Hyundai Genesis
Wind Noise Reduction at the Underbody Using Acoustic Holography

Genesis is the first luxury premium sedan of Hyundai, designed to compete in the world market. Naturally, the car is to provide a high level of acoustic comfort for cabin occupants. One of the aspects in achieving this goal is the reduction of underbody wind noise, the source of which is difficult to locate. The company has been developing acoustic holography for locating noise sources in its anechoic wind tunnel for years. The technical aspects of underbody acoustic holography and how it was applied in the development of Genesis will be introduced.

1 Introduction

Wind noise is the most dominant noise of a vehicle at speeds above 110 km/h. Wind noise can be divided into upperbody wind noise, underbody wind noise, and leak noise depending on its characteristics and source locations. Of these noises, the energy contribution of underbody wind noise to a cabin is found to be more than 50 %. The premium sedan is thus given a very rigorous target in terms of the wind noise coming from its underbody. From its conceptual stages, the underbody wind noise reduction naturally became one of the primary engineering goals.

Most Noise Vibration Harshness (NVH) solutions require identifying their sources. It is, however, difficult to locate underbody noise sources because of the challenge involving underbody measurement. An underbody acoustic holography method, which enables visualisation of vehicle underbody wind noise sources, has been developed. The method involves a 2 t platform in the anechoic wind tunnel, which houses a two-layer microphone array for elimination of sound reflection effect. The Genesis is rightly the first vehicle to be receiving the benefit of this technology, **Figure 1**.

2 Underbody Acoustic Holography

Near-field acoustic holography (NAH) is a very powerful tool for visualising sound [1, 2]. It predicts acoustic pressure of every sound source from just one-plane measurement, **Figure 2**. The process is to simply solve the wave equation after measuring the boundary conditions. The method can render information on noise sources such as their locations and strengths, which engineers are usually interested in. This is possible because holography can accurately predict acoustic pressure on the source plane at which noise sources are located. The theory is well established and has many examples. There are, however, some technical issues for implementing the method to underbody wind noise. They are:

- How to measure sound pressure under a vehicle?
- How to remove noise reflected from ground?
- How to remove self-induced microphone noise due to wind)?
- How to establish the contribution of exterior noise sources to a cabin?

Following sections explain the solutions on the technical issues.

2.1 Underbody Platform

NAH requires pressure measurement on a plane, as mentioned above. However,

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Figure 1: Genesis on a platform for underbody acoustic holography

