Acoustic diagnostic analysis using Boundary Elements

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Abstract

The prediction of sound levels in vehicles and the environment is now a common practice in engineering. This has been made possible by the development of powerful tools based on boundary element techniques. These "first generation" systems provided the user for the first time easy to use tools to predict sound levels. This paper will describe a "second generation" acoustic system based on boundary elements which not only enhances the accuracy of the modelling, but also provides powerful diagnostic facilities to enable the user to identify the main contributions to the sound intensity at a any point of interest. Applications are presented.

1.0 Introduction

The products of many industries can benefit from improved acoustic design. The same technology which has been successfully applied to simulate the performance of structures can be applied to provide the acoustic engineer with the information necessary to ensure the design satisfies performance specifications and/or regulations imposed by governments and standard bodies. The use of computer simulation offers major advantages over trial and error prototyping in the quest for improved products (e.g., quieter products).

Acoustic problems can in general be classified into three categories. Interior problems where the domain is finite (e.g., computing the sound field in a vehicle or building), exterior problems where the domain is infinite (e.g., radiation from a machine or vehicle) and coupled interior/exterior problems where the problem consists of a combination of the first two.

While the finite element method has been used with some limited success in the first category, the major advantages of the boundary element method in the second two categories has enabled it to become the method of choice for most engineers wishing to simulate acoustic problems.

In first generation acoustic analysis systems the software simply predicted the acoustic field due to sound sources or vibrating bodies. The interpretation of the results and following action was the responsibility of the user. In a second generation system the user is not only provided information on the acoustic field, but is also provided with information on the contributions to the sound at a particular point (e.g., the contributions made by sound sources and individual parts of vibrating bodies radiating).

For example, the sound perceived by the driver of a vehicle will be contributed to by many parts of the vibrating vehicle. In a second generation system, not only will the sound level be predicted, but also the proportion of the sound originating from the door panel, the front windscreen and the roof panel etc. This information is invaluable to the designer as the information to correct any problem is immediately available (e.g., where, how and how much).

The balance of the paper will focus on how the contributions can be computed and will provide a number of applications.

2.0 Theoretical Foundations

The basic equation for acoustic wave propagation through an elastic medium is the linear wave equation

$$\nabla^2 u = \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} + b \qquad (1)$$

Where u(x,t) is the velocity potential, c is the speed of sound, b(x,t) is the sound source and x and t are the position and time.

This equation can be expressed as time harmonic and transferred to the Helmholtz equation.

$$\nabla^2 u + k^2 u = b \qquad (2)$$

Where $k = \omega / c$ is the wave number and ω is the angular frequency.

The Helmholtz equation (2) can be expressed in a boundary element formulation as shown in [1]

$$HP = GV + B \qquad (3)$$

Where P and V are the pressure and velocity and B is a body source vector.

The matrix equation H and G are frequency dependent and there is one row and column for each boundary element node in the model.

3.0 Modeling Aspects

Acoustic models can be developed using most general purpose modelers through the link to CAD provided, or using BEASY's own modelling tools. Boundary mesh generation is very simple compared with volume mesh generation and can be completed automatically with little user interaction.

The general acoustic simulation features provided by BEASY are described in [1]. A particular feature of the software is its ability to accurately represent acoustic structures using zones and the impedance of vibrating structural surfaces. Fig 1.

