CASE STUDY

University of Windsor, Canada
Validation of Lecture Hall Acoustics Through Experimental and Computer Analysis

Environmental
ODEON Room Acoustics Modelling Software, DIRAC Room Acoustics Software

Lecture hall acoustics are essential for a positive learning environment. The essential goal of room acoustics is to ensure that every seat is the best seat. This case study presents a comparison between measured and simulated acoustical parameters in a lecture hall. The parameters validated were the reverberation time and the speech intelligibility. Brüel & Kjær's ODEON version 10.0 was the simulation software used to simulate the room and the results obtained at the midrange frequencies were within 5% of the measured acoustical parameters. Large differences were found in the lower frequency range.

Photos courtesy of The University of Windsor

Brüel & Kjær

Introduction

Perception of sound within an enclosed space can be critical depending on its application. Classrooms and auditoriums, for example, are enclosed spaces where the sound quality within the space is important. The main function of these spaces is for sound to be produced by a source, such as a lecturer, which is then received and understood by a listener such as a student. Sound is received in two ways by the listener, directly and indirectly. Direct sound, as the name implies, is sound which travels directly from the source to the listener's ears. According to Noxon[*], only a small percentage of the sound emitted by a source is directly received by the listener. He states that this percentage can be around 0.00017 percent of the total emitted sound per person. The remaining sound is then transferred to the receiver as indirect sound. Indirect sound is sound which is reflected off of the surfaces of the room before reaching the listener. Consequently, it is important for acoustical engineers to carefully consider this indirect sound when designing a room which is to sound pleasant. For example, if a room has reverberations that reach the listener within 50 milliseconds they can actually enhance the perception of speech. Any greater than 50 milliseconds and the sound becomes more difficult to understand.

Not only are the acoustics of a room important for its function but they are also important due to health reasons. For example, lecturers within a poorly designed lecture hall may feel the need to speak at an elevated level which can lead to vocal strain.

Recognition of the importance of room acoustics has led to the development of various software packages which allow the acoustical engineer the ability to simulate and predict the acoustics of a room. Such programs allow a room to be modelled and designed quickly and efficiently before construction even begins. This can amount to substantial savings in time and money for large construction projects.

In the case that follows, the objective is to validate the results of one such simulation software, namely, ODEON. This is to be done by physically evaluating the acoustics of an existing 155 seat lecture hall. The results obtained from this evaluation will then be compared to the results predicted by ODEON and conclusions will be drawn. Additionally, the software will be used to discuss the acoustical behaviour of the room.

Overview of ODEON

ODEON is comprehensive and easy to use software that is used to model and simulate the acoustics of an enclosed space. It was developed at the Technical University of Denmark in conjunction with ODEON A/S. The software is best suited for modelling of any enclosed spaces such as classrooms, auditoriums, concert halls, underground stations and many more. However, in some cases, it can also be used to simulate open air structures such as courtyards and roman style open air auditoriums.

Odeon
ROOM ACOUSTICS SOFTWARE

The software requires a model of the structure which can be imported or created within the software. Then a series of parameters are required before calculation such as noise sources, receivers and surface materials. Once all the required parameters are set then the calculations can be completed. The results are given out in both graphical representations and tables. The most important criteria in room acoustics are usually the reverberation time and the speech intelligibility (STI). The software can also be used to listen to sound in the modelled room which is known as auralisation. The modelling software is used to predict the acoustics of a building or a room as well as to evaluate their quality. An acoustical engineer, after analysing the results, can recommend any improvements that can be made to the room.

Room Geometry Modelling

Evaluation of a room in ODEON requires a geometrical description of the room to be input. This input can be achieved in one of four ways. Firstly, the room can be created using an editor specific to ODEON and secondly the room can be modelled using a CAD software package which is capable of generating dxf files (drawing exchange file). A third way is to use the graphical tool provided in ODEON (Extrusion Modeller) and a fourth way is to use Google Sketchup. Due to its convenience in creating complex geometries, the second

[*] Noxon, Arthur "Auditorium Acoustics 101" Church & Worship Technology April – September 2002

of the four approaches was used. Specific to the analysis under discussion, the room model was generated using AutoCAD which was able to generate the required dxf file format.

