TECHNIQUES FOR USING RAY TRACING FOR COMPLICATED SPACES

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ABSTRACT

During the last decade, the ray tracing method has contributed considerably to improve the prediction accuracy of acoustic room modelling. Ray tracing methods allow the analysis of complicated sound field for any room. However, the use of these methods and their validation are not always trivial. Even so, right and useful modelling is obtained only when each construction stage of the model is well done. The objective of this paper is to present, through a complicated example (a hydroelectric power station), some original techniques of modelling and validation. The identification of noise sources and the determination of their acoustic power, the representation of a non-single point source, the validation and some modelling techniques meant to reduce time computation will be presented. Furthermore, an efficient method for the evaluation of noise reduction provided by the various treatments will also be shown. This method, based on an evaluation of transfer functions between noise sources and different computation points in the room, can be used to choose the best acoustic treatment for a given noise reduction objective. All techniques presented in this paper have been applied and validated on an industrial case.

SOMMAIRE

Durant la dernière décennie, la méthode du tir de rayon a contribué à améliorer considérablement la qualité des prédictions en acoustique prévisionnelle. Cette méthode permet l'analyse du champ sonore de bâtiments complexes à partir de modèles géométriques. Les méthodes d'élaboration et de validation de ces modèles ne sont cependant pas toujours triviales. Pourtant, c'est la qualité de ces méthodes qui rend possible l'obtention d'un modèle juste et utile. L'objectif de cet article est de présenter, à l'aide d'un exemple de modélisation complexe (une centrale hydroélectrique), des techniques originales de modélisation et de validation. La détermination des sources de bruit et de leur puissance acoustique, la représentation des sources non ponctuelles, la validation et les différentes techniques de modélisation pour réduire les temps de calcul seront présentées. De plus, une méthode permettant d'évaluer de façon efficace les réductions de bruit apportées par les différents traitements envisagés sera exposée. Cette méthode, basée sur l'évaluation des fonctions de transfert entre les sources de bruit et les différents points de calcul du bâtiment, permet de choisir le traitement le plus performant en fonction des objectifs de réduction. Toutes les techniques présentées dans cet article ont été appliquées et validées sur un cas industriel.

1 INTRODUCTION

In the field of industrial acoustic room modelling, the main objective is the estimate of the noise reduction of treatments applied on noise sources and/or on room walls. The modelling technique and the estimation of the cost of treatments give industries the opportunity to carry out an optimum choice to reduce the noise levels in their plant. To predict the sound field, industries or acoustic consultants have many available models [1]. Simplified models, based on an empirical formulation or on a data library, can be used to rapidly obtain an estimation of the treatment performance for a simple room. However, for more complicated room cases like the one presented in this paper, the model has to be sufficiently accurate in order to do a suitable evaluation of the various acoustic treatments possible. For these cases, the use of a model that can represent a complicated geometry and frequencies dependency is essential. The ray tracing, based on a geometric method, is an example of a model with appropriate features for complicated room modelling [2 and 3]. RAYSCAT [4] software was used to build the model presented in this paper.

RAYSCAT uses only a ray tracing method and not the hybrid method (images/ray tracing). A large number of rays are launched randomly by each specified noise source. Receivers within a certain volume are used to estimate the noise generated by these sources by summing the energy of the rays passing through the receiver. The walls of the room are modelled by absorbent surfaces. For more information about techniques and hypothesis used by RAYSCAT see reference [4].

Even though the choice of the particular ray tracing model is of primary importance, the various development stages such as the location and determination of the acoustic power of the noise sources, the geometric estimation of the shape of the room, the determination of room wall absorption coefficients and the use of simplifying hypothesis of the model are all equally crucial. So, the objective of this paper is to present a systematic modelling approach in order to obtain an efficient and valid acoustic model for a complicated room. To illustrate this approach, the case of a hydroelectric power station with five floors will be analysed.

The complicated room modelling approach will be presented following these stages:

1. Presentation of the studied case
2. Development of the model and techniques of calculation time reduction
3. Validation of the model with a reference source
4. Identification and acoustic power measurement of noise sources
5. Evaluation techniques of acoustic treatments

2 CASE STUDY DESCRIPTION

Alcan's hydroelectric power station (*Chute-des-Passes*) is located 200 km north of Alma City (Québec, Canada). The building, shown in Figure 1, is underground and has five alternator groups of 250 megawatts each, distributed over five floors. Each group has one turbine and one generator (Figures 2 and 3). The generator head and control instruments are on Floor 5. The generator itself is located on Floor 4, in a large room. The shaft between the generator and the turbine is on Floor 3 and is isolated in a large volute. The turbine is distributed over the first and second floors. The water exhausts from the turbine into a very large spherical valve that takes up most of the space on the Floors 1 and 2. The building has a very complicated geometry. The noise sources are numerous and are distributed on all floors. The objective of the project is to specify what treatments to use, at a minimum cost, to obtain a noise level below 85 dB(A) on Floor 5 (station main floor) and below 87 dB(A) on Floors 1 through 4.

