Conformal Mapping Techniques for Consumer Products

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Mapping techniques with respect to noise source identification have been with us for many years. They have been based on techniques such as intensity mapping, near-field acoustical holography (NAH) and beamforming. They typically produce results that are mapped over flat planes. An obvious improvement would be to be able to map over a conformal surface corresponding to that of the measured object to give a much better visualization of the noise sources. One method investigated for this has been inverse boundary-element modeling (IBEM), but the practical application of this technique is complex. This article describes an alternative method for conformal mapping based on NAH, which proves to be much simpler to apply. The method is made possible through the SONAH algorithm that allows the use of a small, hand-held microphone array, and positional detectors in the array that allow the use of so-called 'patch' holography. The method is illustrated with measurements on a household vacuum cleaner and on a printer.

Practical noise source identification (NSI) began in the early 1980s with the introduction of reliable Sound Intensity measurement techniques with associated mapping.[1] At the same time, the first near-field acoustical holography (NAH) methods were being developed.[2] Sound intensity mapping has been and still is the most popular form of NSI. It has the advantage of requiring relatively unsophisticated equipment, this being a dual-channel analyzer capable of calculating sound intensity, some sort of sound intensity probe, and some mapping software. Figure 1 gives an example of a three-dimensional intensity map of a domestic vacuum cleaner produced using such equipment. Apart from the continuous improvements introduced by better measurement technology, the method has seen little further development over the past 20 years.

In the same timeframe, however, NAH has seen considerable progress, with the algorithms being developed to take advantage of the ever-increasing amount of processing power that was becoming available. The first major new development was the introduction of transient-NAH in the year 2000, which allowed mapping of non-stationary sources.[3] This was followed by the SONAH algorithm in 2003 that has considerably improved performance and has opened up the possibility of using small microphone arrays.[4] This in turn has allowed the development of so-called 'patch' holography.

A further development in NSI has been the adoption of beamforming techniques. To a certain extent, these complement the NAH methods, since they can be carried out using the same arrays as NAH, they can be applied to transient events, and while NAH is best in the low- to mid-frequency region, beamforming is best in the mid- to high-frequency region. Beamforming as a technique is described in detail elsewhere.[5]

Returning for a moment to sound intensity mapping, it is typically carried out across a planar surface, although mapping across curved surfaces can be achieved by using other than Cartesian coordinates. With sound intensity mapping, however, you only have knowledge of what is happening with the sound field on the surface where the measurements have been made. But with NAH and beamforming techniques, it is possible to measure in one plane and map in another. This allows projection of the sound field to the surface of the measurement object to allow better visualization of the sound field and better identification of noise sources.

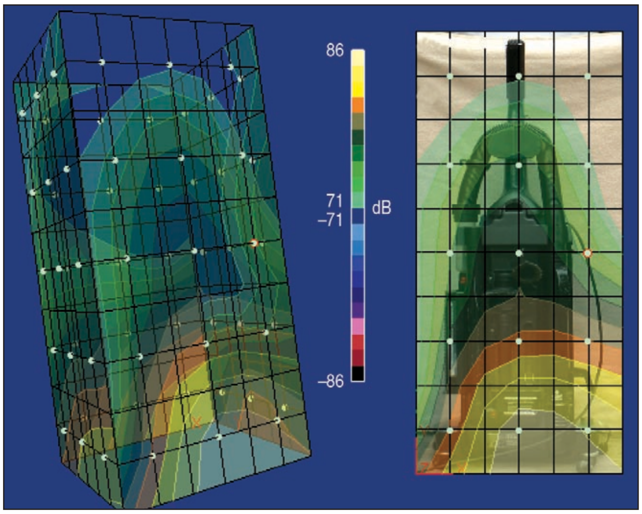

Figure 1. Three-dimensional intensity map of a domestic vacuum cleaner.

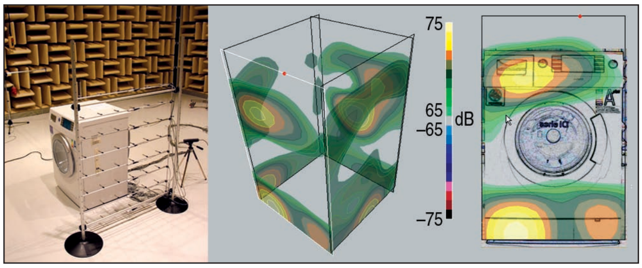

Figure 2. Typical NAH set-up for NSI. Measurement object is a washing machine, and NSI results shown on right-hand side of figure.