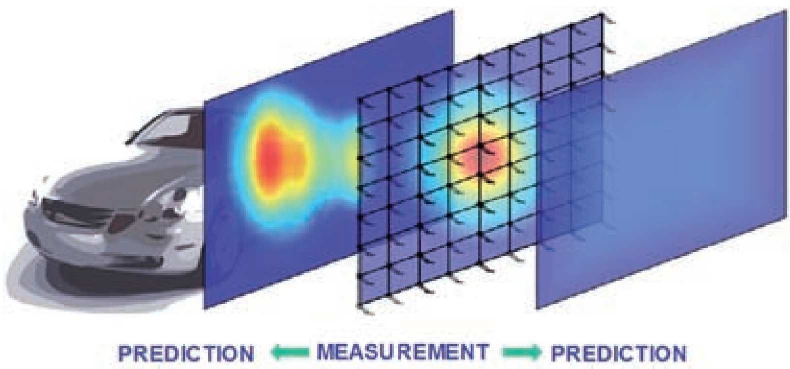


Figure 2: Illustration of near-field acoustic holography

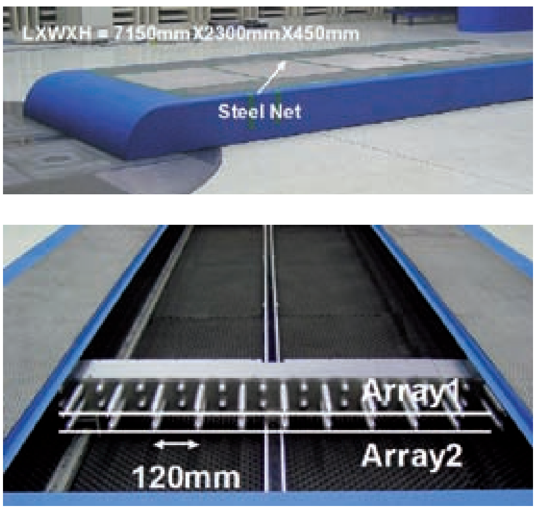


Figure 3: Platform for underbody acoustic holography

the Hyundai Aeroacoustic Wind Tunnel (HAWT) was not designed for measuring underbody noise. Thus a platform shown in **Figure 3** is designed to place a vehicle on it [3]. The platform has dimensions of 7150 mm x 2000 mm x 450 mm and contains a two-layer microphone array consisting of 32 microphones. The array is mounted on a rail, and is movable up and down for scanning. The two-layer array implies two-plane measurement. The microphone spacing is 120 mm. It means that the underbody acoustic holography is applicable up to about 1400 Hz because of spatial aliasing [4]. According to a preliminary study, however, most of the acoustic energy from a vehicle's underbody is concentrated in the range of 20 Hz to 1000 Hz.

Air flow over the platform must be similar to that without the platform. The main factor in preserving the flow characteristics of the vehicle underbody is the shape of the platform head. Although many designs are considered, only three will be mentioned here. The first model aims to generate a boundary layer in front of the platform. The second and third models utilise an elliptic and a circular head, respectively. Numerical analysis of the flow over the platform is performed, and the resulting velocity profiles are compared at various locations. **Figure 4**, left, shows the streamlines along the centreline of the three platforms. Model 1 with a wedge in its head exhibits strong flow disturbance due to reverse flow and flow separation up to about half the length of the platform. With respect to the wedge type leading edge, the rounded heads of models 2 and 3 show moderate distortion of the flow field. Of the two, model 3 with circular head is chosen for its flow similarity with that of underbody without a platform. In addition, a steel-net is installed on the platform for preventing wind from rushing to the microphone array.

Self-noise from the platform must be kept at a sufficiently low level so that it does not interfere with the holography result. When the corners of the platform are kept sharp, significant level of dipole noise from the strong edge vortices is generated. Figure 4, right, illustrates the enhancement of the edge flow using a rounded (50R) corner. The strength of the vortex is seen to decrease significantly when the rounded edge is employed. The streamline with many separation points and reattachment regions prior to the modification also show a significant improvement in the uniformity of the flow after the edges are rounded.

The 32-microphone array can be automatically moved for scanning an underbody plane. Scanning measurement has the same effect as simultaneous measure-

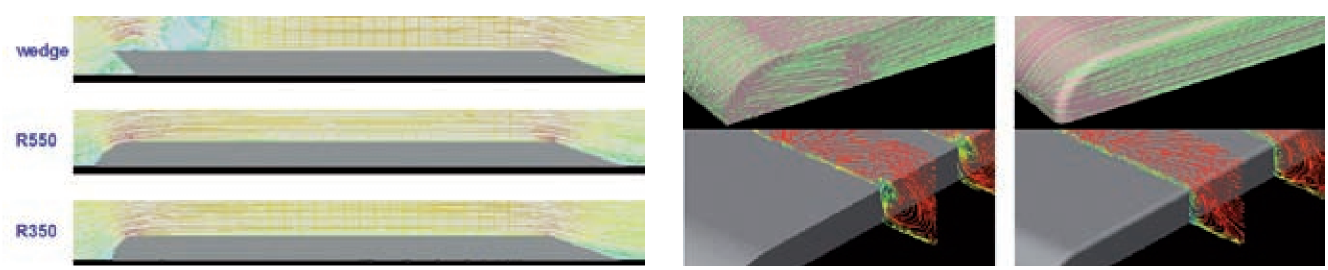


Figure 4: Flow effect of underbody platform; left: streamlines of three head models along a centre line on a platform; right: streamlines near corners with sharp and rounded edge

ment if reference microphones are properly used [5]. The underbody acoustic holography uses 16 reference microphones within a cabin. Placing references within a vehicle is effective because it visualises only noise sources penetrating into the cabin. Signals measured at the underbody can have components not penetrating into a cabin. Correlation between underbody microphones and interior references can reject these undesired components. Therefore its results can show only noise sources related to the cabin noise. The number of references is verified by other holography system of HAWT – Side Acoustic Holography [6]. **Figure 5** shows the result of one 1/3-octave band at 110 km/h using different number of reference microphones. More sources are seen and the result converges as the number increases.