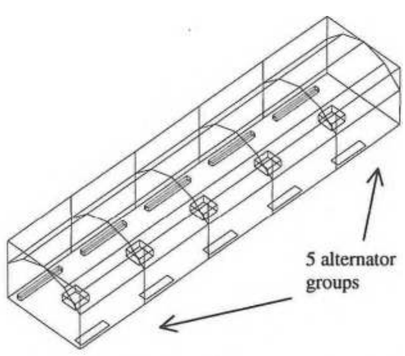

Figure 1 Global diagram of the Floor 5

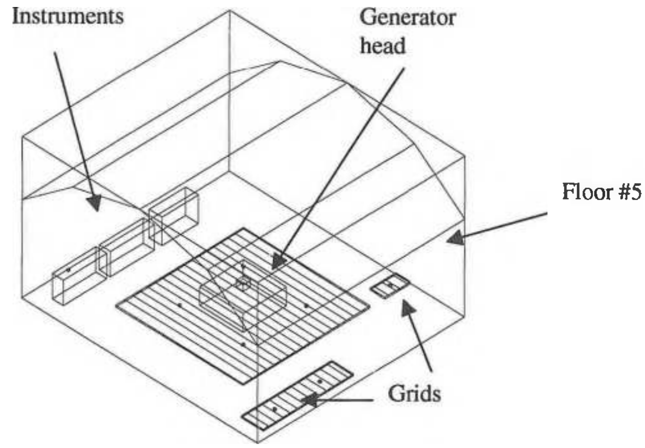

Figure 2 Detailed diagram of one station section for Floor 5

Since Floor 5 is almost totally isolated from the other four floors, the acoustic model of the station is split into two distinctive models: one for the Floors 1 through 4 and a second one for the Floor 5.

2.1 Floor 5

The Floor 5 is 100 m by 15 m and 35 m high. For this floor, the average noise level without treatment was 92.4 dB(A) measured in January 1997. The alternator head is located on this floor. Figure 2 shows a sketch of one alternator group. The noise sources of each alternator head are illustrated with small dots. Among these sources, we can particularly identify the ones associated with open metal grid floor. In fact, the Floor 5 is isolated from all other floors with a rigid floor, but this ventilation grid allows an acoustic link of the Floor 5

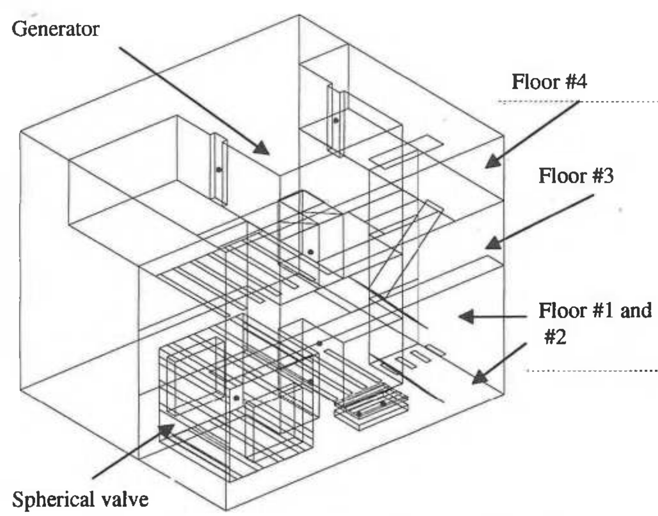

Figure 3 Detailed diagram of one group for first four floors

with the rest of the station. To allow the separation of the station model into two parts, each grid has to be considered as an acoustic source which originates from the noise of the other part of the station. Thus, the grids in Figure 2 are associated with noise sources of the Floor 1 through 4. For instance, a noise level reduction on Floor 4 will reduce the acoustic power of the grid of the Floor 5.

2.2 Floors 1 through 4

The first four floors are, for the most part, composed of open metal grid floor and hence are not isolated from one another. Figure 3 shows a diagram of this second part of the station model for the Floors 1 through 4. The dots on Figure 3 represent noise sources of the model and shows only one of five alternator groups. This group is repeated five times to form five different groups as shown in Figure 4.