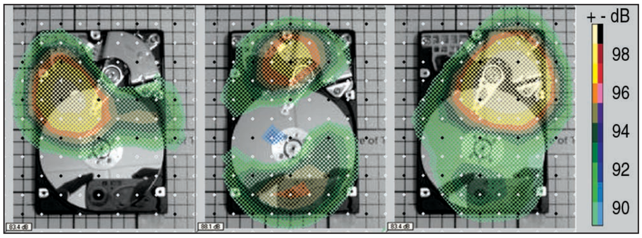

Figure 3. Example of transient NAH on a 3.5-inch disk drive.

Transient NAH and the SONAH Algorithm

Figure 2 shows a typical NAH measurement set-up for NSI on a noise source, in this case a washing machine.[6] It also shows the measurement results taken during the run-up of the spin cycle and plotted as intensity at the surface of the machine in a 1/3-octave frequency range of from 315-1000 Hz. It shows the maximum noise emission to be coming from the soap-dispensing mechanism and the rattling of covers.

Transient NAH uses a microphone array for the measurements, and there must be a minimum of two microphone positions within one wavelength of the highest frequency of interest. (This is a consequence of the sampling theorem, which requires at least two samples per wavelength.) Therefore, the upper frequency limit of the measurement is a function of the grid size of the array. Where measurements to higher frequencies are required, smaller grid spacing must be used. Eventually the size of the microphones begins to place a physical limitation on what is achievable. However, using 1/4-inch-array microphones allows a sufficiently small microphone spacing to be used to allow measurement frequency ranges to approach 5 to 6 kHz.

The low-frequency limit of the measurements is a function of

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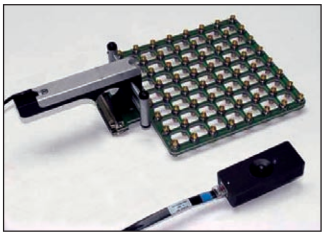

Figure 4. Example of a hand-held array with ultrasonic transducers for detecting array position.

the size of the microphone array. The lowest frequency that can be measured using older NAH algorithms corresponds to where the dimensions of the array are approximately equal to one wavelength, although under certain circumstances where the pressure at the edges of the scan area have dropped off sufficiently, 1/3 of a wavelength is possible. Use of the SONAH algorithm improves this considerably in practice under all circumstances down to 1/8 of a wavelength. It also allows use of an array that is smaller than the measurement object. With traditional NAH, the array must be large enough to cover the whole measurement object, even if only a small part of the object is of interest.

An example of what can be done using the SONAH algorithm and a small array is given in Figure 3, which shows the results of transient NAH measurements on a 3.5-inch disk drive. This measurement is taken using a 6 × 6 array with 3-cm spacing and is just one example of how SONAH is being developed to measure on small and larger objects.

A further benefit of the SONAH algorithm is the possibility of using handheld arrays. Such an array is shown in Figure 4. They can be made as single or double sided for use in a free or diffuse sound fields, respectively. Their original application was real-time noise source location, where with the array in one hand and a miniature display in the other, it was possible to go searching for noise sources. With the addition of a position-detecting system in the array handle, consisting of ultrasonic transmitters, gyroscopes, and DC accelerometers, it became possible to detect the position of the array in space while it was being used to make a measurement. In turn, this gave rise to 'patch' holography.[7] Here measurements could be made with the array at multiple positions and then 'stitched' together to make a continuous map. An example is given in Figure 5.

Mapping Sound Fields onto Nonplanar Surfaces

The techniques so far described typically map over a planar surface. This can be the measurement surface itself or a projection of the measurement surface, depending on the technique used. However, noise sources are rearely composed of planar surfaces, so the next step should be the possibility of mapping at the actual surface of the noise source. This requires alternative techniques

Two such techniques are being developed at Brüel & Kjær. They are inverse boundary-element modelling[8] (IBEM), and conformal mapping. IBEM is a method that allows the modeling of surface vibration based on acoustic noise measurements. An example of a map made using IBEM techniques in shown in Figure 6. IBEM is used to map the entire measurement object and produces a model that can easily become a component of a larger model. However, its practical application has so far proved to be complex.

