Proceedings of the Institute of Acoustics

ALL-SCALE ROOM ACOUSTICS MEASUREMENTS WITH MIDAS

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1. INTRODUCTION

Two techniques are presently available for the acoustical design of concert halls or theatres : computer simulation ; and acoustical scale modeling. Computer simulation has been made popular by computer graphics that allow superb visualisation of virtual spaces. On the other hand, scale models allow interactive visual perception, much needed in acoustical design : students can come with their own cardboards models, test them and readily modify them in order to achieve design goals. Thus acoustical scale modeling can be a powerful tutorial tool.

2. PRINCIPLES

An advantage of acoustical model measurements is that no simplifying assumption is made regarding sound propagation : sound propagates in the same way in a full scale room and in its model. The only difference is that frequency is transposed by a factor equal to the scale factor : thus, 500 Hz at full scale, the region of main speech energy, is transposed to 5 kHz in a 1:10 scale model, and 25 kHz in a 1:50 scale model. This frequency translation imposes great constraints on the equipment, since sound must be sampled at a rate more than twice the highest frequency of interest. Hence MIDAS is compelled to use a state of the art acquisition board : a National Instruments NB-A2000 board with a maximum sampling frequency of 1 MHz. With state of the art microphones that are sensitive up to 160 kHz, two microphones signals, corresponding to the two ears of a listener, can thus be simultaneously recorded in models.

Now, at such high frequencies, the microphone records neither music nor speech, but the response of the model to a very short pulse : the impulse response. Physics ensures that all acoustical properties of the room are captured in its impulse responses. Interested readers are referred to our previous publications.

The main limitations arise from the microphones and the sources. State of the art microphones are expensive and delicate. At large scales (1:10), however, cheap electret microphones prove satisfactory. As regards sources, experience proves the superiority of very short pulses such as those produced by a spark gap, or a small tweeter driven by a pulse generator at larger scales : the different reflections are easily discriminated on displays such as Figure 1, where every vertical stripe corresponds to one reflection whose arrival time and strength can be directly read on the ordinate scales. On the other hand, short pulses lack low frequencies : advanced signal techniques must be called on, at the expense of reflection discrimination.

Other limitations also arise at high frequencies, for example the exaggerated sound absorption by the air which is numerically compensated by MIDAS [1,2,10,11]. Therefore MIDAS does not need air-drying or air replacement and allows free access to models during testing.

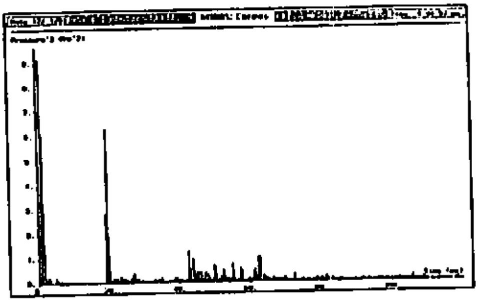

Figure 1: Energy response showing the pattern of reflections.

3. USING MIDAS

3.1. Constructing the model.
Experience has shown that the accuracy of prediction depends solely on the quality of the model construction. A careful realisation of the model geometry is crucial for an accurate early reflection pattern, whereas absorption primarily affects reverberation : the materials covering the walls should have scaled absorption coefficients, especially the audience and seating. Depending on the quality of the model, three levels can be distinguished, corresponding to three different uses of modeling :
• Level 1 consists of small scale models, rendering the main features of the hall only, and built in a few days at low cost with foam core and card, possibly by students. No special care is taken for modeling absorption at this level. Such models are used for educational purposes, at the conceptual design stage for confirmation of basic design, or for research purposes concerning innovation in room shape.
• Level 2 still consists of small scale models, rendering more details of the hall (typically 0.5 mm and 2 deg. on wall positions in models) such as wall diffusers, and built in a few weeks at greater cost with acrylic sheet. Such models are used at the developed design stage in major projects, where precise evaluation of objective indices is required.
• Level 3 consists of large scale models, featuring elaborated details such as seats, carpets and drapes, and built in a few months at considerable cost with timber, metal, acrylic, and particle board. Such models are used for all measurements required in the finished room, and for subjective evaluation with scaled orchestra, vocal sources and listener heads.

