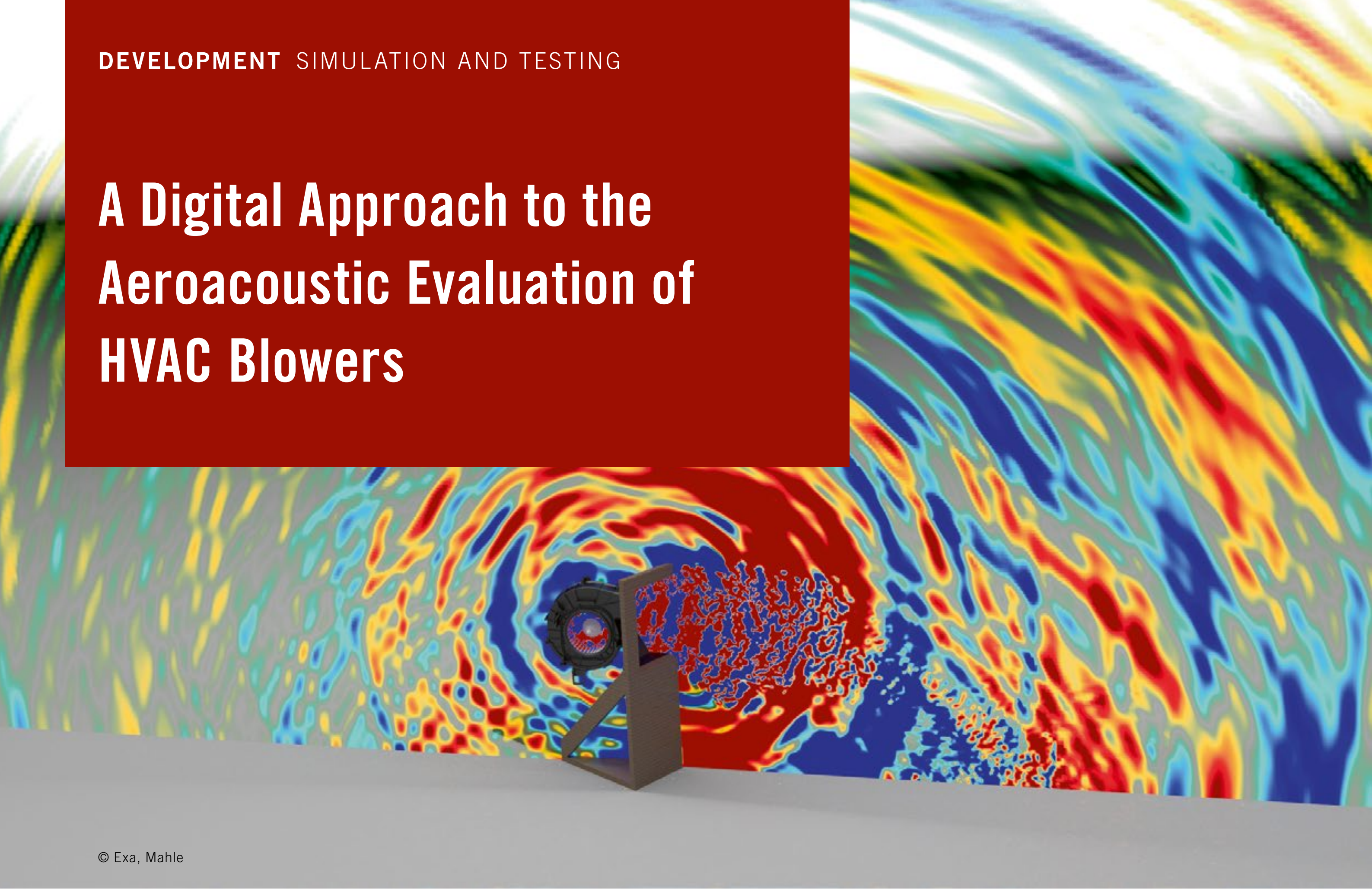
A Digital Approach to the Aeroacoustic Evaluation of HVAC Blowers



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OEMs are increasingly focusing on the acoustic efficiency of components and subsystems in search for an overall reduction of the main noise contributors in passenger cars. This is particularly true with rotating machinery. Exa Corporation and Mahle Luxembourg investigated the prediction of an automotive HVAC module blower using a three-dimensional compressible and unsteady Computational Fluid Dynamics (CFD) solver based on the Lattice-Boltzmann Method.