Conformal mapping is a development of 'patch' holography. In practice, it has proved easier to apply than IBEM methods. Unlike IBEM, where the whole measurement object has to be mapped, conformal mapping can be used to characterize noise emissions from parts of the object. This is described in the following section.

Conformal Mapping Using the SONAH Algorithm

The following describes the procedures for conformal mapping using the SONAH algorithm,[9] illustrating them with measurements on a household vacuum cleaner. The mapping is carried out using one of the handheld arrays described earlier, and the workflow can be summarized as follows:

1. Import or measure geometry
2. Apply mesh (an already-existing mesh can also be imported, avoiding the need for Step 1)
3. Measure patches
4. Are more measurements needed?
5. Calculate results
6. Map noise sources

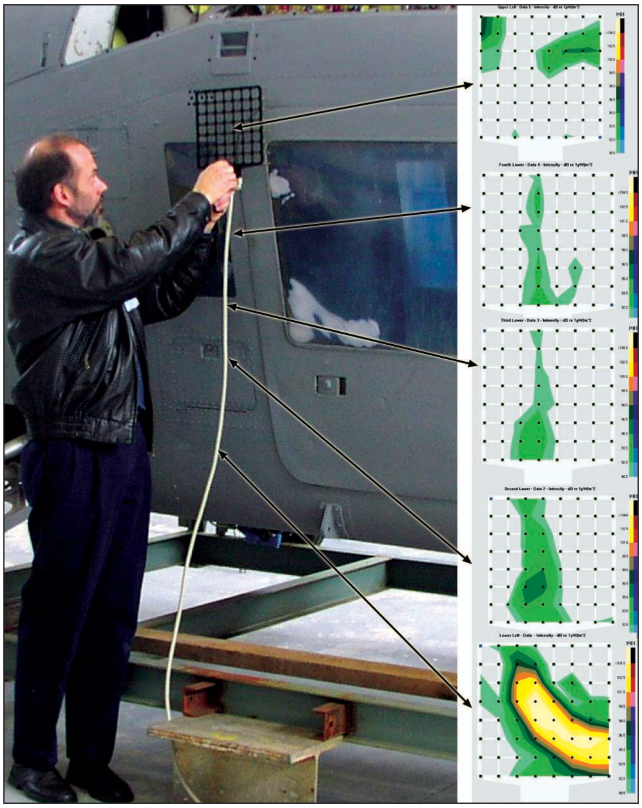

Figure 5. Example of "patch" holography.

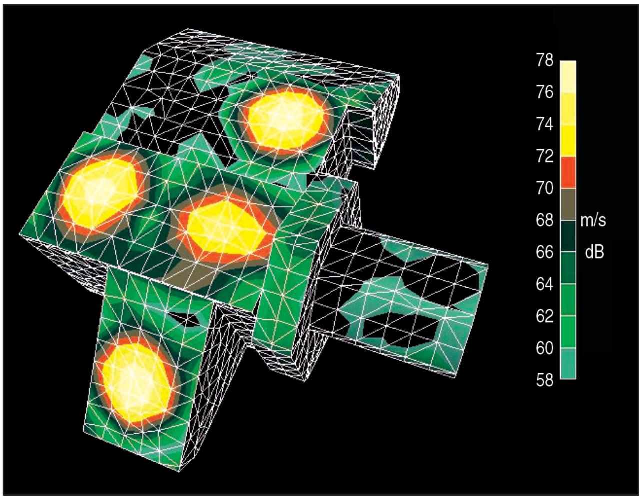

Figure 6. Example of noise map of an engine simulator produced using IBEM.

Import or Measure Geometry. Conformal mapping requires a source geometry for the measurement object. Where a source geometry already exists, it can be imported. CAD surface geometries can be imported from the IGES file format, which is one of the most widely used CAD formats worldwide. It allows file import from CATIA, Solid Edge, Pro-Engineer, NX, Rhino, and so on. Otherwise, the source geometry can be measured.

