APPLICATION OF NEAR-FIELD ACOUSTIC HOLOGRAPHY IN PRESENCE OF HIGH TEMPERATURE GRADIENT: EXPERIMENTAL UNCERTAINTY ANALYSIS

R. Di Sante, M. Martarelli, G.M. Revel, E. P. Tomasini

Università degli Studi di Ancona
Dipartimento di Meccanica
Via Brecce Bianche
60131 ANCONA, ITALIA
Tel (39) (071) 2204441, Fax (39) (071) 2204813
E-mail: revel@mehp1.unian.it

ABSTRACT

Near-field Acoustic Holography (NAH) has been shown to be a powerful tool for the study of sound radiation from vibrating structures. It provides the reconstruction of acoustic pressure, intensity and particle velocity in the space starting from pressure measurements made on a plane array near the vibrating structure. The reconstruction of the sound field is based on measurement of cross-spectra in the scan plane and on the application of 2D-spatial Fourier transformations. As a basic hypothesis it is clearly required the wavelength of sound propagation to be constant over the considered space. However, this hypothesis may not be satisfied if measurements are performed in presence of high temperature gradients, as the wavelength will be different along the reconstruction path. The effect of this modifying input can be a significant uncertainty in the final results.

In order to assess uncertainty of NAH results in presence of significant temperature gradients, in this work an experimental analysis has been performed on a muffler for automotive applications heated at 170°C. The NAH results have been checked in terms of velocity distribution computed on the structure surface. To this aim, measurements taken by a scanning laser Doppler vibrometer (SLDV) have been used for comparison.

The present work has been carried out in the framework of the “ACES” project GRD1-1999-11202 founded by European Community.

INTRODUCTION

Near-field Acoustic Holography is a powerful technique for calculating 3-D acoustic fields generated by vibrating objects behaving as acoustic sources [1]. The STSF (Spatial Transformation of Sound Fields [2]) technique from B&K employed in this paper is a practical method applying the NAH to determine the acoustic field from measurements performed simultaneously over a plane array of microphones.

The advantage of the STSF is the high resolution in noise sources localisation with respect to the acoustic intensity technique, for example. In fact by using the intensity technique it is usually not possible to distinguish complex acoustic sources, if they are spatially closer than half the wavelength of the sound frequency considered. On the contrary, by STSF technique the reconstruction of the pressure field in a plane very close to the sources is allowed by the calculated back propagation of the measured pressure field. In addition, this technique takes into account also contributions from the near field.

Several acoustic properties can be computed by this method as active and reactive intensity, sound power and pressure and also the particle velocity on the structure surface. This latter parameter can be used for the localisation of the portions of the structure vibrating at highest level which are called “hot spots”. In this paper an accuracy analysis of the STSF technique is described in relation to the influence of the working temperature of the object under test. In fact, the sound velocity depends on the temperature and this may become a problem since the basic hypothesis of NAH is that the sound velocity is constant over the whole field of propagation. If the temperature is high on the object surface and decreases on the space around it, this hypothesis fails and the acoustic field computation may be wrong. In order to check the accuracy of the method at whatever temperature two measurements have been performed and compared at room temperature and with the object surface at 170°C. Unavoidably the results were different because of the structural behaviour changes induced by the temperature gradients. A further validation then was needed to check if they were correct, in order to clarify if the differences are due only to structural changes or also to the influence of temperature on STSF results.

The most suitable technique for this task has been identified in the Scanning Laser Doppler Vibrometry (SLDV) which allows us to measure surface velocities on a spatial grid of points over the object under test. An SLDV is an instrument constituted of two main parts: a single-point laser vibrometer (which measures the point velocity by exploiting the Doppler effect) and a scanning system that allows the laser beam to move over different points on the measurement grid defined over the object surface. With this arrangement the scan across also a large vibrating surface becomes fast and easy to control.

The reference case used to perform the analysis is an automotive muffler, a complex, largely damped structure whose main characteristic is to work at high temperature condition. The muffler was heated at about 170°C excited by a shaker and measured in a semi-anechoic room by NAH, at different frequencies.
The distribution of the vibration velocities in correspondence of the plane tangent to the curved surface of the muffler, obtained using NAH, has been compared to the vibration map measured by the laser instrument. Comparisons allows to determine the degree of accuracy in the NAH measurements and calculations in presence of high temperature gradients.