TACKLE THE EXPERIMENTAL CHALLENGES

Experimental methods have been used historically with trial-and-error approaches to reduce the most obvious noise sources, eventually producing sufficiently quiet products. But they have also shown limitations such as lengthy testing phases, expensive prototypes, and mechanical and aerodynamic constraints. Applying a digital approach can help address these challenges, while offering a clearer understanding of the noise generation mechanisms so that efficiency can be further improved.

Exa PowerFlow, a transient and compressible CFD solver based on the Lattice-Boltzmann Method (LBM), has been used to digitally predict noise levels of HVAC subsystems [1]. Focus here is on the first phase of this implementation: the numerical evaluation of flow-induced noise radiated by HVAC blower units, and the solver ability at locating the noise-generating flow features.

BUILDING CONFIDENCE IN THE DIGITAL PROCESS

The overall goal of the project is to validate the predictability of the aeroacoustic performance of an HVAC module using simulation results. Many factors can interfere with accuracy when comparing experimental and simulation results, especially the differences between the real-world geometry of the tested product compared to its nominal Computer-Aided Design (CAD). As aeroacoustics is sensitive to fine geometry details, an approach focused on a less complex subsystem to validate the numerical method can reduce uncertainties. The first phase of the project thus focuses on noise predictions for an HVAC module blower mounted on a simplified bench, which consists of a centrifugal wheel rotating in a scroll and blowing into a diffuser expansion.

The experimental environment follows ISO 3744 [2]. A standard diffuser is attached at the outlet of the scroll and the system is mounted on a simplified support.

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Ten equally spaced microphones are placed on a 2-m radius hemisphere centred on the bench, **FIGURE 1**; they are used to record pressure histories and to compute Sound Pressure Levels (SPLs) and Sound Power Level (SWL).

The experimental SWL spectrum is plotted in **FIGURE 2**. A Blade Passing Frequency (BPF) peak at 1700 Hz is clearly visible on the spectrum but the main contributions to overall noise levels and acoustic power come from broadband noise. Four main humps in the spectrum are visible, around 450, 900, 1500, and 2050 Hz. The highest noise level happens at the second hump, at 840 Hz, higher than the BPF peak.

As the tested module is a production part, the complete CAD data is available for the entire system. All details are kept during the preparation of the surface mesh, while additional features are manually added to account for discrepancies with the tested model. The bench is modelled as well and the whole system is placed in a large hemi-anechoic (reflective floor) simulation domain. The rotational speed of the blower is set to 2500 rpm, same as in experiment. The rotating blower wheel is handled using a Local Reference Frame (LRF) domain, which is separated from the fixed outer domain by a closed interface. This sliding mesh LRF scheme has been validated in multiple studies [3]. A Variable Resolution (VR) regions strategy following best practices is adopted, with specific regions defined around the blower to capture all flow-induced noise-generating mechanisms. Local resolution at the microphone locations is set to ensure the propagation of acoustic waves up to 5 kHz [4].

Simulations based on LBM simultaneously resolve flow and acoustic field. Acoustic waves generated in the source regions are propagated to the far-field, and pressure histories at the microphone locations can be recorded directly. Experimental and simulation SWLs are derived from the SPLs computed using the ten microphones pressure signals. Acoustic pressure time series at microphones are here computed two ways:

1. Directly recorded at the microphone locations. Acoustic waves generated by the flow are propagated by the LBM solver to the microphone locations.
2. Calculated using an acoustic propagation solver based on a Ffowcs-Williams and Hawkings (FW-H) method [5]. The FW-H method can help at verifying any direct propagation limitation from directly propagated simulated waves.