Measurement of the source geometry is achieved through probes attached to the array handle. Figure 7 illustrates this procedure in progress for a small vehicle. The measurement is made using the position-detecting system integrated into the array handle, together with some modeling software. The procedure is to make contact with the measurement object using the probes at multiple points on the object's surface. This way, the source geometry can be built up, The source geometry measured for the vehicle is also shown in Figure 7.

The amount of detail in the source geometry is up to the user. It can be in detail, and outline, or even just a plane, As noted earlier, the procedure is illustrated by measurements on a domestic

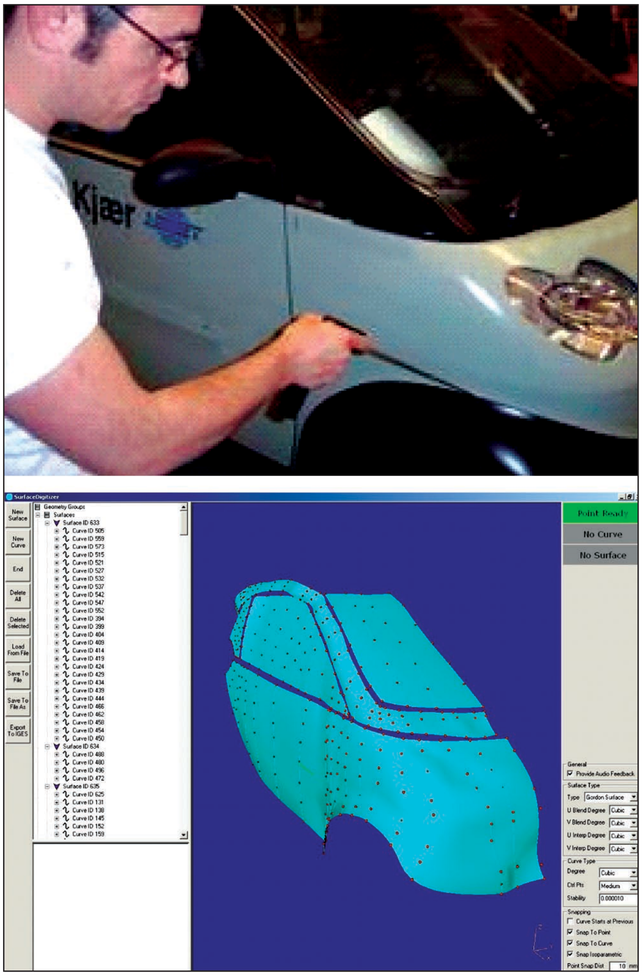

Figure 7. Measurement of the source geometry for small vehicle.

Figure 8. Vacuum cleaner used as noise source and its measured geometry.

vacuum cleaner. The vacuum cleaner is shown in Figure 8.

Apply Mesh. The calculation and mapping of results require a mesh, which converts the source geometry from a continuous surface to a series of discrete points. The density of the mesh depends on the required frequency range, level of detail and resolution. Selected parts of the source geometry can be meshed to any desired density using a built-in mesher. Selected points can be tagged to allow easy identification of surface features. The source geometry of the vacuum cleaner, generated using the procedure described in the previous section, and the associated mesh is shown in Figure 9.

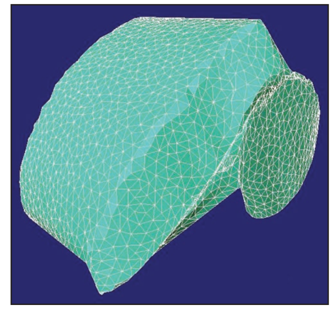

Figure 9. Source geometry of vacuum cleaner and associated mesh.

Where a mesh already exists for the measurement object, it can be imported. This is useful if a mesh has already been generated using CAE software, for instance UGS FEMAP, Altair Hypermesh, MSC, Patran, ANSYS, and so on. This also avoids the need to generate a source geometry.

Measure Patches. The patches are measured, for instance, using the handheld array described earlier. The measurements are made:
- Close to the source
- At accessible positions
- In enough places to cover the area to be mapped

Patches can overlap and be at different angles and depths, with the three-dimendional position of each patch being automatically registered through position detection system of the handheld array.

Calculation. Calculations are made on sets of measurement data and can be made at the same time as the measurements or later as post-processing. As part of the calculation, it is necessary to choose:
- Which measurement to use
- Which mesh to use
- The time interval for the calculation
- The frequency range of the calculation
- What parameter to map – sound intensity, sound pressure, particle velocity, or associated parameters, for example
- The presentation of the results – 1/1 octave, 1/3 octave, FFT, etc. Default calculation setups can be stored and recalled for later use.