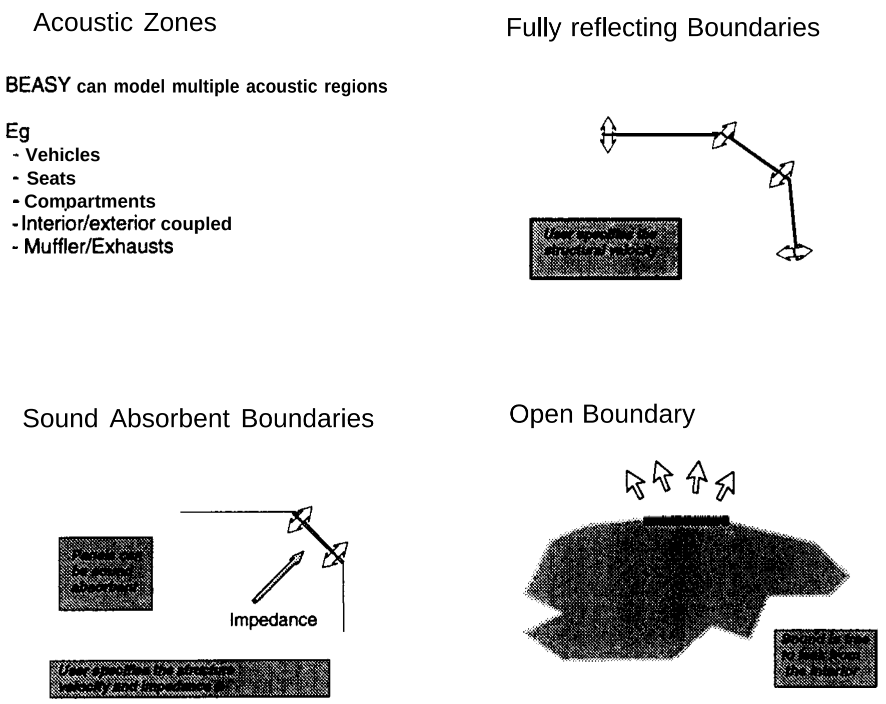


FIGURE 1. Modeling features of the system. Regions of different acoustic properties are possible as well as sound absorbing vibrating surfaces.

4.0 Diagnostic Analysis

Having computed the acoustic field, the acoustic variables are known at all the node points on the boundary and can be evaluated at any point inside the domain using the internal point equation.

$$Pressure = \sum_{1}^{Noofelements} gv - \sum_{1}^{Noofelements} hp \qquad (4)$$

Equation (4) provides the means to compute the pressure (and any other acoustic variable) inside the acoustic region. Where the right hand side is the solution on the boundary of the model. By computing the contribution of vibrating panels to a specific point in space, the identity of the parts of the structure which have a dominant role in producing the sound can be determined. The contribution to the pressure at an internal point can be evaluated by examining the two items separately.

The contribution from the velocity on the boundary is:-

$$Pressure^{Pressure} = - \sum_{1}^{Noofelements} hp \qquad (5)$$

The contribution from the pressure term is:-

$$Pressure^{Velocity} = \sum^{Noofelements} gv \tag{6}$$

The influence of a particular node element or group of elements can also be computed using the same equations. If we consider the boundary solution to be unity then the influences can also be computed.

$$Influence_i^{Velocity} = g_i \tag{7}$$

$$Influence_i^{Pressure} = hi \tag{8}$$

The influence gives quantitative information on the affect a particular part of the structure will have on for example the sound pressure or intensity at a particular point. Due to the phase angle the contribution from a particular part of the model can be positive or negative. Therefore an additional contribution can be computed in which only the terms which are in phase with the actual solution at the internal point are evaluated.

Combining all the above interpretation of the internal point equations with graphical displays provide the user with very powerful tools to interpret the results of an acoustic problem, diagnose the key elements in the design and determine design changes both quantitatively and qualitatively.

An example of a display of the acoustic contributions is shown in Fig 4. In the diagram the acoustic contributions can be displayed over individual elements or complete boundary panels.

This procedure can be evaluated at no significant computational costs.

5.0 True contribution or redistributed contribution

Whilst the above procedure is powerful and adds significantly to the value of the simulation, it has a major drawback in that it fails to distinguish between the sound originating on that particular section of the structure and the acoustic field which is radiated elsewhere and simply reflected from that part of the structure.

The method for determining the true contribution was first published by [2]. In this approach the boundary element equation (3) are used to separate the terms.