Fortunately, ODEON does not require that every little detail within the room be modelled. For example, rather than modelling the audience/seating within the room, which would require a significant amount of time, ODEON stipulates that modelling the audience as boxes will suffice. As a result of this approximation however it is required to assign an overall material property to the boxes (the details of materials in ODEON are to be discussed later). This approximation greatly simplifies the modelling procedure without introducing significant error in the results.

Due to the lack or required detail, a number of simplifications were made to the model of the room under study to make the drawing procedure less time-consuming. First of all, the audience area was not modelled as a box as described by ODEON. Rather, the desks of the seating area were included but the chairs were not included due to the fact that most of the chair's surface is hidden by the desk as shown in Figure 1. Secondly, the doors, windows, and whiteboard were not modelled exactly. Instead they were drawn as simple rectangles flush with the walls. A comparison between the actual and modelled window can be seen in Figure 1. Lastly, the room modelled has a lot of walls with treated acoustic panels composed of more than one material as seen in Figure 1. Rather than drawing these panels in great detail, they were simply drawn as a uniform surface which can then be assigned composite material properties. All the approximations were made due to the simplification that they provided little cost to accuracy. On completion of the room geometry, the model can then be input into ODEON where materials will be assigned to the surfaces and the analysis carried out. This will be discussed later.

Fig. 1
Pictures of actual room and modelled room. Note the comparison of the window, seats and acoustic walls with the modelled room shown to the right.

Measurement Procedure Using DIRAC

Reverberation Time

The acoustical evaluation of the lecture hall was achieved by measurement of the reverberation time and the speech intelligibility metrics using Brüel & Kjær's DIRAC software. DIRAC Room Acoustics software is used for measuring various acoustical parameters based on the measurement and analysis of impulse responses. DIRAC also provides a convenient method to compare the measurements to the predictions in ODEON.

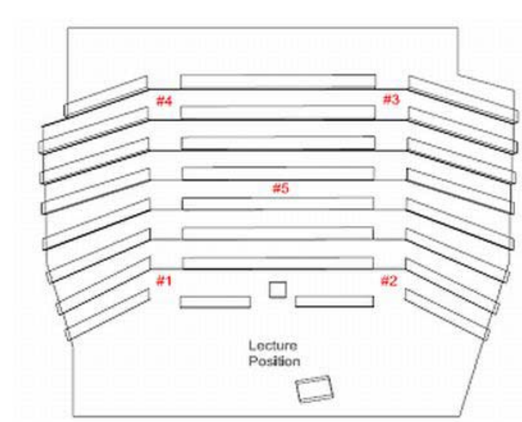


Fig. 2
Reverberation Times Source/Receiver Positions

Reverberation time of the lecture hall was measured as per ISO 3382 standard – "Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters". ISO 3382 is an international standard that specifies the procedure in measuring the reverberation time in a room with reference to other acoustical parameters. Reverberation time is a measure of the decay time for sound in a room after the excitation stops. It is the time for a 60 dB drop in level. The decay is measured at a 30 dB drop then extrapolated to the 60 dB range. The reverberation time was measured in 1/1-octave frequency band and averaged at the most significant bands (500 Hz and 1000 Hz) as per ISO 3382 standard. The standard specifies a receiver height to be 1.2 metres which is representative of a seated listener's ear height and a source height of 1.5 metres. The initial reverberation times were obtained by placing a source at position 1 and the receiver at position 2. A total of 20 reverberation times were achieved within the lecture hall by alternating the source and receiver positions around the room from position 1 to position 5. See Figure 2 for the various positions of receiver and source.