A good agreement is observed between experimental and simulated direct acoustic power levels, **FIGURE 3**, with predictions within ± 2 dB(A) accuracy in 1/3rd octave bands between 250 and 1250 Hz. Variations are visible below 250 Hz, potentially explained from the use of short signals for the spectral processing of simulation results. Above 1250 Hz, the predicted results are underestimated by 2 to 3 dB(A), still in acceptable agreement with experiment. While predicted SWL using the direct approach or the FW-H method is very similar in the mid-frequency range, the most significant change is the improvement of the high frequency levels. The predicted acoustic power spectrum using the FW-H method shows a very good accuracy within 2 dB(A) of experiment from 250 Hz up to 4 kHz, validating the ability

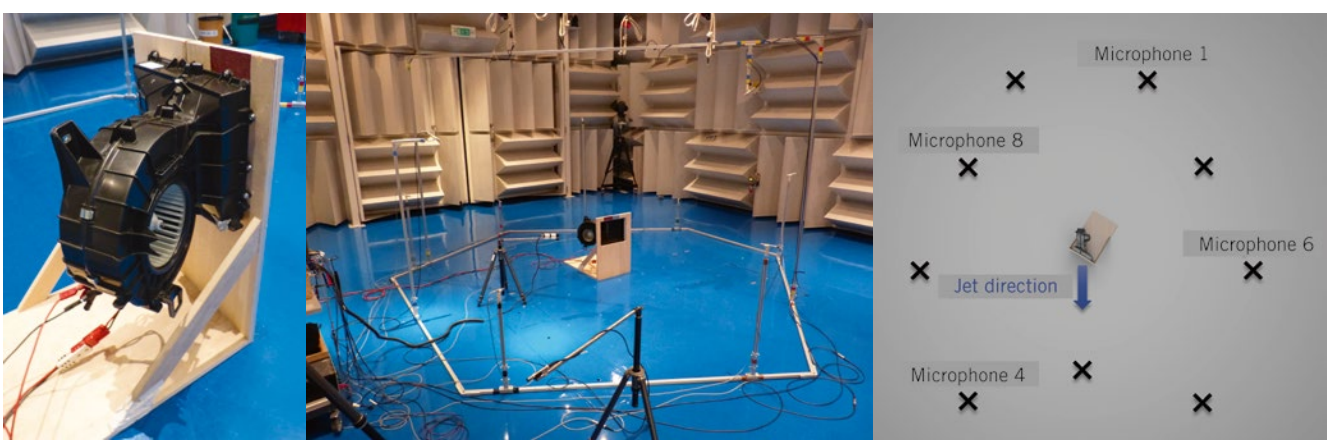
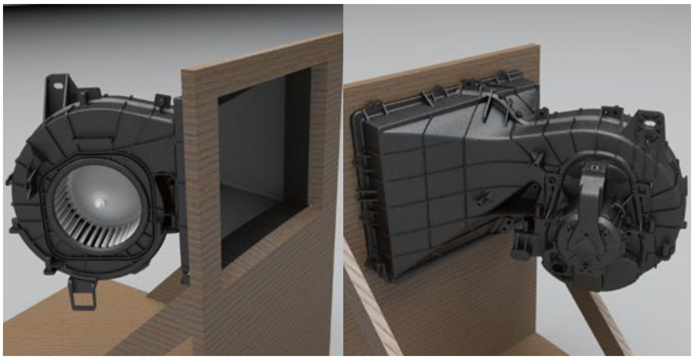


FIGURE 1 Experimental setup (left and centre) and microphones position seen from top (right) (© Exa, Mahle)



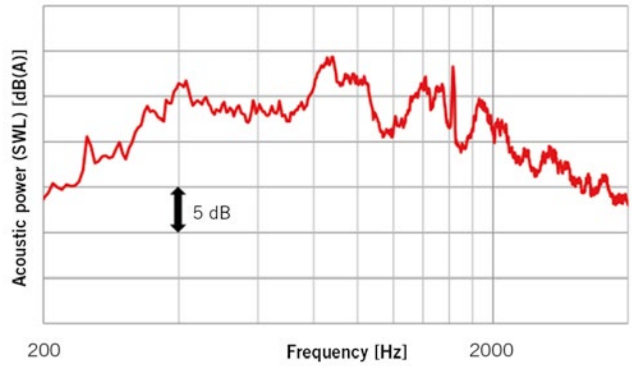


FIGURE 2 Numerical model (left) and experimental acoustic power spectrum (right) (© Exa, Mahle)

of the solution at predicting accurately the performance of the sub-system.