By ignoring the body term and rearranging (3), the pressure on the boundary can be expressed in terms of the boundary velocity.

$$P = H^{-1}GV \tag{9}$$

Thus by substituting (9) into (4) the pressure at an internal point can be expressed purely in terms of the boundary velocity.

$$Pressure = (g^t - h^t H^{-1} G)\ V \tag{10}$$

Where g^t and h^t are the vectors of the internal point influence functions for point i.

Equation (10) therefore allows us to compute both the true influence and total contribution of a part of the structure to the sound level at a particular point.

The contributions given by equation (10) is based on the assumption that the pressure at both the part of the structure under consideration and the internal point position is in phase. A more realistic contribution is obtained by taking into account any differences in phase

$$Pressure = \{(g^t - h^t H^{-1} G) V\} \times \cos(\phi_s - \phi_i) \tag{11}$$

Where ϕ_s=Phase angle of the pressure on the structure, ϕ_i=the phase angle of the pressure at the internal point. (Note if a structural panel has zero velocity its contribution will be zero. Whereas the previous contribution methods would produce a non zero contribution.)

The penalty for this increased precision in diagnosis is a higher computation cost, but it provides a much greater precision and a major benefit to the user.

6.0 BEASY Contributions List

Using the above approach a wide range of contribution terms can be computed which provide an insight into the behaviour of any acoustic problem and provides the information necessary to reduce sound levels.

The contributions list includes:

1. Type A

   Total contribution given by equation (4). Note this includes both pressure and velocity contributions

2. Type B

   Pressure contribution given by equation (5). i.e. The contribution from the pressure on the surface of the model.

3. Type C

   Velocity contribution given by equation (6). i.e. The contribution from the velocity on the surface of the model.

4. Type D

   Total contribution given by equation (10). i.e. The true or redistributed contribution. This is probably the most useful as it identifies the contribution originating at the part of the model under consideration.

5. Type E

   Influence coefficient for the pressure on the surface as given by equation (5). Multiplying the influence coefficient by the surface pressure will reveal the sound contribution.

6. Type F

   Influence coefficient for the velocity on the surface as given by equation (6). Multiplying the influence coefficient by the surface velocity will reveal the sound contribution

7. Type H&G

Total contribution as given by equation (11). In this case the contribution takes into account the difference in phase of the model surface velocity and the pressure at the internal point.

In all the above cases the contribution can be the value, percentage value or density the contribution.

7.0 Application

In order to demonstrate the effectiveness of the diagnostic methodology two example applications are presented.

7.1 Example1

In this application the first class of diagnostic tools is used to determine the sound leaking from the inside of a vessel. The model as shown in Fig. 2 consists of a cylindrical vessel with a door opening, through which sound from a sound source situated some distance from the vessel can propagate. The vessel is the only object described with elements as it is assumed that the vessel is surrounded by an infinite medium.

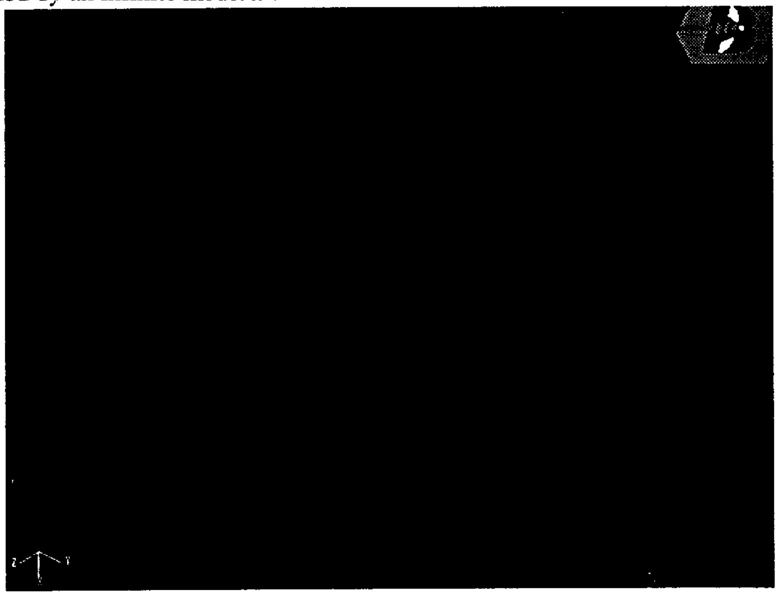


FIGURE 2. Boundary element model of the vessel. Note the fluid region is represented as an infinite boundary element zone, hence the only elements are placed on the vessel itself

