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ULTRASONIC WAVES - WOOD STRUCTURE INTERACTION

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INTRODUCTION

The importance of microsctrure in controlling mechanical properties of solids is of corse, well established. The ultrasonic nondestructive methods are particularly useful to explain the links between morphological parameters and mechanical properties of materials.
Wood is a solid exhibiting orthotropic symmetry (9 constants). The elastic behaviour of wood material can be determined from ultrasonic velocity measurements. Like most biològical materials, wood is heterogenous. However a non random organisation of anatomical elements suggests to consider it as homogeneous anisotropic medium at macroscopic level for overall acoustical caracterisation. This assumption allows the use of the theory of wave propagation in orthorombic solids for the investigation of wood anisotropy. (The waves can be assumed to be plane and the wavelength long compared with the characteristics of specimens).

The ultrasonic waves propagating in wood have a high potential for extracting informations related to its structure that acts as a filter. An accurate estimation of the mechanical behaviour of solid wood requires simultaneous views on structure and propagation phenomena. An excellent review of the litterature on methodology of elastic constants measurements and wood microstructure modelling is reported by (1).

The purpose of this paper is to examine the interaction between ultrasonic waves (bulk and surface waves) and wood anisotropy induced by specific disposition of anatomical elements during the life of tree.

THEORETICAL CONSIDERATIONS

Many of fundamental aspects of elastic wave propagation in orthorombic solids have been presented by numerous authors (2). To avoid unnecessary duplication, material on basic wave propagation phenomena has been excluded from the present text.

The philosophy adopted here is to estimate the interaction between ultrasonic waves and wood anatomical structure through the 9 stiffness values that characterise the elastical behaviour of this material.
The 6 diagonal terms of C (matrix) can easily be obtained from in-axis bulk waves (longitudinal and transversal) velocity measurements in time domaine. The three off-diagonal terms are much more difficult to be determined. Both bulk and surface waves are used in this case (3).

The first approach to C_{ij} determination requires repeated off-axis measurements, using bulk waves. The C_{ij} terms were computed from each value of velocity measured on the corresponding off-axis angle. Finally a choice criterion in selecting one C_{ij} value was adopted in focusing on the range of variation of technical constants deduced from (C) matrix. (i.e. all E moduli positive and E_1 maximum.. The C_{ij} terms are a function of the velocity of propagation of quasi-longitudinal or quasi-transversal waves (V), the corresponding diagonal terms (C_{ii})of (C) matrix and the n_i components of propagation vector (eq.1)

$$C_{ij} = f\ (V,\ C_{ii},\ n_i) \tag{1}$$

The three off-diagonal terms are much more difficult to obtain from bulk waves than the diagonal terms, but they are also more representative of the anisotropy of wood species, thant the C_{ii}.

The second approach to C_{ij} measurements was possible using surface waves. The direct determination of one off-diagonal term is possible using the eq. (2) :

$$MC_{ij}^{\ 4} + NC_{ij}^{\ 2} + P = 0 \tag{2}$$

where M, N, P are real coefficients involving the diagonal terms of (C) matrix and the measured values of surface velocity in specific conditions (4).

This approach was introduced because it seems that surface acoustic waves are very sensitive to structural feature of propagating medium. However it is well known that surface acoustic wave particle motion is elliptical and therefore very likely to undergo modulation by wood microstructure.
On the other hand, surface acoustic waves approach permits to check the consistency of C_{ij} terms determined from bulk waves procedure.

MATERIALS AND METHOD

Species listed below were investigated :

Hardwoods : Acer pseudoplatanus L. (of curly structure) - Curly maple ;
Aesculus hippocastanum M. - Horse chestnut ;
Fagus sylvatica L. - Beech ;
Liriodendron tulipifera L. - Tulip tree ;
Quercus petraea Liebl. - Oak ;

Softwoods : Picea abies L. Karst - Spruce ;
Picea sitkensis (Bong) Carr - Sitka spruce ;
Pseudotsuga menziesii (Mirb) Franco - Douglas fir.

The bulk velocity measurements were carried out using classical contact pulse technique with standard Panametrics equipment on multifaced disk specimens Ø = 35 mm ; h = 20 mm. One disk corresponds to one plane of elastic symmetry and three samples are therefore required for complete characterisation of one species. The specific sample design permits successive off-axis bulk velocity measurements by step of 15°. The wideband Panametrics transducers, 1 MHz were V105 and V153.

Surface waves velocities measurements were performed using Steinkamp narrowband transducers connected to a Panametrics 5052 UA analyser. 200 Hz was found to be an appropriate repetition rate. The output signal was fed into Schlumberger 5220 oscilloscope permitting easy transmitting times readings. This particular chain is by no means the most appropriate one for surface waves investigation. It is worth recalling however that the proposed method can only be interesting if surface and bulk waves velocities are read simultaneously.

As a consequence, a method similar to the acoustic stimulation technique reported by VARY (5) was prefered to a conventional surface waves transducers arrangement. Surface waves were produced by a bulk to surface mode conversion process. Conversion was achieved by fitting the emitter on the upper edge of the block cut at 45°. The receiver was located 200 mm away from the emitter on the free surface of the block (600 x 180 x 90 mm). Because of sample limitation, only two species (beech and spruce) were tested using surface waves.

RESULTS AND DISCUSSIONS

Complete results of stiffness terms determined from bulk waves velocities are summarized in table 1.

As a general comment of diagonal stiffness terms, C_{11} is always greater than C_{22} and C_{33}. The longitudinal orientation of cells along the L axis is the best explanation of the specific ordering of stiffnesses and implicitely of velocities since cell walls provides a continuous waves path. Accordingly, the continuous and uniform structure of softwoods structure buit of long anatomical elements, provides high values of acoustical constants. To explore further the significance of the factor - two - discrepancy between the values of C_{22} and C_{33}, these results will be related to the alignment of tracheids or fibers in R direction and to the random distribution in T direction. This disposition of anatomical elements have also a significant influence of shear waves propagation ($C_{66} > C_{55} > C_{44}$).