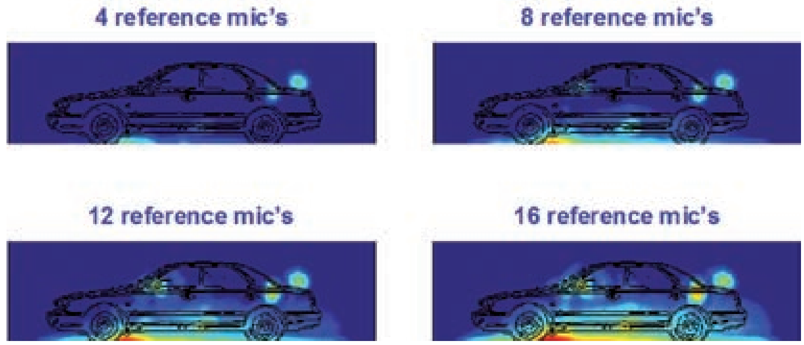


Figure 5: Side acoustic holography result using different number of reference microphones

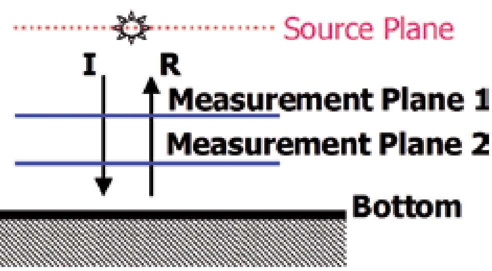


Figure 6: Illustration of incident and reflected wave

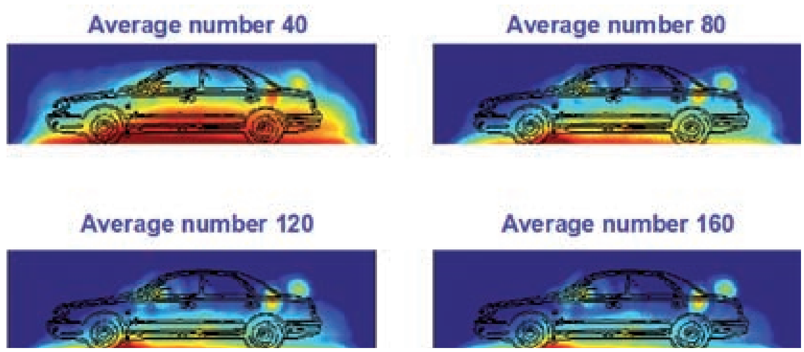


Figure 7: Side acoustic holography result using different number of average

2.2 Removal of Reflected Wave

Underbody acoustic holography must take the wave reflection from ground into consideration. Reflected waves can lower the resolution and lead to wrong source position due to a lot of image sources. The effect of reflected waves must thus be eliminated to accurately assess the noise sources among various parts of the vehicle's underbody. One of the measures considered is the placement of absorptive material into the platform. However it is not sufficient for low frequency wave reflection. Thus a two-layer measurement method with an appropriate signal processing is adopted in order to reduce the distortion by the reflected waves.

NAH requires only one-plane measurement in a free field without reflection. In no reflection case, the boundary – enclosing an interest region – consists of a measurement plane and other surface at infinity. The surface at infinity satisfies the so-called Sommerfeld radiation condition and does not contribute to the region of interest. If there is reflection, however, the other surface does not satisfy Sommerfeld radiation condition. Therefore more information on the boundary is needed. This physical situation leads to two-plane measurement [7].

In general, the acoustic field above the ground can be considered as a superposition of incident and reflected waves, **Figure 6**. It means that there are mathematically two unknowns – incident and reflected waves. A two-plane measurement thus gives sufficient information to solve for the two unknowns [7].

2.3 Reduction of Self-Induced Microphone Noise

Measuring acoustic pressure within a flow field inevitably involves the effect of turbulence near the microphone. The array microphones in underbody acoustic holography have the same problem because they are in a flow field. Windscreens are used to reduce the self-induced noise of microphones but they are not sufficient.

As already mentioned, reference microphones are placed in the cabin. The microphones help to visualise only those noise sources contributing to the interior noise. Self-induced microphone noise does not penetrate into a cabin. Therefore the interior references can reject the self-induced noise. This is one of the advantages of using correlation, often called cross-spectrum or coherence. To utilise the full advantage of coherence, however, many averaging sequence is required [8]. Self-induced noise effect disappears as the averaging number increases. **Figure 7** shows 110 km/h holography results using different number of averaging [6]. The sources can be seen more clearly with increasing the average number. Underbody acoustic holography uses a minimum 160 average number.

