Proceedings of the Institute of Acoustics

ESSENTIAL FACTORS IN THE PREDICTION OF SOUND DISTRIBUTION IN FACTORY SPACES USING THE RAY TRACING MODEL OF ONDET AND BARBRY

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1. INTRODUCTION

Computer modelling for the prediction of sound distribution in factory spaces has been extensively researched during the last ten years. The Ondet and Barbry program, Raycub, has emerged as the most accurate computer model, with many authors[1,2] independently using their own data to validate the model.

This paper describes the validation of an extended version of Raycub, which was used to examine which parameters have the most influence on accuracy. The parameters considered included source directivity, the precision of the description of the factory geometry, the zoning of factory fittings and the size of the cell mesh used.

2. RAYCUB

Raycub is a steady state model which uses ray tracing as its basis, modelling sound as separate independent rays emanating from a point source omni-directionally. The rays reflect specularly a specified number of times from the surfaces defined within the model. The energy of a ray diminishes through surface absorption, absorption by the fittings, distance travelled and air absorption.

Geometry

The geometry of the space is defined using three dimensional plane equations, thus allowing considerable flexibility in the accuracy of the representation. Constraints are placed on the plane equations to totally define the exact surfaces of the space. For example, multi-section roofs, split construction walls or intruding walls are defined in this way.

Cell Mesh

The space is divided into a mesh of cubic cells, each of which has an associated acoustic energy level. The energy of a cell is the sum of the acoustic energy of the rays which pass through it. The number of rays is directly related to the cell size.

Sources

A source is defined as a point in three dimensional space using coordinate geometry, with an associated sound power level. In the original model each source is assumed to be omni-directional, with all rays having an equal amount of energy. The number of rays, R_m, attributed to source m is given by

$$R_m = \frac{2^{\left\{\frac{L_{w_m}-L_{w_{min}}}{3}\right\}}}{\sum_{s=1}^{n} 2^{\left\{\frac{L_{w_s}-L_{w_{min}}}{3}\right\}}} * R_f, \text{ where } R_f = \frac{10 * V_f}{V_c}$$

where L_{wm} is the sound power level of source m, L_{wmin} is the lowest source sound power level, n is the total number of sources, R_f is the number of rays necessary to model the factory, V_f is the volume of the factory (m^3) and V_c is the volume of each cell (m^3).

Fittings

Raycub takes account of the fittings of a factory which may include equipment, machines, pipes, stock or barriers. The space is divided by planes into zones, each zone being a fitted volume that contains a distinct group of fittings.

Each zone has two associated parameters : the scattering frequency and the average reflection coefficient of its fittings. The reciprocal of the scattering frequency gives the mean-free path length between fittings. After travelling this distance a ray is randomly reflected and attenuated by the average absorption for the zone. The scattering frequency, q_z, of zone z is defined by

$$q_z = \sum_{f=1}^{n} \frac{S_f}{4 * V_z}$$

where n is the number of fittings in z, S_f is the surface area of a fitting and V_z is the zonal volume.

Air Absorption

Air absorption is incorporated on the basis of attenuation per metre and is described by

$$A = e^{-h \cdot d}$$

where A is the air absorption factor, h is the air attenuation (dB/m) and d is the distance the ray has travelled (m).

3. MODIFICATIONS TO RAYCUB

The extensions to the Raycub model involved rewriting and restructuring the program, so enabling the inclusion of source directivity, a zone generating system and prediction analysis.

The model method used to previously validate Raycub[1] involved describing the exact geometry, assuming omni-directional sources, zoning the fittings in the space as equal volumes using the minimal number of zonal planes and taking a cell size of $1m^3$.

Cell Size

Although Raycub has been shown to be accurate in predicting factory noise, it has a prohibitively long run-time. This is mainly due to the fact that the number of rays from each source is directly related to the cell size.

The original model representation used a cell volume of $1m^3$. It was decided to investigate the effect on accuracy of changing the cell dimension from 1 to 2 metres, thus giving a cell volume of $8m^3$. This increase in cell volume gives a eight fold decrease in the number of rays required to model the space, and a consequent reduction in run-time. The receiver height has to be located centrally, so this is usually the determining factor for the cell side dimension.

Geometry and Zoning

It was also decided to investigate the effects on predictions of using complex geometric representations of a space, and different zonal divisions to describe more precisely the layout of the fittings.

