MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

A Simulation and Diagnosis of Flow Induced Duct Noise

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ABSTRACT

For the comport quality of vehicle, reduction of noise radiated from HVAC system has been requested for years and the demands are increasing due to recent trend of electrification of vehicle which is typically quieter than that of ICE. Large contribution to the HVAC noise is typically coming from flow induced noise of which source is generated at fan(s) and/or wall(s) of the HVAC. One of the ways to predict the HVAC noise is to solve it by compressible CFD directly. However, in such case, it is difficult to diagnose the acoustic characteristics how the acoustic wave propagates through the HVAC casing and is amplified by the acoustic modes since the acoustic response is likely masked by the hydrodynamic response. Knowledge of acoustic characteristics are sometimes helpful to find countermeasure to reduce those noise. This paper therefore solves the flow induced noise of a simple duct by the acoustic BEM based simulation utilizing the fluctuating surface pressure obtained by the incompressible CFD to be able to diagnose the acoustic characteristics. Some diagnoses are then performed such as the source area contribution to SPL at a microphone to investigate relationship of source and acoustic characteristics at the frequency of interest.

Keywords: Flow induced noise, duct noise, CAA, source contribution
I-INCE Classification of Subject Number: 26, 76

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1. INTRODUCTION

On HVAC development, noise is getting more of importance under the circumstance of being shifting to the electrification of car which typically makes the noise quieter than ICE vehicles so that the noise from an HVAC can be perceived by passengers. Most of the factors that determine the HVAC noise are induced by flow such as the noise generated from the fan(s) and the noise generated at the duct wall(s).

Those flow induced noise were difficult to solve in the past since describing the acoustic behaviour in CFD requires fine meshes which are in general computationally inefficient. The difficulty is getting resolving due to the recent availability of high performance computational resources [1]. However, it is still time consuming work. Hence number of iterations to find better designs is limited.

Diagnosis approaches are therefore requested to be able to efficiently do design exploration. One diagnosis approach is to visualize the noise source such as the Lighthill source [2] and the Powell source [3] based on CFD result using functionalities available in various CFD codes. But, for the HVAC application that includes duct, unlike free field propagation, acoustic path characteristic of the duct often affects much on the response due to acoustic scattering and/or diffraction within the duct, which aren't accounted for in the noise source visualization. For example, large noise source at inefficient location in terms of acoustic path doesn't contribute to noise radiation and vice versa.

In this paper, a simple duct is considered. A flow induced duct noise is predicted using a vibro-acoustic approach that utilizes CFD results. The accuracy of the vibro-acoustic modelling is shown by comparing against test. Also contribution spectra from partitioned source regions are plotted. The contributions are further investigated by separating factors of response into noise source and acoustic path.

2. DUCT MODEL

The duct model used in this paper is described in Figure 1. The duct model has 100mm x 100mm cross section and has inlet chamber in order to reduce turbulence at inlet side. The length of the duct including the chamber is totally 1150mm and the length of 100mm x 100mm cross section part is 500mm. First and second flow disturbances are placed at 225mm and 350mm away from the outlet side end of the duct, respectively. The flow speed is 15m/s. A microphone is placed at 150mm away from the duct outlet end with 45deg offset in order to avoid recording hydrodynamic pressure and to record only acoustic pressure in the measurement.