2.4 Contribution Analysis

Previously, the procedure of measuring sound and removing noises – reflected waves and self-induced microphone

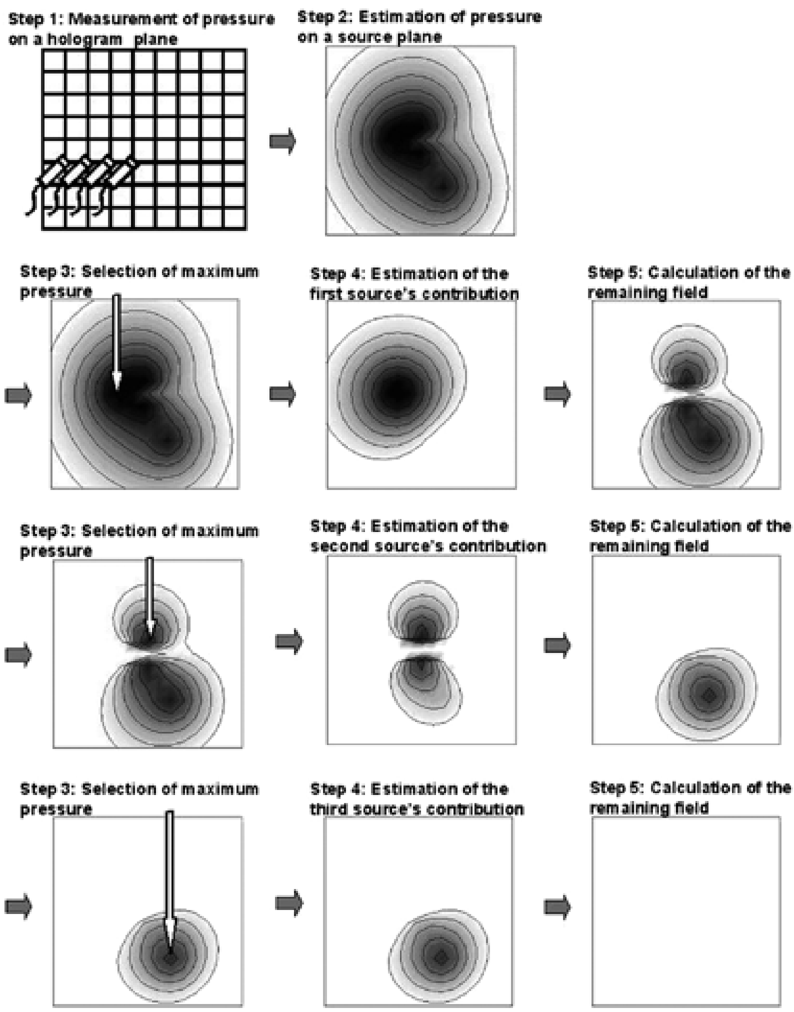


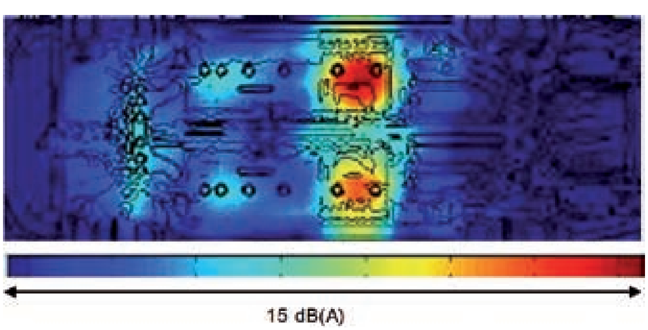
Figure 8: Contribution analysis procedures for acoustic holography

noise – at the vehicle's underbody was explained. With the method, acoustic holography can be achieved for a vehicle's underbody. It is sufficient for visualisation and source identification. However, engineers are much more interested in how much the individual sources contribute to the cabin noise. Following discussion shows how the holography result can effectively be used to quantitatively analyse the contribution of each source to the interior cabin noise.

As already explained, correlation between the interior and exterior signals can effectively remove undesired noises, namely the ones not penetrating into the cabin. Correlation can also be used for evaluating exterior source contributions to the interior noise by considering a particular source and neglecting others as undesired noises. Therefore the sound pressure at a particular position, which is affected by only a particular source, is to be considered. By correlation, the pressure signal can select only the contribution of the particular source and reject the contributions of other sources at exterior and interior field.