To ensure that the reverberation times obtained were good quality, which is required for the accurate determination of T30 (reverberation time), the INR (Impulse to Noise Ratio) values were verified over the frequency range of the impulse response to ensure the measurement was good quality. Impulse to Noise Ratio is a general measurement quality parameter which relates to the system measurement. Most practical measurements have an INR range of 35 to 60 dB. The ideal reverberation times for this type of lecture hall are 1.0 to 1.6 sec.

Speech Intelligibility Measurement:

The speech intelligibility measurement of the lecture hall was achieved by similar measurements to that of the reverberation time. Speech Intelligibility measurements were obtained by placing the source at the front of the room to simulate a lecturer. The receiver was then placed within the room at various positions at a height of 1.2 metres for a total of 15 measurements. The ESweep signal as well as the male filter in DIRAC was used to obtain the impulse response for the speech intelligibility metrics. The ESweeps signals are frequencies that increase exponentially over time. ESweeps signals were used since they provide better quality results. See Figure 7 (right) for the various positions of receiver and source to obtain STI measurements.

The quality of the impulse response is critical for the determination of the Speech Intelligibility. A high-quality impulse response is an Impulse-to-Noise Ratio (INR) of 15 dB or greater. Another verification to ensure the speech intelligibility measurements are acceptable is the Signal-to-Noise Ratio (SNR). Signal-to-noise ratio is not an actual room acoustical parameter but describes the signal quality measurements. The SNR value greater than 15 dB over the frequency range of 125 Hz to 8 kHz indicates the noise has negligible impact on the speech intelligibility.

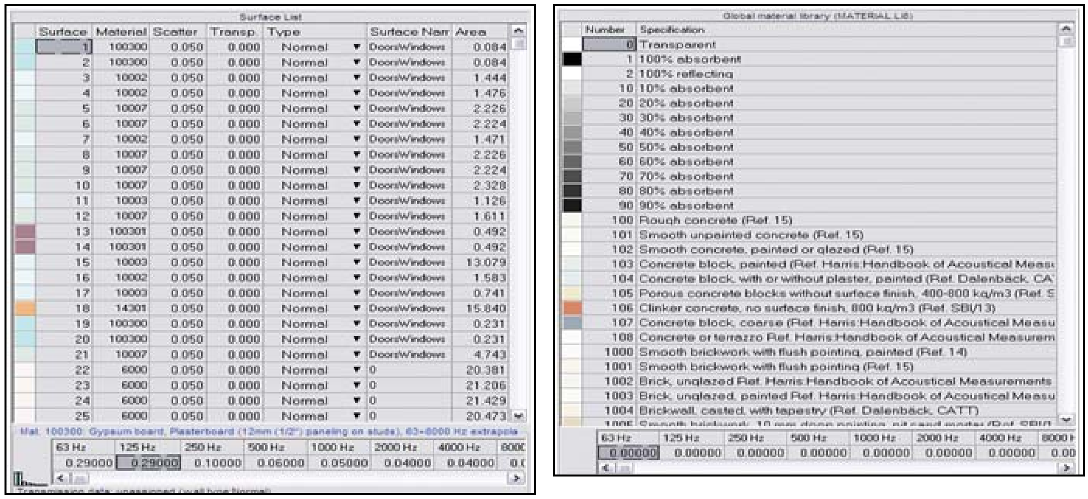
The Speech Transmission Index (STI) is the most comprehensive and important speech intelligibility parameter in DIRAC and is used to quantify verbal communication quality. STI relates to speech intelligibility by a range of STI values from 0.0 being poor speech intelligibility up to 1.00 which is excellent speech intelligibility.