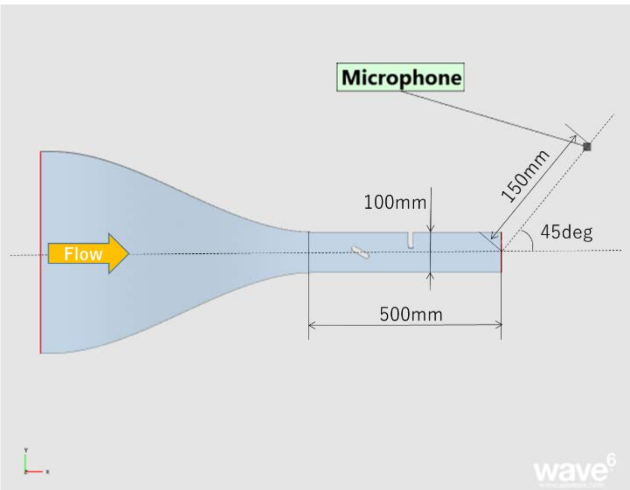

Figure 1. The duct model considered

3. SIMULATION MODEL

An objective of this study is to diagnose response in terms of noise source and acoustic path of the duct. For such diagnosing purpose, as it can separate response into noise source and acoustic path, it is typically suitable to use vibro-acoustic simulation together with acoustic analogy utilizing incompressible CFD results rather than solve it with compressible CFD directly. (The merit of separation approach isn't only for the diagnosis but also for a case in which interest is on noise absorption by sound treatment of which frequency dependent characteristic is complex.) Note here that as well known acoustic analogy approaches are only valid for the low Mach flow (i.e. $M<0.3$), but the HVAC application typically satisfies the assumption.

3.1 Vibro-Acoustic Model

The famous acoustic analogies are the Lighthill [2] and the Curle [4] / FW-H [5] approaches. The former one is volume based approach that is sometimes impractical to handle CFD data due to its huge data size, especially when solving system level model. Therefore, the latter surface based approach is often preferred because the CFD data to handle is drastically reduced compared to that required by the volume base approach. However, these surface based approach doesn't take into account scattering and/or diffraction effect at duct walls where noise source exists when used with incompressible CFD data, while the scattering and/or diffraction effect isn't negligible for the duct application.

In this paper, the non-compact acoustic analogy (NCAA) that can take into account the scattering and/or diffraction at the duct walls is employed, which is implemented in the commercial vibro-acosutic software "wave6" [6]. The NCAA is surface based method and used with BEM which accounts for the scattering and/or diffraction at the duct walls. Since it is the surface based acoustic analogy, it only requires fluctuating surface pressure (FSP) on the BEM surfaces for modelling noise sources. The BEM model is then solved with the sources on the wall. The pressure response solved by the NCAA is pressure difference between compressible and incompressible fluid like the acoustic perturbation equation [7], which can be typically taken as approximately acoustic component in many instances.

Figure 2 shows an overview of the model. The mesh size of the BEM model is 10mm such that the BEM model can solve up to frequency of interest. The NCAA sources are applied to the duct surface where the cross section is of 100mm x 100mm size. The inlet chamber is excluded from the NCAA source region because the FSP on the chamber is very small and negligible compared to that lies on duct surface.

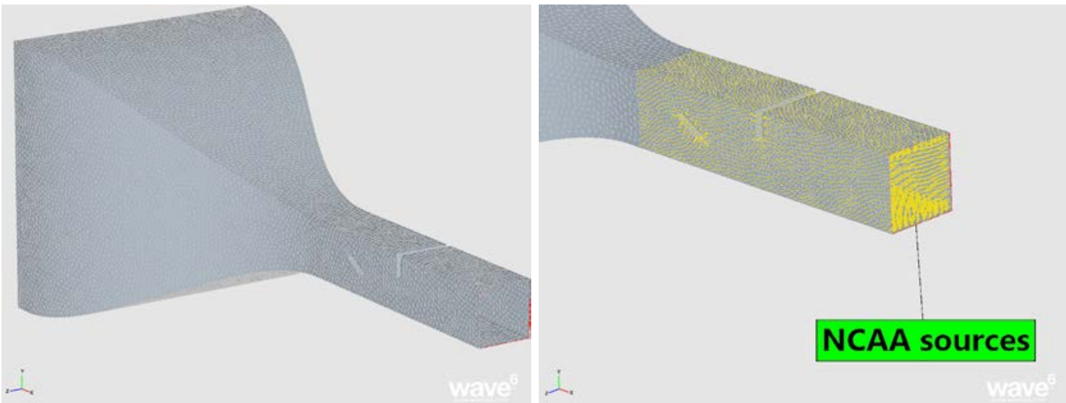

Figure 2. The BEM model (left) and source region (right)

3.2 CFD Results

Incompressible CFD solve is performed prior to the vibro-acoustic analysis using commercial CFD software "Star-CCM+". The CFD model is meshed with 1-2 mm polyhedral mesh size. Number of mesh of the CFD model is totally about 4 million. LES turbulence model is employed and 2nd order difference scheme is used for time and space. The CFD model is solved with time step of 1e-5 sec. An example of incompressible CFD results at particular second is shown in Figure 3. Only surface pressure data on the duct is exported to external file in time domain then it is imported into wave6 in which time domain data is converted to frequency domain data by performing FFT. Since the flow is random steady behaviour, Welch method is employed to calculated average response in wave6.

