USING ROOM ACOUSTICS MEASURES TO UNDERSTAND A LARGE ROOM AND SOUND REINFORCEMENT SYSTEM

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1 INTRODUCTION

The measurements reported in this paper were made in the Canadian House of Commons to assess acoustical conditions before planned major renovations. They are used here to illustrate how one may evaluate natural acoustics and amplified sound conditions in a large room where speech communication is important.

There are 305 Members of Parliament (MPs) in the Canadian House of Commons who sit at desks in two opposing groups. When they speak, they stand at their desk and address the Speaker of the House who regulates debates, rather than talk from a common podium as occurs in some legislatures[1]. Members of the public can listen to debates from the galleries above the MPs. These include narrow side galleries behind the MPs and larger galleries at either end of the House with steeply raked seating. There are microphones for each MP set into their desks which are used for, translation services, recording, radio and television broadcasts of speeches, as well as for sound reinforcement. There are a number of column loudspeakers in the two end galleries pointing towards the public seating.

2 MEASURES AND CRITERIA

To achieve optimum room acoustics for (unamplified) speech, we should try to: maximize direct sound and early-arriving reflections of speech sounds, and minimize late-arriving speech sounds and ambient noise. The maximizing of early-arriving speech sounds relative to late-arriving speech sounds can be assessed in terms of early-to-late arriving sound ratios (C_{50}) or early-to-total sound ratios (D_{50}). A C_{50} value of +1 dB or greater has been suggested[2] to be required for good conditions for speech communication. This would correspond to a D_{50} of 0.56. Barron[3] has recommended D_{50} values should be at least 0.50 to provide acceptable conditions in theatres. Reverberation times (T_{60}) and early decay times (EDT) are usually recommended[3] to be about 1.0 s for large rooms used for unamplified speech. It is important that speech levels are well above ambient noise levels and hence it is important to have sufficient Strength values (G). Barron indicates that G values should be at least 0 dB in theatres, but much higher values are recommended for large concert halls (1.5 to 5.5 dB) and recital halls (9 to 13 dB)[4].

Maximum acceptable ambient noise levels for theatres and other larger rooms for speech communication have been recommended to be no more than NC30 or approximately 35 dBA[5].

The Speech Transmission Index (STI) assesses both the signal-to-noise and room acoustics aspects of conditions for speech communication and STI values of ≥ 0.6 are required for 'Good' conditions for speech communication[6].

3 NATURAL ACOUSTICS MEASUREMENTS

Room acoustics measurements were made for natural acoustics conditions using a dodecahedron sound source because this source would provide more reproducible results (in either post renovation measurements or in computer model studies) and represents the average of a talker directing their voice to all listeners as they speak. Measurements were made for the 60 combinations of 3 source positions and 20 receiver positions. The 3 source positions and the 10 main floor receiver positions are shown in Fig. 1. There were 10 more receiver positions in the galleries.

The ambient noise levels obtained at main floors seats are plotted in Fig. 2. Similar results were obtained at the gallery level seats. Many results are no more than NC 30 and the average A-weighted level was 38 dBA.

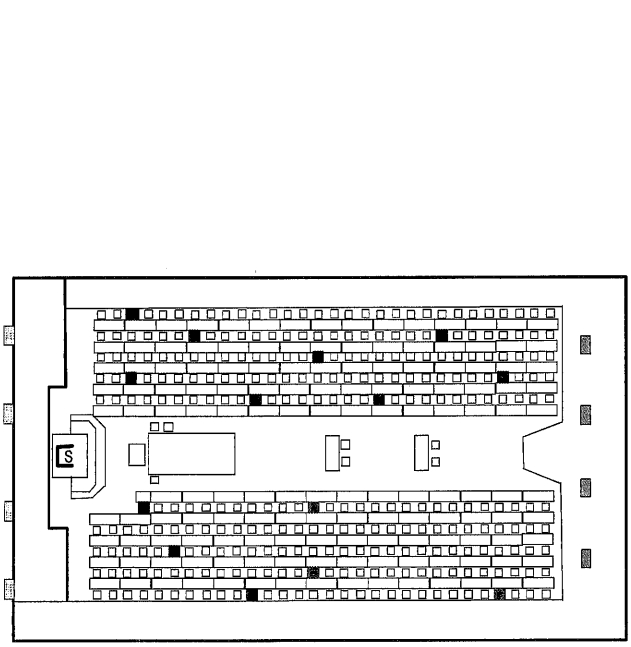

Fig. 1 Plan of main floor showing 3 source positions (red) and 10 receiver positions plus extra position at upper left. 'S' indicates location of the Speaker of the House.