Simulation using ODEON

The model of the room created in the CAD software had to be imported into the modelling software before an analysis could be performed on it. The import function requires a few parameters to be specified such as the tolerances, connections between surfaces and the position of the coordinate system. The connections are important as the software requires the enclosed space to be without significant gaps otherwise the analysis would fail. The model was created with specified dimensions in millimetres which were also specified during the import settings. The tolerances were selected to be medium so as to avoid errors in the resulting 3D model. The software had extensive guidelines on the process of modelling and also some general rules that had to be followed if the model was to be successfully imported and used. The software gives the user an option to check if the imported or created model fulfils its requirements and if not it specifies where the problem occurs. This debugger was used to find some surface overlaps and warps and thus the designer was asked to make appropriate changes to the CAD model. The software allows the user to control the conditions in the model such as temperature and humidity and the background sound power levels. These values are used to calculate the STI value of the room over a frequency range.

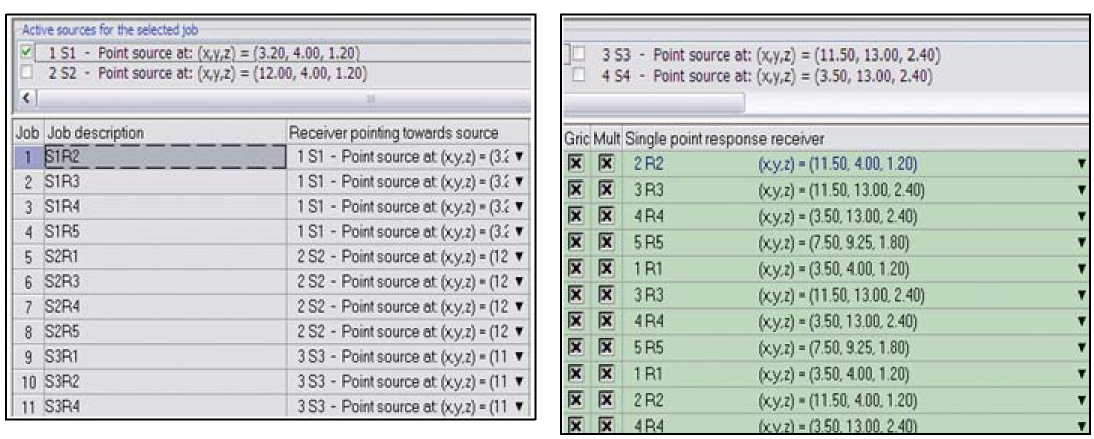
The next task once the model was imported and all the defects sorted was to assign materials to the surface of the room. This process went through some obstacles as the blueprints were a bit vague on the materials used on the surface. Most of the materials used in the room were pretty common such as linoleum floors and gypsum board but there were some parts of the room that used some special acoustic and thermal materials. The software has its own basic database of materials in which more can be added when the data is available (See Figure 3 for a reference shot of materials list and assignments). The software requires absorption data for the material in selective frequencies which would be only available through the manufacturer and which could not be obtained. The material data was eventually determined from physical inspection and some advanced calculations based on the concept of Helmholtz resonators. A basic inspection of the room was conducted through a function provided by the software. The setting of the scattering coefficient or sometimes known as diffusion coefficient for the materials was also considered. These are not usually stated by the manufacturer but the software can take them into consideration. The software manual gives some help in this area by stating a general range for these coefficients in common situations and materials. These recommendations were used to set these coefficients in the manual.

Fig. 3
Material List and assignments



The next step involved setting up sound sources and receivers. The model was specified so as to closely conform to the measured positions and values. The receivers were created and their positions were specified according to the given data. The sources required a bit more input as the position and direction of the source needs to be specified. This also requires the directivity of the sound source to be set and in the case of the model this was set to Omni as an Omnidirectional speaker was used to measure the room. The analysis is done through the aid of specific jobs. This option in the software allows the user to specify an analysis to a single job which can involve either one source-receiver combination or multiple source-receivers combination. The setting up of the job entirely depends on the set of circumstances and the requirements of the user. In the end the user can set up multiple jobs so as to analyse different scenarios. The setup of the jobs was kept similar to the actual calculations done for reverberation times and STI measurements as shown in Figure 4. A series of five jobs were created with each job having a single source active and four receivers for the analysis. Once the setup is complete and all the parameters fixed then all the jobs can be run simultaneously to complete the analysis. This part of the process takes some time and considerable processing power as the software goes through advanced calculations to determine the results.

