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자동차의 음향잡음의 원인규명 방안

Acoustic Noise Source Identification in the Automotive Industry

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Abstract

We have all heard sounds that did not sound "right" while riding in an automobile. Objectionable sounds are difficult to find and understand because the sound field is complex and dynamic in the near field of an automobile. Many different noise sources and transmission paths must be understood before an engineering change can be recommended. This paper reviews the fundamental characterization of sound and discusses the Sound Intensity measurement technique. Sound intensity measurements locate sources and sinks of acoustic energy. Used with narrowband analysis equipment, acoustic noise sources can be identified.

Sound intensity measurements are made in-situ and do not require special anechoic facilities. The measurement results in a vector representation of the near field sound field and can discriminate between multiple sound sources.

Sound Characterization

What is sound? Sound is a wave that travels through some medium. Usually, we think of sound as traveling through the air but sound also travels through liquids and solids. Sound waves have a frequency, an amplitude, a phase and a direction. All of these quantities are important to completely characterize a sound field.

Sound fields change with time, making speech and music possible. The transient nature of many sounds, however, makes them difficult to characterize as frequency, amplitude and direction now become functions of time.

This paper will deal with essentially steady state sound fields. A steady state sound field can be measured accurately and economically with a small number of microphones scanned over the measurement plane. Dynamic sound fields would themselves change before the measurement plane can be scanned and so require a dedicated microphone for each measurement point in space.

The common electromechanical speaker demonstrates the sound parameters that can be measured. The voice coil vibration induces waves in the air of a certain amplitude and frequency. These waves travel both through the air and through the speaker housing and are affected by the transfer function of those materials. The airborne sound waves impinge on the speaker housing and add their contribution to the overall field we hear.

Define Sound Pressure, Intensity and Power

A microphone measures sound pressure - waves in the air bend the diaphragm which is converted to an electrical signal we measure directly with instrumentation. Commonly, this quantity is reported as *sound pressure level* or *SPL*. Sound pressure at a point in space can be a useful measure, but sound pressure does not tell us enough for the near field environment we see in automotive applications. We need to know the direction of the sound too.

The vector equivalent of sound pressure is *sound intensity*. Sound intensity is measured directly in the time domain or is calculated from frequency domain spectra. In the time domain, sound intensity is the time average of the product of the instantaneous sound pressure and the instantaneous particle velocity component along the axis between two closely spaced microphones. The time domain formulation works well with 1/3 octave digital filter implementations. Narrow band frequency domain spectra can also be used. Sound intensity is proportional to the imaginary part of the cross spectrum. In the following equations, P_1 and P_2 are the instantaneous pressures measured at two microphones Δr apart. The constant ρ is the density of air and ω is frequency. S_1 and S_2 are the linear spectra as measured at the two microphones.

Equation 1: Time domain formulation of Sound Intensity

$$I(t) = -\frac{P_1(t) + P_2(t)}{2 \cdot \rho \cdot \Delta r} \cdot \int (P_2(t) - P_1(t))dt$$

Equation 2: Frequency domain formulation of Sound Intensity

$$I(\omega) = -\frac{\mathrm{Im}(G_{12}(\omega))}{\rho \cdot \Delta r \cdot \omega}, \quad where \quad G_{12} = S_1^* \cdot S_2$$

Sound intensity is measured with a pair of microphones spaced a small fraction of an acoustic wavelength apart. A single pair of microphones measures the sound field with respect to a measurement plane perpendicular to the line between the two microphones. Six pairs of microphones are required to calculate the field in the X, Y and Z directions to completely characterize the direction of the sound field. We will see that noise sources can be located by moving a sound intensity probe [see Figure 1] and noting whether the intensity is positive and thus in front of the probe or negative when the sound is behind the probe. When the probe indicates a zero intensity, then the noise is somewhere in the plane between the two microphones. Turn the probe ninety degrees and locate the noise in both the X and Y directions.