Fig. 3 plots average decay time results. T_{60} values are an average of all 60 measurements. The error bars show little spatial variation of T_{60} values and the mid-frequency T_{60} are about 1.5 s. The average EDT values from receiver positions in the galleries have higher values than for the main floor receiver positions. Fig. 4 shows quite substantial differences between C_{50} values at main floor locations and gallery locations. C_{50} values are higher at main floor locations at least partly due to their closer location to the sound source positions, and the lower C_{50} values at gallery locations may be related to the longer EDT values at those positions.

It is important to have high G values to ensure adequate speech levels. However, it is also desired that speech sounds should be predominantly direct and early arriving reflections of speech sounds. To see all of these issues in one graph, Fig. 5 plots average G values along with average G_{50} and GL values that directly indicate the relative strength of the early-arriving and late-arriving sounds respectively. Results are given separately for main floor and gallery areas. The G values peak in the 1000 Hz octave band and are about 2 dB higher for main floor locations than for the gallery level locations.

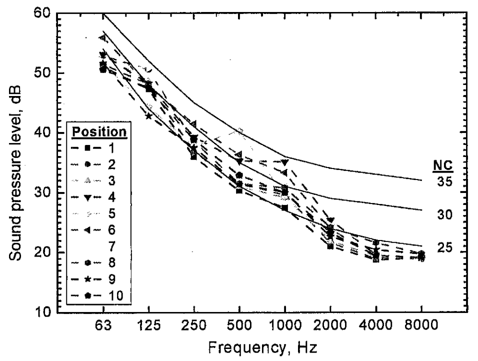

Fig. 2 Measured ambient noise levels at 10 main floor receivers.

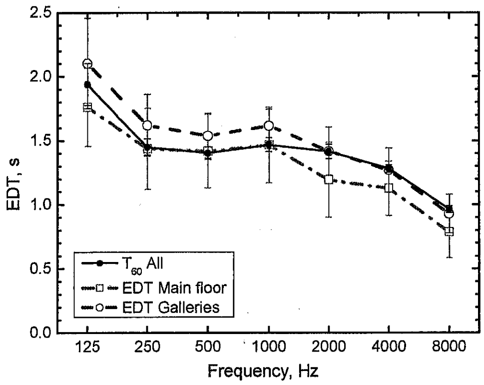

Fig. 3 Average and standard deviations for T_{60} over all positions and for EDT over main floor and gallery locations.

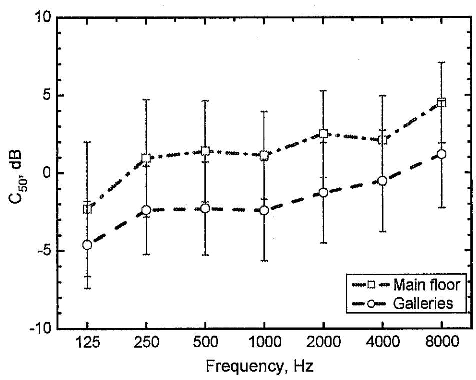

Fig. 4 Average and standard deviations of C_{50} over main floor and gallery locations.

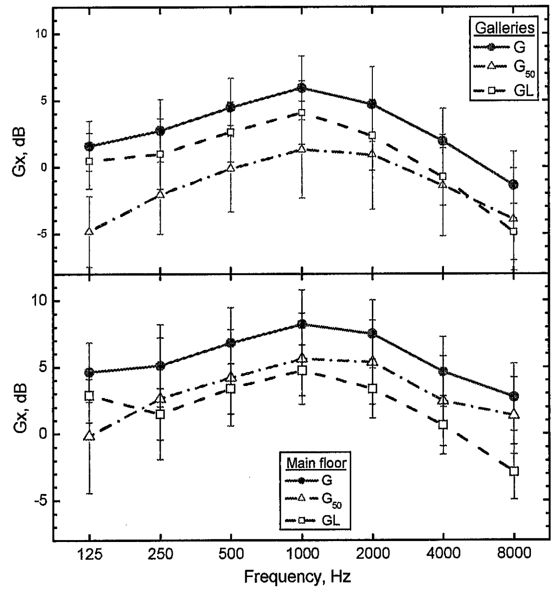

Fig. 5 Average and standard deviations of G, G_{50} and GL for gallery locations (upper) and main floor locations (lower).