On the other hand, the annual ring structure (with latewood having almost solid thickwalled cells and with earlywood having thinwalled cells) induces wave guide effect in both longitudinal and transversal propagating waves. In fig. 1 are shown the discrepancies in shear velocities $V_{44} = (V_{RT} + V_{RT})/2$ and in $V_{55} = (V_{LT} + V_{TL})/2$. The modulation by the structure of shear waves is strongly related to both the propagation and polarisation directions. For softwood with a pronounced annual ring structure the differences between V_{TR} and V_{RT} are 10 % ... 15 % and for the ring porous hardwood oak, the difference is 17 %. For diffuse porous hardwoods which have only small differences between earlywood and latewoods, like the 4 other species analysed, the discrepancy between the two values is only about 5 %.

Another interesting case to be reported here is that of spruce wood long time stored in water and infected by Bacillus subtilis (6). The pit tori, composed mainly by pectine is destroyed by this bacterial attack. Measuring the shear velocity V_{44} on the same disk specimens before and after attack, 21 % decrea-

Species	Density	Diagonal constants						Off diagonal constants			Optimisation criteria
		C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}	C_{12}	C_{13}	C_{23}	
Horse chestnut	510	116,62	27,23	9,74	1,47	6,93	12,24	25,81	10,45	12,90	C_{ij} maximum from shear waves
Tulip tree	574	181,62	24,05	13,11	1,84	9,29	11,46	24,61	28,35	8,20	
Beech	674	173,25	32,62	16,40	6,21	10,87	15,18	30,36	16,89	7,42	
Curly Maple	700	132,46	46,95	25,64	4,61	15,09	21,29	33,84	18,58	22,31	
Oak	600	154,29	25,58	14,19	2,79	9,41	14,34	2,31	1,16	6,03	C_{ij} minimum from shear waves
Commun Spruce	485	139,23	12,10	6,37	1,10	7,33	8,48	2,84	2,31	7,60	
Sitka Spruce	450	128,80	21,00	10,80	0,91	11,10	12,25	10,29	3,96	10,29	
Douglas	440	133,10	23,89	17,42	1,38	12,12	12,15	15,00	10,06	12,46	

N.B. - (C) matrix is defined in rectangular coördinates 1, 2, 3 corresponding to the natural axes of wood symmetry L, R, T.

TABLE 1

Terms of complete stiffness matrix determined from bulk waves velocity measurements

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TABLE 2 : Shear velocity V_{44} on sound and bacterial attacked spruce wood

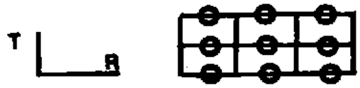
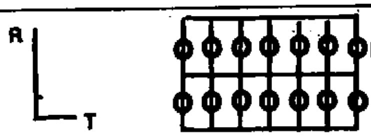
V_{44}	Sound wood	Attacked wood	Difference %	Diagramatic view of wood cells
V_{RT}	637	607	9	
V_{TR}	664	525	21	

TABLE 3 : Surface acoustic waves velocities and corresponding off-diagonal terms of (C) matrix

Species	Surface wave velocity (m/s) measured values			Off-diagonal terms (10^8 N/cm2)		
	12	13	23	C_{12}	C_{13}	C_{23}
beech	1451	1238	914	34,42	18,61	10,67
spruce	1294	1193	385	3,78	3,58	7,80

TABLE 4 : Wood anisotropy expressed by the ratio of acoustic invariants

Species	HARDWOODS					SOFTWOODS		
	Horse chestnut	Tulip tree	Beech	Curly maple	Oak	Commun spruce	Sitka spruce	Douglas
Ratio of invariant	0,51	0,43	0,52	0,63	0,488	0,355	0,446	0,497

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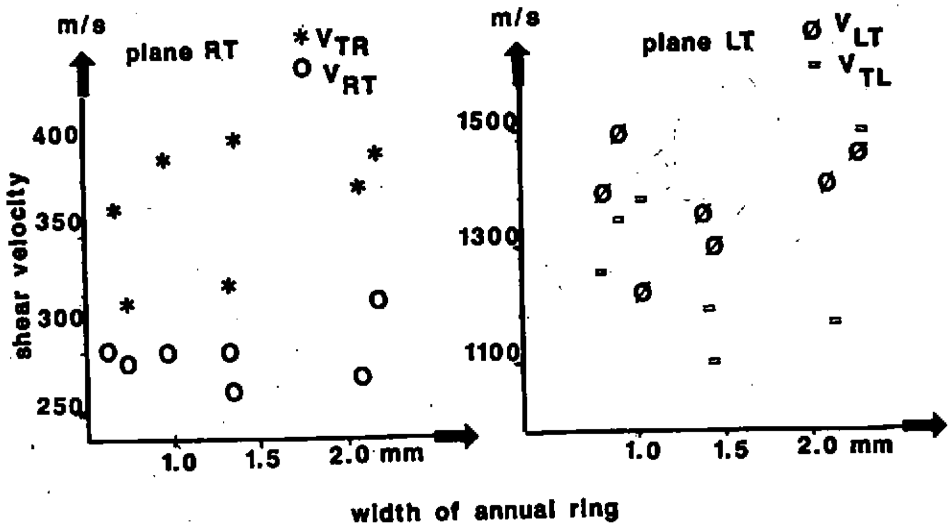
sing in V_{TR} value was observed. The value of V_{RT} was less affected (9 %) : table 2. When we compare these two values, the importance of polarisation vector seems to be evident for the ultrasonic-anatomical structure approach.

FIGURE 1
Discrepances in shear velocity due to wave guide effect in Spruce



A very concise approach to waveguide effects and dispersive propagation due to interaction of elastic waves with the medium microstructure will be commented further for the dispersive propagation in RT plane. The propagation normal to the layering shows stop band effects (1, 7). Up to this point the wavelength λ was assumed to be much larger than the material microscopic dimensions. However, as soon as the λ matches the internal dimensions of the substrate, complicated periodic structure and waveguide effects can occure. Consequently the wave velocity is now dependent of λ and frequency. The pulse cannot propagate with unalterate shape since its different frequency components are propagating with different velocities. Furthermore, the microstructure - wavelength interaction is evident. The material behaves like a filter with alternate pass band and stop bands.

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However, waveguide effects must be taken into account to understand the influence of the geometrical and structural dimensions of specimen (in our case, multifaced dis), on the propagating elastic waves. In our paper this aspect is illustrated by the C_{ij} terms for which two different optimisation procedure were adopted (i.e. maximum value for diffuse porous species and minimum values for ring porous oak and softwoods, on which more evident stop band and pass band effect is expected). The continuum theory wich ignores the ring structure of wood can be use stafely only if the wavelength is long compared with the ring spacing, with the proportion of the latewood in the ring and fiber dimensions.