The height of each floor is 15m. The noise levels for this staion without any acoustic treatment were measured in January 97 and the average levels for each floor are:

Floor 1: 101.4 dB(A)

Floor 2: 102.4 dB(A)

Floor 3: 100.1 dB(A)

Floor 4: 97.20 dB(A)

3. ACOUSTIC MODEL DEVELOPMENT

The objective of this section is to present the modelling and time calculation reduction techniques.

3.1 Noise source models

The source representation is very important while modelling a room's acoustics. Sometimes, in order to estimate the local effect of an acoustic treatment with precision, the overall dimensions of the source has to be included in the room model. The majority of the acoustic modelling method such as ray tracing (the software RAYCAT) uses only a single point source representation. To consider the overall dimensions of the source, a technique based on the source's geometric representation with spaced out surfaces is suggested. For example, the spherical valves, one of most important station noise sources, are represented as shown on Figure 5. The overall dimensions of this source are important (valve diameter of 20 m) and it cannot be represented with a single point source.

One or several single point sources, inside a spaced surface network, launch rays that are distributed in a uniform way at the source's surface. The inner surface of the non-single point source is absolutely reflective so that the ray amplitude is not reduced. To be safe, the reflection number considered in the ray tracing program can be increased to a certain number, such that after those number of reflections, the ray leaves the inside of the source. This method allows a greater representation of a source's overall dimensions and the acoustic energy distribution is better represented.

The way to validate this technique is not direct. The model validation stage allows the validation of the extended source representation. The acoustic power of the extended source has to be measured and a reference source should be used to determine the absorption coefficient of the room (see Section 4.1). The reflection number and the space left between the surfaces can then be adjusted to fit the noise levels generated by the model with experimental measurements. When the number of non-single point noise sources is large, the validation process of this representation technique is not easy and sometimes impossible. In this case, the representation can be done without validation and the adjustment of the representation parameter should be done following the experience of the model designer. We suggest increasing by 10 the number of reflections and using a spacing that opens 30% of the source surface.

This way of representing sources is not always necessary. In our case, only two types of sources are represented by spaced surfaces. The other sources are represented by single point sources. The source size compared to the room volume is the most important criterion in order to use the single point source hypothesis. If the source volume is less than 1% of

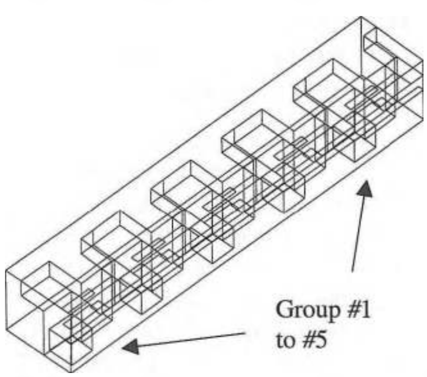

Figure 4 Global station diagram for first four floors

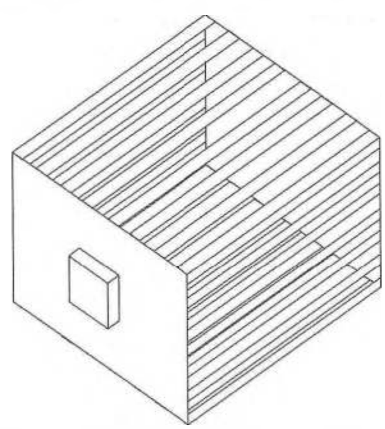

Figure 5 Example of a non-single point noise source

the room's volume, a single point representation can be used. But, if the acoustic field near the source is an important information for the designer of the model, the suggested criterion (1%) is not suitable.

3.2 Hypothesis to reduce the calculation time

When the room's geometry is complicated, the calculation time quickly becomes a major constraint. Reducing time hypotheses in the model becomes necessary. The objective of the next section is to present methods allowing time calculation reduction.

In the case of the ray tracing technique, the calculation time is linked to three parameters:

1. The size of reception cells in comparison to room dimensions
2. The number of reflections used by each ray and the number of rays
3. The room complexity (or the number of surfaces)

3.2.1 Size of reception cells

The reception cells' volume is the most important factor for calculation time. So, it is essential to choose an optimal size for receivers. The larger the cells are, the shorter the calculation time is. On the other hand, with large cells, local noise variations are not well represented. For an industrial case, the main objective is to determine the global acoustic noise reduction of treatments. To evaluate these reductions, all that is necessary are some large receivers allowing a global evaluation in a relatively large space of the room. For the case of the hydroelectric power station, the cell size has been adjusted so that cells take up the biggest space possible between each station objects (2 m). It is important that model objects (or surfaces) do not clutter the cells used to calculate the noise reduction. The cell size must be reduced to enable the calculation of the noise level in a confined space.