The sound source is represented by a point source. The objective of the study is to determine not only the overall acoustic field but in particular the sound reflected from within the vessel back through the opening and detected at a specific point where an internal point is located.

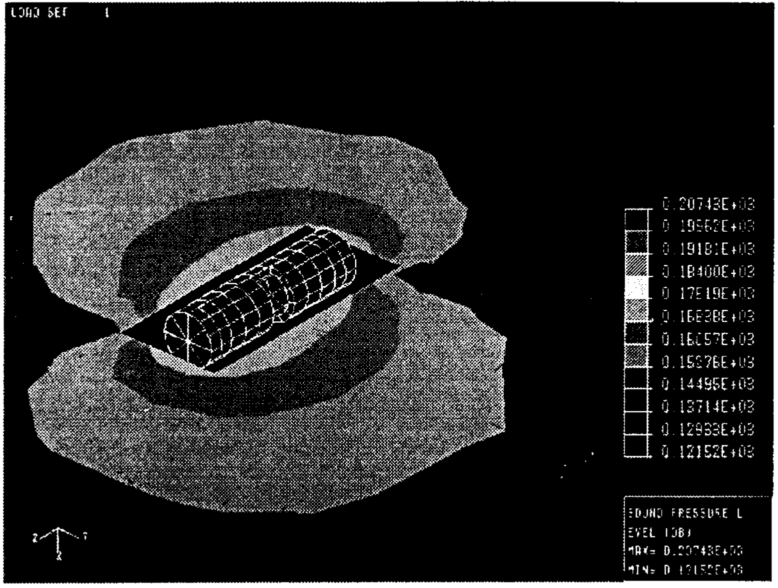


FIGURE 3. BEASY model of the vessel and the surrounding sound **field. Note the elements only describe** the vessel and the region surrounding the vessel is assumed to be **infinite.**

The sound pressure distribution surrounding the vessel is also shown in Fig. 3. In this case the vessel is not vibrating, hence it is not the source of any sound. Therefore in this case the amount of energy returned from the surfaces inside the vessel is of interest. This information can be computed using the diagnostic analysis. The information can be displayed in two ways, either as a contour display on the vessel Fig. 4, or as a histogram Fig. 5. Where each bar represents a Particular section of the structure

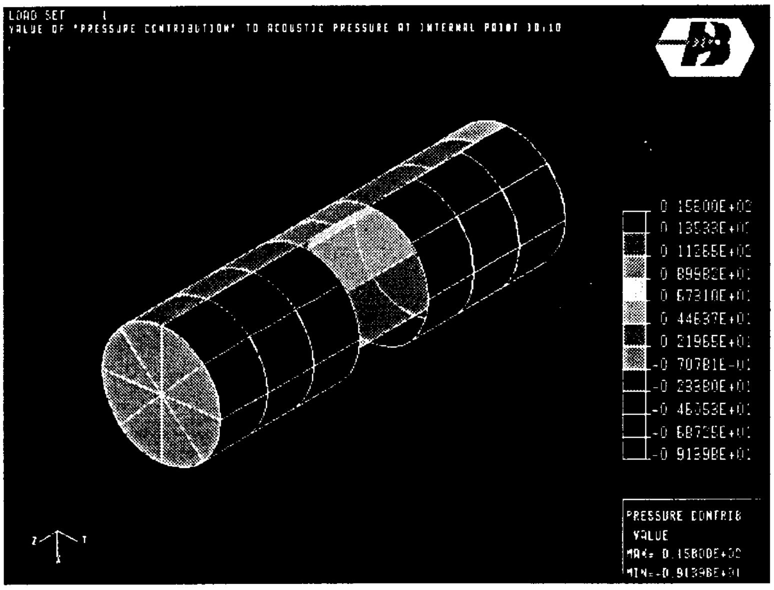


FIGURE 4. **Contour** display of the contribution of the **elements** describing the inside **surfaces of the vessel** to the sound level at the reference point of interest (**described** by an internal **point). Note** the distribution is not symmetric as the sound source is positioned offset from a line normal to the **vessel opening.**