The diffuse porous hardwoods with a very small proportion of the latewood in the annual ring semms to be much near to the hypothesis of continuum theory than the softwoods and oak. Similarities between the behaviour in acoustic field of oak and softwoods can also be deduced if we compare the corresponding acoustic emission responses under four-point bending tests (8).

It is advisable now to compare the species used traditionaly by violin makers : the spruce and the curly maple. Spruce with a rather simple structure under the microscope appears to be acousticaly much more complex than the curly maple which exhibits a tremendous structural dissorder, that probably induces an acoustic homogeneity (9).

Of peculiar interest is the examination of the relationships between the optimum value of C_{ij} and the corresponding propagation angle, when bulk velocities are employed. A remarkable result is the 45° angle observed in all three symmetry planes of curly maple. Examination of the microphotographs leads to the conclusion that the obvious structural dissorder induces homogeneity reflected in acoustical properties of this species.
Detailed analysis of hardwoods microphotographs related to the optimum C_{ij} values, emphasizes the influence of rays on the acoustical anisotropy of wood. In RT plane the corresponding propagation angle for C_{ij} optimum is 30° versus R axis for tulip tree, beech and horse chestnut and 15° for douglas and Sitka spruce.

However, the spatial filtering action of wood structure is easy to be tied up with the surface velocities, through the calculation of the three corresponding C_{ij} terms. The results are given in table 3. Good agreement between bulk and surface C_{ij} terms was obtained. The consistency of the optimisation procedure for bulk C_{ij} terms was checked.

Comming back to bulk waves and dealing with corresponding elastic-waves-topological features of analysed specimens, it will be convenient to note that in LT plane, for all species an intersection occurs between quasi-transversal and shear velocity curves. This means that the propagating waves are modulated by the anatomical elements and at this angle of intersection both shear type of waves merge into a single wave, forcing their polarisation. As a structural parameter of influence we can advance the microfibril disposition in cell wall. The angle of intersection of both curves is 21° ... 27° versus L axis for softwoods and 34° ... 44° for hardwoods. Further researches are needed using SEM and X-ray diffraction technique to identify more exactly this angle

and to compare this value with ultrasonic prediction.
The effect of discontinuities in wood anatomical structure can be observed by studing its anisotropy. In previous studies the velocity curves were used to express the anisotropy as :

- a ratio of longitudinal or transversal velocities between axes, by 6 numbers (V_{11}/V_{22} ; V_{11}/V_{33}, ...). This ratio is roughly like 1 : 2 : 3 for hardwoods and 1 : 2,5 : 3,5 for softwoods.
- a ratio of transversal velocities in axes by 3 numbers (V_{66}/V_{55}, ...), roughly like 1 for V_{66}/V_{55} and quite 5 for V_{55}/V_{44} in softwoods.
- a ratio of acoustic invariants by only one number as a combination of values of invariants in the 3 main symmetry planes ($I = I_{23}/(I_{12} + I_{13})$: 0,5).

This unique global value is characteristic for every wood species (table 4). It is to note that for isotropic solids the ratio must be 1. These results emphasize that the overall acoustical behaviour of hardwoods, having high density, is less anisotropicthan that of species having low density and typical softwood or ring porous structure.

CONCLUDING REMARKS

In summary this study has shown that by a suitable combination of theoretical considerations on wave propagation and experiments, considerably insight can be gain into wood anatomical structure when ultrasonics were used.
Our investigation was limited to time domaine. Particular specimens were designed in order that a maximum number of velocity measurements might be achieved on the same sample.
In subsequent papers it is hoped to examine the propagation phenomena related to wood structural features in frequency domaine. The choice of the most interesting frequency field of investigation must be related to the wavelength comparable with fibers dimensions, that behave like elementary resonators. Only the frequency component that matches the natural frequency of those resonators can give a detailed answer to ultrasonic waves-wood structure interaction, and in the same time to explaine the overall wood acoustical properties. Interrelations among velocity, attenuation and frequency can reveal so much about the elastic, microstructural and hence strength properties of wood material.

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IMPROVEMENT OF ENSEMBLE CONDITIONS IN AN EXISTING HALL

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INTRODUCTION

Soon after the inauguration in 1946 of the concert hall 'Studio One' in the Danish Broadcasting Building, members of the broadcasting symphony orchestra began to criticize the acoustic conditions for not allowing them to hear each other sufficiently. The hall, which has a volume of 11.700 m^2 and seats about 1100, has a wide fan shape and a high vaulted ceiling as shown in figure 1. The hall is further described in [1].

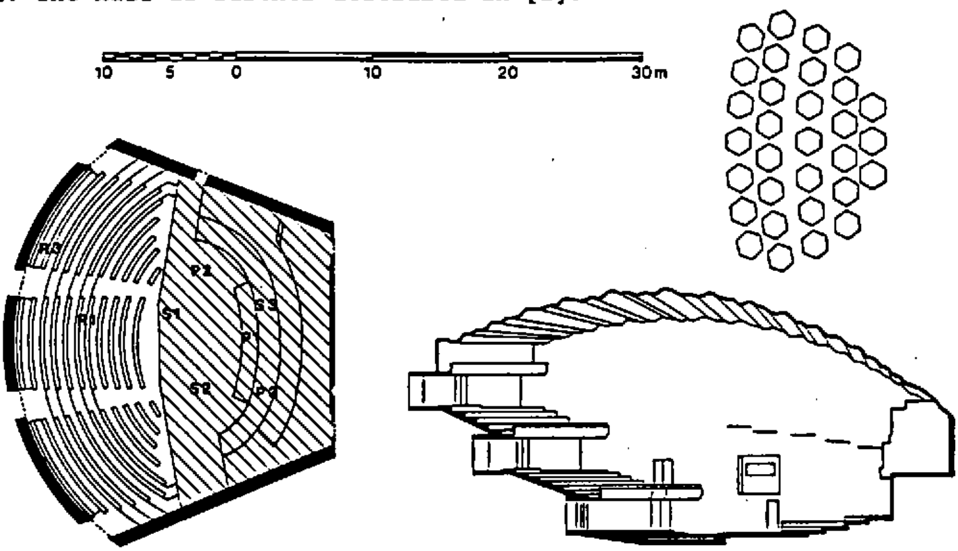

FIG. 1 : Plan and section of The Danish Radio Concert Hall showing the existing reflector array placed over the orchestra platform.