The analysis of the SPLs in **FIGURE 4** shows a strong directivity based on the location of the microphones. Direct simulation results at high frequencies for the microphones on the opposite side of the jet are underpredicted from 4 to 5 dB(A). However, the accuracy is better for the lateral microphones, and the microphone on the jet side shows the best accuracy, within 2 to 3 dB(A) of experiment up to 3 kHz. Moreover, the comparison of predicted SPLs using the FW-H method and experiments shows an overall improved agreement at high frequencies, especially for microphones located on the opposite side of the jet. The FW-H method can then help at alleviating the limitations of the direct approach for far-field microphones.

Overall, this study demonstrated that the simulation results can accurately predict noise levels at the microphones location, bringing confidence for the capture of the noise-generating flow features and enabling analysis of the noise mechanisms to improve the module design. Further improving the accuracy is possible, but the associated complexity in terms of computational cost and of assessment of all experimental uncertainties makes it very challenging and not suitable for a production environment.

LEVERAGING NOISE SOURCE INSIGHTS TO IMPROVE DESIGN

As observed in **FIGURE 3**, the acoustic power spectrum in narrow bands shows that the main noise contributors are in the 750 to 1050 Hz frequency range. The Flow-induced Noise Detection (FIND) method [6] can then be used to identify the broadband noise sources associated to this frequency range to target relevant design features.

Three main noise-generating regions are identified in **FIGURE 5** from isosurfaces of acoustic power volume density, a quantity measuring the acoustic power radiated by sources within each measurement cell: the region located between the motor cooling channel entrance and the scroll cut-off, at the bottom of the wheel; the region located at the inlet of the scroll; and the region located between the wheel and the scroll below the cut-off (1, 2 and 3 in **FIGURE 5**).

These three noise-regions are associated respectively to three flow mechanisms illustrated in **FIGURE 6**:

1. The cooling channel entrance causes a flow stagnation region topped by high velocity. Turbulence is then generated and convected towards the blower neck below the wheel. Turbulence from the blade wake is also pushed towards the bottom of the wheel and a strong turbulence mixing happens in this region.
2. At the tip gap of the wheel, close to the blower neck, a flow recirculation between the blades generates high level turbulent mixing.
3. Turbulence mixing of the blades wakes hits the blower neck.

As three major noise-generating regions have been identified, the design of the module could be improved by modifying the relevant geometry features. For example, the cooling channel design entrance could be modified to reduce the local flow stagnation and associated turbulence generation, and changes in the bottom blades design and wheel gap size could help at reducing noise levels.

A DIGITAL HVAC SYSTEMS ACOUSTIC FACILITY

A computational approach based on LBM was applied to simultaneously recover the turbulent flow and the corresponding acoustic field of an HVAC module blower. The validation of predicted noise levels against experimental data provided confidence in the accuracy of the digital solution so that it can be used in the production process.

Leveraging the recorded simulation data, additional post-processing provided invaluable insight in the noise sources mechanisms responsible for flow-in-

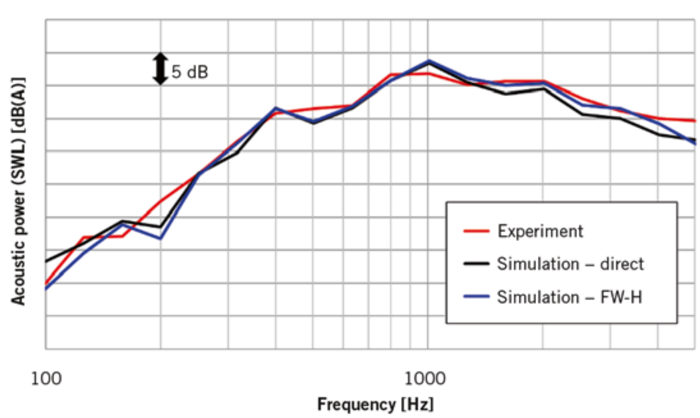


FIGURE 3 Acoustic power spectrum: experiment, direct prediction and FW-H (© Exa, Mahle)