3.2.2 Number of rays and reflections

In a way to be sure that a sufficient number of rays, randomly launched, will be intercepted by reception cells, the number of rays for each sources has to be adjusted according to the room's free space and the cell size. A simple rule is proposed by RAYSCAT [4]:

$$NBR_{ray} = \frac{10 \cdot V_{room}}{V_{cell}}$$

where V_{room} is the free volume of the room and V_{cell} is the cell volume.

The total number of rays has to be distributed according to each sources acoustic power. For instance, with three sources of 90 dB, 90 dB and 93 dB and 20000 rays to launch, the ray distribution is given in Table 1.

Table #1 Ray distribution example according to the source power

Source	Global power (dB)	Number of rays
#1	90	5000
#2	90	5000
#3	93	10000

The number of reflections to take into account for each ray is adjusted according to many factors (room wall acoustic absorption, number of obstacles or model plans and global size of the room). To choose the number of reflections, the ray's residual level after *n* reflections can be used. But this residual level has to be 10 dB below the average level, calculated at reception cells. This way, the contribution of lost rays will be insignificant. The residual level is a standard output information of RAYSCAT. Generally, 30 reflections are correct (add 10 reflections for each non-single point source represented by spaced plans).

3.2.3 Room complexity

The room complexity increases the calculation time. The more surfaces in the room, the longer the calculation time. The model designer has to take into account the room's general geometry but he has to refrain from using a too complicated representation. For instance, the spherical form representation has to be defined with separated flat surfaces. This approach rapidly increases the number of surfaces and, consequently, the calculation time. In general, the use of a low resolution for spherical forms is enough. For example, the Floor 5 of the hydroelectric power station has a concave shaped ceiling. This ceiling form is well represented by only four (4) flat surfaces (see Figure 6).

Another way to diminish the number of surfaces of the model is to use the room's symmetry. In the case of the station, five identical posts are distributed lengthways (see Figure 1). The model of Figure 6 is for Post 3, at the station's middle. The two other posts, on both sides of Post 3 are simulated with reflective (or virtual) walls.

The hypothesis is valid only if there is symmetry for both the geometry and the noise sources. Furthermore, the model of Figure 6 considers an infinity of image posts on each sides of Post 3. Since there are only five real posts, it is important that the contribution of the image post, higher than second order, be negligible (lower than 10 dB). This constraint has been verified with the help of reference source at the time of the global model calibration (see Section 4). This last technique to reduce the calculation time is very delicate. It can be used only if there is no doubt about its validity. Furthermore, it must be pointed out that the model results are good only for the middle section of the hydroelectric power station.

4 SOURCE CHARACTERISATION

The acoustic source's characteristics have to be determined precisely to obtain good predictions of the sound field inside the room. Generally, the techniques used to identify noise sources are based on a certain acoustic industrial experience. The purpose of this section is to present a structured approach that allows the evaluation of the noise source and its acoustic power in an effective way. This approach for the hydroelectric power station is described below.

4.1 Model validation

The validation stage allows the appropriate evaluation of many parameters that give an accurate acoustic model. The general idea with this verification is to use a source with an already known acoustic power and a series of measurements of the whole room's noise level. With the measurement of the noise level generated by the reference source, it is possible to calibrate the model, that is to determine the absorption coefficients of the room wall material and to adjust the clutter of the room [4].

The noise level measurement at the time of calibration can be done with the normal noise inside the room but only if levels generated by the reference source can be distinguished from the ones generated by room sources. To make this distinction easier, the use of a multi-harmonic generator is desirable. Ideally, the harmonic frequencies should be generated at each central frequency of octave band, but these frequencies have to be different from the component of room noise sources. The reference source has to be powerful enough to be able to generate emerging rays of at least 10 dB higher in comparison with the normal noise inside the room at each octave band frequency. The acoustic power of the reference source has to be determined with precision. To have great precision, the acoustic power evaluation of this source can be done outside, in free field conditions.