During the early fifties, a number of experiments were carried out in attempts to improve the ensemble conditions, and as a result an array of hexagonal reflectors was suspended under the high ceiling. The effect of these was noticeable but still limited, and the complaints have prevailed until the present day.

However, recently a new chief conductor was appointed for the orchestra, who convinced the management that this problem would have to be solved. Otherwise it would not be possible to improve the quality of the orchestra as hoped for, - and he would resign!

Therefore, a renovation project was started, which has been unique in the sense that all the time and funds necessary for investigating the problem and finding the best solutions possible have been available. As a consequence of this, we were asked to advise on and conduct the necessary experiments.

First a series of experiments in a 1:20 scale model were carried out to indicate which of several suggested means would be most effective. Following this, full scale experiments in the hall including both objective measurements and subjective tests with the orchestra were carried out to check the effects of these means in practice.

Besides providing the necessary results, the experiments also shed some light on problems that we had encountered in our previous research on orchestra platform acoustics: the fact that musicians change their criteria for judging acoustic quality depending on the experimental situation - and the difficulty of determining these criteria at all. Therefore, the review of the experiments in the following will also include their relationship to our previous experiences within this field.

MODEL INVESTIGATIONS

All previous research has indicated, that the direct sound transmission among the players and the presence of early reflections on the platform are essential room acoustic factors for ease of ensemble, e.g. [2],[3],[4]. Therefore the means proposed for improving the conditions were all concerned with modifying the platform area.

Measurement technique

A 1:20 scale model of the stage end of the hall was build, equipped with a number of expanded polystyrene blocks to simulate musician absorption and diffraction. Impulse response measurements were carried out in the various configurations, and the amount of early reflected energy was evaluated using the parameter:

$$ST' = 10*\log\frac{E(10-100ms)}{E(0-10ms)} -12 \text{ dB}, \qquad (1)$$

which is a modified version of the parameter 'Support'. In a previous field study Support had shown the highest correlation with musicians' general preferences [5].

The source/microphone distance was equivalent to 4 meters in full scale, and a free sightline was always ensured between source and receiver. The bandwidth covered two octaves corresponding to from 250 to 1000 Hz in full scale, and for each platform configuration the results were averaged over four measurement positions.

Results

Of the various means suggested, the following turned out to be effective as well as acceptable by the architect and users:

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1) Changing the plane sidewalls in the platform area into a zig-zag shape in order to make them reflect sound back to the musicians more effectively.
2) Lowering the height of and/or redesigning the ceiling reflectors.
3) Moving the orchestra two metres further backwards on the platform (which can be incorporated in an already necessary redesign of the whole platform floor).

The best shape of the wall reflectors was found to be as shown in figure 2. Actually, the upper, tilted part is responsible for most of the improvement, obviously because it allows reflection angles which are not affected by attenuation at grazing incidence by the musicians.

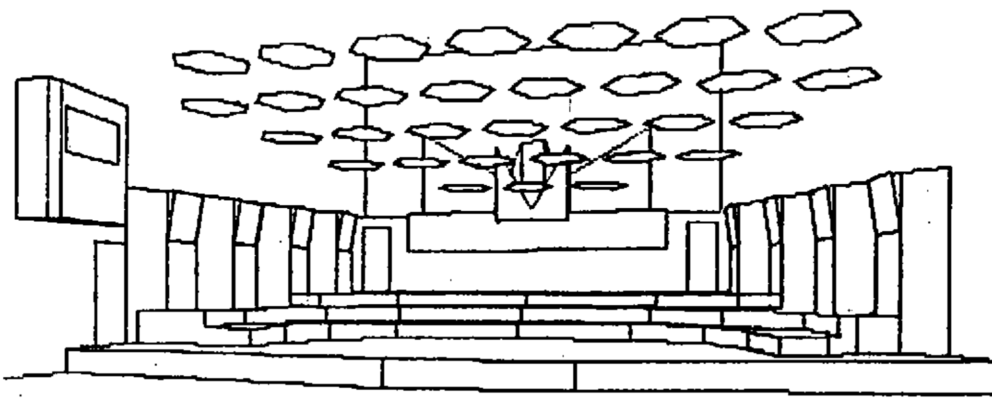

Figure 2 : Sketch of the wall reflector design and ceiling reflector height recommended after the model tests.

For practical reasons the model and full scale experiments were carried out with the existing array regardless of the fact, that a new array would most likely employ reflectors of different size and shape. Lowering the ceiling reflectors two meters from their usual position about seven meters above the floor had a very large effect compared to the other alterations.

The quantitative results from the model tests are not directly comparable with the full scale data in figure 4 because of the differences in measurement techniques. Still, the correlation between the two sets of data was high: 0.97. Therefore presentation of objective, quantitative data has been restricted to the full scale experiments described below.

FULL SCALE INVESTIGATIONS

Measurement techniques

In order to test the subjective effects of the proposed alterations a full factorial experiment was designed, in which all combinations of the variables could be presented to the orchestra. Thus, two wall configurations (plane or as in fig. 2), two orchestra placings (as usual or moved two metres backwards), and three ceiling heights (max. raised = 14 meters was included in order to allow measurement of the effect in the normal position) resulted in a total of twelve situations to be tested.

In each situation, the orchestra played three excerpts from works by Beethoven, Brahms and Debussy lasting 12 minutes in total, upon which the members evaluated the ease of hearing themselves (HS) and others (HO) on two scales in a questionnaire. Including instruction, training, and breaks for resting and changing the conditions, the experiments with the orchestra lasted two full work days.

Objective measurements on the platform were carried out in all twelve situations using the techniques described in [6] and with the three source receiver positions shown in fig. 1. During the measurements, the platform was empty; but equipped with chairs and music stands. Parameters describing early reflection energy: Support with 100 and 200 ms integration limit (ST1 and ST2 respectively) and Early Ensemble Level (EEL), were measured as well as Reverberation time (RT) and parameters related to the ratio between early and late energy: Early Decay Time (EDT), Centre Time (TS) and Clarity (C). Like ST1 and ST2, Clarity was also measured at a one meter distance from the source (CS), at which position it is a measure of the reverberation level (although with inverted sign [5]).