**ACOUSTIC HологRAPHY**

Acoustic holography has been conceived around 1950 and since that moment it has become an increasingly powerful research tool. The great utility of holographic data arises from its high information content. In fact, data recorded on a two-dimensional surface (the hologram) may be used to reconstruct the entire three-dimensional images. In near-field acoustic holography (NAH), the recording of the sound pressure field on a two-dimensional surface can be used to determine the three-dimensional sound pressure field existing around the sound sources. Typical results of a NAH analysis are also the particle velocity field, the acoustic vector intensity field, the surface velocity and intensity of a vibrating source.

Holography measurements of a wave field are made on a two-dimensional surface, and then used to calculate the complete wave field in three-dimensional space, by assuming that the acoustic propagation obeys the wave equation. The sources of the wave field may be scattering or diffracting objects or active sources. Measurements are usually made on a planar surface (the hologram plane) and these data are used to reconstruct the three-dimensional field by employing a known Green’s function.

The work of Shewell and Wolf [3] on inverse diffraction of monochromatic (single frequency) coherent wave fields constitutes a basis for acoustic holography. Their plane to plane diffraction theory allows prediction of the field closer to the source than the measurement plane. Evanescent waves are, however, not reconstructed which is usually not of great interest in optics, but of major importance in acoustics, where the wavelength is often not small compared to the size of the source.

The Spatial Transformation of Sound Fields (STSF) technique developed at Brüel & Kjaer (partner of the European project ACES) and used in the present work applies NAH and Helmholtz’ Integral Equation (HIE) in connection with a cross-spectral description of the sound field [2]. Basically, from cross-spectra measured over a planar surface close to the source, a principal component representation of the sound field is extracted. Any power descriptor of the sound field (intensity, sound pressure, etc.) can be investigated by means of NAH, while the more distant field can be determined by application of Helmholtz’ integral equation. Compared to various other NAH techniques, the cross-spectra formulation presents no restrictions on the coherence and bandwidth of the sound field and, given that the sound source is stationary, does not require simultaneous measurements.

The STSF computation assumes that the propagation of acoustic field takes place in a homogeneous medium and in relation to the temperature it means that this parameter is required to be constant in the region between the measurement plane and the calculation plane. Otherwise, if the temperature changes between different portions of the propagation space, different sound velocities and therefore different wavelengths will occur. This variation will affect the holographic calculation by defocusing the results since the main error introduced will be a phase shift due to the incorrect wavelength considered in the simulation of sound propagation.

From theory for the application of the STSF technique in regions with significant temperature gradients the phase error will be smaller than 45° if the product of the reconstruction distance (between the sound source and the scan array) in wavelengths and the temperature difference in °C is kept smaller than 140. However, in practice, defocusing will appear at high frequency also when the product exceeds 70, while for products smaller than 20 other errors dominate.

**HEATING PROCEDURE**

As previously stated, the case study approached in this work is an automotive muffler. The heating of the muffler surface and the control of the thermal distribution over the surface itself is an important step in the analysis of the temperature effect on the STSF calculation. Firstly it is important to reproduce the heating condition realised during the working life of the muffler into which a warm flow is going through during operation. Secondly a quick heating procedure should be used and easy to be monitored. This is due to the fact that the acoustic measurements must be performed with several positions of the array of microphones (interlaced positions). Since the measurement area has to be bigger than the source size (i.e. the scan area has been chosen to be 1.40×1.70 m) and the microphone antenna has fixed dimensions (in this case 0.4×0.5 m it being constituted of 5 microphones along the x-direction and 6 along the y-direction) the scan array positions are directly identified as 9. When the measurement is performed at high temperature it is rigorously required that the temperature over the surface of the muffler is the same at each position of the microphone array. Therefore, after any displacement of the array, the muffler has to be re-heated and the temperature reached re-measured. A slow heating procedure will then makes the whole measurement really time-consuming.