In all models, access must be provided for installing sources and receivers at several positions. A minimum of 3 source positions and 7 receiver positions is necessary for a meaningful statistical analysis of the results.

3.2. Configuring MIDAS.
MIDAS has been designed for being operable by non-specialists. Beside a model, the equipment needed consists of a sound generator, one or two microphones with their amplifiers, and a computer of the Macintosh II family with the National Instruments NB-A2000 acquisition board

connected to the output of the microphone amplifiers. When starting MIDAS, a few parameters must be defined in the main menu. The main ones are the scale of the model (which may be 1:1), and the atmospheric conditions at the time of the acquisition. The latter are required for compensating for air absorption. The user can also specify the set of indices that should be computed, depending on the use of the room (music, or speech). Notice that an optional automatic procedure facilitates the use of MIDAS, and that a comprehensive on-line help can be called at all times, ensuring the user-friendliness of MIDAS.

3.3 Tuning.

The first step consists in optimising the system for subsequent measurements. Pulses are regularly emitted in the model by the source, and the corresponding impulse response is received by the microphone, collected by the computer via its acquisition board and displayed in real time on the screen of the computer. Thus, timing and sound levels can be adjusted for optimal display of the microphone signal.

In tuning mode, the impulse response is displayed after each acquisition. Hence, by moving a reflector inside the model, the modification of the acoustical response can be immediately seen. Thus, interactive design is possible to achieve certain desired time patterns in the reflection sequence. Since each display roughly takes one second, the acoustical consequences of design alterations can be understood within a few minutes.

3.4 Measuring.

A measurement sequence consists of an acquisition, the computation of objective indices, and the display of the results. The latter includes all major room acoustical indices, both in table and graphic form : total sound level and reverberation time, as well as indices related to speech intelligibility or to the clarity of music (see references). As an example, Figure 2 displays a typical reverberation curve. The advantage of objective indices is their relevance for evaluating the acoustical quality of a room. Unfortunately, they remain very abstract for the non-specialist. By making objective indices readily available to students, MIDAS can be used to illustrate how indices are related to the geometry of a room. Further, since MIDAS is an all-scale measurement system, the same indices can be evaluated in rooms of known qualities, thus helping students to realise that optimum ranges exist for each index.

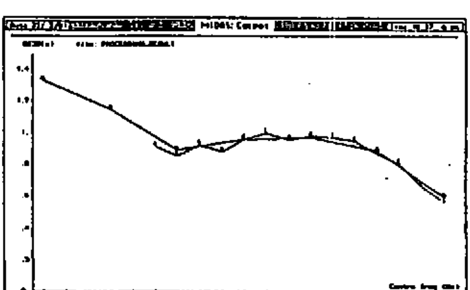

Figure 2: Reverberation time vs. octave and third-octave bands.

4. OUTPUTS.

MIDAS outputs results as ASCII files that contain the values taken by the indices for each frequency band defined by the user. These ASCII files can be internally processed to compute statistics of the results, to plot each index as a function of frequency, or externally processed on spread sheets. Further, all plots displayed by MIDAS can be saved in a format compatible with graphic editors (MacPaint or MacDraw) for subsequent editing and publication. Also there exists a set of side-programs that make use of the ASCII results file for deriving buiding acoustics indices (mainly sound absorption and transmission), thus enlarging the scope of MIDAS.
All impulse responses recorded by MIDAS can be saved for subsequent processing. Thus, the same responses can be successively analysed for different uses of a room (music, speech, etc.) or measurements can be compared with target responses or to previous results after modifications of a model.

5. EXAMPLE

Intensive investigations have been carried out during the renovation of the Théâtre Municipal in Le Mans. It contains 1009 seats on a ground floor and two frontal balconies. A 1:50 model was built in acrylic sheet (1 week's work, $4000). Seating is modeled with light, woven cloth over vertical plastic strips. Except for the stage curtains, no additional absorption has been modeled.

