Uncertainty of array-based measurement of radiated and absorbed sound intensity

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A B S T R A C T

Patch near-field acoustic holography (NAH) coupled with an array of sound intensity probes allows separating the sound field incident on a surface from the one radiated by the surface itself. Although the measurement principle has been successfully used to separate the noise source contribution from disturbing sources and/or noise reflections, the method accuracy has not been investigated in the literature. We describe the results of experiments meant to evaluate the uncertainty in the identification of noise radiated by vibrating panels with different absorption characteristics in presence of an incident acoustic radiation using the statistically optimized near-field acoustic holography. Measurement errors were evaluated through tests performed in controlled acoustic conditions. Results evidenced that the measurement uncertainty depends on the accuracy of the microphone array positioning and on the incident sound field. These conclusions were in agreement with the results obtained by simulations in the phase of instrument optimization.

1. Introduction

Despite the diffusion of measurement systems based on the near-field acoustic holography (NAH), the number of researches focused on their uncertainty is limited [1–5]. In general, the study of instrumental uncertainty in acoustics is not as diffused as for other kind of measurements [6], mainly because there are many factors (e.g. the measurand variability or the randomness of events that may occur during on-field measurements) whose contribution on data variability may be larger than the instrument uncertainty itself.

NAH [7] requires that the sound pressure tends to zero at the extremes of the measurement surface, in order to limit the truncation errors [8]. An accurate reconstruction of the sound field can be obtained with a large holographic plane that requires a large microphone array or multiple positioning of a small array in order to cover a large area with different measurements. Among the patch techniques, the statistically optimal near-field acoustical holography (SONAH) avoids the errors caused by the use of spatial Fourier transform by calculating the plane-to-plane reconstruction in the spatial domain instead of the spatial frequency domain [9]. SONAH can be used to measure the acoustic radiation of mechanical elements with an indirect measurement principle [10,11]. For current purposes, it is necessary to identify the different total intensity (I_{tot}) components at the vicinity of the panel: the radiated intensity (hereinafter I_{rad}), the incident intensity (I_{inc}) and the scattered intensity (I_{sc}). This can be performed using two parallel planar arrays of microphones (referred to as dual layer array, DLA). With measurements taken simultaneously in two parallel planes, it is possible to distinguish and resolve the incident (I_{inc}) and outgoing (I_{out}) sound field components with sources on opposite sides of the array. In order to separate the different components of the outgoing field (I_{out}), two measurement sessions are needed:

(1) Surface properties measurements (SPM), where the incident sound field created by a set of loudspeaker is used to estimate the surface admittance and absorption coefficient.
(2) Operational measurement (OM), where data derived in the SPM are used to separate I_{tot} in its three components I_{rad}, I_{inc} and I_{sc}.

In this paper, we describe the result of experiments performed to identify the uncertainty of measurements based on patch NAH using a microphone-array in a double layer configuration. The proposed approach for the evaluation of uncertainty can be summarized as follows:

1. Identification of the candidate factors that may affect the performances of the instrument starting from a literature analysis;
2. Experimental session in an anechoic room to identify the measurement repeatability and reproducibility;

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3. Comparison with the results obtained in the instrument design phase (described in Ref. [5]), in which an innovative method was used to predict the instrument uncertainty;

The paper is presented as follows: Section 2 describes the proposed method; experimental results are presented in Section 3 and discussed in Section 4. The paper conclusions are drawn in Section 5.

2. Method

SONAH measurement uncertainty has been estimated with experiments performed in controlled conditions, using design of experiments (DOE) to optimize the efforts for an exhaustive characterization.

2.1. Overview

Four series of experiments are performed in an anechoic room. In the simplest one, the DLA is used to measure the sound intensity emitted by a plate without disturbances, at a single array position. Even in this case, the error depends on where the calculation points are with respect to the array, on the array positioning method, on the source characteristics and on the adopted regularization algorithm. In the second series of experiments, each measurement is a combination of two array positions. The analysis of variance (ANOVA) is initially performed on the results of measurement of the surface properties, to identify the effect of the loudspeaker position, of the array positioning method and of the overlap between neighboring array positions. During the operational measurements, ANOVA is used to identify the effect of the emitting surface property, array positioning method and overlap on the radiated intensity. In the last series of experiments, the admittance-based and the energy-based approaches are compared with different incident noise levels.

The expected results derived from the analyses are the identification of the level of disturbances acceptable to obtain the desired measurement uncertainty and the comparison of experimental results with the ones of simulations performed in the design phase.

2.2. Experimental setup

Tests were performed in the anechoic room at Brüel & Kjaer SVM A/S in Naerum, Denmark. Vibration generated by a piezoelectric shaker (sine on random excitation with four tonal components at 500, 1000, 2000 and 4000 Hz) was imposed to two elastically suspended aluminum plates 500x600 mm in size. The first one was flat and 1 mm thick. The second one was 2 mm thick and 15° bent in the center. In both cases, the shaker was fixed with three screws (in central position on the flat plate, below the corner of the bent plate). The DLA was set-up with two 8x8 microphones arrays with a 30 mm spacing, (both between the two planes and between neighboring microphones in each plane). The DLA position was determined by an infrared positioning system (3D Creator WU-0695-W-001). Three omni-directional loudspeakers were used to create the incident field in both the operational and surface property measurement sessions. The experimental setup is shown in Fig. 1.

2.3. Experiments

Repeatability is defined by the ISO VIM [12] as the closeness of the agreement between the results of successive measurements of the same measurand, carried out under the same conditions. Reproducibility is the closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions. The repeatability has been evaluated with experiments in which the only active source is the shaker; in these conditions, I_{rad} and I_{tot} are coincident. Tests were performed with two DLA positioning methods (hand held and tripod) on two plates. With the tripod positioning, the repeatability was evaluated with 8 identical measurements with a unique DLA position. The reproducibility was evaluated by removing and replacing the DLA in front of the vibrating plate in a nominally identical position. In hand-held measurements, the repeatability was evaluated with six repetitions carried out by a single operator in nominally identical conditions. The reproducibility was assessed starting from the results of tests carried out by three operators.