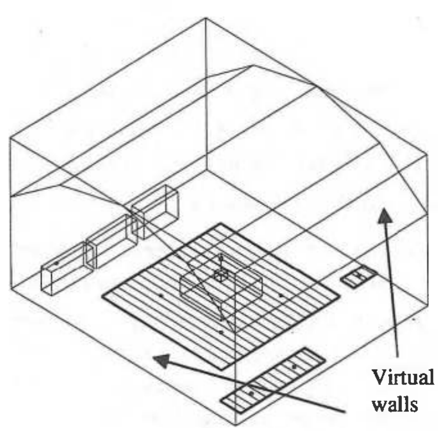

Figure 6 Model of the Floor 5

For the station's case, the model used to validate the absorption parameters and the room clutter is different from the one used to evaluate potential treatments. The symmetry of the station allows carrying out an important simplification since only one alternator group is taking into account (see Section 3.2). At the time of the validation, it is essential to consider the entire room, because it has only one source and the symmetry hypothesis is not appropriate. To determine absorption coefficients and clutter parameters, two preliminary models of Floors 1 through 4 and Floor 5 have been done. These two preliminary models are shown on Figures 1 and 4. For these two models, the station is entirely represented and the geometry is roughly defined. For instance, a cube represents the spherical forms and noise levels are calculated on relatively large spaces, with the intention of reducing the calculation time. At the calibration phase, only the reference source is included in the model. A priori, the standard parameters are used for the absorption parameters of the station wall. An estimation of the clutter can be done with this formula proposed by RAYSCAT [4]:

$$Q = \frac{1}{4 * V_{room}} \bullet \sum_{1}^{10} S_{obs.}$$

where, Q is the scattering coefficients, V_{room} is the room volume and $S_{obs.}$ is the obstacle surface.

Simulations with these estimations of the acoustic parameters and comparison with noise levels generated by the reference source allow the adjustment of absorption coefficients and room clutter. Most of the time the adjustments are minor (±5%). For an adjustment higher than 5%, the geometric representation must be re-evaluated.

4.2 Source identification

Almost 15 noise sources were identified on the 5 station floors during the first site visit. This first identification had been done with a simple sound level meter and hearing perceptions inside the station. At this stage, the acoustic power of the potential noise source is measured. This evaluation can be done from pressure measures if appropriate methods are used [5 and 6] or, ideally, with a conventional intensity measurement technique [7]. Often, it is difficult to take an acoustic power measure in an industrial background when sources are large or when other noisy sources are close. The techniques and the power measurement hypotheses have to be well known to obtain a precise value. After the source power measurement, the negligible sources (global power 15 dB below the average power of other sources) can be eliminated from the model. Table 2 describes station sources and their acoustic power.

Table #2 Station sources and their acoustic power

Sources	Power dB(A)
Floor #1 to #4	
Vacuum corridor	97.6
Eductors	101.5
Well door	104.1
Ventilation pipe	110.9
Spherical valve	100.6
Shutters	104.2
Stator passage	88.5
Ventilator floor #3	93
Stator door	91.5
Floor #5	
Ventilation grid	104.0
Removable floor	100.2
Control panel ventilator	96.6
Entry stairs	95.9

During the first visit, a very precise identification of all sources is not likely. To be sure that no sources are forgotten, verification with the acoustic model has to be done.

4.3 Validation of sources and their power

When the model is calibrated and principal sources are identified and quantified, some simulations can be done with all the room-identified sources. The measured noise levels (Stage 2 of the methodology) are compared with the noise level calculated with the calibrated model. For the case of the station, Table 3 shows a comparison of the global average noise level for all floors.

Table #3 Comparison of the global average noise level

Floor	Model dB(A)	Measure dB(A)	Delta
#1	101	101.4	0.4
#2	102	102.4	0.4
#3	100	100.1	0.1
#4	97	97.2	0.2
#5	92	92.4	0.4

All differences are less than 0.4 dB. So, the model is well calibrated and sources are correctly identified. At this stage, the model can be used to evaluate various acoustic treatments.

When the acoustic model validation with the help of a reference source is completed (Stage 1 of the methodology), only 2 or 3 iterations are necessary to obtain good results. At this stage, the differences are associated, most of the time, with forgotten sources. In this case, the Stage 3 of the methodology should be done again.

5 ACOUSTIC TREATMENT EVALUATION

5.1 General methodology

To obtain an optimum treatment for a particular noise reduction project, it is desirable to evaluate a maximum of potential treatments. On the other hand, the calculation time associated with each treatment evaluation becomes an important constraint. A practical way to bypass this problem is the use of an evaluation method based on transfer functions between the model sources and a receiver group chosen by the user. For a particular source, the transfer functions are simply obtained by the difference between the source power and the noise levels obtained at the receiver group.