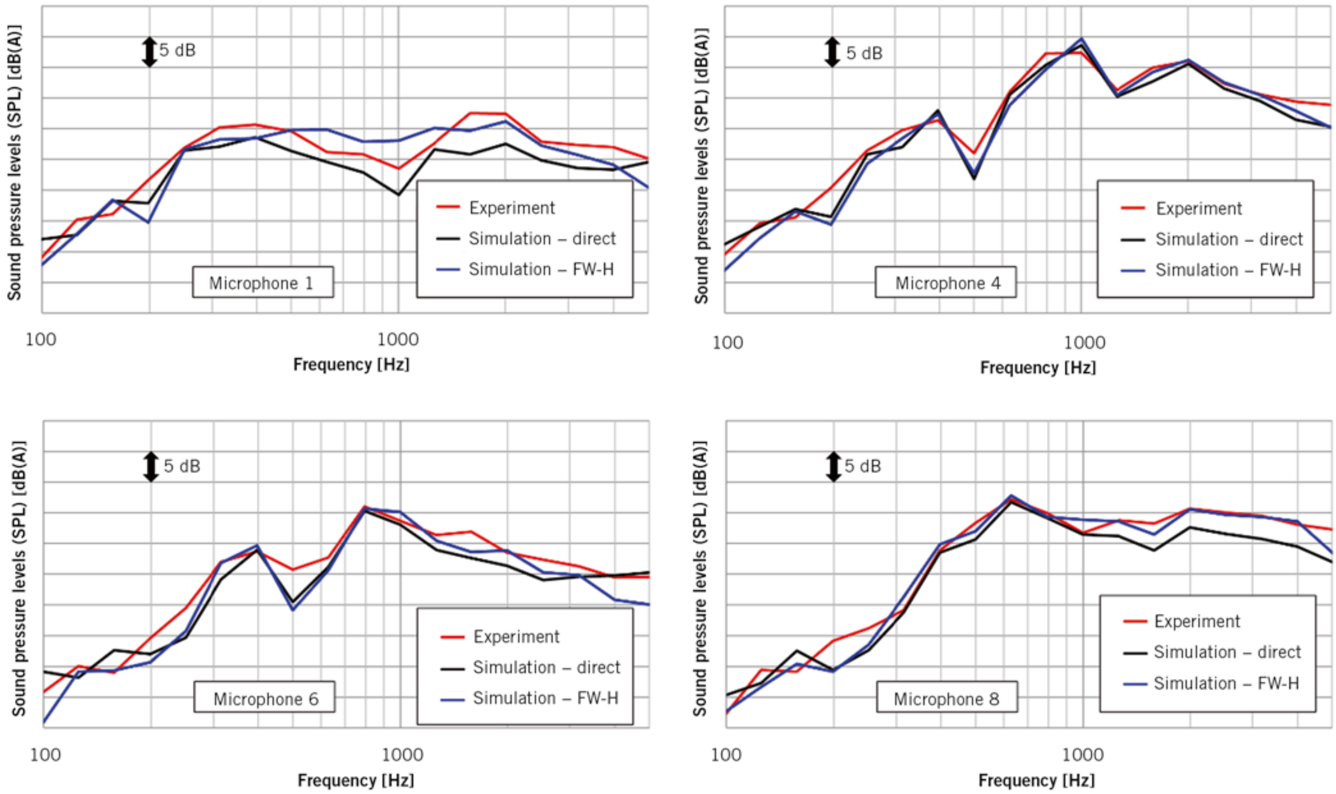


FIGURE 4 Sound pressure levels at four microphones: experiment, direct prediction and FW-H (© Exa, Mahle)

duced noise. Consequently, it enabled a more efficient acoustic design process for HVAC systems focused on noise-generating design features.