Admittance and absorption coefficient uncertainties (U_{adm} and U_{abs}) were evaluated with the A approach of the ISO-GUM [13] creating an incident sound field on the bent panel covered by two foam types with three omnidirectional loudspeakers. The sound sources (emitting incoherent white noise) were located at different heights at a distance of 2 m from the panel. SONAH was used to identify the sound pressure and the particle velocity on the panel surface, and thus to estimate the panel admittance and absorption coefficient. The results of each measurement session are the local admittance and absorption values: local data have been summarized with the mean (hereinafter referred to as average admittance μ_{adm} or absorption μ_{abs}) and with the standard deviation σ_{adm} and σ_{abs}. Given that the output of the SPM is the averaged absorption coefficient over pre-defined control areas, we have chosen to replace σ_{abs} with the difference between μ_{abs} measured on the two control areas (the upper and lower panel half). Two full 2^3 designs (investigation of 3 factors, each of them assuming 2 values [14]) were adopted with three repetitions for each test; totally, 24 tests were performed. Investigated factors were the DLA positioning method (tripod – hand held), the position of the loudspeakers during the surface properties measurement session (symmetrical and asymmetrical) and the array position overlap (with 1 or 3 overlapped microphone rows, as in Fig. 2). In the symmetrical configuration, the central loudspeaker were located in front of the shaker and the other two were placed 2 m apart. Conversely, in the asymmetrical configuration the central loudspeaker was moved 0.3 m apart from one of the two side sources.

The mapped areas with a “low” and with a “high” overlapping led to different mapping area sizes (882 cm^2 and 756 cm^2 respectively), since the adoption of a large overlap between two adjacent DLA positions leads to a smaller total area. Since the surface is homogeneous, the surface properties are reasonably constant on the whole surface; consequently, the computation of the averaged admittance (or absorption coefficient) on different areas leads to similar results. Results were analyzed using the ANOVA.

Uncertainty in operational measurements has been identified with two series of tests. In the first one, the investigated factors were the I_{inc} level and the SPM data used to estimate the admittance (included to investigate the effect of SPM repeatability on OM). Consequently, the SPM factor assumed three values, i.e. the three different experimental sessions in which the surface admittance has been measured. I_{inc} assumed two values: the low one was 5 dB smaller than I_{rad}, while the high level was 10 dB larger than I_{rad}. In the second series of tests, the investigated factors were the DLA positioning method (tripod – hand held), the array overlapping and the level of the incident sound field (white noise uncorrelated with the shaker stimulus). Both series of tests include 24 measurements (8 configurations of the 2^3 design, repeated three times each); in each of the 24 OM tests, I_{rad} can be computed using any result of the surface measurement session. Consequently over 1000 I_{rad} estimations can be theoretically computed (the combination of 24 operational tests, 24 surface tests and the use of admission and absorption coefficient). In order to ease the results analysis, I_{rad} was computed using a single estimation of the surface

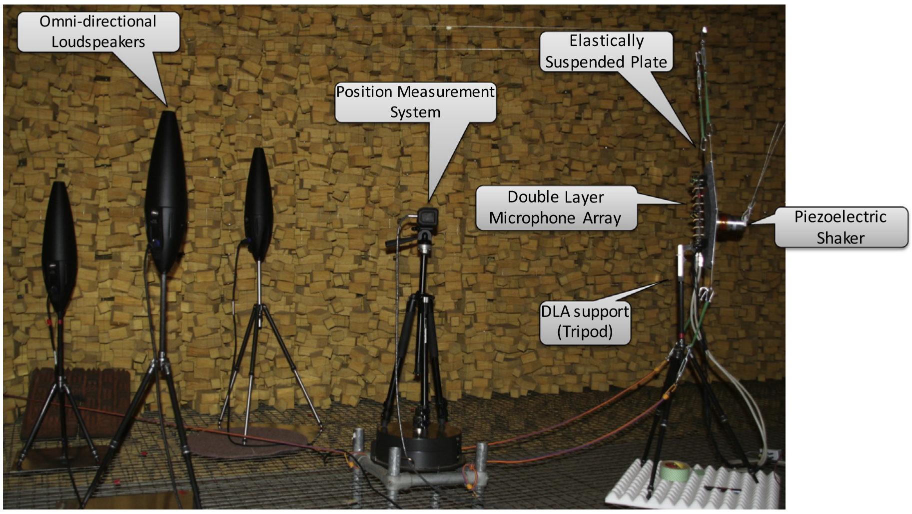

Fig. 1. Experimental setup for repeatability and reproducibility of measurements. The picture shows the tripod mounted DLA configuration.

admittance and adopting the average of I_{rad} over the calculation area as ANOVA response variable.

The last analysis was the investigation of the effect of I_{inc} magnitude on I_{rad} measured by SONAH. Accuracy limitations arise because of the hypothesis introduced by the proposed approach (locally reacting surface for correct admittance-based measurements, incoherent incident and emitted sound fields for absorption-based measurements). The validity of these hypotheses was verified creating a controlled background (incident) noise with different levels. Measurements were performed on the thick bent panel with a single DLA position (the center of the array was placed in front of the point where the bent plate is fixed to the shaker). Tests were only performed with the tripod positioning and with the thick absorbing foam. The shaker stimulus was a sine on random signal as in the other tests and the incident sound field was the white noise emitted by the three omnidirectional loudspeakers placed at two meters from the panel in an asymmetrical configuration. The output of the three loudspeakers were incoherent with the shaker stimulus. The incident intensity level was changed by adjusting the loudspeakers volume, while the vibration generated by the shaker was constant (I_{rad} was therefore constant as well). I_{rad} estimated by the proposed approach is expected to be independent from the incident field and, given that I_{rad} was measured also when I_{inc} was null, it is possible to estimate the measurement error as the difference from the reference ($I_{inc} = 0$) condition.