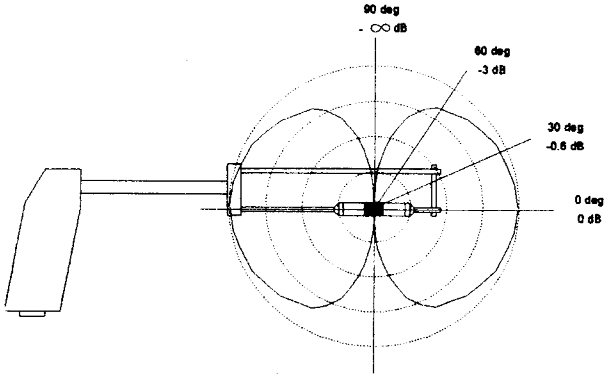


Figure 1: Sound Intensity Probe with cosine sensitivity characteristic

Sound power is the total acoustic energy emitted from a device expressed in units of Watts. Sound power is often the ultimate measure of interest as it allows us to objectively compare whether one device is louder than another. Noise regulations are often written in terms of sound power and so this quantity is important to evaluate for regulatory compliance.

Source	Sound Power Level (dB re 10^{-12} W)
Jet airliner	167 dB
Large orchestra	130 dB
Conversational speech	73 dB
Laserjet printer	50 dB
Whisper	30 dB

Table 1: Sound Pressure Level for common sounds

Sound power is not directly measured but rather must be calculated from either sound pressure or sound intensity measurements.

Calculate Sound Power from Sound Pressure Measurements

Sound power is the overall acoustic contribution from a device but sound pressure measurements are made at a single point. How do we reconcile these two differences? The exact answer is to integrate the sound pressure from all points around the device and sum up the total power, but a more practical solution is to say that the sound pressure at one point is the same as the pressure at nearby points. This is, of course, strictly false yet standardized measurement procedures will give repeatable results with acceptable accuracy.

ISO Standard 7779, "Measurement of airborne noise emitted by computer and business equipment," specifies that nine microphones should be placed around an imaginary cube about the device we want to measure [see Figure 2]. Microphones are placed in the middle of each cube face and at the four corners at the top of the cube. The cube is sufficiently large so that measurements are made in the far field. The test is done on an acoustically reflective surface such as a hard floor.

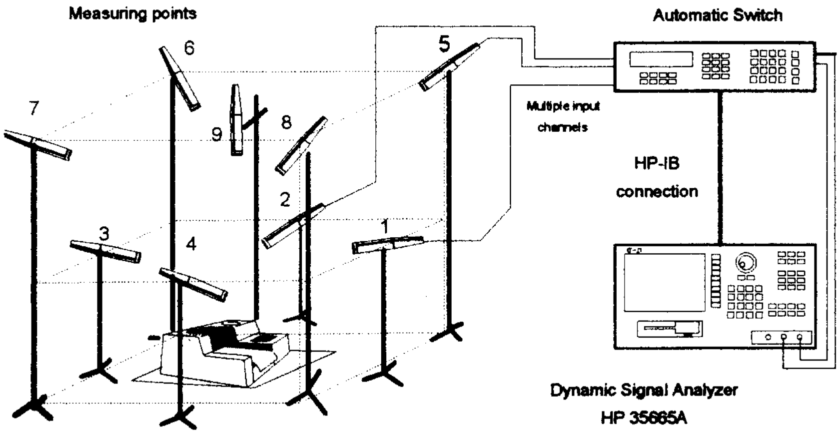


Figure 2: ISO 7779, Measurement of airborne noise emitted by computer and business equipment

Using a Dynamic Signal Analyzer and a programmable switch, each microphone is measured in turn and the overall sound power is computed with a computer program.

This method has the advantage of being standardized and readily available instrumentation may be used. However, there are several disadvantages to this method, especially for automotive applications. First, the microphones are sensitive to noise both from the device under test and from other noises in the environment. Reflected noise is also a problem. To solve these problems, the test must be done in an expensive anechoic chamber. Specialized chambers may be acceptable for office equipment but they are less suited for whole automobile tests and certainly impractical for road tests.

Measurements must also be done in the far field so that we can assume that the sound field over a wide area (i.e. a cube face) can be accurately represented by a single microphone.

We are also limited in the amount of data we can collect - we can tell which cube face is the noisiest, but we cannot locate where that noise is coming from.

Calculate Sound Power from Sound Intensity Measurements

Sound intensity is a significant improvement because an anechoic chamber is not required and measurements can be made close to the device in the near field. Also, measurements are not contaminated by continuous background noise.