When the calibration of the acoustic model is appropriate, a calculus for a particular geometric and acoustic configuration of the room (wall absorption coefficients and the clutter of the room) allows the evaluation of the transfer functions between each sources and different receiver groups. The position choice of the receiver group is done according to project objectives. For instance, for the case of the central area, the receiver groups have been chosen so as to obtain averages for each five floors.

The frequencies dependent transfer functions can be used with a spreadsheet to re-evaluate the global average noise levels for each receiver group with the following formula:

$$Niv_{global_i} = 10 * \log_{10}\left(\sum_{S=1}^{n}\sum_{f=1}^{m} 10^{\frac{P_{sf} - H_{sf_i}}{10}}\right)$$

where, H_{sf} represents the transfer function between the source *s* at the frequency *f* for a particular receiver group *i*, and where P_{sf} (dB) represents the measured acoustic power of the source *s* at the frequency *f*.

The above formula, with many source treatment combinations, can be used to check the redefinition of P_{sf} (source acoustic powers). This allows the rapid estimation of the complete set of source treatments. On the other hand, if the treatment consists of geometric or room absorption property modifications, the transfer functions (H_{sf}) have to be re-evaluated with the acoustic model.

Table 4 Acoustic treatment example for the first station floor

	Source power	Pressure level	Transfer function	Source treatment	Room treatment	Noise level (with treatments)
Sources	dB(A)	dB(A)	dB	dB	dB	dB(A)
Vacuum corridor	97.6	88.1	9.5	20	1.9	66.2
Eductors	101.5	93.3	8.2	20	1.9	71.4
Well door	104.1	89.2	14.9	20	3.4	65.8
Ventilation pipe	110.9	100.1	10.8	20	2.6	77.5
Spherical valve	100.6	89.2	11.4	0	2.3	86.9
Shutters	104.2	85.5	18.7	15	2.2	68.3
Stator passage	88.5	71	17.5	10	2.6	58.4
Ventilator floor #3	93	74.3	18.7	0	2	72.3
Stator door	91.5	74.2	17.3	0	2.6	71.6
					Total	**88.0**

5.2 Results for the station

Table 4 shows an analysis example carried out on a standard spreadsheet (Excel) for the first floor only. The measured global acoustic power for each source (P_S) is on Row 2. Column 3 shows the associated noise level of each source for initial conditions (without any treatments). The noise levels without treatment are calculated from the transfer functions shown on Column 4 (H_{Si}). Column 5 gives the estimated reduction of each source treatments. For instance, in the analysed case of Table 4, a treatment of 20 dB is considered to reduce the noise of the aspirator corridor. Column 6 shows transfer function reductions from a room acoustic treatment. For instance, the addition of absorbent material on some station walls reduces all the room transfer functions. In general, these reductions are different for each source because the room treatment effect varies according to the position and characteristics of the source. The evaluation of the transfer function reductions (Column 6) has to be done from the acoustic model. However, when evaluated, these reductions will be independent of the future source treatments. Column 7 gives the noise level generated by each source considering sources and room treatments. Finally, the global level of the first floor is obtained with the contribution summation of all sources. The same procedure has been used for each floor.

Once implemented, the source treatments have to be checked before the evaluation of the model prediction's quality. The source treatments are tested with acoustic intensity or acoustic pressure measurements depending on which acoustic power measurement method is used. When all treatments were implanted, an average noise level measurement was taken for each station floor. Table 5 shows measurement results. The model is accurate because differences between predicted and measured noise levels are small for the entire floor.

6 CONCLUSION

This paper has presented various original techniques, which can be used to develop an acoustic model. The technique used for non-single point sources allows representing the acoustic energy distribution and the overall dimensions of a large source. Furthermore, many aspects to reduce calculation time have been displayed. The appropriate choice of calculation parameters (number of launched rays, size of reception cells and number of considered reflections) and a simplification using the room symmetry allows the reduction of the calculation time. The source identification technique is based on a structured iterative method. With this process, the noise source identification is efficient and very accurate. Since it has an important impact on all subsequent results, the noise source identification accuracy is crucial for a good acoustic model. A method based on transfer functions between the sources and different receiver groups has also

Table 5. Predicted and measured average noise levels for each station floor

Floor	Without treatment	With treatment			
	Measures dB(A)	Measures dB(A)	Prediction dB(A)	Difference dB	Reduction dB
#1	101,4	87.5	88.0	+0.5	13.9
#2	102.4	87.5	87.9	+0.4	14.9
#3	100.1	88.0	87.7	-0.3	12.1
#4	97.2	88.0	87.5	-0.5	9.2
#5	92.4	83.0	84.1	+1.1	9.4

been presented in this paper. This technique has demonstrated a greater efficiency for the rapid evaluation of the potential acoustic treatments.