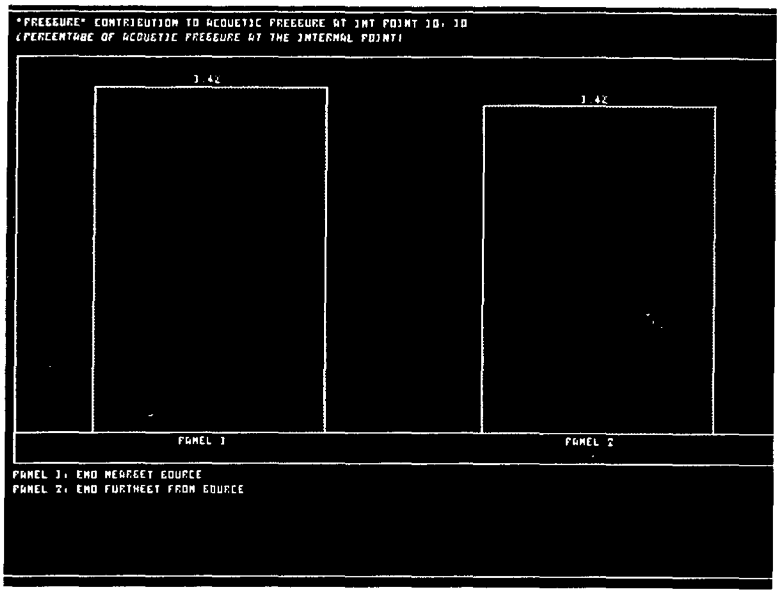


FIGURE 5. Histogram displaying the percentage contributions to the sound level **at the** reference **point.** Each bar represents the contribution of part of the vessel **structure.** In this case it is the internal end panels of the **vessel.The** results show the **panels** contribute just over **3%** each to the sound at the reference **point.**

7.2 Example 2

In the second application the sound levels inside the passenger compartment of a vehicle is simulated. All of the structural panels of the vehicle are vibrating and hence radiating sound energy. The objective of the study in this case is to determine the sound levels in the vehicle and to determine the contribution of individual parts of the structure to the sound level at particular points of interest.

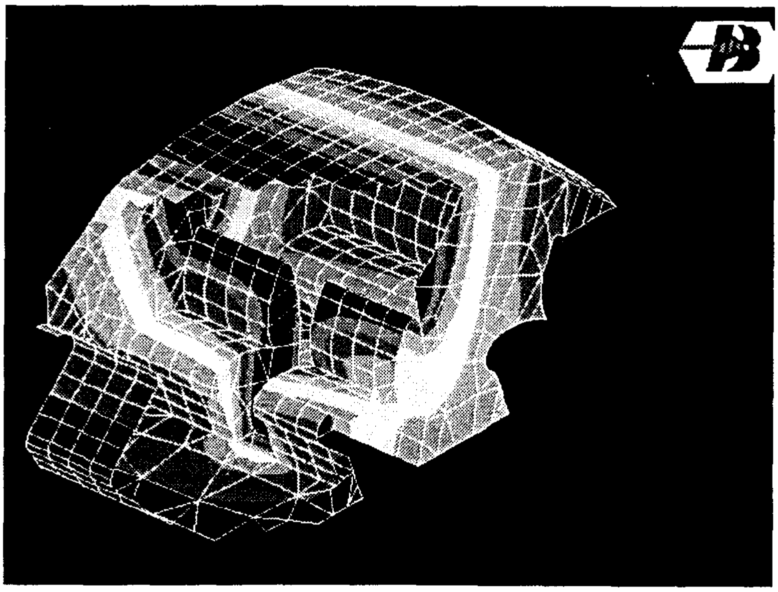


FIGURE 6. Acoustic model of the vehicle showing contours of the sound pressure level on the surface of the **structure.** Note some of the elements have been cut away to reveal the **internal structure.**

The vehicle model is shown in Fig. 6. The structural velocities and impedance values can be either specified by the user, imported from a vehicle structural analysis or imported from a measurement system.