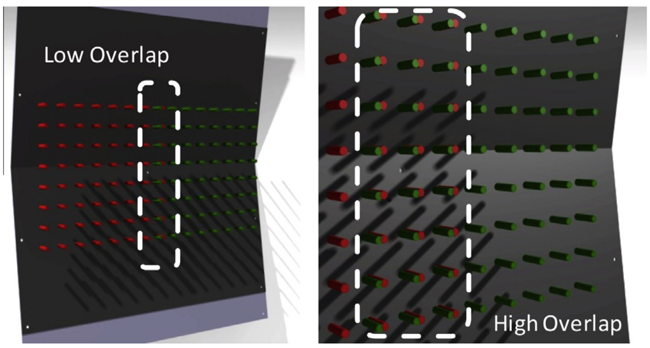

Fig. 2. Scheme of the DLA positions when the overlap is low (left) and high (right).

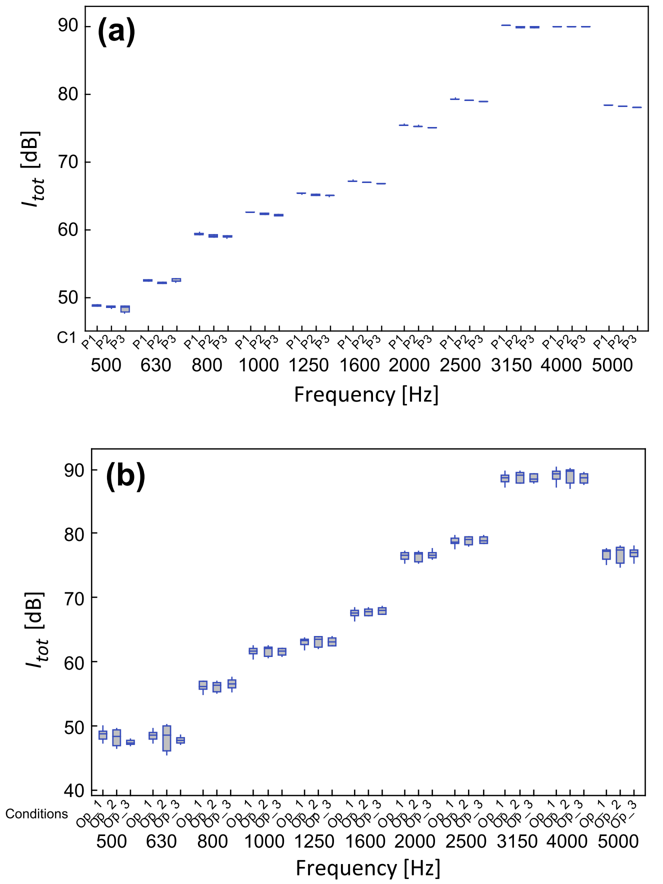

Fig. 3. Boxplots of the repeatability tests. Results of measurements performed with tripod positioning (a) and hand-held array (b).

3. Experimental results

3.1. Measurements repeatability and reproducibility

Results of repeatability and reproducibility tests are summarized in Fig. 3. Plots show that measurements performed with the tripod positioning are averagely more repeatable than those performed with the hand-held DLA and that the measurement variability is smaller at high frequencies. Results evidenced that at frequencies larger than 1 kHz the standard deviation of each positioning (repeatability) is smaller than 0.05 dB. The repeatability of hand-held measurements is close to 1 dB. The RMS of the difference between the mean values measured in the two conditions is 1.9 dB. Such a value can be reasonably endorsed to the DLA motion during the measurement and by the sound field modification introduced by the operator. Given that the error compensation in this case seems at least questionable, the bias error and the repeatability contribution have to be added in quadrature, thus leading to an uncertainty of 2.1 dB.

The reproducibility was assessed by grouping the three repetitions to summarize the dispersion of results of similar experiments performed, for instance, in different sessions or by different operators. Fig. 4 shows the I_{tot} average and standard deviation. Despite the similarity of the mean values, the standard deviation is at most 0.3 dB with the tripod positioning and 1 dB in hand-held tests. The reproducibility also depends on the frequency: with tripod positioning best results are obtained between 3000 and 5000 Hz, that is where the signal to noise ratio is more favorable. Low frequency results are also satisfying, with reproducibility lower than 0.3 dB. In hand-held tests the reproducibility has a minimum (0.7 dB) between 1000 and 2500 Hz. This can be explained with the large phase changes due to the displacement of the DLA during measurements (the position is not stable) that are more important at high frequencies, where I_{rad} intensity gradients are larger.

3.2. Admittance and absorption coefficient uncertainty

The admittance and the absorption coefficient were studied using the boxplots, as shown in the next figures. Graphs summarize all the results of the factorial DOE, i.e. the 24 results of tests (8 configurations of the 2^3 design repeated three times). Fig. 5 shows μ_{adm} and σ_{adm} of the thin foam. Fig. 6 shows μ_{abs} for the upper and lower panel areas.

Values in Figs. 5 and 6 are the results of the combination between the test repeatability and the effect of the investigated factors. A preliminary analysis of the influencing parameters was performed analyzing the boxplots obtained by grouping data belonging to the same family. μ_{adm} depends on the loudspeaker configuration, on the DLA positioning (variability with manual positioning is larger) and sometimes on the overlap; μ_{abs} is less dependent from the investigated factors. The comparison of data obtained with the thick and the thin foams showed that measurement dispersion is larger (at most 10%) with poorly absorbent materials. Such an issue – that is generated by a larger effect of the independent variables and not by a larger data dispersion, as later pointed out – is not critical: in presence of very reflective

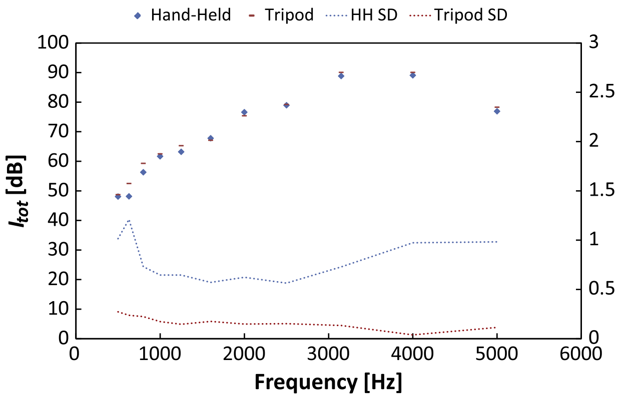

Fig. 4. Average values (Points, primary *Y* axis) and standard deviation (dotted lines, secondary *y* axis) of hand-held and tripod tests.