Fig. 4
Job List and Results window



ODEON Simulation

Reverberation Time

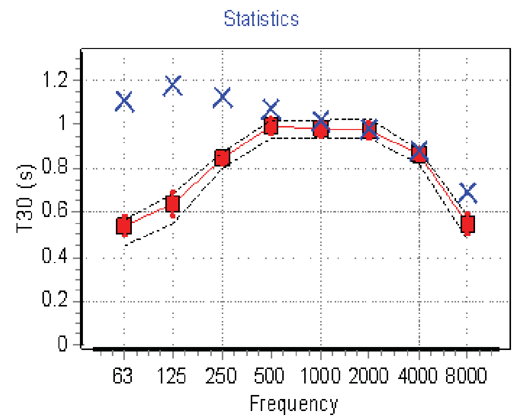


Fig. 5
Mean measured and Simulated T30

According to the results from ODEON, the room had a global reverberation time of 1.01 s for an unoccupied room. This number is to be compared to the actual reverberation time of 1.03 s. Since sound parameters depend on the position of the sound source, one of the sources in the front of the room was selected and the reverberation time (T30) at 500 Hz and 1000 Hz were averaged to obtain the value. When the mean measured values and the mean simulated values are compared, see Figure 5, the values for the mid frequency band, 250 Hz – 2000 Hz were within 5%, signifying a good model result according to the ODEON Manual. Figure 6 (left) shows T30 differing with receivers at a frequency of 1000 Hz with the values at each receiver having very little difference. The second graph in Figure 6 (right) is T30 with frequency at receiver 5 showing that T30 changes with frequency. The simulated values at frequencies below 250 Hz did not follow the trend of the measured values. The values in the lower frequencies have large differences which may be due to absorption coefficients of some materials used in the room. When absorption coefficient measurements are done in a reverberant room, a piece of the material is used for the test and these are the values used in the ODEON.

