. The interference between the direct wave and the reflections off the floor is responsible for the general features of the dip while the scattering from the seat tops is responsible in the "fine structure" of the frequency response particularly at high frequencies.

The interference pattern due to reflections from a surface have been observed and predicted by others [Pierce & Noyes, 1938], [Ingard, 1951]. The theory which gained acceptance after 1964 was that the so called seat dip effect occurs at the frequencies at which the seat height is equal to one quarter wavelength. This suggests a simple resonance effect [Sessler & West, 1964]. The concept of an interference phenomenon was first proposed by Shultz & Watters [1964] however in the majority of the literature the term resonance is still used to describe the phenomenon [Bradley, 1991].

The analytical work is used to interpret the experimental data obtained by others. and on our current analytical work. The preliminary results reported here indicate that the observed so called seat dip effect is not due to a resonance effect associated with the height of the seat but is due to an interference between the direct wave and the wave scattered from portions of the floor in front and behind the seat where the receiver is located.

The preliminary hypothesis presented here accounts for some of the experimentally observed dependence of the seat dip frequency on the angle of incidence of the source, on the position and height of the receiver , and on the physical parameters of the material. The full wave model takes into account the distance from the receiver to all scattering points on the surface and the scattering coefficient is computed for all values of the angle of incidence and of the angle of scatter. The effective "interference distance" resulting in the cancellation of the direct wave is always greater that the receiver's height but the contributions from points away from the receiver become smaller and smaller as the distance to these points is increased.

At this time, it is interesting to recall the equation proposed by Shultz and Watters [1964]:

$$P = P_0\left[1 - e^{i2k\xi \tan\phi}\right] \qquad (1)$$

In the above equation, ϕ refers to the angle of incidence of the source measured with respect to the horizontal axis, thus 0º would denote grazing incidence.

An application of this formula would yield to a cancellation of the direct wave at a frequency when the wavelength of the incident sound is equal to twice the receiver's height ξ times the tangent of the angle of incidence measured with respect to the plane of incidence. Using, a receiver height of 130 mm (representative of a scaled listener's ear) and an angle of incidence of 30º, this condition would translate into a dip frequency of 1142 Hz, a value very close to that observed experimentally by Bradley in scale models [Bradley, 1991]. However, as grazing incidence is approached, the equation yields a value of frequency of 1812 Hz for 20º incidence, a high value which is not observed experimentally and the error increases as grazing incidence is further approached. Similarly, at near normal incidence, equation (1) yields a value of interference frequency which does not compare well with the experimental values since the tangent term rapidly approaches ∞.

In the full wave model however, since the integrated distance corresponding to the distance at which the interference occurs is always larger than ξ it will yield a lower principal dip frequency than what would be obtained by simply considering the result of an interference from the point located immediately under the receiver. Finally, it is interesting to note that the interference distance resulting from the full wave model, and corresponding to the half-wavelength of the frequency at which the seat dip effect is observed would be very comparable to twice the seat height, thus bringing a new light on the fact that the seat dip was seen to appear at a frequency where the height of the seats is equal to 1/4 of the wavelength of the impinging sound waves.

• **Influence of seat spacing**

A phenomenon which can be observed in Bradley's experimental data is that as the seat spacing is decreased, the frequency responses for various angles of incidence tend to "spread out" as the frequency is increased (the more widely spaced configuration yielding the lowest amount of separation between curves when the angle of incidence is varied). Based on the hypothesis presented here, this phenomenon should be observed since as the frequency is increased, the scattering effect due to the top of the seat will be felt more if they are closely spaced apart as they will form a larger apparent surface relative to the floor than if they are widely spaced apart. The experiments used 1:10 simplified model seats of two different heights (76 mm and 152 mm) with seat-to-seat spacing varying between 49 mm and 152 mm. When the experimental data resulting from a 49 mm spacing, 76 mm spacing and 152 mm spacing are compared, it is noticed that the high frequency scattering is effectively maximum for the 49 mm case.

We thus believe that it is appropriate to infer that the ratio between the surface presented by the seat tops and that of the floor in front of the receiver greatly influences the frequency at which the seat dip occurs. This statement is in agreement with some the conclusions reached by De Bruijn [1967]. If one was to make the top of the seats very wide, leaving little space for the floor, one should notice the dip to occur at a higher frequency, all other factors being kept the same.

• **Influence of receiver position**

Based on our proposed hypothesis that the seat dip is primarily caused by an interference at the receiver position between the direct wave and the floor reflection in front of the listener, the frequency at which the dip occurs should decrease as the receiver is moved further back from the source since the contributed reflections from the floor in front of the receiver will increase, thus yielding a larger average

interference distance and thus a lower frequency. However, since the scattering contributions from the surface points are weighted by the distance from the receiver to the scattering point, the dip frequency would tend to reach a limit value since the scattered contribution from points far away from the receiver will have little contribution. This "gradual development" of the seat dip was effectively observed by Sessler & West [1964] when they varied the receiver position from the first row to the back off the hall. The same observation was made by Shultz and Watters in real hall measurements [1964].

The interference model proposed here would also be expected to predict the general features of the dip (width and level) as the receiver is moved away from the source. With the receiver very close to the source, the direct wave would receive very little attenuation and the response from the forward pressure should be basically flat. Since the reflections from the floor surface in front of the receiver increase as the receiver is moved away from the source, the level of the interference would be also expected to increase but since the interference would be the result of more reflections as the receiver is moved away from the source, one would expect a "smearing" in the sharpness of the dip. This phenomenon was experimentally observed by Bradley [1991].

• **Influence of receiver height**

Our hypothesis also accounts for observed changes in the dip level and frequency as the height of the receiver is varied. Calling upon the interference model proposed here, one would expect that an increase in the height of the receiver would result into the dip occurring at a lower frequency. Also, as the receiver's height is increased, the level of the reflections from the floor would be reduced and as such the interference should be weaker thus resulting in a reduced dip level. Both these effect were clearly observed by Shultz and Watters [1964].

• Influence of angle of incidence of the source

The experimental data has always shown a dependence between the angle of incidence of the source and the frequency at which the dip occurs. As grazing incidence is approached, the dip shifts to a higher frequency. The hypothesis presented here would also account for this phenomenon: As the source approaches grazing incidence, a lesser portion of the floor in front of the receiver is illuminated by the source and as such the interference between the direct wave and the reflections from the top of the seats will become a larger contributing factor to the response. Since the surface delimited by the top of the seats is closer to the receiver than that of the floor, one would expect the interference to occur at a higher frequency. One would also expect that this phenomenon would be related to the position of the receiver and would occur more systematically when the receiver is further away from the source since there would be a larger number of seat tops available in front of the receiver to contribute to the interference.

Conclusion

The hypothesis presented here is based on preliminary results obtained from analytical work currently in progress. The hypothesis provides a physical explanation which accounts for the dependence of the seat dip on the geometrical parameters of the surface, on the receiver position and height, and on the angle of incidence of the source. The computer implementation of our full wave model is currently under way and will allow us to proceed with a parametric study aimed at investigating the effect that factors such as receiver height, receiver position, angle of incidence of the source, physical parameters of the materials and geometrical parameters of the model, have on the frequency at which the seat dip occurs and on the qualitative and quantitative features of this phenomenon.

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