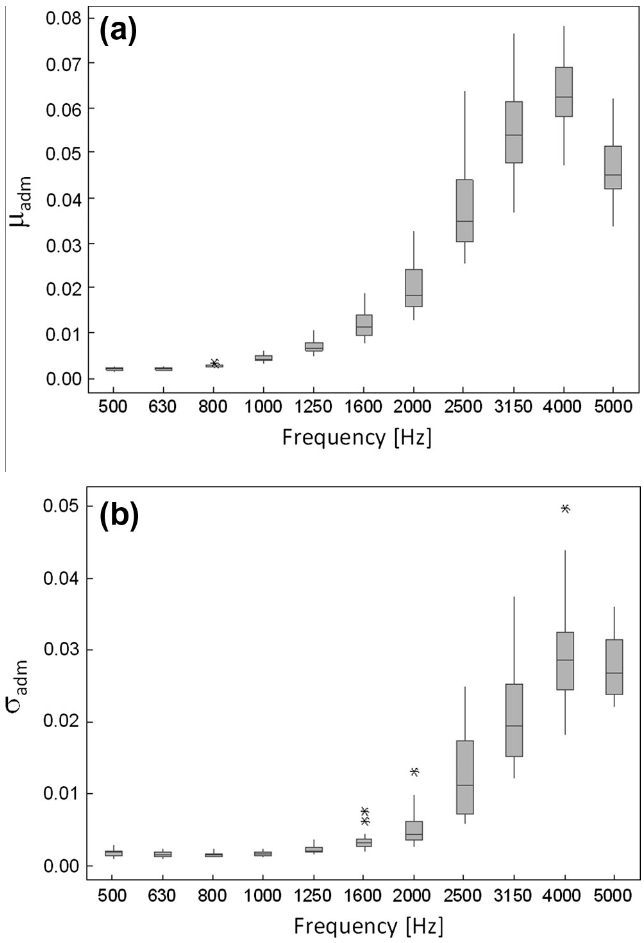

Fig. 5. Spatially averaged admittance modulus (top) and admittance modulus local variability (bottom).

surfaces, the I_{sc} is almost equal to I_{inc} and, consequently, I_{rad} is equal to I_{tot}.

ANOVA *P*-values showed that all the three independent variables affect the measured surface properties, although effects are not systematic and depend on the frequency. The accuracy of the linear regression model was satisfying (ANOVA hypotheses on the residuals always verified and R^2 was larger than 0.7) but the coefficients varied for the thin and the thick foams. The usefulness of the regression model is therefore limited and it was chosen not to include the regression results in the paper. The factor with the largest influence on the measured surface properties was the loudspeaker position, which influenced both μ_{adm} and μ_{abs} at frequencies larger than 1000 Hz on the thick foam and between 1000 and 4000 Hz on the thin foam. The dependence of μ_{adm} and μ_{abs} from the loudspeakers position was investigated by analyzing the sound pressure and the I_{tot} generated by the loudspeakers used during the SPM. Results (Fig. 7) shows the non-uniform pressure distribution obtained with the asymmetrical configuration, that may be among the causes of the poor estimation of the surface characteristics, as discussed in Section 4.

The effect of overlapping was investigated with the boxplots of μ_{adm} and μ_{abs} (Figs. 8 and 9); results showed that a large superposition of the DLA in consecutive measurements usually grants a superior repeatability and, consequently, an overlap of two or three rows of microphones is suggested. Also the use of tripod (coherently with what was found in the repeatability and reproducibility tests) reduces the data dispersion and has to be preferred to the hand-held positioning. The influence of

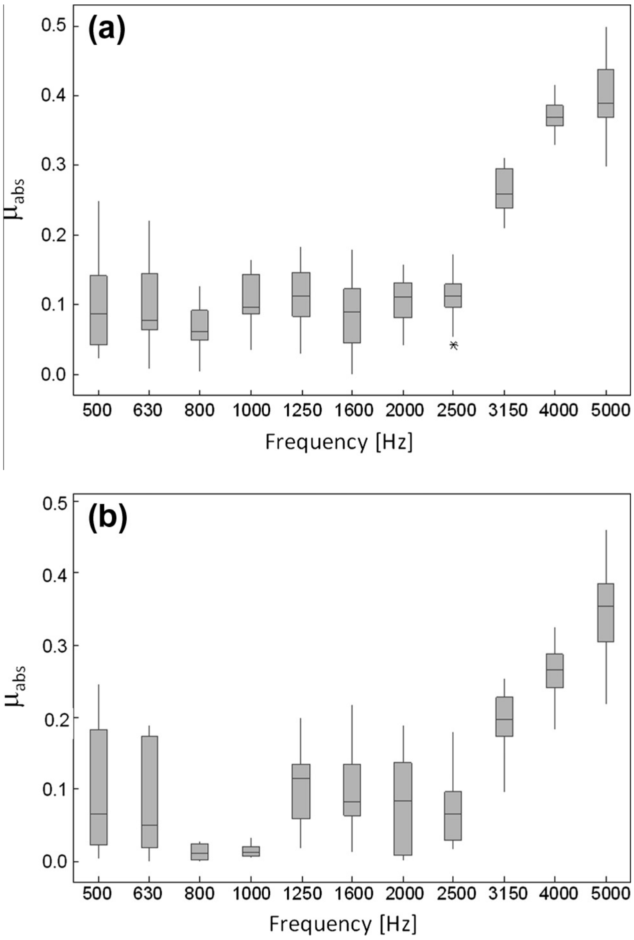

Fig. 6. Average absorption coefficient on the upper (a) and on the lower (b) half of the panel.