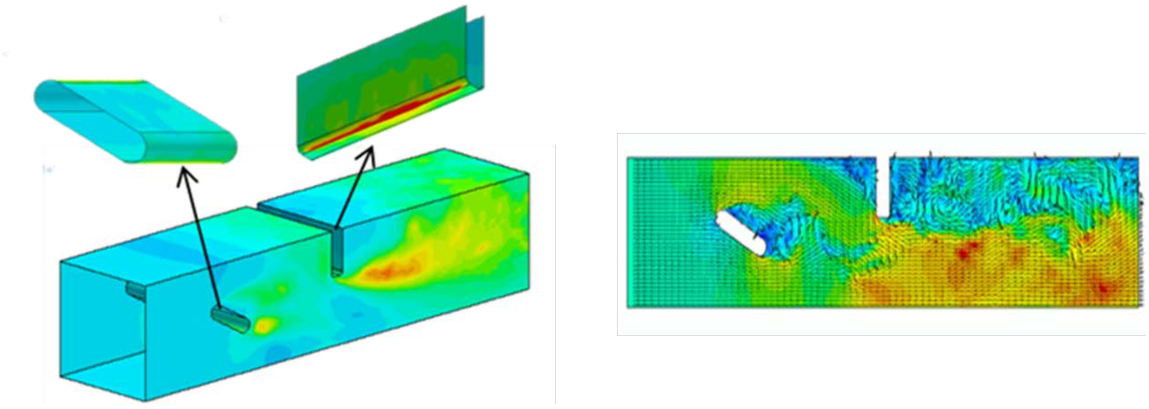

Figure 3. An example of CFD result at particular second. Left: surface pressure fluctuation of the duct. Right: velocity distribution at middle plane of the duct

4. DIAGNOSIS

4.1 Prediction Result and Contribution Spectra with respect to Source Regions

Prediction result using the model described in the previous sections is plotted in Figure 4 together with contributions from each source region illustrated in Figure 5. It can be observed that the NCAA model shows good agreement against measured data.

One might think that noise source region where high FSP is happening due to turbulence by the disturbances (i.e. FSP at first and second disturbances) would dominantly determine the SPL at the microphone. Indeed, as seen Figures 6-8, the first disturbance has high FSP at each frequency. But in Figure 4, contribution from the source region 1 is only contributing around 1.6kHz while the source region 2 and 3 are highly contributing at the other frequencies. This indicates that not only noise source level but also acoustic path character is important. That means that noise source identification isn't so useful for finding better designs on the flow induced duct application. Further diagnosis on these source region contributions is discussed in following section.

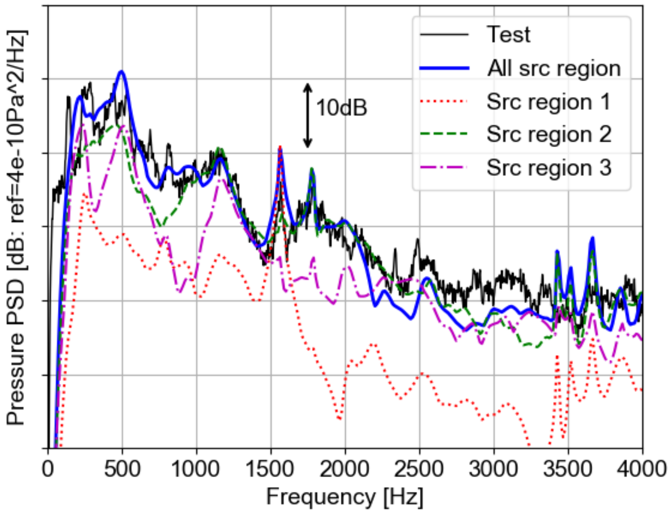

Figure 4. Measured and predicted SPL at microphone together with contribution plot from each source region defined in Figure 7.