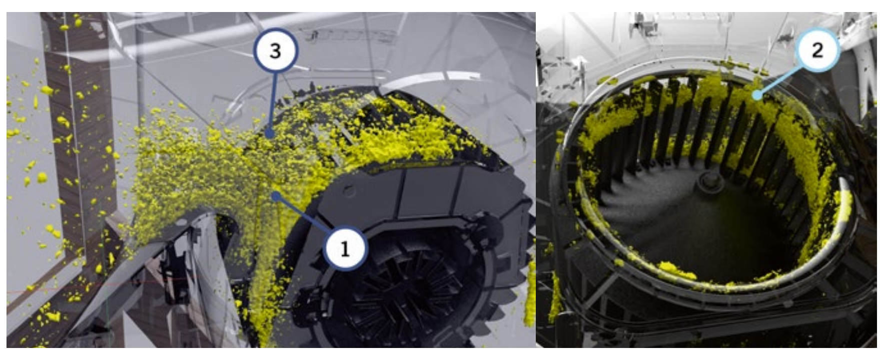


FIGURE 5 Acoustic power volume density isosurfaces identifying three main noise-generating regions (© Exa, Mahle)

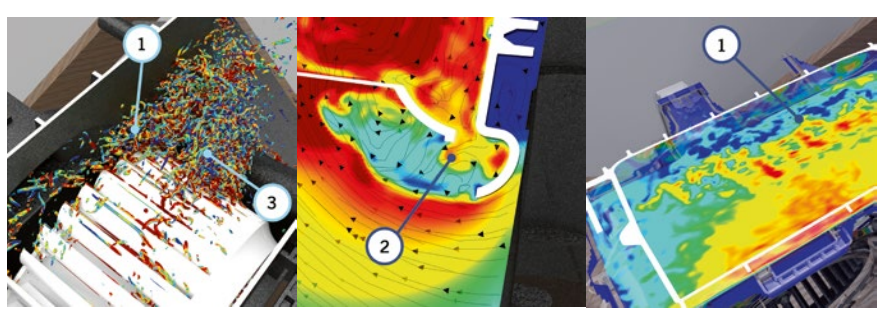


FIGURE 6 Flow visualisation illustrating flow mechanisms correlating with identified noise sources; lambda 2 isosurface coloured by vorticity magnitude (left) and velocity magnitude (centre and right) (© Exa, Mahle)

REFERENCES

[1] Le Goff, V.; Le Henaff, B.; Piellard, M.; Pihet, D.; Coutty, B.: Towards a Full Digital Approach for Aeroacoustics Evaluation of Automotive Engine Cooling Fans and HVAC Blowers. Fan 2015, Lyon, France, 2015

[2] ISO 3744: Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Engineering methods for an essentially free field over a reflecting plane. Dissertation, 2010

[3] Piellard, M.; Coutty, B.; Le Goff, V.; Pérot, F.; Vidal, V: Direct aeroacoustics simulation of automotive engine cooling fan system: effect of upstream geometry on broadband noise. 20th AIAA/CEAS Aeroacoustics Conference, Atlanta, GA, 2014

[4] Brès, G. A.; Pérot, F.; Freed, D.: Properties of the Lattice Boltzmann Method for Acoustics. 15th AIAA/CEAS Aeroacoustics Conference, Miami, Florida, USA, 2009

[5] Brès, G. A.; Pérot, F.; Freed, D.: A Ffowcs Williams-Hawkings Solver for Lattice Boltzmann Based Computational Aeroacoustics. AIAA Paper 2010-3711, of the 16th AIAA/CEAS Aeroacoustics Conference, Stockholm, 2010

[6] Mann, A.; Pérot, F.; Meskine, M.; Kim, M. S.: Designing quieter HVAC systems coupling LBM and flow-induced noise source identification methods. 10th FKFS Conference, Stuttgart, Germany, 2015