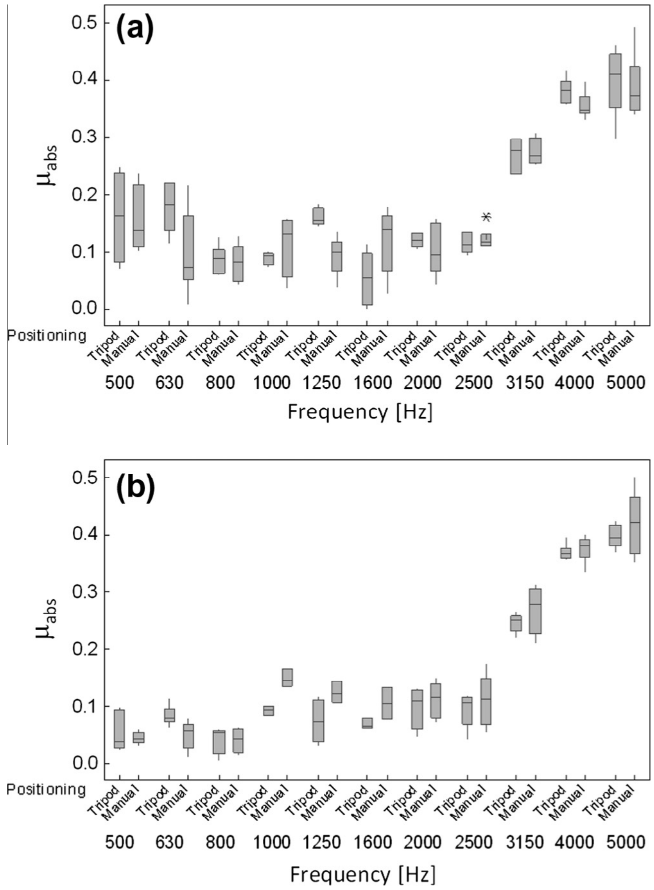

Fig. 8. μ_{abs} Boxplots (thin foam) with low (a) and high (b) overlap. The lower data dispersion below 1 kHz in plot (b) is evident, as the difference between tripod and hand-held array at high frequency in plot (b).

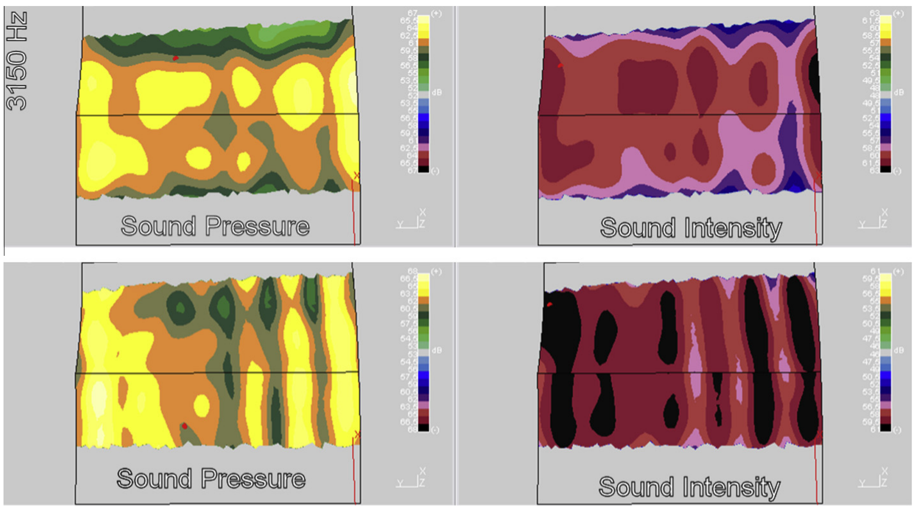

Fig. 7. Sound pressure and I_{tot} at 3150 Hz generated by the loudspeakers in the symmetrical configuration (row 1) and in the asymmetrical configuration (row 2). One can notice the non-uniform pressure distribution that probably leads to a different admittance estimation.

overlapping on σ_{adm} and σ_{abs} is larger than the influence of overlapping on μ_{adm} and μ_{abs}. The difference between the average values in parts a and b of Figs. 8 and 9 can be attributed to the different areas observed with high and low overlap. Admittance differences are particularly evident at 5 kHz, where the effect of tests reproducibility and local admittance variations may be not negligible; as later explained, these effects are included in the uncertainty budget.

U_{abs} and U_{adm} (the uncertainties of the absorption coefficient and of the admittance) were estimated through the standard deviation of tests performed under repeatability and reproducibility conditions. The latters, in absence of systematic errors, are

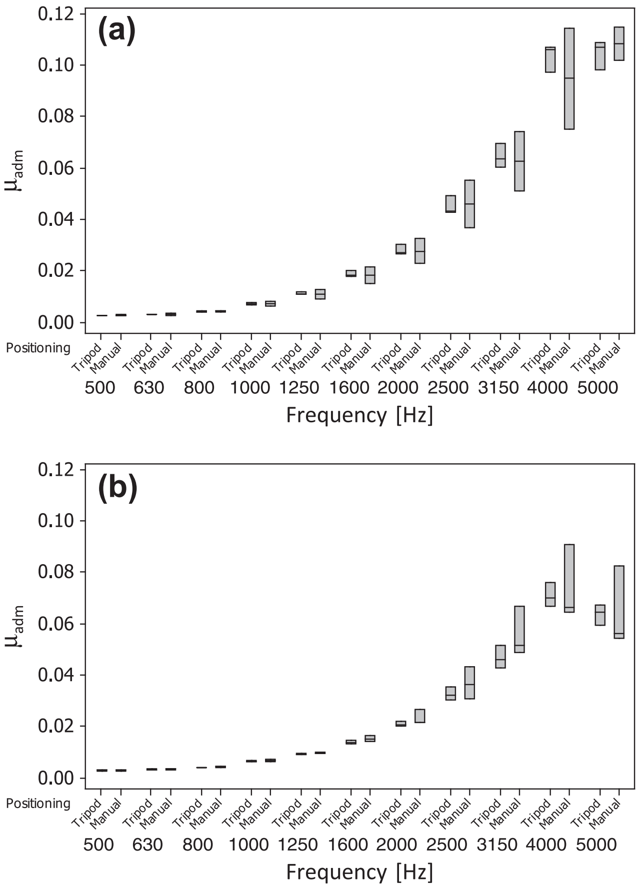

Fig. 9. Boxplots of the admittance modulus (thick absorbent foam) with the symmetrical loudspeaker positioning with low (a) and high (b) overlap. The lowest data dispersion at high frequency obtained with the tripod positioning and high overlap is evident.