Following these requirements a thermal gun was identified to be the most suitable device for the muffler surface heating. The advantages of this instruments are not only the fastness for achieving the temperatures of interest and the complete simulation of the muffler operating conditions (warm flow) but also the easiness of use and the characteristic of being a non-invasive method.

The mean heating temperature was chosen considering two needs:

1. a significant ∆T between the muffler surface and the scan array is required in order to have a temperature gradient in the near field, and
2. a reasonable time of intermediate heating between two subsequent holographic measurements (and then of the total time for the acoustic measurement).

The best heating procedure for achieving these demands consisted on heating the muffler for 15 minutes by using the thermal gun until a thermocouple
fixed on the upper side by cement for high temperature reached 170°C. A settling time of 2 minutes was then waited in order to have a good repeatability of the temperature values after every heating cycle (± 2°C). The temperature changes during the heating procedure were monitored by attaching three thermocouples on the lower side of the muffler and one on the upper side and it was checked that after the waiting time for each thermocouple the temperature revealed was always the same. In Figure 1 is reported the thermocouples location and in Figure 2 the temperature changes during the waiting time of 2 minutes.

![Figure 1 Reference thermocouples.](image)

![Figure 2 Behaviour of reference thermocouples during subsequent cooling cycles.](image)

It can be noticed that after every heating cycle (also the waiting time of two minutes being considered) the maximum temperature on the muffler surface was always 170°C in the location of thermocouple 4 and 2.

The temperature gradient analysis performed for the monitoring of the repeatability of the heating procedure at each array position was also done by employing an IR camera. The temperature distribution over the whole muffler surface (upper side) could then be taken under control at each scan array position, see Figure 3. The temperature distribution at the beginning of the holographic measurement showed a very good repeatability.

Following the heating procedure described above the muffler surface was heated at the temperature of 170°C. The thermal gradient between the source and the microphones array was then of 142.5°C, the averaged temperature over the measurement area being 27.5°C.

![Figure 3 Thermal distribution after the heating (top; the lighter areas correspond to warmer areas) and after the waiting period of 2 minutes (bottom).](image)

**ACOUSTIC MEASUREMENTS**

The high temperature acoustic holography test has been carried out in a semi-anechoic room using the STSF system. The experimental set-up used is shown in Figure 4. The muffler was leant on two lateral metallic supports coated with spongy material in order to simulate a condition constraint-free. The supports were chosen sufficiently high in order to keep the object distant from the ground and to be able to consider the measurement in free-field propagating condition. For this purpose the ground was also covered by sound-absorbing material. In Figure 4 is also shown how the muffler heating is realised and monitored: the thermal gun is inserted on the external pipe and the thermocouples attached on the object surface are used for reading the temperature distribution. The computer for the acquisition of the thermocouples output is shown in the picture as well.

The measured frequency range was 850-1300 Hz and therefore a scanning microphone spacing of 100 mm was sufficient. The distance between the muffler and the scan array of microphones was set to 110 mm it having to be equal or bigger than the microphone spacing. With these parameters the above mentioned product between the thermal gradient (142.5°C) and the reconstruction distance in wavelengths (0.5) was 71.25, bigger than 70.

A set of five reference transducers has been positioned under the muffler. In this arrangement there is certainly a redundancy on references since according to the STSF theory it is necessary to consider as many references as the virtual uncorrelated or partially correlated sources expected. In the actual case the potential sources are all structural and related then to the excitation force produced by the shaker. Therefore the sources should be fully correlated for every frequency of excitation. Nevertheless in order to analyse the possible existence of partially correlated sources, it has been decided to perform the measurement with five references and evaluate
afterwards the superposition between them. The eigenvalue analysis confirmed that the sources are fully correlated in almost all the frequency range considered. This indicates that a smaller number of references could be sufficient to reconstruct the acoustic field.