All techniques presented in this paper have been evaluated on the particular case of the hydroelectric power station of Alcan. These techniques have allowed the evaluation, with success and efficiency, the optimum treatment to obtain the noise reduction objectives of the company.

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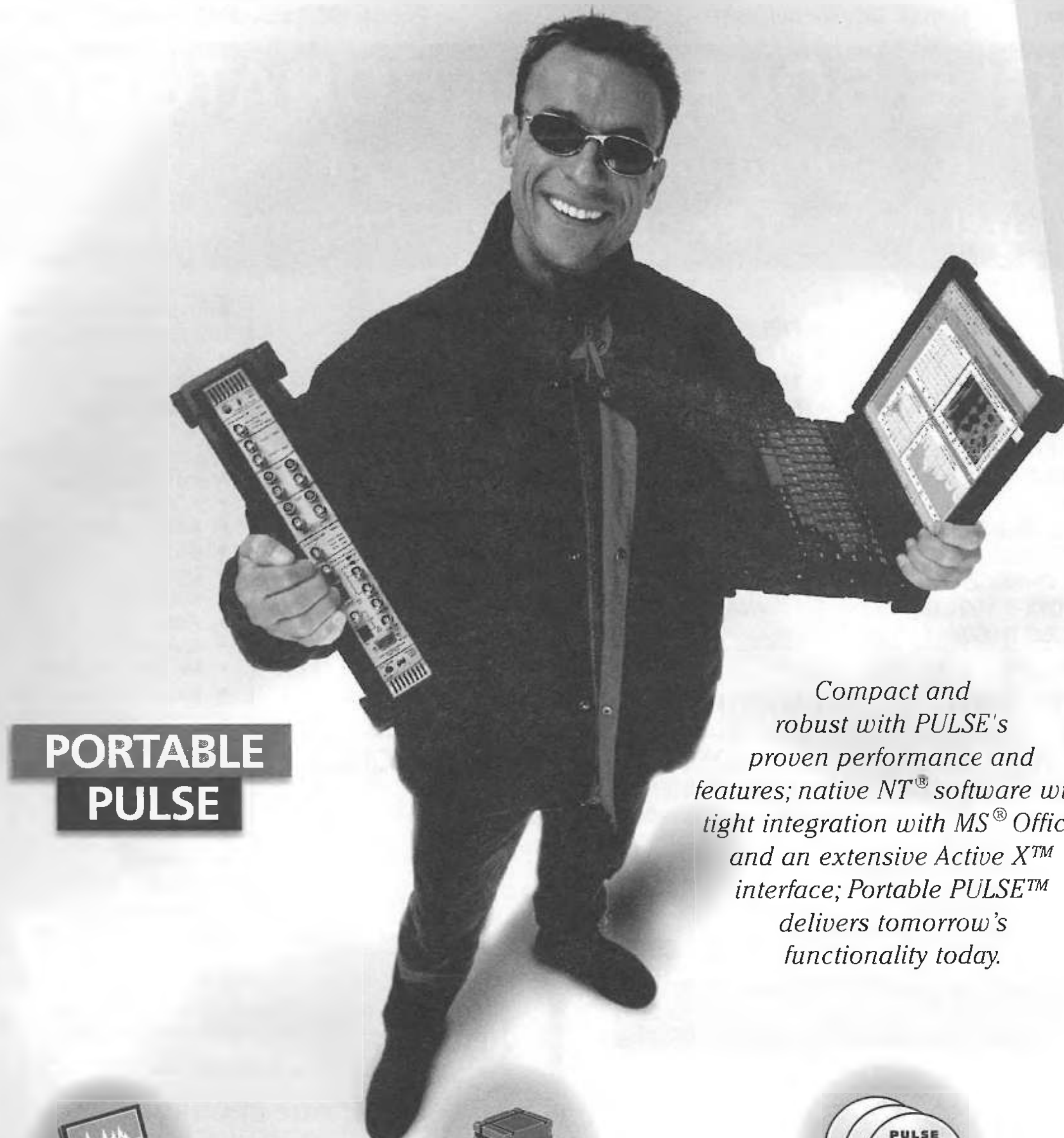

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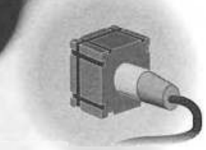