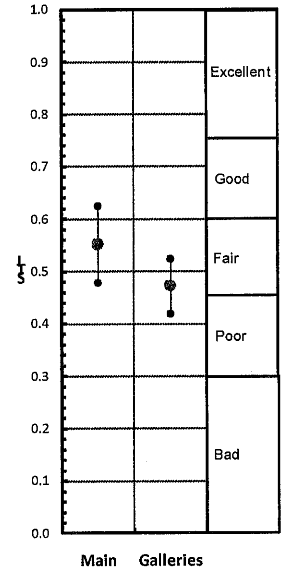

Fig. 6 Average and standard deviations of STI values for main floor and gallery locations.

However, the main floor locations have relatively stronger G_{50} values and the gallery seats have relatively stronger GL values. Thus speech levels are not only stronger at main floor locations, but speech will also have greater clarity (as already seen from the C_{50} results).

Although these results indicate that conditions are a little too noisy and too reverberant to be ideal, it is not clear how acceptable the combination is. STI values provide a single number rating that should be at least 0.6 to provide "Good" conditions for speech. The measured STI values in Fig. 6 show that most STI values measured are below this criterion and on average conditions are less acceptable in the galleries than on the main floor.

4 ESTIMATING THE EFFECTS OF MODIFICATIONS

The measured results give a clear indication that ambient noise levels should be reduced and that absorption should be added to reduce reverberation times and late-arriving sound levels. We can estimate the effects of various improvements using a combination of Barron's revised theory[3] and useful-to-detrimental sound ratios[2,7].

Barron's theory can predict G, G_{50}, GL and C_{50} values from reverberation times, room volumes and source-receiver distances. It has been shown to work quite well in many large auditoria. To determine whether it is appropriate to predict changes to the House of Commons, predictions were first compared with measured values. Fig. 7 plots measured and predicted G, G_{50} and GL values versus source-receiver-distance. For some measurements the direct path from the source to the receiver was partially blocked, usually when the source on the main floor was not completely visible at the gallery level receiver positions above. These data have been marked with a black filled circle within the larger unfilled symbols. We would expect G_{50} values to be most reduced at these blocked locations as is seen to occur in the middle panel of this graph. While there seems to be a systematic trend for the blocked locations to have lower than predicted G and G_{50} values, it is not true for GL values because the late arriving sound is not affected by this problem. For the measurement from source C to receiver 10, both source and receiver were a little under the side gallery and both early and late-arriving sounds are reduced a little relative to the predictions. Other than for these explainable exceptions, the predictions agree well with the measured results and we can be confident that proposed modifications can be investigated using Barron's theory.

To predict the combined effects of reduced ambient noise levels and modified room acoustics we could use a room acoustics computer model, but it would be quite time consuming to enter the coordinates of the room. We can make predictions more simply using useful-to-detrimental sound ratios (e.g. U_{50}) that combine both signal-to-noise and room acoustics effects into a single quantity. U_{50} values are the ratio of the sum of direct and early-arriving speech energy (E) to the sum of the late-arriving speech energy (L) and the ambient noise (N) where the early period is defined as the first 50 ms after the arrival of the direct sound. That is,

$$U_{50} = 10 \log\{E/(L+N)\}, \text{ dB}$$

U_{50} values can be calculated from C_{50} values along with speech and noise levels at each listener position[8]. Speech levels at each receiver position were calculated assuming ANSI raised speech levels[9] 1 m from the source and using the measured G values at each receiver position. Measured ambient noise levels were also used.

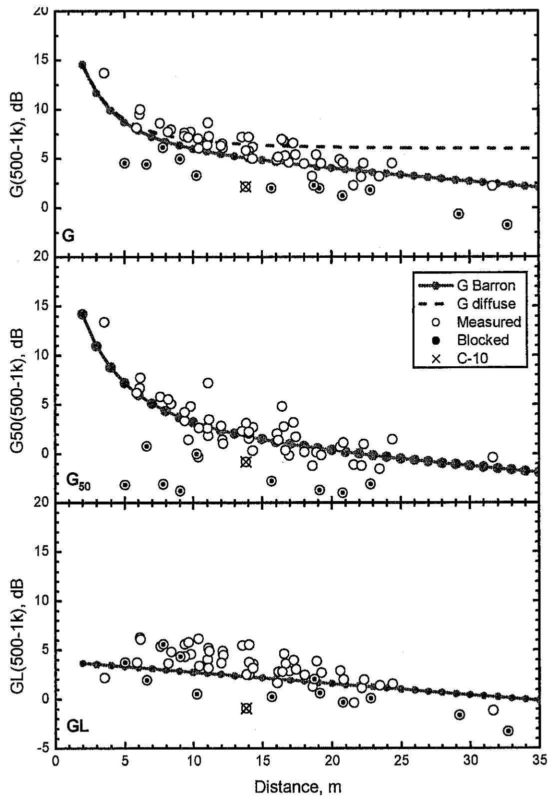

Fig. 7 Comparison of measured and predicted values of G, G_{50} and GL versus source-receiver distance using Barron's revised theory.