5.1. Equipment

Measurements were carried in the model using a spark gap as source and an 1/8" condenser microphone. The spark gap generates very short sound pulses (about 20 μs), leading to a usable frequency band extending from 5 to 150 kHz equivalent to 100 Hz - 3 kHz at full scale. Indices are therefore evaluated in the 125 Hz to 2 kHz octaves (full scale equivalent). In the full scale hall, a pistol gun was used. Its sound was recorded by electret microphones. Impulsive sound bursts proved better suited to measurements than pseudo-random noise, because impulse sources have better omnidirectional characteristics at all frequencies, and because reflections are more easily discriminated on echograms measured with impulse sources.
The major inconvenience of impulse sources is the lack of stability of the sound level they generate. This inconvenience is cicumvented by coherent averaging of several impulse responses, leading to less than 12% variations over the whole bandwidth for 16 averages (0.5 dB) and even less than 5% below 100kHz (0.2 dB). On the other hand, the spectrum is quite stable, though weak at both low and high frequencies, but this can be compensated by MIDAS. Table I illustrates the influence of this compensation on indices for measurements taken with pistol shots processed with and without reference to a calibration measurements.

ΔEDT	ΔRT30	ΔC80	ΔTc	ΔAmpli	ΔSTI
9%	25%	1.4dB	20%	2.5dB	0%

Table 1: The influence of source spectrum on measurements.

5.2. Measurement Accuracy

A range of additional factors influences measurement accuracy. In Table II, we have selected the major sources of influence and present the corresponding standard deviations in the model (exept for line c where maximum deviations are indicated), both for full band and octave band processing. In the latter case, the worst octave band is indicated where relevant. The sources of influence are :

a. repeatability, when transducers are not repositioned in the model between measurements, and it is clear that repeatability is excellent,

b. microphone directivity. Measurements on the model taken with a nose cone fitted to the 1/8" microphone were compared to measurements taken with the usual grid,

c. microphone positioning, when the microphone is moved within 1 cm3 inside the model. Standard deviations are similar to the ones reported in literature for full scale measurements [13],

d. adjustment (within reasonable limits) of software parameters used in signal processing.

The overall accuracy of measurements in models is also evaluated at the bottom of Table II. It should be noticed that RASTI is only relevant to full band measurements and does not appears therefore in the octave lines. Table II indicates that the major source of measurement errors are the directivity and positioning of microphones.

As regards microphone positioning, critical positions were discarded when evaluating deviations for Table II. Critical positions are found around the symmetry plane of the room. At these positions, reflections from lateral walls are symmetrical and can interfere with each other, leading to strong fluctuations of most indices.

		ΔEDT	ΔRT30	ΔC80	ΔTc	ΔAmpli	ΔRASTI
a. Repeatability	(full band)	1%	1%	0,1dB	2%	0,1dB	0%
without replacement	(octaves)	1%	1%	0,2dB	4%	0,2dB	----
b. Microphone	(full band)	3%	2%	1,3dB	10%	0,7dB	0%
directivity	(octave 2kHz)	6%	3%	1,9dB	14%	1,2dB	----
c. Microphone	(full band)	6%	4%	0,5dB	6%	0,5dB	1%
positioning	(octave 125Hz)	12%	5%	1,1dB	10%	0,9dB	----
d. Software	(full band)	2%	2%	0,2dB	2%	0,1dB	1%
parameters	(octaves)	7%	4%	0,8dB	5%	0,5dB	----
Overall	(full band)	7%	5%	0,7dB	7%	0,6dB	1%
accuracy	(mean over octaves)	10%	7%	1,4dB	10%	1,2dB	----

Table II: The major influences on the accuracy of index calculation.