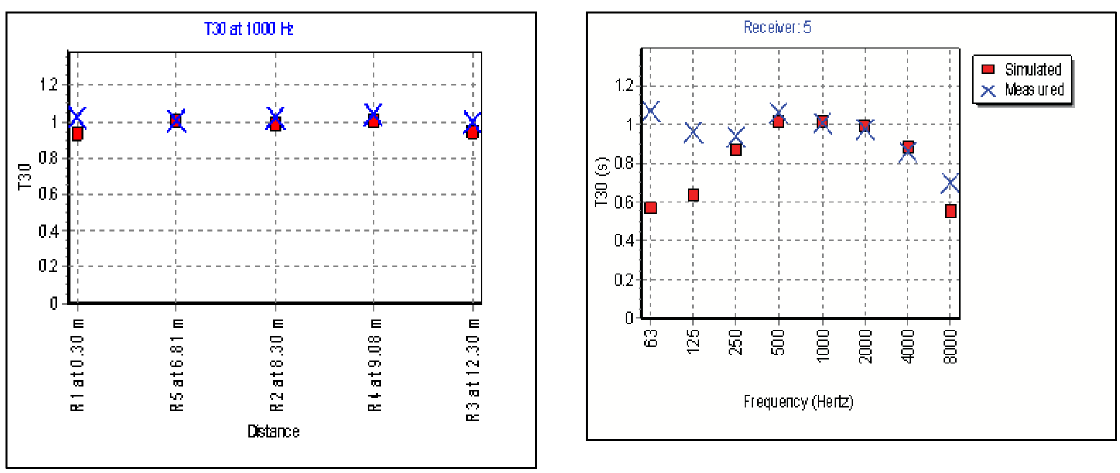
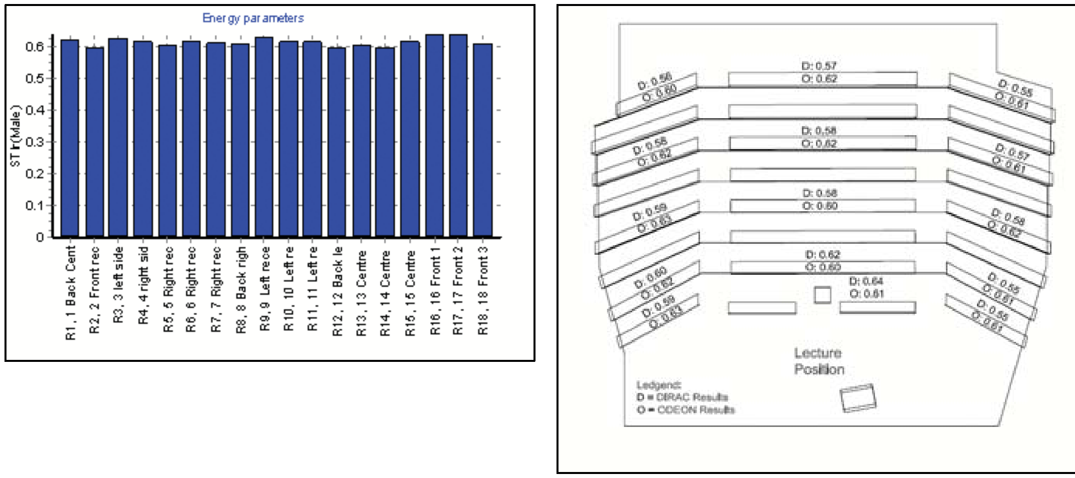


Fig. 6
Left:T30 at 1000 Hz for Various Receivers; Right: T30 at Receiver 5 over Frequency Range

Speech Transmission Index

The STI (male) values were taken over 18 receivers as shown in Figure 7 (left). Speech Intelligibility at a listener's position depends on speech signal to background noise ratio and reverberation time. Conditions which were similar to those used during actual measurements were considered, such as temperature and humidity which were 21.6°C and 30% RH respectively. The STI values on all receivers were averaged by the simulation software to obtain a value of 0.62. Rooms within values of 0.6 – 0.75 are classified as rooms with good speech intelligibility. For a model to be accurate, the STI values must be within ±0.05 the measured value. Figure 7 (right) shows a map of the room with the measured and simulated STI values at 15 receivers. Most of the simulated values fall within the limit with the others slightly above.

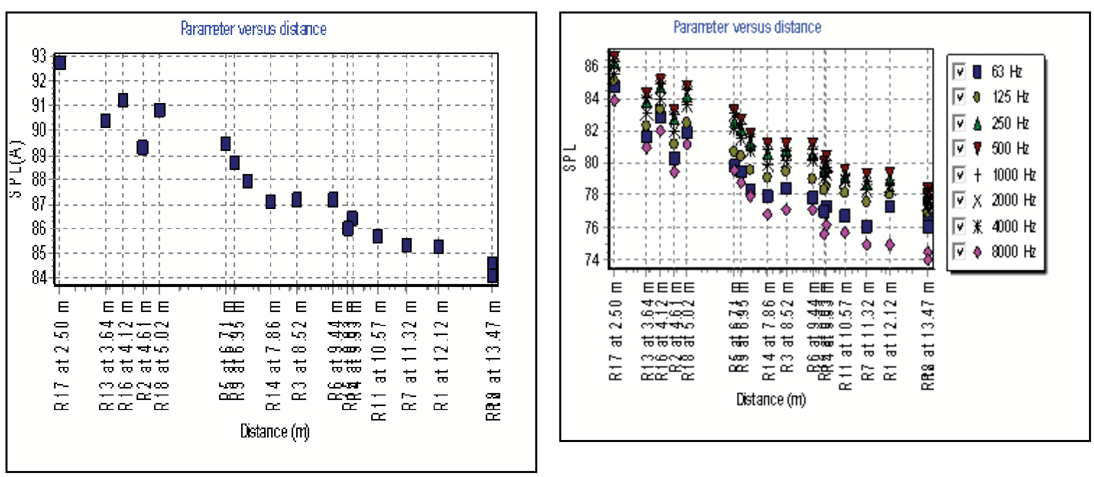
Fig. 7
Left: STI for various receivers; Right: Measured and Simulated STI Values