The problem with using U_{50} values is that there is no standard procedure for combining information at different frequencies or for the relative importance of signal-to-noise and room acoustics factors. There is also no agreed upon relationship between U_{50} values and speech intelligibility scores. For the purposes of demonstrating their usefulness, U_{50} values were calculated by combining octave band values following the procedure used in calculating Articulation Index and STI values and using the frequency weightings from the STI measure[6]. These were related to word intelligibility scores from several studies involving word intelligibility tests in simulated sound fields as shown in Fig. 8. There is moderate scatter about the best fit regression line and the related R^2 is 0.96. This regression line was used to estimate intelligibility scores associated with calculated U_{50} values.

U_{50} values were calculated for both reduced ambient noise levels and added sound absorption to the room (i.e. decreased T_{60}). Ambient noise levels were reduced by 5 and 10 dB as well as a 5 dB increase to better illustrate the trends. Absorption was added to reduce the mid-frequency T_{60} to 1.0 s and also absorption was reduced to increase T_{60}

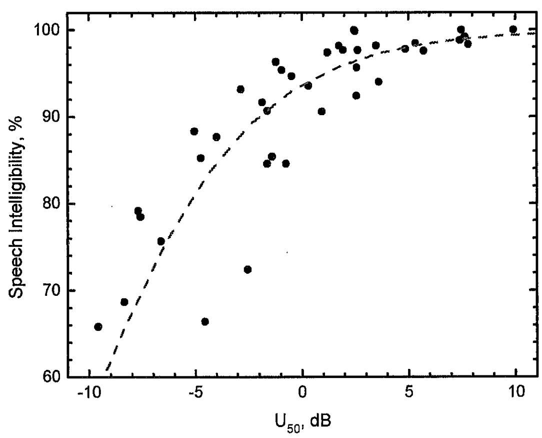

Fig. 8 Word intelligibility scores versus U_{50} values.

to 2.0 s. Fig. 9 shows the resulting speech intelligibility scores and how changes to both the T_{60} values and ambient noise levels can significantly increase speech intelligibility. In addition to these effects it is estimated that early sound levels could be increased at least 1 dB with an improved design of surfaces to provide stronger early-arriving speech sounds at main floor locations. This would increase the maximum speech intelligibility to 97% if added to the best added absorption and reduced ambient noise case. These significant improvements seem to be convincing enough to argue for such modifications. Of course, in designing the actual changes a room acoustics computer model would be important for determining how best to improve early-arriving speech sound levels.

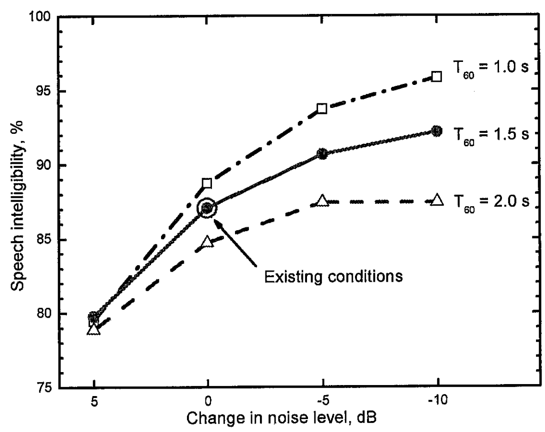

Fig. 9 Calculated speech intelligibility scores for changes to ambient noise levels and sound absorption.

5 ASSESSING THE SOUND REINFORCEMENT SYSTEM

Although ISO 3382-1[10] makes no mention of sound reinforcement systems (SRS), it is proposed that the quantities used to assess the acoustical quality of large rooms are also very appropriate for assessing SRS because we understand these quantities and know the values we would like to achieve to have satisfactory sound quality. There are obviously many other details about an SRS that must also be considered such as those related to the quality and setup of the equipment. These might include the frequency response of the SRS and the amount of distortion produced by it. These are recognized as important but not considered here.