In this application all of the structure is both radiating sound and reflecting sound. Therefore to determine the true contribution of a particular part of the structure to the sound level at a particular point in the vehicle the second class of diagnostic tools has to be used. e.g. Equation (11).

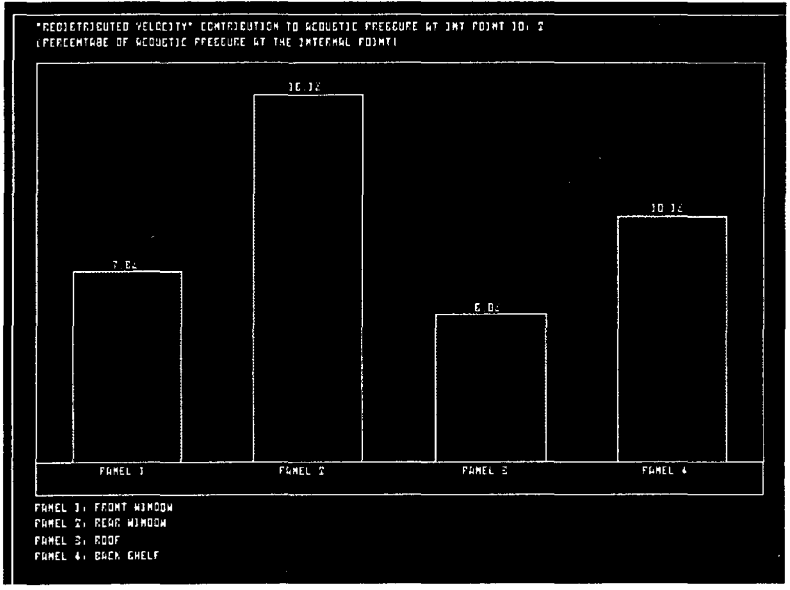


FIGURE 7. Display of the true contribution to the sound level of various part of the vehicle structure (Front window, Rear Window, Roof, Back Shelf). The information can be displayed as either a percentage of the sound at the internal point or as the sound level contributed

Figure7 shows the contribution to the sound level at a point inside the vehicle from various structural panel of the vehicle. Each bar indicates the sound contributed from the panel.In this case the contribution display indicates that the vibration of the rear window causes 16% of the sound at the selected internal point and the back shelf contributes 10%.With this information the engineer can take effective action to reduce the sound levels, because the diagnostic analysis has indicated which parts of the structure are causing the most sound and by how much. The bars on the graph also provide sensitivity information as the sound contribution is directly dependent proportional to the structural velocity and the impedance.

The influence coefficients of the true contribution also provide information on how the sound level can be reduced. In Fig 8 the contour display of the coefficients show the influence of various parts of the structure. If it is assumed that the velocity of the structure is 1 everywhere the display shows the expected contribution from each element.