Results

Responses from 71 musicians were subjected to analysis of variance. On the HO-scale the three room variables tested accounted for 24% of the variance, but on the HS-scale, it was only 9%. (The remaining variation in the responses is related to instrumental and personal differences plus usual experimental error.) Still, the correlation between the HO and HS responses is very high (0.75), indicating that the HO data simply reflect the musicians' judgments more clearly than the HS data does. This is in line with many comments on differences in HS conditions being very small in this experiment. Therefore, for each of the twelve situations, only the averaged HO score is shown in figure 3.

Figure 3 also shows the corresponding ST1 data averaged over the three positions and over four 1/1 octave bands from 250 to 2000 Hz. The figure only contains the ST1 data, because these showed the highest correlation with the subjective data (see table 1). Fortunately ST1 was also the parameter whose values best resembled the model measurements.

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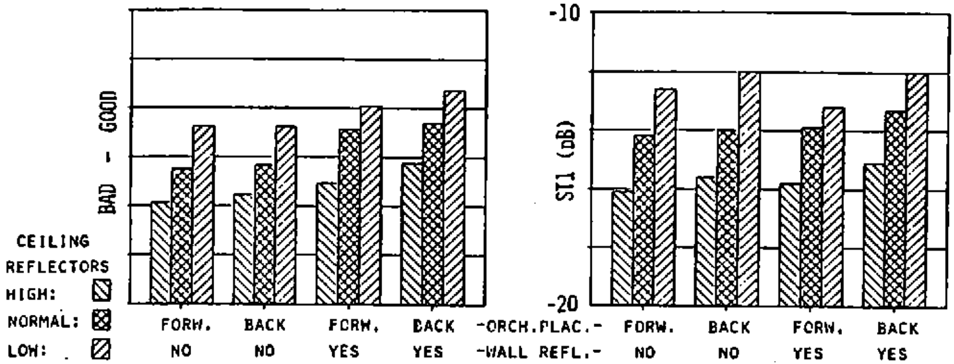

Fig. 3: Left: Subject averaged ratings for ease of hearing other orchestra members (HO) for each of twelve configurations of the orchestra platform in the DR Concert Hall.
Right: Corresponding ST1 values.

The two bar charts in figure 3 representing the subjective and the objective measurements respectively look very much the same, and the correlation coefficient between the two sets of data is 0.91. Judged from the subjective measurements, all three modifications have a significant and positive effect, whereas objectively the wall reflectors provide significant improvement <u>only</u> in cases where the ceiling reflectors are <u>not</u> in their lowest position; i.e. in this case the overhead reflections are so strong, that the walls provide no further improvement. Both sets of measurements also indicate, that the largest effect is provided by the ceiling reflectors.

Analyzing the objective data per position revealed, that the effect of the wall reflectors was highest in pos.3, i.e. close to the walls, whereas the ceiling reflectors were most effective in the two other positions, where the walls contribute less. This points to a need for combining the two means in order to serve all areas on the platform.

The averaged subjective results indicate, that the best situation is created by combining all three variables: having the ceilingreflectors in their lowest setting, and the wall reflectorsmounted, and moving the orchestra to the rearmost position. Actually, the subjective results in fig. 3 indicate, that moving the orchestra backwards is only effective when the wall reflectors are mounted. This was especially noticeable in the string and woodwind player responses. Brass and percussion players did not like this combination because it resulted in too powerful reflections of their own sound. However, this can probably be avoided by making areas of the new walls absorptive near these groups.

The only general negative comment about the alterations tested was that the sound quality suffered, when the ceiling reflectors were in their lowest position. We will try to investigate whether this coloration (?) problem can be avoided with a new reflector design.

DISCUSSION

<u>Improvement of early energy level in DR compared to other halls</u>
The range of ST1-variation possible in the DR hall is quite large: approximately +/- 2 dB from the -14.2 dB in the normal situation (the second bar from the left in the ST1 graph in fig.3). For comparison, the highest ST1 value we have found so far (in a 'proper' concert hall) is -10.9 dB in Tivoli Concert Hall, which has a very good reputation for ease of ensemble. At the other end of the scale we found in Odense Concert Hall -16.6 dB. Ways of improving the ensemble conditions in this hall are currently being discussed.

Without comments, the following mean ST1 values recently measured in internationally wellknown halls could also be mentioned: Musikverein Wien: -13.0 dB, Barbican Concert Hall: -13.3 dB, Royal Festival Hall: -16.0 dB, and Usher Hall: -16.3 dB.

<u>Comparisons with previous field experiments</u>
The subjective experiment described above has been simple in the sense, that the subjects were only asked to judge one room acoustic aspect: 'ease of ensemble playing', but still the nagging question arises, whether this was actually the criterion on which they based their judgments. The relevance of this question became evident after two previous field experiments in Danish and British halls respectively.

In both cases questionnaires with seven different scales were used in an attempt to cover all aspects in the room acoustic experience, but in both sets of data factor analysis revealed that the musicians had judged the acoustics in only two dimensions. Of these one was nearly equal to the timbre scale and objectively correlated with the frequency variation of EDT.

The other dimension to be discussed here was determined by all the other scales, which all showed a very high mutual correlation. Besides, this dimension accounted for a much bigger portion of the variance than the timbre dimension, and could therefore becalled the overall quality dimension. In other words themusicians did not distinguish between intellectually differentaspects such as ease of ensemble, reverberance and support of the sound from their own instrument. Therefore, only the objective correlates can hint at which aspect(s) they actually based their overall quality judgement on.

Table 1 show the correlation coefficients between a number of objective room acoustic parameters and the HO and HS responses for each of the three experiments. The differences between the

Obj. parameters :		RT	EDT	TS	C	EEL	CS	ST1	ST2
Seven Danish Halls (1985)	HO:							0.69	0.77
	HS:							0.76	**0.91**
Eight British Halls (1986)	HO:	**0.86**	0.75	0.79	-0.72				
	HS:	**0.91**	0.82	**0.84**	-0.75				
DR Concert Hall, twelve config. (1987)	HO:		**-0.72**	**-0.76**	**0.80**	0.64	0.62	**0.91**	**0.91**
	HS:		-0.63	-0.60	0.64			**0.70**	**0.72**

Table 1 : Correlation coefficients from three different field experiments between judgments along subjective scales and a selection of objective parameters. Only coefficients significant at a 10% level are shown, 5% levels are underlined, 1% levels are written in bold numbers. 'HO': scale for ease of hearing others,'HS': scale for hearing oneself; but in the 1985 and 1986 experiments, both scales represents more likely: 'overall quality'.

correlations from the Danish and the British survey are striking. Obviously the overall quality judgements have been governed by aspects related to early energy in the Danish halls, whereas in the British halls, the touring Danish orchestra focussed on aspects related to reverberation. The only obvious difference between the two investigations is, that the orchestra was familiar with the Danish halls; but not with the British ones. Therefore the hypothesis is, that only after having had some time to adjust to a new hall, it becomes possible to evaluate other aspects than reverberation, which in turn seems less important in familiar halls.