The same acoustic measurements were performed at room temperature of the muffler in order to discover how the acoustic holography was sensitive to the temperature effect. Power spectra computed on the muffler surface at the two different conditions are shown in Figure 5. The spectra are completely different and the main visible change can be noticed on the flattening of amplitude at all the spectral components in particular between 950 and 1150 Hz. Also a comparison between intensity maps calculated on the muffler surface in correspondence of frequency peaks occurring in the structure in both the conditions shows the complete uncorrelation between the results at ambient and high temperature (see Figure 6 and Figure 7). Such a difference on the results can be explained with the variation of the structural properties of the muffler when the temperature conditions changes largely and not only with modifying inputs for STSF measurements. In order to validate this hypothesis vibration measurements are needed.
STRUCTURAL VIBRATION MEASUREMENTS

As stated above the SLDV technique was found to be the most suitable for validating the acoustic holography measurements performed by STSF. In fact the velocity maps measured over a grid of points (specifically 16×36 positions) on the muffler surface by the laser Doppler vibrometer can be directly correlated, a part of some geometrical uncertainties which can be neglected [4], to the particle velocity computed by the STSF software over a plane coincident with the muffler surface itself. The experimental set-up was identical to the one used for the acoustic holography acquisition and measurements were performed at the same conditions of temperature: room temperature (22°C) and 170°C on the muffler. Similar heating procedure and temperature monitoring was applied as shown in Figure 8. The frequency range and frequency resolution were chosen identical to the range measured and to the synthesis frequency bandwidth used in the calculation by STSF. Specifically the range of interest was between 800 and 1300 Hz with a resolution of 5 Hz; the spectral magnitudes averaged over all the acquisition points for both the condition of ambient and high temperature are illustrated in Figure 9. The same behaviour noticed for the acoustic spectra can be pointed out here, i.e. the spectrum measured at higher temperature is completely different from the one found at ambient temperature and, as before, it is levelled down in the range 950-1150 Hz.

The temperature gradients influences the structural properties as it can be seen also from the comparison of velocity maps for frequency peaks occurring in both the two temperature conditions, see Figure 10 and Figure 11. Even though the influences of temperature gradients on structural properties have been demonstrated by the above shown results, the effect of thermal dishomogeneity on the STSF calculation must still be proved. This will be done in the next section by comparing the corresponding velocity maps at ambient and high temperature computed by STSF and directly measured by SLDV.
DISCUSSION AND COMPARISON OF RESULTS

The comparison of the spectra acquired by SLDV and calculated by STSF shows a similar behaviour in the whole frequency range. In Figure 12 the spectra from SLDV and STSF obtained at room temperature are superimposed while in Figure 13 the same ones derived at high temperature are shown.

The comparison shows that the spectra seem to be coincident in both the conditions, although the STSF results present a less smooth course.

CONCLUSION

In this work the effect of high temperature gradients on NAH results have been investigated. An experimental uncertainty analysis has been performed on a muffler for automotive applications heated at 170°C. The uncertainty in the results was qualitatively assessed by comparison with results from vibration measurements by laser techniques.
According to the theory, the temperature gradient should act as a modifying input for acoustic holography as it modifies the wavelength in the space where the acoustic field is constructed.

The results showed that this effect is actually present, although the identification of the parts with higher vibration ("hot spots") is still possible. The effect is mainly a random noise in the holographic maps which gives a defocusing in the spatial description of these parts.

These results should be taken into account for many practical applications, as suggested by B&K, when the investigated object is at a temperature significantly different from the microphone array one (e.g. measurement on an engine in running conditions).

ACKNOWLEDGMENTS

The authors acknowledge the support of the European Growth Project “ACES Optimal Acoustic Equivalent Source Descriptors for Automotive Noise Modelling” GRD1-1999-11202, for the support for the research developed and described in this paper. Special thanks are due to the partners and colleagues in the project and specifically Prof. M. A. Hamdi and Dr. A. Omrani from STRACO, Dr. J. Hald and Dr. J. Morkholt from Bruel & Kier, Dr. X. Ouisse and Dr. Mein from PSA, Dr. R. Helber and Dr. C. Glandier from Daimler-Chrysler and Dr. E. U. Seamann from Continental.

REFERENCES


Figure 14 Comparison between the maps measured by SLDV and computed by STSF at different frequency peaks for the muffler at room temperature.

Figure 15 Comparison between the maps measured by SLDV and computed by STSF at different frequency peaks for the muffler at 170°C.