unbiased estimators of the measurement uncertainty as per A zapproach of the ISO-GUM [13]. The overall U_{abs} including all the tested measurement conditions was 0.05 (the absorption coefficient values ranged between 0.07 and 0.40). The lowest measurement uncertainty was obtained using tripod positioning and high overlapping; in these conditions, U_{abs} was 0.02. Similarly, the average U_{adm} including all the tested measurement conditions was 0.006 m^3/Ns, with the admittance ranging between 0.003 and 0.08 m^3/Ns. Also in this case the lowest uncertainty was obtained with tripod positioning and high overlapping; in these conditions U_{adm} was 0.002 m^3/Ns. The lowest relative uncertainties were respectively 12% (absorption coefficient) and 8% (admittance).

3.3. Influencing parameters in operational measurements

The first ANOVA investigated the effect of the SPM repeatability and background noise on I_{rad}. Results evidenced that the SPM repeatability does not affect I_{rad}, while the effect of I_{inc} is systematic (P-value = 0 at all the frequencies). The second ANOVA was performed to analyze the effect of the DLA overlapping, positioning method and I_{inc} level. Also in this case, the effect of background noise was systematic (P-value = 0 at all the frequencies). The overlap and the DLA positioning affected the measurement from 500 to 3150 Hz; outside from this range, the effect was not systematic.

Results of the two ANOVAs evidenced that it is not possible to identify the radiated intensity if the latter is much smaller than the total intensity and that the effect of the I_{inc} level is by far superior with respect to the array positioning method and overlap. The comparison between I_{rad} measured with high and low I_{inc} shows that both the local I_{rad} values (Fig. 10) and in the averaged values (Fig. 11) are biased if I_{inc} is too large.

Owing to the two-level factorial design and to the large difference between the "low" and "high" I_{inc} levels, it was not possible to determine the maximum incident noise that still allows correct measurements. I_{rad} measurement accuracy is limited if the hypotheses of the proposed approach (locally reacting surface for correct admittance-based measurements, incoherent incident and emitted sound fields for absorption-based measurements) are not fulfilled. The limitations deriving from these two hypotheses were verified through tests performed increasing the incident background noise with the "one factor at a time" approach [15]. I_{inc} modified I_{tot} in front of the shaker from 73 dB (reference condition) to 72 dB (L4), 68 dB (L3), 60 dB (L2), and 58 dB (L1). I_{rad} integrated on the calculation area is shown in Fig. 12. Plots show that I_{rad} is more accurately determined with the absorption approach, since levels up to L2 provide measurements that differ from the reference condition by less than 2 dB. The admittance-based test is more sensitive to the incident field (maximum error 6 dB). I_{tot} and I_{rad} measured with L2 I_{inc} level are shown in Fig. 13: although in these conditions the measurement error is larger than the test repeatability, the I_{rad} pattern is correctly identified (i.e. comparable to the one shown in Fig. 10(a)).

4. Discussion

Performances of the statistically optimal near-field acoustic holography for the measurement of the radiated intensity were tested in several configurations. The experimental results evidenced that the I_{tot} measurement repeatability is between 0.05 and 0.15 dB in the range 500–5000 Hz; the experiments reproducibility, in the same frequency range, was lower than 0.5 dB in the range 500–5000 Hz. In these tests, measurements performed with hand-held DLA were different from those performed with tripod mounting (average difference of 2 dB) and suffered from a larger variability (standard deviation up to 1 dB).

The uncertainty of the admittance – absorption coefficient mainly depends on the sound field used for the acoustical surface excitation; the I_{rad} uncertainty deriving from this factor can be estimated using more surface properties sessions performed with different incident fields. With an uncorrelated incident field, the absorption-based approach is less sensitive to background noise

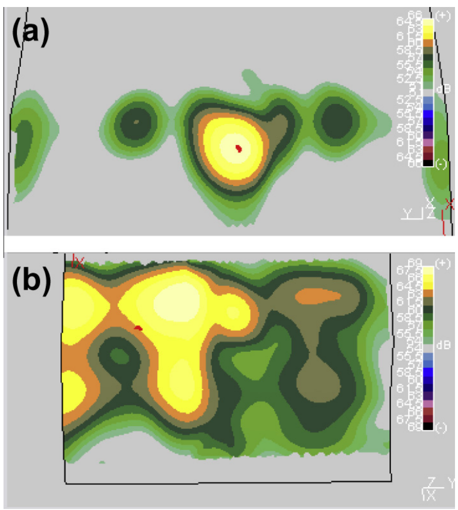

Fig. 10. Admittance based I_{rad} at 4000 Hz, measured with tripod positioning small overlap, low (a) and high (b) background levels.

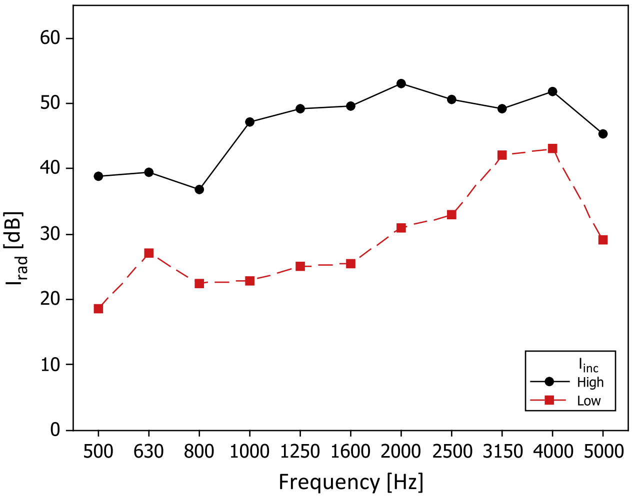

Fig. 11. Comparison between the I_{rad} with low and high background levels: the overestimation occurring with the high I_{inc} level is evident.