These advantages accrue because sound intensity is a vector technique and can isolate noise sources within a measurement cube from those outside the cube. Sound power is calculated as the surface integral of sound intensity measurements.

$$\underset{\text{Sound Power}}{W} = \underset{\text{Surface Integration}}{\int_{s}} \overset{\text{Sound Intensity}}{\vec{I}} \cdot \vec{ds}$$

- Vector quantity
- Enclosed measurement surface

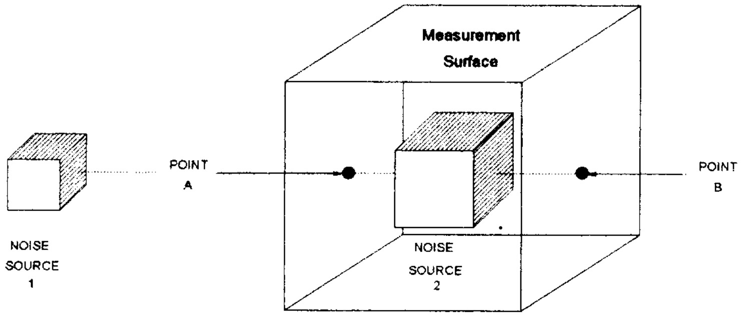


Figure 3: Sound Power calculated from Sound Intensity

The sound intensity measurement is done by scanning the sound intensity probe over the sides and top of the imaginary cube that defines the measurement surface. As we see in Figure 3, when we measure the left face of the cube, noise from the external source flows into the cube but that same noise flows out of the cube when we measure the right face. There is no net effect from the external noise when we perform the vector addition of the intensity on the left and right face of the cube.

However, sound intensity measurements require more data points than sound power techniques. Either we do a spatial integration by scanning the sound intensity probe over the measurement surface integrating all the while or many discrete points are measured in succession and later accumulated into a single value. Scanning a sound intensity probe requires some practice and is similar in principle to using a paint sprayer. The probe is moved at a constant speed back and forth over the measurement surface then another pass is made moving the probe over the same area only now in an up and down direction.

The discrete point technique collects data at more locations that can be used to map the location of noise sources. Since most sound intensity probes have control buttons on the hand grip, measurements proceed very quickly. The discrete point method is more accurate than the scanning method because the measurement time is controlled more accurately.

Sound Source Identification with Sound Intensity Maps

We use sound power to characterize a device. Sound power data tells us objectively whether a device is too loud, e.g., do we have a problem or not? Given that we do have further work to do, we must next locate noise sources.

Sound intensity measured at a finely spaced grid of discrete points builds a map of sound sources. This measurement is made in the near field, close to the device under test: under the hood, in the passenger cabin. As we saw in Equations 1 and 2, sound intensity is calculated in the time domain or in the frequency domain. Sound intensity calculated in the time domain can be run through digital filters and converted into the octave domain. This works well for wideband noise such as air flow from a blower. Alternatively, narrowband tones are more accurately measured in the frequency domain.

A sound intensity map is a contour plot of intensity for either an octave band or a frequency bin over the measurement surface. There may be many frequency bands of interest and thus you may find several intensity maps useful to locate a specific sound.