In the survey of Danish halls, the correlations appear much like in the DR experiment, where only two scales were used. It is even possible that the fact that the highest correlation appears for the HS scale in the Danish halls is due to the musicians regarding the quality of sound from their own instruments being the most important aspect in this survey.

Likewise the highest correlation in the DR experiment appearing at the HO scale may indicate that here ease of ensemble really was the criterion used - as hoped for. The correlations with the early/late ratio parameters is a consequence of only the early sound having been changed in this experiment, and it is worth noticing, that here the signs of the correlations with these parameters are even reversed compared to the British survey.

Thus, the results of such experiments can be seen to depend on the subjects previous experience, which questions they are asked, as well as on the context of physical variables.

<u>The fiasco of the objective ensemble parameter EEL ?</u>
It is somehow disappointing that the ease of hearing others on the platform is more highly correlated with ST1 than with EEL. While ST1 only measures the contribution of early reflections at a distance one meter from the source, EEL was designed also to consider the influence of delay and attenuation of the direct sound over longer distances. However, the reason might well be, that the subjective judgments by the orchestra members are governed by an even greater number of complex factors, including how sounds from a great number of different sources are transmitted along many different paths - and finally the mutual masking and importance of these sounds.

Measuring EEL at the three positions in figure 1, only the transmission of one source along three direct sound paths on the platform was considered. Therefore, with the question of interest being the very complex judgement on ease of ensemble, and not just the ease with which sound from the three source positions can be heard at the three microphone positions, it is not unlikely that the averaged judgments are better described by just measuring ST1, i.e. the contribution from early reflections. Besides, the layout of the orchestra was the same throughout the experiment, and the means tested were expected to cause chances in the early reflection energy only.

CONCLUSIONS

The experiments reported have shown, that with the means suggested substantial improvements in ensemble conditions are possible in the DR Concert Hall. The largest effect was due to the overhead reflectors, which however need to be designed with great care in order to avoid coloration phenomena.

The improvements are very well described objectively by the ST1 parameter, which in previous field experiments also showed the highest correlation with musicians' general preferences in halls which they are familiar with.

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A MODULATION APPROACH TO MUSICAL ENSEMBLE

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INTRODUCTION - MECHANISMS OF ENSEMBLE

'Ensemble' amongst a group of musicians is a complex thing. When a group is performing 'with good ensemble', they in some way exhibit a unity of purpose, and are consistent in many aspects of their individual performances. Pitch, timing, phrasing, articulation, dynamics and timbre are all constituents of good or bad ensemble. The two most fundamental and necessary elements are agreement on pitch and on timing. Of these, synchronisation of timing is the most amenable to being investigated in a room-acoustics context. Several studies have been carried out, with explicit or implicit emphasis on this aspect of ensemble [1, 2].

The task of synchronisation is primarily concerned with ensuring that the moments of attack of notes in different parts occur in consistent relations to each other, such that the desired rhythmic patterns are conveyed to the audience, and the desired tempo is maintained. (The rhythmic pattern perceived does not necessarily correspond to that produced, and the desired tempo need not be constant.) In order to achieve this, various kinds of cues are used by the musicians to check their 'internal clocks', which control their actions. These cues may be visual (watching movements of each other or a conductor), pitch-based (detecting moments of pitch change), or amplitude-based (detecting variations in others' output levels). The importance of the different types of cue depends to a great extent on the musical context [3].

This paper considers how the passage and detection of information about attack moments may be altered as amplitude modulation conditions vary. By taking a view based on modulation concepts, diverse effects of the room and musical material can be brought together, and a number of well-known performance effects follow naturally from such an approach. The results of subjective laboratory experiments confirm the applicability in principle of these methods, and indicate that high early/late energy ratios on the concert platform may not always suffice for good ensemble conditions.

MODULATION MODEL OF ENSEMBLE INFORMATION TRANSFER

The acoustic features which enable the perception of attack moments are more or less sudden changes of amplitude or pitch at note boundaries. At the level of critical bands within the hearing mechanism, the detection of pitch changes corresponds to detection of amplitude changes across critical bands. In principle therefore it might be possible to unify pitch and amplitude cues, though no attempt to do so is made here. Only 'explicit' (i.e. overall) amplitude variation is considered, and pitch variation is ignored for the time being.

A musician attempting to synchronise with others hears three classes of signal: (i) his own output ("SELF"), (ii) that received from other(s) he wishes to synchronise with ("OTHER"), and (iii) any remaining parts of the instrumentation which do not serve to provide useful rhythmic information (held, chords, rapid figurations, etc., termed "INTERFERENCE"). The modulations of OTHER, providing cues, are reduced by transmission through the room. In addition, SELF and INTERFERENCE both contain modulations, which will further reduce the perceptibility of the modulations of OTHER. The situation may be summarised as in Fig. 1, where the modulation characteristics of the various elements are represented in a spectral form. The receiving musician presumably bases his synchronisation decisions on some analysis of the modulations of OTHER which remain unmasked after passing through the physical system. This may involve weightings in the carrier and modulation domains according to the sensitivity to and/or utility of various frequency regions.

It is clear that the description of a given situation for ensemble involves not only the transmission path between players. Source signal characteristics, and the relations in levels and modulations between the various signals are also important.