Source Directivity

The original version of Raycub treats each source as omni-directional, radiating rays randomly in all directions. The extended Raycub model takes into account source directivity by treating directivity factors as probabilities. When a random emanation direction is chosen for a ray the directivity factor, Q, for that direction is used as the probability of that event happening. If the directivity factor for a ray is greater than one then the ray definitely travels in the randomly chosen direction, with Q-1 rays following in the same direction.

When measuring the sound power of a machine in situ as data for input to the model, the directivity is interpolated from the sound pressure level measurements taken around the machine.

4. VALIDATION

Three fitted factories and one empty space were chosen to demonstrate the effects of the modifications on the accuracy and run-time of the model. Validation of the model took the form of comparing the predicted noise levels with the noise survey measurements.

When accurately describing a factory the problematic measurement is that of the surface area of the fittings, which is required to calculate the scattering frequency. This area is impossible to measure in operating factories, so an approximation is made by taking the surface area of a box the dimensions of which are the outer dimensions of the fitting.

When modelling zones it was thought that an approach which divided a space into zones representing all of the fitted areas should be used, as opposed to a minimal number of equal zone volumes used in previous validations[1,2].

The Spaces

Case 1. This was an empty space of dimensions 54m by 16m with a pitched roof, rising from 10.6m to 14.6m. The walls were all of a brick construction; the ceiling was two-thirds panelled and one-third glazed; concrete covered the floor; and situated at one end was a small office. A single speaker was used as a sound source.

Case 2. This was a duct shaped fitted factory with a length of 108m, a width of 24m and a height of 10.9m. The wall construction was a combination of brick, plastic panels and glass, the ceiling being plastic panels and perforated fibre board with a mineral wool infill. The fittings fell into four groups: half the floor area was used as a storage area for small steel boxes, a quarter for metal-working machines, the remainder of the floor space for metal workbenches, and the roof contained two rail cranes and associated fittings.

The space was modelled twice due to the complex layout of the fittings: first, with a speaker as the only noise source (Case 2a) and secondly with thirteen metal working machines operating (Case 2b).

Case 3. The geometric dimensions of the third space were 75m by 40.8m with a rectangularly corrugated roof from 12.2m to 13m high. The building had a modern steel frame construction with walls of aluminium, concrete and brick; the floor was of concrete; and the light-weight aluminium ceiling contained a rail crane across its full width. Offices were situated in the corner forming three internal surfaces. The noise sources were seventeen large metal working machines which were arranged in three lines.

Case 4. A brewery packaging plant formed the fourth space with dimensions of 80m by 53m and a multi-pitched roof rising from 7.3m to 10m. The brewery had a modern construction with painted brick walls, a concrete floor, and a ceiling of plastic on fibreboard backed to aluminium. The fittings were all metal and evenly distributed around the floor area. An office was situated across the full width of the factory at one end. There were three types of noise source: filling machines, air jets and conveyor belts.

Modelling Description

The fitted factories had their fittings modelled at three levels of detail. The lowest level consisted of modelling the fittings assuming an isotropic distribution. The second level modelled the fittings on the floor by defining a zonal plane at the average fitting height. The third representation modelled the fittings as accurately as possible, using between two and thirty-two zones.

All factories had their shape described both simply and with all the complex geometric details. The simple model used a parallelapiped representation with an average absorption coefficient for each surface. The complex geometrical description included multi-surface walls, multi-section roofs, offices and intruding walls.

For Case 1, the complex geometry consisted of a pitched roof and two internal walls, with a fitted roof zone representing the roof structure. As this factory contained no machines the simple representation was modelled as an empty space.

The complex geometry of Case 2 included the longer walls being split into three distinct areas: brick, plastic and glass. The space was split into two groups of fitted zones, one near the floor and one in the roof. The floor zones represented the machines sectioned off from the stock and the workbenches, using two fitting heights. The roof zone consisted of the crane and the roof structure.

The complex geometry of Case 3 involved describing the corner office and metal screened areas; and zoning the space into floor and roof zones, representing the machines and the crane respectively.

For Case 4, the complex geometry consisted of a full width office and a multi-pitched roof, the long walls being divided into the painted brick and the cladded areas. The fittings were distributed evenly over the floor, so only a single zonal plane at their average height was required, dividing the space into two zones.

Directivity Validation

A test was carried out to examine the effect on predictions in both fitted and unfitted spaces of using directivity data interpolated from the shop floor measurements, rather than complete directivity information.