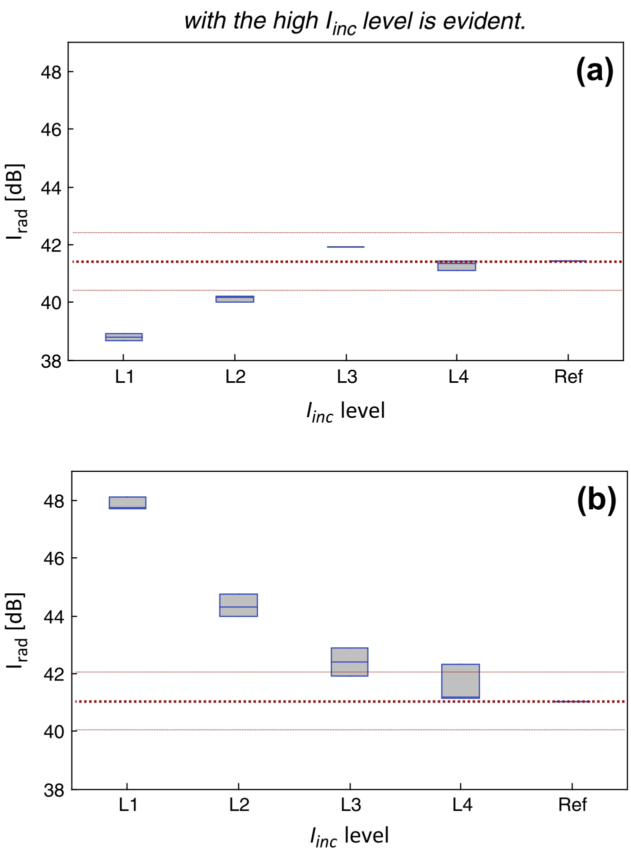

Fig. 12. Dependence of absorption-based (a) and admittance-based (b) I_{rad} from the incident noise level. The horizontal lines indicate the reference value ± the experiment reproducibility.

than the admittance one. Performances with correlated sound fields were not verified.

4.1. Repeatability

The lowest measurement uncertainty boundary is the measurement repeatability that, according to our tests, was lower than 0.05 dB between 500 and 5000 Hz. This value represents the total intensity measurement uncertainty whenever the DLA position is

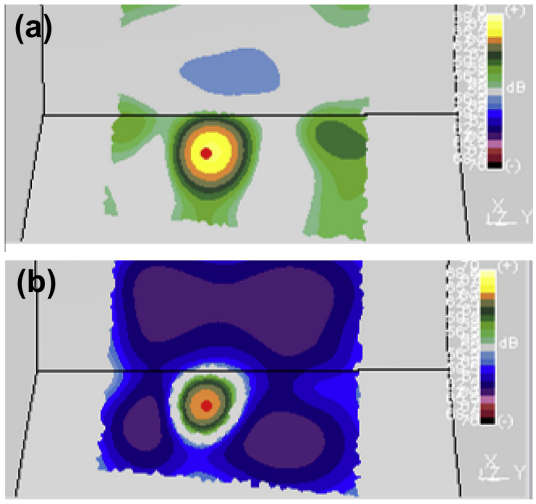

Fig. 13. Comparison between the radiated intensity (a) and the total intensity (b) (L2 condition).

stable during the measurement. The lower boundary of experiments reproducibility was 0.3 dB: this value indicated the expected difference between two nominally identical total intensity measurements performed in the best possible conditions. The reproducibility of intensity measurement performed with hand-held DLA was 2 dB, a value that can be often tolerated in common acoustic measurements.

Differences between hand-positioning and tripod measurements are due to the displacement of the DLA during the data acquisition and to the sound field modification due to the vicinity of the human body to the vibrating plate. Results are consistent with the ones obtained from simulations performed in the instrument design phase [5], which evidenced that the array positioning errors affected the measurements especially above 1500 Hz. An index of the measurement quality, under this perspective, is given by the DLA displacement during the data acquisition, that is a parameter that can be derived from the DLA optical position measurement system. The repeatability of hand-held tests was lower than 0.8 dB (typical values 0.2–0.4 dB) and a difference of 1.9 dB between tripod and hand-held tests indicated a non-negligible effect of the operator body. Results were independent from the panel geometry and from the surface absorption characteristics.

4.2. Absorption coefficient

Experimental results evidenced that, in the tested conditions, the average admittance and absorption coefficient uncertainties were respectively 8% and 12% using a symmetrical loudspeakers and tripod DLA positioning and approximately twice larger with asymmetrical loudspeaker configuration and hand-held DLA. It is therefore desirable in SPM to create a uniform incident field, that is the one granting an optimal signal to noise ratio on the surface. A possible method to estimate the effect of SPM uncertainty is the estimation of the surface characteristics using more loudspeaker configurations. Different radiated intensity estimations can be determined using the different surface properties identified with the different loudspeakers configurations. The I_{rad} variability is indicative of the uncertainty deriving from the surface properties.

Results obtained with a tripod positioning are generally more repeatable than the hand-held DLA ones; the mean value with the two supporting methods, though, is independent on the positioning (differences comparable to the measurement repeatability). Results were found to be more repeatable with a high overlapping, especially at low frequencies. Conclusions were similar with the two tested absorbing materials, indicating that results do not depend on the particular experimental setup. Conversely, the ANOVA regression model differed from panel to panel, showing that a systematic compensation of errors is not possible.