5.3. Comparison between full scale and model

Echograms measured in the model are very similar to echograms measured in the full scale theatre. Differences are nevertheless observed where the model geometry does not properly mirror the full scale. In our model, this was the case on the second balcony, because of a deficient ceiling. The deviations between mean reverberation times in model and full scale theatre amount to 2% at 125 and 250 Hz octaves, then rise to 10% at 500 Hz and 20% at 1 kHz and 2 kHz. This excessive absorption at high frequencies is partly due to viscothermal absorption on the walls (5% at 100 kHz), but mostly to an unrealistic modeling of the stage curtains. In fact, the absorption of the stage curtains was never evaluated in the full scale theatre. Reverberation time at 2 kHz increases by 20% in the model when removing this curtains. This example illustrates the absolute necessity of matching carefully absorption inside the model for quantitative evaluation of indices.

As a consequence, it is unrealistic to compare the actual values taken by the indices in the model and in the theatre (Table III). A more realistic approach consists in classifying results according to 4 situations :

- ••• : both model and theatre measurements lead to high index values (relative to the respective ranges in either model or theatre) ;
- •• : both model and theatre measurements lead to mean index values ;
- • : both model and theatre measurements lead to low index values ;
- xxxx : measurements lead to very different index values.

Beside the discrepancies related to reverberation, analysis of Table III reveals that most dicrepancies are found either at positions where the model does not mirror properly the theatre, or at positions located on the symmetry axis of the room, that is, at critical positions. On the other hand, general tendencies are well modeled, especially for the total sound level, which shows the strongest correlation with the overall subjective impression, and for STI ; and the standard deviations evaluated over the 7 positions are similar for all indices in the model and in the theatre.

Theatre du Mans. Hall - Model comparison

(88-2800Hz ; Calibration ON ; Pink filter ON)

		Stalls			1st balcony		2nd balcony	
		E1	L1	K24	O1	U24	BB1	KK22
EDT (s)	hall	1,05	0,98	0,88	0,77	0,67	0,97	0,80
	model	0,92	0,84	0,80	0,75	0,53	0,87	0,71
		•••	•••	••	••	•	•••	••
RT (s)	hall	1,19	1,22	1,25	1,24	1,10	1,10	1,07
	model	1,00	1,10	1,08	0,98	1,13	1,16	1,00
					xxxx		xxxx	
EDT/RT	hall	0,88	0,80	0,70	0,62	0,61	0,88	0,75
	model	0,92	0,76	0,74	0,77	0,47	0,75	0,71
		•••	••	••	xxxx	•	xxxx	••
C80 (dB)	hall	3,2	4,4	5,9	6,1	6,6	1,3	5,3
	model	4,4	5,8	5,8	5,6	8,1	2,8	5,6
		••	xxxx	•••	•••	•••	•	•••
Tc (ms)	hall	73	58	51	56	44	78	54
	model	64	53	51	52	40	69	55
		•••	••	••	••	•	•••	••
Ampli (dB)	hall	8,3	3,2	3,5	7,5	6,2	3,9	3,8
	model	6,8	4,0	2,9	5,0	4,4	3,2	-0,6
		•••	••	••	•••	•••	••	xxxx
STI	hall	0,58	0,63	0,65	0,63	0,68	0,57	0,65
	model	0,60	0,66	0,64	0,66	0,69	0,59	0,63
		•	••	••	••	••	•	••

Table III : Comparison of full-band indicies in model and theatre (see text)

5. CONLUSION

Work on acoustical models at Auckland School of Architecture has proved to be a very efficient method for introducing students to room acoustics : they had no difficulty in learning how to use MIDAS, which proved to be a powerful tutorial tool. Many student theses have been undertaken using MIDAS, and one of them received the Robert Bradford Newman award (modification of the Council Room of the University of Auckland based on a 1:20 model study).

MIDAS has also been used for various consultancy jobs, both at full-scale (final objective evaluation of the Concert Hall and Lyric Theatre of the Hong-Kong Cultural Centre, Théâtre Municipal in Le Mans, etc.) and on models. For that purpose, a library of materials of matched absorption is under development, at least for the major model scales. A variety of research works [3, 4, 5, 9] has also been carried out using MIDAS. Present research aims towards "listening into the models" to enhance the tutorial aspect of acoustical scale modeling.

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