Sound Pressure Level

Figure 8 (left) shows that the sound pressure level at each receiver generally decreases with increasing distance from the sound source. It can also be noticed that at R16 and R18 in particular, the A-weighted sound pressure level increased despite increasing distance. These receivers are at points where multiple reflections were found and which may have caused the increase. Figure 8 (right) shows the sound pressure level decreasing with increasing distance but at each frequency from 63 – 8000 Hz. Notice that at each receiver, the frequencies 500 – 2000 Hz have the highest sound pressure levels which are desirable for the purpose of the room as these frequencies define human speech intelligibility.

Fig. 8
Left: A-Weighted Sound Pressure Level at Various Receivers; Right: Sound Pressure Levels over the broadband at various receiver positions



Sound Behaviour

Sound rays from the point source were found to bounce around the front of the lecture hall before moving to the back over time. This signifies the possibility of echoes occurring in the front of the room due to multiple reflections. This occurrence was expected and confirms the echoes that can be heard in some areas in the front part of the room.

Error

Discrepancies in the measured and predicted results are explained by a number of error sources stated by ODEON:

- Approximations made by ODEON
- Less than ideal calculation parameters input by the user
- Imprecise materials data – this is one of the largest sources of error in ODEON. It is important to note that the low frequency material data has a higher degree of error due to modal effects that occur during measurement of the absorption data
- Inaccuracy of room geometry
- Measured data for comparison with ODEON results contains error

Recommendations

The recommendations from this case study are:

- Obtain a set of as built drawings for the room to be tested. It was beneficial to this project that a set of as-built drawings were obtained. The as-built drawings greatly reduced design time of the room in creating a CAD model and were very helpful for materials used within the room
- Obtain the absorption coefficient of applicable materials for room to be modelled. It was observed that using materials data that did not fit the room created inaccurate results. Discussions with the actual manufacturers produced the material and its corresponding absorption coefficient over the frequency ranges required
- Future considerations could be considered for providing a treatment to mitigate the echo that was observed in the front of the lecture hall. The modelling software can be used to evaluate any proposals

Conclusion

The main purpose of this case was to validate the results of the modelling software and compare these results to the actual acoustical measurements of the lecture hall. The modelling software generated results for reverberation time of 1.01 s. This was within the 5% of the actual result of 1.03 s. A similar study has been carried out by Hodgson[*] where the acoustics of a machine shop were evaluated with a simulation program and then compared to the actual measured results. In his study Hodgson found that the simulation program predicted the acoustics of the shop with very good accuracy. He did observe, however, that the accuracy was lower at low frequencies and higher at high frequencies due to modal effects.

A majority of the STI values obtained from the modelling software were within the 5% range in comparison to the measured values. However, there were some STI values that were out of range. It is not expected that the results will be exactly the same due to measurement error and modelling software calculation errors.

The modelling software’s predictive capabilities have been validated due to the observance of the echo in both the room and model. It can also play an actual sound to predict how that sound in the lecture hall will be perceived.

2011-10

[*] Hodgson, M. 1989. Case History: Factory Noise Prediction Using Ray Tracing – Experimental Validation and the Effectiveness of Noise Control Measures. Noise Control Engineering Journal, 33: 97-104

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