The reliability of I_{rad} measurements can be quantified using the measurement uncertainty. The latter can be computed, for instance, using different surface property estimations using the A approach of the ISO GUM. If the I_{rad} computations based on different surface property estimations are compatible (differences smaller than the reproducibility of experiments), I_{rad} is equal to the one measured with $I_{inc} = 0$ and, consequently, is correctly estimated. A snapshot of the components of I_{rad} uncertainty can be easily obtained considering that I_{rad} with the absorption approach is computed subtracting the incident-scattered intensity from I_{tot}. The combined uncertainty is therefore

$$U_{Irad} = \sqrt{U_{Itot}^2 + (I_{inc} \cdot U_{\alpha})^2 + (\alpha \cdot U_{Iinc})^2} \quad (1)$$

Uncertainties of Eq. (1) have been determined in the experiments described in Section 3. The uncertainty of the radiated intensity computed as per Eq. (1) is shown in Fig. 14: the plot shows that measurement accuracy depends on the combination between the incident intensity and the absorption coefficient. In particular, the uncertainty is nearly insensitive to the absorption coefficient if I_{inc} is much smaller than I_{rad}. Conversely, if the incident intensity is comparable or larger than I_{rad} measurements are more accurate if the absorption coefficient is small. In this case, the incident intensity is almost equal to the scattered intensity and $I_{rad} = I_{tot}$.

Another way to assess the reliability of result is the creation of an artificial incident sound field in operational condition, in addition to the real incident sound field already existing. If I_{rad} measured with the artificial incident field is compatible with the original one, then the method is correctly suppressing the background noise contribution. This approach, however, requires additional investigation and its study is deserved to forthcoming works.

Based on the above considerations, a correct I_{rad} measurement procedure has to be performed as follows:

i. Repetition of SPM sessions with different loudspeakers positions, with the DLA mechanically positioned (tripod or robot) and with a patch overlap of two or three rows;
ii. OM performed with a mechanical positioning of the DLA and with a large overlap;
iii. I_{rad} computation with both the admittance and the absorption based approaches, on the basis of the estimations of the surface properties obtained at point (i);

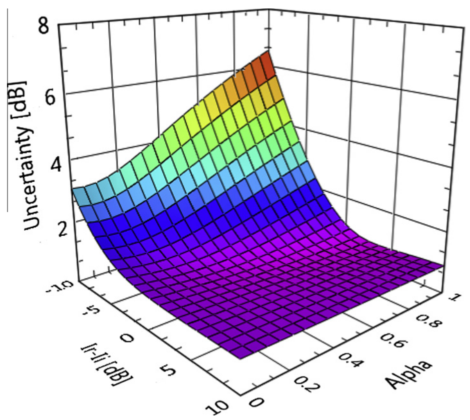

Fig. 14. Radiated intensity uncertainty estimated using Eq. (1) and results described in Section 3 (absorption-based method). Uncertainty is plotted versus the incident intensity level and surface absorption coefficient.

iv. Computation of I_{rad} as per ISO GUM A approach: the measurement is the average of I_{rad} computed at point (iii); if I_{rad} is larger than I_{inc} (i.e. if the measure is not affected by systematic errors), measurement uncertainty is the standard deviation of measurements computed at point (iii) divided by the square root of the number of tests repetition.

Results evidenced that when the difference between the admittance-based and the absorption-based I_{rad} is larger than the test repeatability, the measurement uncertainty can be evaluated using Eq. (1) starting from I_{rad} and I_{inc} estimated by SONAH.

5. Conclusions

This paper analyzed the accuracy of an indirect measurement principle for the identification of sound intensity radiated by vibrating panels. The different uncertainty components have been experimentally identified from tests performed in controlled acoustic conditions. Results evidenced that the method is accurate when the incident sound intensity is comparable with (or smaller than) the sound intensity radiated by the panel. When the radiated intensity is smaller than the incident one it is possible to compute I_{rad} as the average of different SPM (tests repetitions and, in some conditions, admittance/absorption approaches). This case, however, is generally not relevant, given that if the radiation of a surface is negligible with respect to the incident intensity, an accurate I_{rad} measurement is mostly an academic exercise.

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References

[1] Di Sante R, Martarelli M, Revel G, Tomasini E. Application of near-field acoustic holography in presence of high temperature gradient: experimental uncertainty analysis. Proc SPIE – Int Soc Opt Eng; 2002.
[2] Di Giuseppe A, Martarelli M, Revel GM, Tomasini EP. Experimental sensitivity analysis for near-field acoustic holography. Proc Int Conf Noise Vibr Eng 2002:1799–807.
[3] Hald J. Patch near-field acoustical holography using a new statistically optimal method. In: Proceedings of internoise 2003. Jeju, Korea; 2003. p. 2203–10.
[4] Hald J, Gomes J. A comparison of two patch NAH methods. In: Proceedings of internoise 2006, vol. 8. Honolulu, USA; 2006. p. 5628–37.
[5] Moschioni G, Saggin B, Tarabini M, Hald J, Morkholt J. Use of design of experiments and Monte Carlo method for instruments optimal design. Measurement 2012;46:976–84.
[6] Moschioni G, Saggin B, Tarabini M. 3-D sound intensity measurements: accuracy enhancements with virtual-instrument-based technology. IEEE Trans Instrum Measure 2008;57:1820–9.
[7] Hald J. Basic theory and properties of statistically optimized near-field acoustical holography. J Acoust Soc Am 2009;125:2105.
[8] Yang C, Chen J, Li J, Xue W. Simulation and experimental investigations for the patch near-field acoustical holography. Proc Inst Mech Eng Part C 2008;222:945–53.
[9] Steiner R, Hald J. Near-field acoustical holography without the errors and limitations caused by the use of spatial DFT. Int J Acoust Vibr 2001;6:83–9.
[10] Hald J, Morkholt J, Hardy P, Trentin D, Bach-Andersen M, Keith G. Array based measurement of radiated and absorbed sound intensity components. In: Proceedings of EuroNoise; 2008.
[11] Hald J, Nielsen F, Blaabjerg C. Patch NAH for noise source mapping in cabin environments. In: Proceedings of SAE noise and vibration conference and exhibition; 2005.
[12] BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, OIML. International Vocabulary of Metrology–Basic and general concepts and associated terms (VIM), JCGM 200: 2008, ISO/IEC Guide 99, 2008. <www.bipm.org/publications/guides/vim.html>.
[13] ISO GUIDE 98 part 3. Guide to expression of uncertainty in measurements (GUM 1995). International Organization for Standardization; 2008.
[14] Montgomery DC. Design & analysis of experiments. 5th ed. John Wiley; 2000.
[15] Doebelin E. Measurement systems: application and design. 5th ed. McGraw Hill; 2004.