Room acoustics parameters with the SRS operating were measured using a small 100 mm diameter driver in a small sealed enclosure. It was positioned 1.5 m high at source position A in Fig. 1. pointing roughly towards the Speaker of the House. It was intended to represent a standing MP making a speech. The SRS has microphones for each MP but only 2 are connected at a given time. These are the microphone on the desk of the MP who is speaking and the next closest microphone in the direction towards the Speaker of the House. These microphones would have been about 1 m from the test loudspeaker representing an MP talker.

Fig. 10 shows the average measured STI values with the SRS on and off for averages over main floor and over gallery level positions. These differences are slightly different than those in Fig. 6 because of the different loudspeakers used. Fig. 10 shows that STI values were reduced at main floor locations with the SRS on and increased at locations at gallery locations. Only a few main floor locations are above the STI criterion of at least 0.6.

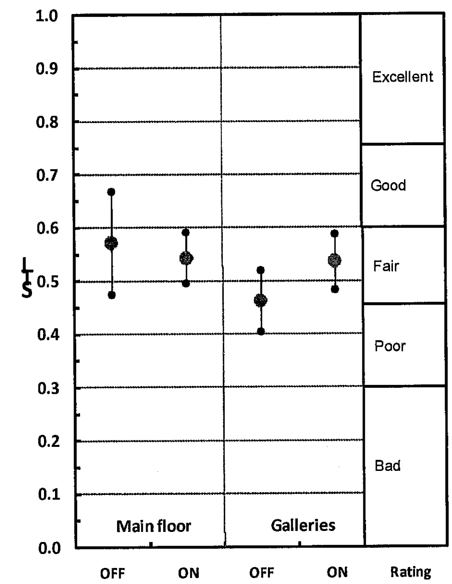

Fig. 10 Main floor and gallery level STI averages and standard deviations with SRS on and off.

Thus the SRS is not helpful at main floor locations, and is helpful but not good enough at gallery locations.

The average changes in room acoustics parameters when the SRS is turned on are examined to help understand how one might improve the SRS. Fig. 11 shows the change in G values when the SRS is turned on, averaged over all measurement positions. The system is capable of increasing speech levels by up to 10 dB on average. There is a large dip in the ΔG values at 500 Hz which is probably not the equipment but the fact that the discreetly mounted microphones are about 1m from the sound source representing a typical talker. For this configuration floor reflections or reflections from desk tops could cause destructive interference effects that could explain the 500 Hz dip in ΔG values. There are small changes in decay times illustrated in Fig. 12. The SRS leads to small increases in T_{60} values and EDT values at main floor seats, but decreases in EDT at gallery locations. C_{50} values are increased slightly at gallery locations and more substantially reduced at main floor locations in Fig. 13.

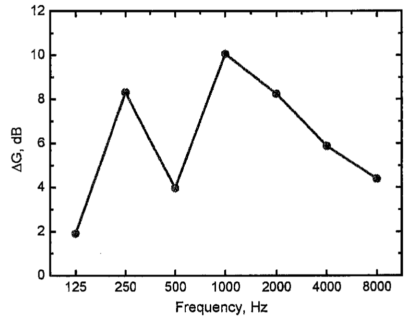

Fig. 11 Change in average G values when SRS is turned on.

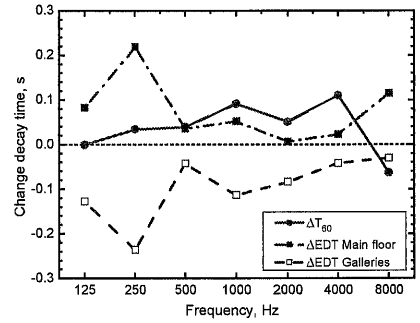

Fig 12 Change in decay times when SRS is turned on.

As for the natural acoustics results, the effects of the SRS can be more easily understood by comparing changes in G, G_{50} and GL values for both main floor and gallery level seats as is shown in Fig. 14. The total G values are increased less at main floor locations and for these locations the late arriving sound is increased more than the early arriving sound. At the gallery locations the effects of the SRS are larger and G_{50} values are increased more than GL values. The SRS functions as intended at the gallery locations but provides only modest improvements.