Acoustic holography can predict sound pressure at a source position enabling it to be used as a tool to evaluate source contributions. **Figure 8** illustrates this procedure. The first stage involves measuring sound pressure at a measurement plane. Secondly, pressure on a source plane is calculated. The source of the maximum sound pressure is then identified, and is assumed to be the result of a particular source. By using correlation, the contribution of the first source at exterior and interior is estimated. The rest of the acoustic field without the first source contribution is obtained. From the residual acoustic field, the procedure is iterated from identifying the next source to obtaining the residual acoustic field. Its detailed procedure is described in [9]. One advantage of this method is that it does not need to estimate transfer functions from exterior to interior, which often require heavy experiments, because it uses only correlation between signals.

Figure 9, left, shows an experimental result to verify this contribution analysis procedure [10]. Through underbody acoustic holography, some noise sources



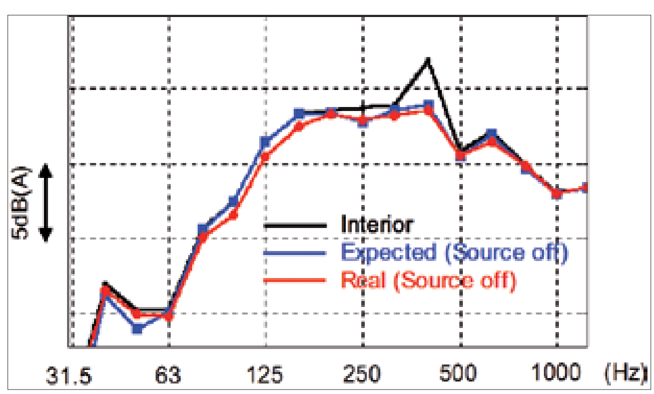


Figure 9: An example to verify contribution analysis procedures for acoustic holography; left: underbody noise sources; right: interior spectra of a vehicle