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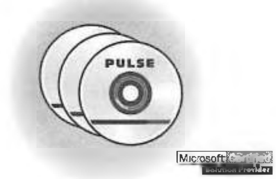

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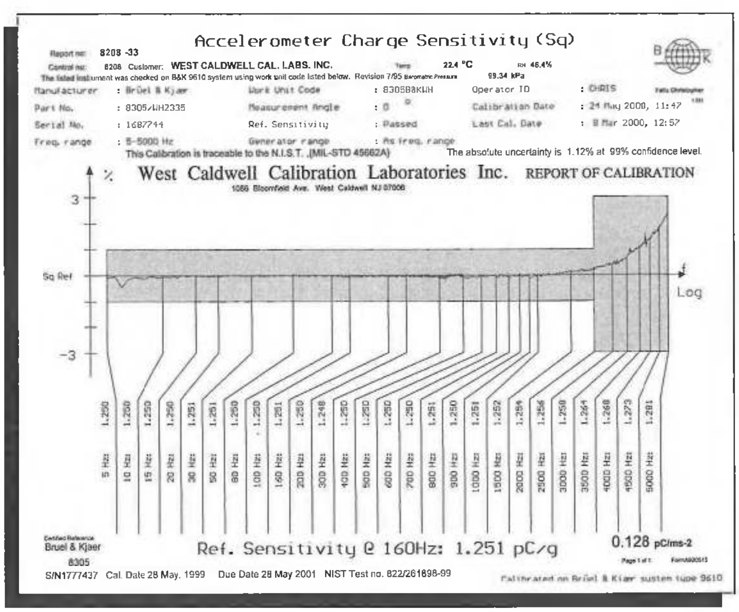

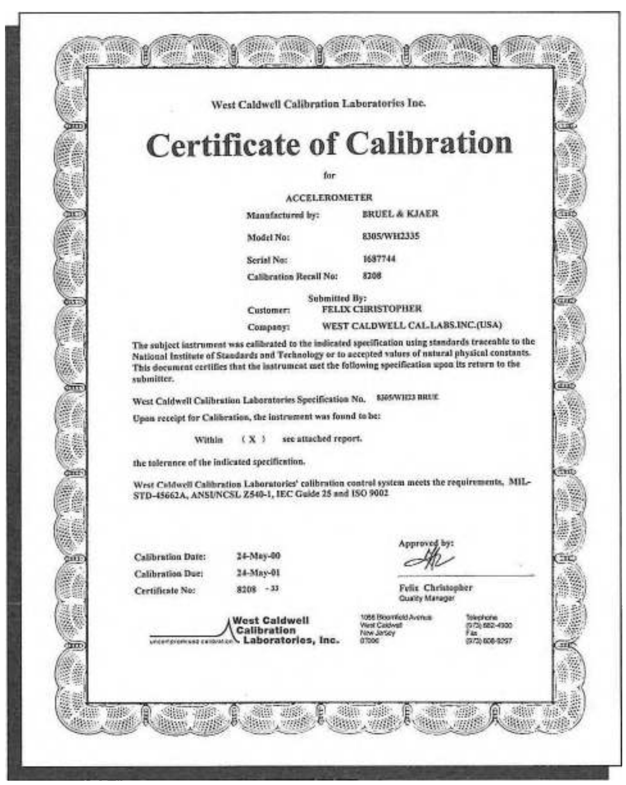

West Caldwell Calibration Laboratories Inc.

Certificate of Calibration

for

ACCELEROMETER

Manufactured by: BRUEL & KJAER
Model No: 8305/WH2335
Serial No: 1687744
Calibration Recall No: 8208

Submitted By:
Customer: FELIX CHRISTOPHER
Company: WEST CALDWELL CAL.LABS.INC.(USA)

The subject instrument was calibrated to the indicated specification using standards traceable to the National Institute of Standards and Technology or to accepted values of natural physical constants. This document certifies that the instrument met the following specification upon its return to the submitter.

West Caldwell Calibration Laboratories Specification No. 8305/WH23 BRUE

Upon receipt for Calibration, the instrument was found to be:

Within (X) see attached report.

the tolerance of the indicated specification.

West Caldwell Calibration Laboratories' calibration control system meets the requirements, MIL-STD-45662A, ANSI/NCSL Z540-1, IEC Guide 25 and ISO 9002

Calibration Date: 24-May-00
Calibration Due: 24-May-01
Certificate No: 8208 -33

Approved by:
Felix Christopher
Quality Manager

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