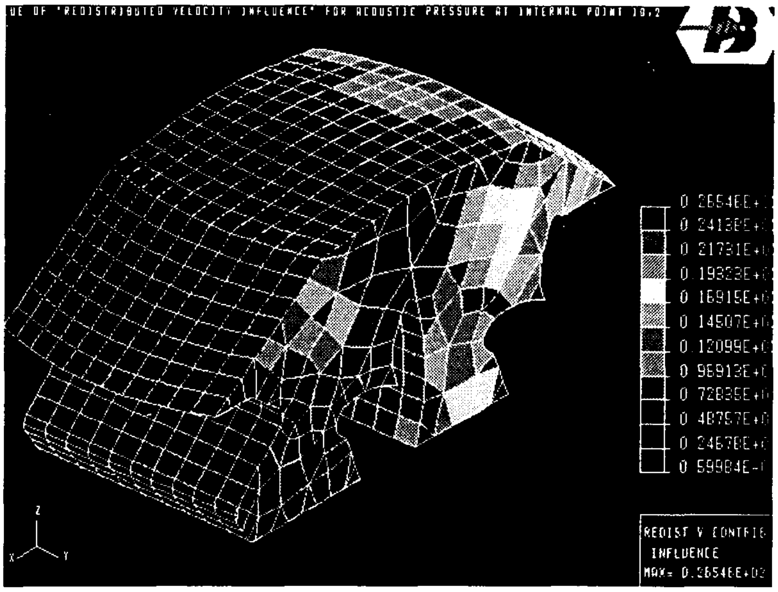


FIGURE 8. Contour display of the Influence coefficients for the true contribution

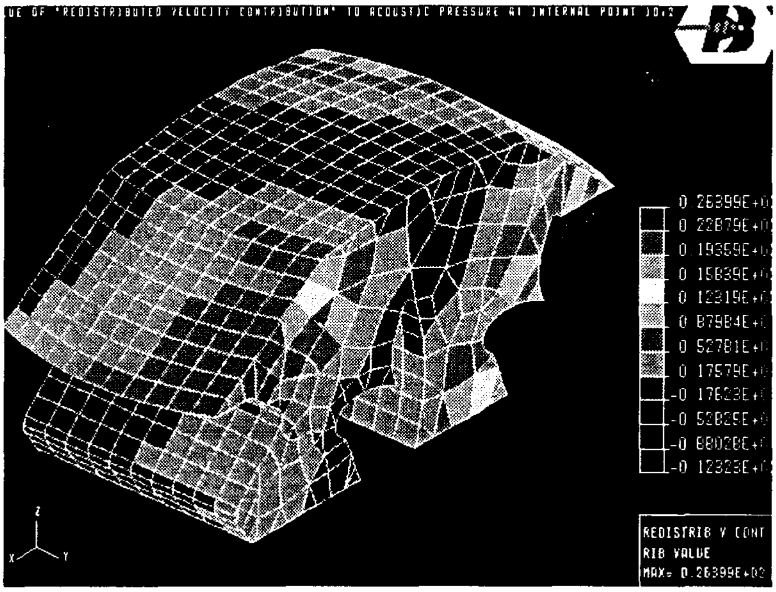
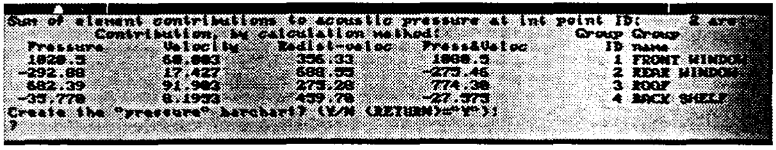


FIGURE 9. Contour display of the true contributions of each element to the sound level at the internal **point.**

The contributions can also be displayed in numerical form.



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Sum of element contributions to acoustic pressure at int point ID:      2 are:
         Contribution, by calculation method:                     Group Group
  Pressure        Velocity      Redist-veloc    Press&Veloc          ID name
   1820.5          68.083        356.33          1008.5               1 FRONT WINDOW
  -292.88          17.427        688.55         -275.46               2 REAR WINDOW
   682.39          91.903        275.28          774.38               3 ROOF
  -35.770          8.1953        439.70         -27.373               4 BACK SHELF
Create the "pressure" barchart? (Y/N (RETURN)="Y"):
?
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FIGURE 10. Tabular display of contributions from the vehicle body panels

The sound level experienced by a passenger in the rear of the vehicle can be easily computed by simply placing an internal point at that location.