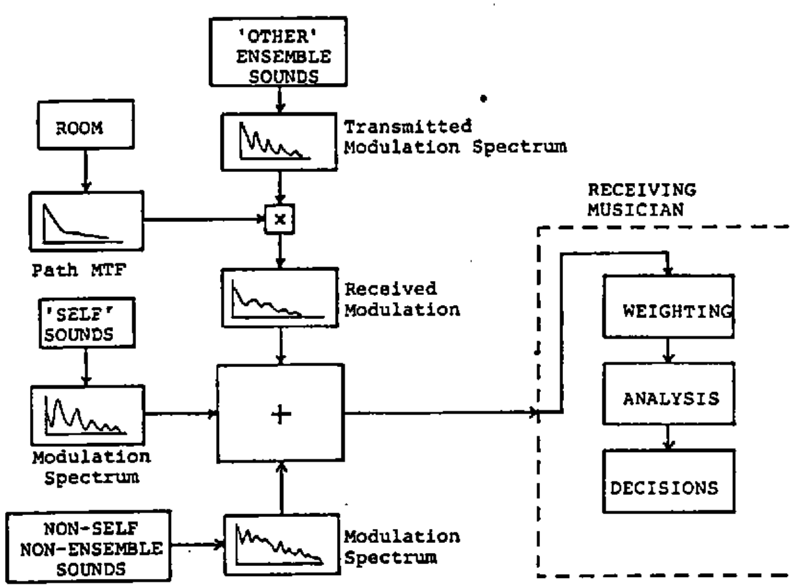

Fig. 1 The passage of modulations from source (OTHER) to receiving musician.

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MODULATION PROPERTIES OF MUSIC SIGNALS

The amplitude envelope of a music signals is generally non-stationary: that is, there is no lower limit to the modulation frequencies present in it, and the form of the short-term modulation spectrum changes with time. The envelope of music's modulation spectrum varies with 1/F down to at least 10^{-3} Hz [4]. Due to the fact that most music has a tempo, with events grouped and repeated in binary and tertiary ways, there is a complex harmonic structure in the spectrum. Local and structural features of the music contribute at different levels to the form of the modulation spectrum. It is not possible to define the ranges of frequency over which different features operate, since they all overlap. However a rough division can be made according to the regions in which each feature has its principal action, as shown below.

Modulation Freq. Range	Musical Feature
Ultra-low	Sections, Phrases
Low to Mid	Rhythm
High	Attack characteristics

Given a suitable choice of musical example, analysis bandwidth and time window length, each of these may clearly be seen in modulation spectra from music.

In order to synchronise correctly, a musician must
(a) locate the current position in the musical text, and
(b) know the precise moment at which to play his next note.
These two tasks overlap; (a) is facilitated by hearing sections, phrases and rhythm patterns, and (b) by rhythm and attack transients. Modulation transfer in rooms is almost always good at very low frequencies, and poor at high frequencies. This corresponds to the observation that 'local' synchronisation (task (b) above) is lost before text location (task (a)), as performance conditions deteriorate from the ideal.

THE MUSICIAN AS MODULATION SPECTRUM ANALYZER

In order to succeed in task (b) outlined above, the musician must estimate the current tempo, and locate 'the beat' relative to his internal time reference. This can be restated, and fruitfully examined, as a problem of spectral analysis: From the short-term spectrum of the received modulation, the musician must extract the harmonic spacing (to give the tempo), and evaluate the phase (to locate the time reference). Musicians may well carry out such analysis in a different way, but spectra are most easily discussed, and any analogous process (e.g. correlation) would yield the same effects.

With a spectrum analyzer model, a number of real-life situations causing loss of synchronisation are correctly predicted:
(a) Room reverberation:
Fig. 2(a) shows the modulation transfer function (MTF) of an

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Fig. 2(a)

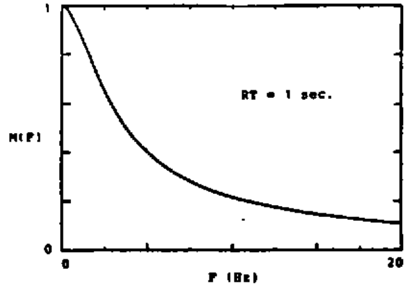

Fig. 2(b)

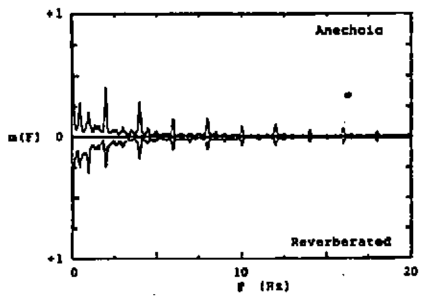

Fig. 2 (a) Modulation Transfer Function of an ideal reverberation process. (b) Modulation spectra (normalised to DC) before and after reverberation.

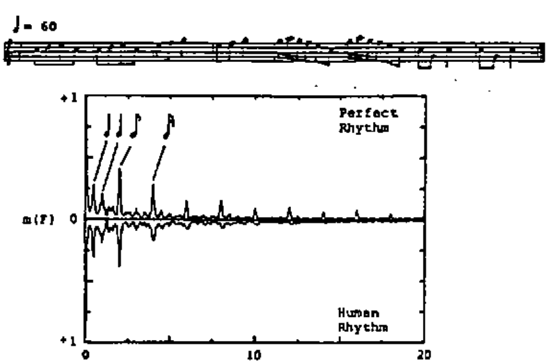

Fig. 3 Modulation spectra of 'Frère Jacques' performed with perfect rhythm (above) and with human error (below). Accentuation of attacks identical in both cases.

exponential reverberation process - a low-pass modulation filter. In Fig. 2(b) are shown modulation spectra of a piece of music before and after transmission through a room with reverberation. Whilst still being essentially harmonic, the higher frequency and intermediate peaks are less well-defined after transmission. Thus the analysis problem is harder, resulting in poorer ensemble. The loss is greater, the more reverberant the room is.

(b) INTERFERENCE sounds:

Steady-state sounds increase the DC modulation component and thus reduce the modulation depth of all non-DC components, making detection harder. Asynchronous INTERFERENCE (trills, flourishes etc.) fill in the gaps between the harmonics, making identification of the peaks less easy.

(c) Inaccurate performance by OTHER:

Fig. 3 shows the modulation spectrum of the same piece, both in a performance with perfectly regulated rhythm, and in a human performance. In the latter case the peaks are broader and smaller, and the tempo will be less easy to decide upon.

(d) Real tempo changes:

The effect of real tempo changes is similar to that of bad performance, but more systematic. Harmonic peaks become smeared, and thereby harder to analyze. The faster the rate of tempo change, the worse the effect. This concurs with actual experience.

All the above effects are additive. The last two mentioned illustrate that the musician's modulation spectrum analyser is faced with the standard averaging-time dilemma; it should be long enough to average out small random errors and give an accurate long-term tempo estimate, but short enough to track genuine tempo changes. Fulfilment of both conditions may be possible under ideal conditions, but impossible in, for instance, a more reverberant room.