The directivity of the speaker used in Cases 1 and 2a was measured in an anechoic chamber to produce a directivity graph. Noise levels in Cases 1 and 2a were predicted using the most accurate version of the model with both the interpolated directivity data and the anechoic chamber directivity measurements.

Table 1 shows the averaged absolute dB(lin) errors calculated logarithmically for both cases.

Table 1 Comparison of Averaged Errors for Factory and Anechoic Directivities.

	Factory Directivity	Anechoic Directivity
Case 1	1.0	0.8
Case 2a	1.3	1.2

It can seen that using directivity data measured in an anechoic chamber gives only a marginal increase in accuracy compared with using interpolated directivity information, in both a fitted and an unfitted space.

5. RESULTS

The model has been used to predict noise levels in linear dB, and the predicted levels compared with the measured levels. The average absolute errors in dB between predicted and measured levels have been calculated logarithmically.

Complex Geometry and Zoning Results

In testing the effects of complex representation of a space, all sources were assumed to be omni-directional and a 1m^3 cell size was used.

Table 2 shows the absolute errors for predictions in the empty space, Case 1, and Table 3 shows the errors for fitted factories, Cases 2 to 4. "Floor zoning" refers to the second modelling level and "Full zoning" to the third level.

Table 2 Averaged Errors for the Empty Space (Case 1)

	Simple Geometry Empty Zone	Complex Geometry Empty Zone	Simple Geometry Roof Zone	Complex Geometry Roof Zone
Case 1	2.3	1.6	1.7	1.6

Table 3 Averaged Errors for the Fitted Factories (Cases 2 to 4)

Case	Simple Geo. Isotropic Zoning	Complex Geo. Isotropic Zoning	Simple Geo. Floor Zoning	Complex Geo. Floor Zoning	Simple Geo. Full Zoning	Complex Geo. Full Zoning
2a	1.9	2.3	1.8	1.9	1.8	1.5
2b	1.4	2.0	1.4	1.3	1.1	1.1
3	3.1	2.7	1.5	1.3	1.0	0.9
4	3.3	2.9	1.3	1.1	1.3*	1.1*

*Full zoning consisted of only the floor zone

Source Directivity and Cell Mesh

The highest level of model representation included the exact geometric details from the complex model and full zoning, plus directivity information taken from the shop floor source sound level measurements.

The effect on accuracy of using a larger cell size was investigated, using the same high level of representation. Table 3 shows the average errors for Cases 1 to 4, using a cubic cell side of 1m and 2m.

Table 4 Errors with Directivity and Varying Cell Size

	Complex Geometry $1m^3$ Cells Factory Directivity Full Zoning	Complex Geometry $8m^3$ Cells Factory Directivity Full Zoning
Case 1	0.8	1.0
Case 2a	1.3	1.3
Case 2b	1.2	1.2
Case 3	---	0.9*
Case 4	1.0	1.6

*Directivity data was not available for this space so omni-directional sources were assumed.

6. DISCUSSION

Table 2 shows that a complex geometrical description of an empty space gives a significant improvement in accuracy when only one zone is used. However, when the space is divided into two zones there is very little difference between the two geometrical representations. This indicates that the fittings contribute more than the geometry of the space to the prediction accuracy.

Table 3 shows that, overall, for fitted factories the accuracy of the model is marginally improved by using a complex description of the space. However, as in the case of the empty space, it can be seen that it is the precision of the zoning of the space which has the greater effect on accuracy. The three levels of zoning detail gave progressively improved predictions for both the simple and the complex geometry.

Comparing Tables 3 and 4 shows that the inclusion of directivity leads to an overall marginal increase in accuracy for fitted factories. However, this small increase is probably due to the fact that the machines were not highly directional. In the case of the empty space the improvement with directivity was significantly greater.

Table 4 shows that doubling the cell dimension slightly reduces the accuracy, but by an acceptable amount for the significant run-time improvement.

7. CONCLUSION

The original Raycub model produces accurate predictions for both fitted and unfitted factories. The extended Raycub program describes a factory space and the noise sources more precisely and provides consistently better results.

The most important factor which affects the accuracy of predictions is the choice of zoning, the smallest errors occurring when the zonal description of fittings is a precise as possible. In all cases a complex geometrical representation further increases the accuracy of predictions.

The inclusion of directivity leads to a further increase in the precision of the model. Using a larger cell size results in greatly reduced run-time while giving only a minimal reduction in accuracy.

8. REFERENCES

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