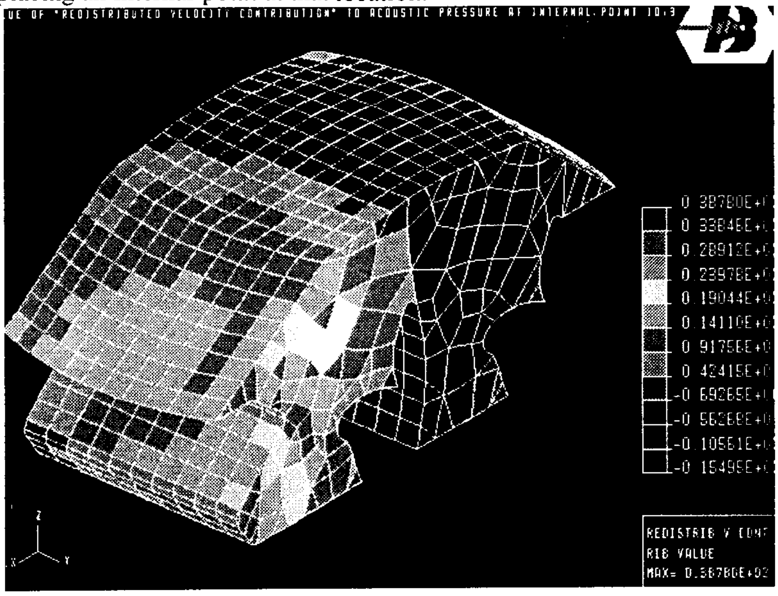

FIGURE 11. Contour display of the true or redistributed contributions to the sound level experienced by a passenger in the rear of the vehicle.

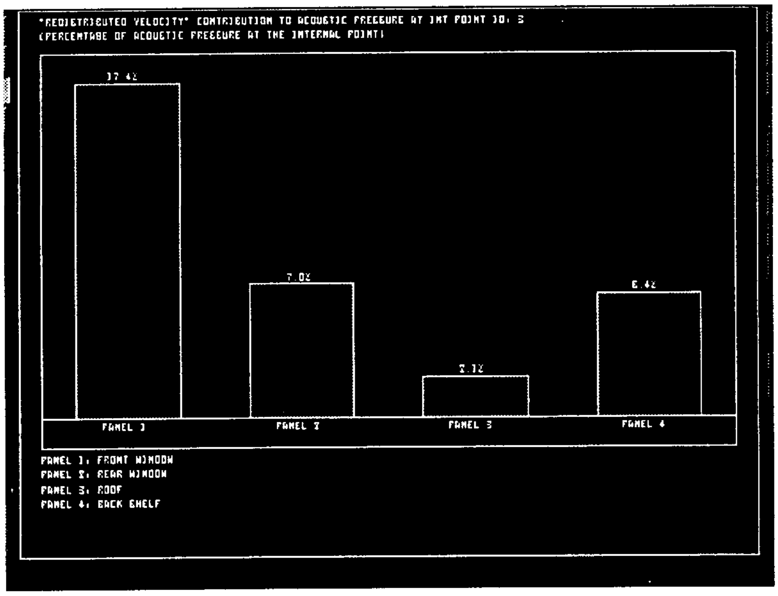

FIGURE 12. Table of contributions to the sound experienced by the rear seat passenger. Contributions are shown for the Front Window, Rear window, Roof and the back shelf.

In Fig. 7 the panel contributions to the sound experienced by a passenger in the front seat was displayed. In this case the front window contributed 8% and the rear window 16%. Fig 12 shows the equivalent data for the passenger seated in the rear of the vehicle.

8.0 Conclusions

The role of a second generation acoustic simulation tool has been described and the theoretical basis for the diagnostic tools presented.

Two classes of diagnostic tools have been developed to provide the engineer with precise information on the importance of individual parts and structures in the model to the level of the sound. The use of the diagnostic tools substantially enhances the quality and usability of the acoustic simulating tool.

Applications of the tools have been presented for interior vehicle acoustics and exterior problems.

References

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