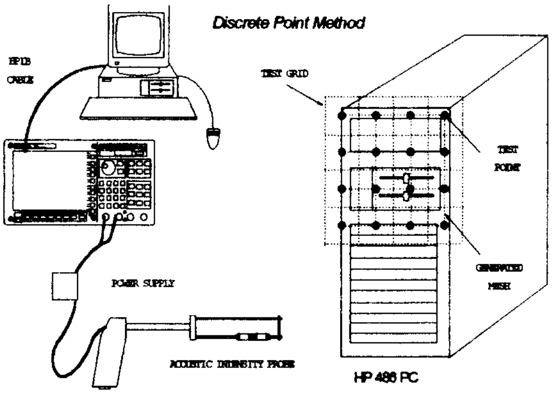


Figure 4: Sound Intensity measurement

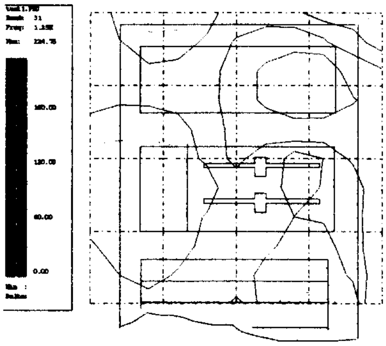


Figure 5: Sound Intensity Map

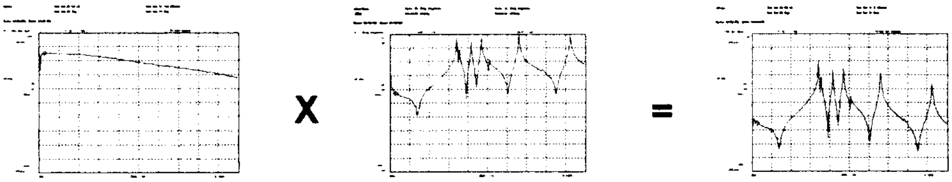
Figures 4 and 5 show the sound intensity measurement technique and the resulting contour map of intensity values for a certain frequency band. The sound intensity probe makes a sequence of measurements over a discrete grid while under the control of the HP 35670 Dynamic Signal Analyzer.

The personal computer reads the data and produces the contour plot.

Troubleshooting

We have progressed from quantifying the problem using sound power measurements to locating the major noise sources with sound intensity. Now we have to solve the problem.

Acoustic treatments can be applied directly to where the noise leaves the device or we can attack the problem at its source. Stimulus response measurements track the propagation of vibration energy along a structure. These measurements can be as simple as a two channel frequency response between the engine block and the body frame or multiple input, multiple output modal tests.



Input spectrum of sound

Frequency response of structure (Path)

Output spectrum of sound

Figure 6: Structural properties influence sound transmission

Assuming linearity, you can predict the output spectrum of sound if you know the input sound spectrum and the frequency response of the sound path. This is important because the frequency response of the transmission path can be changed with structural modifications, e.g. add fasteners to restrict movement or add dampers to absorb vibration between structural members. These changes must be made in concert with acoustic measurements. It does little good to dampen vibration at 100 Hz when you are trying to remove a 1000 Hz noise.

Two common ways to measure structural vibration characteristics are with the impact test or with shaker tests. Impact tests use portable two or four channel instrumentation. A single channel measures the impact force from an instrumented hammer and the other channels measure the response at fixed locations on the structure. The impact hammer roves around the structure. With impact testing, the fixed accelerometers are located where you expect the structure to be excited and the hammer hits the response points. This is indeed the reverse of what you would expect, but the reciprocity principle states that the stimulus and response points may be interchanged for linear systems.

Shaker tests are often performed with multichannel instrumentation systems. The shakers are attached to the expected excitation points and accelerometers are placed around the structure. Impact tests are relatively inexpensive and may be done in-situ but shaker tests will deliver more accurate results because data is taken simultaneously at all response points.

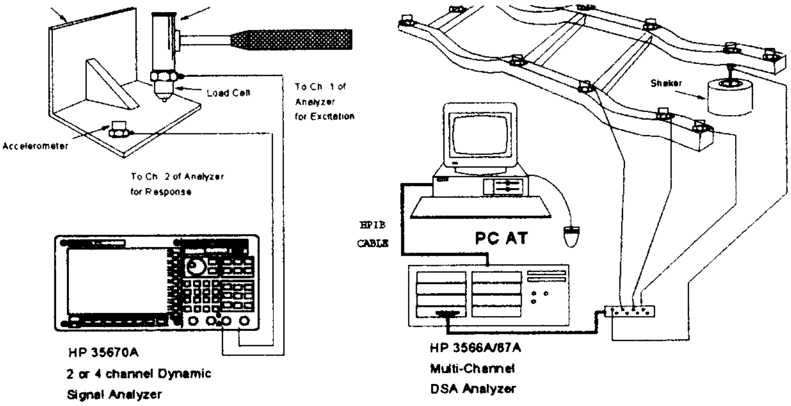


Figure 7: Structural Testing Setups

Conclusion

Sound power characterizes the acoustic performance of a device. It is used for regulatory compliance and to objectively compare devices. Sound power is calculated either from sound pressure measurements or from sound intensity measurements. Sound intensity measurements may be done in-situ and is much less sensitive to constant background noise. Sound intensity can also be used to locate sound sources.

Once noise sources are located, structural testing identifies the transmission path for vibration.