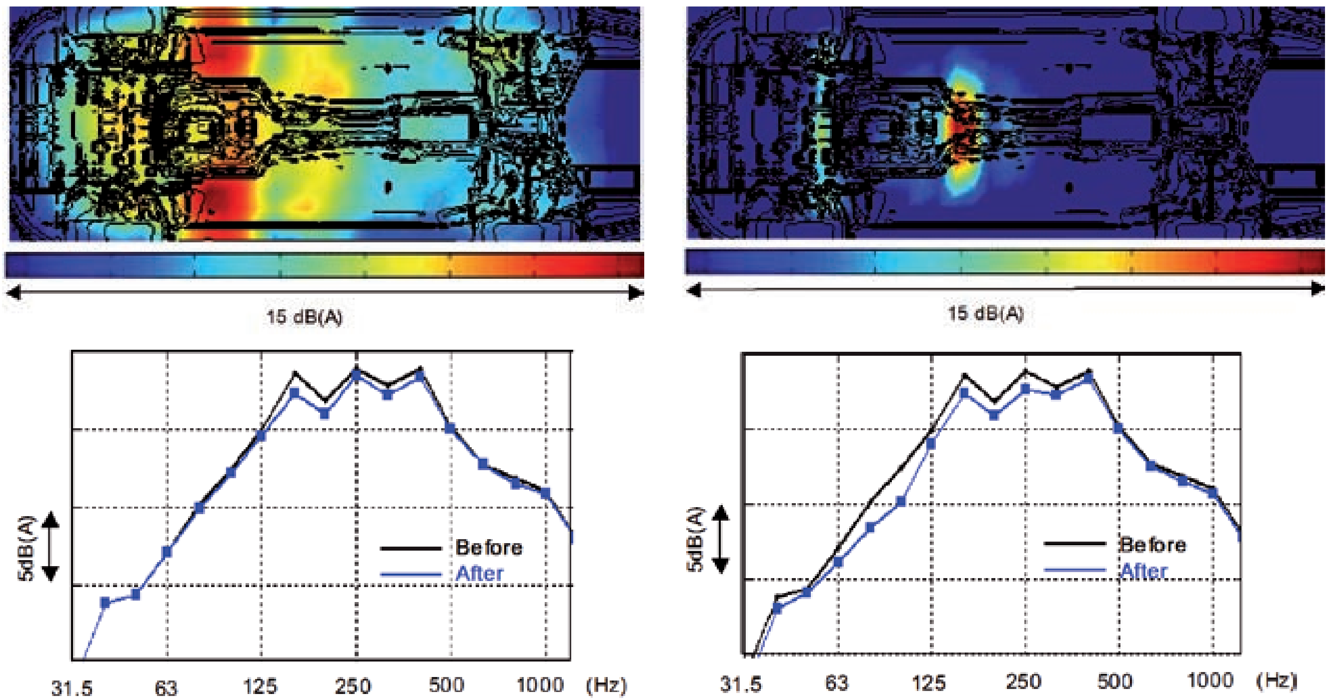


Figure 10: Underbody acoustic holography results of the Genesis; left: a noise source at the start point of centre floor undercover; right: a source at a heat protector

are found that generate cavity noises. Their contribution at interior field is estimated by above procedure. The blue line of Figure 9, right, shows an expected spectrum when the sources are turned off. The red line shows a real spectrum when a countermeasure is applied to the source. The predicted noise spectrum is very similar to the measured result.

3 Genesis: Underbody Noise Source

Underbody acoustic holography of the Genesis is performed several times during its development stages. **Figure 10** shows some of the results. Figure 10, left, shows a noise source generated at the centre floor. The contribution analysis tells that it is a major source with a frequency of 160 Hz. A countermeasure is applied to the sound generating part through design change, and the interior noise is improved. The interior noise spectra before and after the countermeasure is shown in Figure 10, left. Figure 10, right, shows a noise source at the edge of a heat protector, which gives rise to noise below 400 Hz.

The vibration of the heat protector is found to be the noise source. Reinforcing the structure for stiffness causes vibration to decrease and the interior noise to improve. Reducing these noises leads to the reduction of interior overall noise level by more than 1 dB(A). These are just some examples of how the acoustic holography helps to identify noise sources and to improve the interior noise level. With the help of underbody acoustic holography, the noise target level of the new vehicle is successfully met at the very early stages of development.

4 Conclusions

The Hyundai development of underbody acoustic holography as an application to the new passenger car Genesis had to overcome some technical difficulties – sound measurement of underbody, removal of reflected waves, reduction of microphone's self-induced noise, and contribution analysis. Important breakthrough came from underbody platform design and the use of correlation between signals. Receiving the full benefits of underbody acoustic holography, the new car not only achieved best-in-class cabin noise level, but also achieved that level in the very early stages of development.

References

[1] Williams, E. G.; Maynard, J.D.: Holographic Imaging without the Wavelength Resolution Limit. Phys. Rev. Lett. 45, pp 554-557, 1980

[2] Weinreich, G.; Arnold, E. B.: Method for Measuring Acoustic Radiation Fields. J. Acoust. Soc. Am. 68, pp 404-411, 1980

[3] Ih, K. D.; Lee, J.; Kim, Y.-H.: Development of Vehicle Underbody Acoustic Holography. SAE Paper No. 2002-01-1240, 2002

[4] Veronesi, W. A.; Maynard, J. D.: Nearfield Acoustic Holography (NAH) II, Holographic Reconstruction Algorithms and Aomputer Implementation. J. Acoust. Soc. Am. 81, pp 1307-1322, 1987

[5] Hald, J.: STSF – a unique technique for scan-based near-field acoustic holography without restrictions on coherence. Bruel & Kjaer Technical Review No. 1, 1989

[6] Nam, K.-U.; Kim, Y.-H.: Low Coherence Acoustic Holography. Proc. Inter-Noise 2003, pp 3213-3218, 2003

[7] Tamura, M.: Spatial Fourier Transform Method of Measuring Reflection Coefficients at Oblique Incidence. In: Theory and Numerical examples. J. Acoust. Soc. Am. 88, pp 2259-2264, 1990

[8] Bendat, J. S.; Piersol, A. G.: Random Data: Analysis and Measurement Procedures. 2nd Edition (Wiley, New York, 1986), pp 164-251

[9] Nam, K.-U.; Kim, Y.-H.: A Partial Field Decomposition Algorithm and its Examples for Near-field Acoustic Holography. J. Acoust. Soc. Am. 116, pp 172-185, 2004

[10] Ih, K. D.; Nam, K.-U.; Jung, S. G.: Wind Noise Reduction of Vehicles Using Underbody Acoustic Holography. SAE Paper No. 2005-01-0605, 2005