It may be noted that under adverse conditions the ensemble difficulty may be eased by altering the performance. In more reverberant conditions, a lower tempo may be chosen. This shifts all the modulation harmonics downwards, so they are attenuated less by the reverberation's low-pass filter effect (cf. Fig. 2). Attack transient modulations may be enhanced by altering the sharpness of articulation of notes. Ritardandi and accelerandi may be made more gradual to ease the averaging-time dilemma. General modulation depth may be restored by playing long-held supporting chords relatively more quietly, hence reducing the DC modulation component.

EXPERIMENTAL INVESTIGATIONS AND RELATIONS TO ROOM ACOUSTICS

Laboratory experiments were carried out in which musicians performed tasks of ensemble playing in simulated sound field conditions [5]. The transmission path between players was controlled, along with the balance between SELF, OTHER and INTERFERENCE signals, within approximately realistic limits. The musicians made judgements of how easy it was to gain ensemble information from the OTHER player. This experimental setup corresponds to the systematization shown in Fig. 1 (and hopefully real life too). The 'external world' portion of Fig. 1 is a modulation transmission system consisting of a room response and two noises. If SELF and INTERFERENCE are assumed to be constant in level, the total MTF of this system is given by

$$M_{tot}(f,F) = M_{path}(f,F) * \frac{1}{1 + 10^{-(Lo-Ls)/10} + 10^{-(Lo-Li)/10}}$$

Eqn. 1.

where f is carrier frequency,
F is modulation frequency,
M_{path} is the room MTF from source (OTHER) to receiver,
Lo, Ls, Li are the average levels of
OTHER, SELF and INTERFERENCE respectively.

In order to obtain a single figure M_{tot} for each experimental condition, a flat weighting was applied for f, and for F between 0.25 and 16 Hz. Empirical constants were inserted into the signal-to-noise ratios Lo-Ls and Lo-Li to account for the subjective effect of the actual non-steadiness of SELF and INTERFERENCE. Thus M_{tot} becomes

$$M_{tot} = \overline{M}_{path}(0.25\text{-}16\ Hz) * \frac{1}{1 + 10^{-(Lo-Ls+Ks)/10} + 10^{-(Lo-Li+Ki)/10}}$$

Eqn. 2.

Values of M_{tot} were obtained for all the conditions to which subjects were exposed, and compared with their subjective ratings of 'Hearing-of-OTHER' (i.e. ease of synchronisation). The result is shown in Fig. 4. The consistency of the trend in Fig. 4 encourages the belief that the modulation model relates quite closely to the synchronisation process, at least for the range of situations tested. This range included musical factors as well as the path between players. Conventional room-acoustic parameters have no way of coping with this complexity.

The results of this investigation are in agreement with previous studies about the importance of early energy. The path MTF can easily be related to the room impulse response, and generally less reverberation and more early energy give higher MTF values. However the MTF method diverges from conventional predictions under some circumstances. In the second (noise) term of Eqn. 1, Lo, Ls and Li are dependent both on the output power of the instruments and on the room response. Increasing the total energy of the impulse response will increase Lo and Li (Ls is virtually room-independent, since the direct sound dominates). There are circumstances in which an increase in reverberant energy will lead to a gain in the noise term which is larger than the loss in the path term. This was observed in the subjective results. When OTHER is relatively quiet, any increase in its energy is desirable, even if it is reverberant energy. Thus it is necessary to ensure that

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the overall energy density on the platform is acceptable, and not only that the early/late ratio is high. (This is also necessary for balance between hearing other players and hearing one's self.)

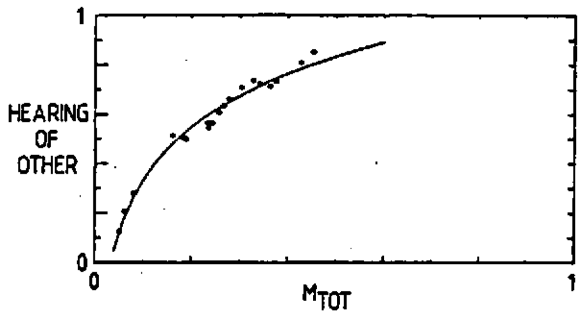

Fig. 4   Subjective ratings of ease of hearing OTHER vs. Mtot. (Subjective ratings averaged across 23 subjects.)

The modulation approach encompasses conventional methods and results, but also allows effects resulting from the nature of the musical activity to be dealt with in a unified way.

IMPORTANT MODULATION FREQUENCIES

The shape of the curve in Fig. 4 was not highly sensitive to the range of modulation frequencies chosen for the estimate of $\overline{M}_{path}$ in Eqn. 2. However it is reasonable to expect that different ranges have differing utility for the extraction of tempo. Since the designer's task is to optimise conditions, the MTF should be maximised in the most useful frequency ranges. Hence it is worth studying what frequencies contribute most to tempo perception.

Modulation frequencies less than about 0.5 Hz (corresponding roughly to phrases and sections) lead to perception of individual events, not a stream with a tempo. At such low frequencies, the room has very little effect anyway. High modulation frequencies, above about 20 Hz, are perceived as a single continuous event (when heard in isolation), again having no tempo. These high frequencies more normally occur as components of the attack transients, and are thus probably useful. The region between approximately 0.5 and 4 Hz is probably the most important. This is where tempos lie, and is also the range of speeds at which people's 'internal clocks' can be made to run. Room design can greatly affect transmission of modulations in the middle and high frequency regions.

Current work is aimed at discovering how the different modulation frequency ranges contribute to tempo perception, and how modulations may mask each other. Preliminary results appear to confirm the above suppositions.

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CONCLUSIONS

One of the most important constituents of ensemble is temporal synchronisation. The level of synchronisation achieved is dependent on the combination of musical and room conditions. Modulation concepts provide a way to begin to deal with this complex situation, by considering signal characteristics to be the essential element, rather than the transmission system as such. Considering the musician as acting in some way analogous to a 'modulation spectrum analyzer', leads to consistent justifications of some real-life ensemble phenomena.

Laboratory experiments with musicians suggest that the effects of interacting musical and room conditions are broadly predicted by a modulation transfer model. This model incorporates predictions consistent with previous studies, but extends the capability towards a more complete description of the performance situation.

Different modulation frequency ranges can be associated to some extent with different levels of structure in the music. At present work is in progress to study how different frequency ranges are used in tempo detection, and how their utility relates to structural features.

ACKNOWLEDGEMENTS

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