Mapping. Some conformal maps for the vacuum cleaner are shown in Figure 10. They are mapped as intensity in selected 1/3 octave. They show the major noise sources to be the nozzle and the fan exhaust.

The maps made are three-dimensional displays, with sound power calculation available for user-defined three-dimensional areas to allow ranking of partial sources. A fixed map layout can be selected, for example, 1 × 1, 1 × 2, 2 × 2 etc., independent of the display screen resolution, and individual displays can be aligned in terms of selected point, frequency, viewing angle and measurement dataset. They can be used to inspect the data from a single dataset from multiple views, to compare different frequencies from the same dataset and to compare different datasets in helping to locate and identify noise sources.

Example of Conformal Mapping on a Printer. Figures 11 through 13 show an example on conformal mapping on a printer. Figure 11 shows the printer with the cover open and with the cover closed. Figure 12 shows conformal maps of intensity for the printer with the cover open (left) and with the cover closed (right) for the 2-kHz, 1/3 octave. For ease of comparison, they are plotted using the same scaling. Figure 13 shows similar broadband (125 Hz-2.5 kHz) plots. The right-hand plot of Figure 12 (cover closed) quite clearly shows leakage taking place around the cover edge. The broadband results (Figure 13) show leakage taking place not only around the edge of the cover, but also through the cover itself.

Conclusions

Conformal Mapping using the SONAH algorithm is a natural extension of NAH techniques that offers mapping of sound intensity, sound pressure, or particle velocity directly on the surface geometry of any arbitrary shape. It offers better visualization of noise sources, making them more understandable to non-acousticians. There is a simple workflow to obtain such maps with a reduction of time-consuming preparation when compared with other methods, and measurements are made using a handheld array at random and accessible position around the source. Conformal mapping is therefore a valuable new tool in the area of NSI.

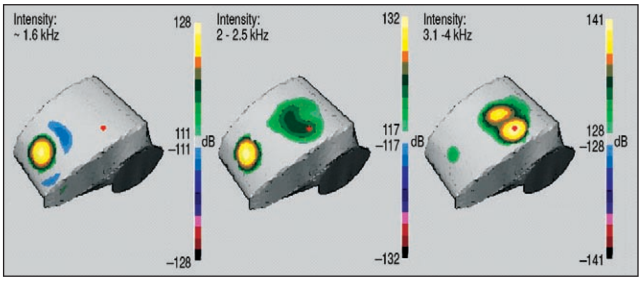

Figure 10. Conformal maps for a vacuum cleaner.

Figure 11. Printer with cover open (left) and cover closed (right).

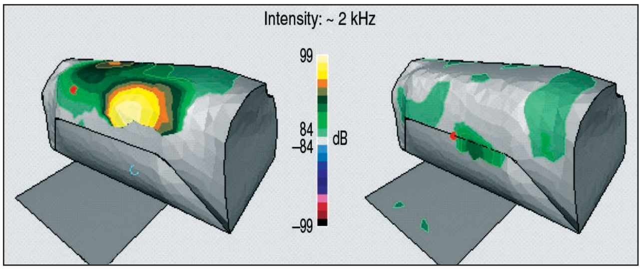

Figure 12. Plot of intensity for 2-kHz, 1/3 octave with cover open (left) and the cover closed (right). Note leakage around the edges of the cover when closed.

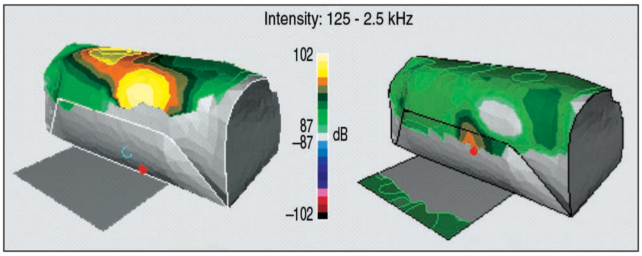

Figure 13. Plot of broadband intensity (125 Hz-2.5 kHz); note how cover (right) now leaks not only around its edges but also through cover itself.

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