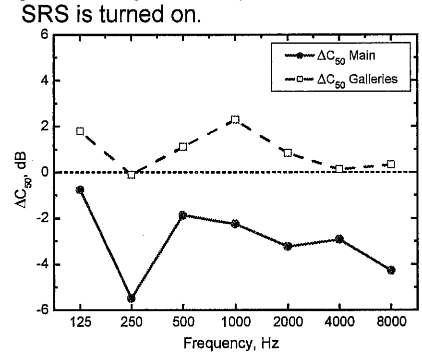

Fig. 13 Change in C_{50} values when the SRS is turned on.

The differences between gallery and main floor seats are easily explained because the only significant system loudspeakers are located pointing towards the seats in the end galleries. This is also seen by comparing impulse responses with the system on and off at each location as shown in the example of Fig. 15. The initial parts of the two impulse responses are almost identical but after about 25 ms the measurement with the SRS on includes significant reflections that are greater in amplitude than the SRS off response. In total more late-arriving sound is added than early-arriving and the clarity of speech would be somewhat reduced.

The overall effectiveness of the SRS was confirmed by using the measured room acoustics parameters with the system on and off, by calculating U_{50} values, and from these predicting speech intelligibility scores. The changes in average conditions for main floor and gallery level locations are indicated in Fig. 16. There are substantial increases in speech intelligibility at gallery locations and small decreases at main floor locations.

6 DISCUSSION

Adding sound absorbing material in the galleries and especially in the end galleries would reduce late arriving-sound to enhance natural acoustics and would reduce the amount of late-arriving sound from the SRS loudspeakers in the end galleries that reflects back to main floor locations as unwanted late-arriving speech sounds. With the addition of improved surfaces for providing increased early reflections on the main floor and reduced ambient noise levels throughout, acceptable natural acoustics conditions could be achieved at main floor locations and would help the success of improvements to the SRS at gallery locations.

7 CONCLUSIONS

Measurements of room acoustics parameters described in ISO3382-1 and some extensions can be an efficient approach to understanding room acoustics conditions for speech and the effect of SRS in these rooms. Combined with Barron's theory and useful-to-detrimental sound ratios, relatively simple calculations can be used to estimate the success of various modifications. New work to evaluate approaches to calculating useful-to-detrimental ratios and to developing a standard format for this measure, should be encouraged.

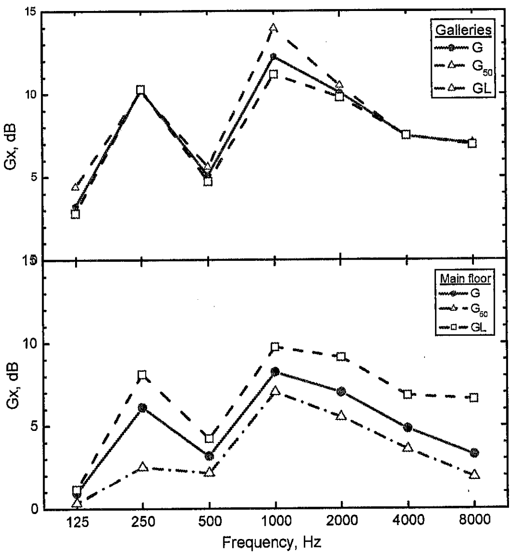

Fig 14 Average changes in G, G_{50} and GL when the SRS is turned on for gallery locations (upper) and main floor locations (lower).

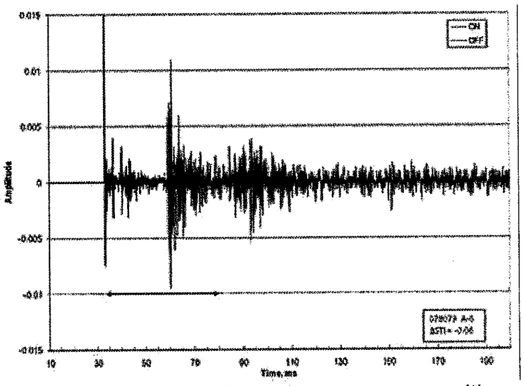

Fig 15 Comparison of impulses responses with SRS on and off.

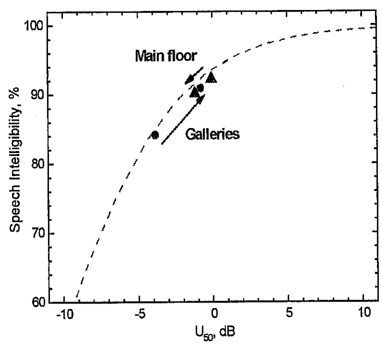

Fig. 16 Changes in calculated speech intelligibility with SRS on and off and regression line from Fig. 8.

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