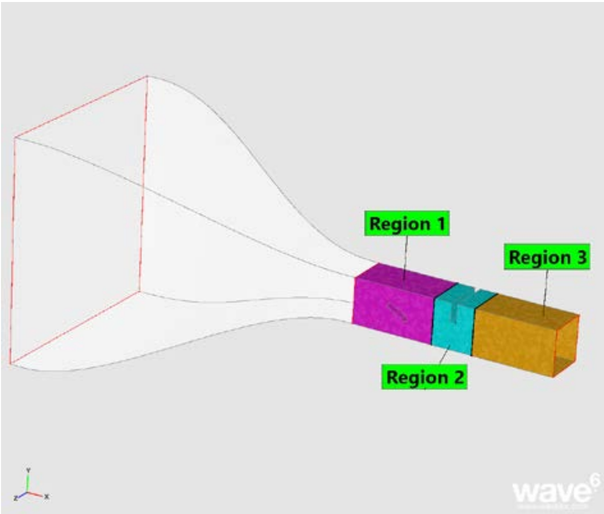

Figure 5. Source region partitioning

4.2 Source / Sensitivity / Contribution Maps

Noise response can be separate into noise source and acoustic path. These factors are plotted separately in Figures 6-8. The noise source of the NCAA used in this study is proportional to the FSP on the duct walls similar to the Curle acoustic analogy [4] hence FSPs on the duct walls are plotted as a value that represents the noise source level. Only amplitude is plotted for the FSP maps as the flow turbulence is random steady behaviour in which phase of FSP is typically negligible. (Note here that the FSP levels in the figures show those of being mapped with conservative approach thus the FSP levels aren't identical to those of CFD results). Acoustic path is represented as sensitivity maps using reciprocity relationship. The sensitivity maps are calculated on the BEM model by putting a monopole load with unit volume velocity at the microphone position then recovering the surface pressure result on the duct walls. The response of p/q (pressure over volume velocity) on the duct wall surface represents sensitivity of the noise source on the duct walls to SPL at the microphone. The sensitivity is solved deterministically such that both amplitude and phase are plotted. There can be seen values that passing zero phase value between –pi and pi in the phase maps of the sensitivities. This is just artificial value due to rendering. The true value of such region jumps from –pi to pi discontinuously. The contribution maps are calculated by multiplying the noise source map with the sensitivity map in abs value at each frequency. That means that phase cancellation isn't taken into account so that the contribution maps don't show exact contributions. Readers need to think of phase cancellation in their mind from the phase maps. All maps are plotted in 30dB range except the phase maps.

Figure 6 shows the results at 1577Hz where a peak with dominant contribution from source region 1 is observed in Figure 4. The peak is due to an acoustic resonance mode with a modeshape that has loop around first disturbance. (The modeshape is resembles to sensitivity map shown in Figure 6.) Due to the sensitivity map, noise source around first disturbance is strengthen and also noise sources at source regions 2 and 3 are weaken so that source region 1 contributes at this frequency.

Figure 7 shows the results at 2003Hz where contribution from source region 2 is high. Similar to the case of 1577Hz, contribution map is affected by the sensitivity map, but the phase of the sensitivity is much important in this case. Phase at tip of the second disturbance in the source region 2 (i.e. region where FSP is high at the second disturbance) is uniform while phase varies between zero and pi at the region where FSP is high in the source region 3 (i.e. region close to the partition between region 2 and 3). The phase variation leads cancellation of the noise source at the source region 3 therefore the contribution from the source region 3 becomes small although the amplitude of the contribution is high in Figure 7.

As frequency goes high, wavelength of acoustic wave becomes short thus phase change happens in small region. Such case is illustrated in Figure 8 of the results at 3308Hz. At this frequency, phase map at the tip of the second disturbance in the source region 2 becomes to have phase variation within the region. As result, contribution from the source region 2 cancels and contribution from the source region 3 becomes high.

Now investigation is made for the SPL at the microphone therefore phase is somewhat important. But if interest is on radiated power from the duct (which is sometimes used for assessing noise level without directivity effect) then phase to radiation power cannot be defined. In such case, the contribution map in Figures 6-8 would directly indicate contribution to the radiation power.

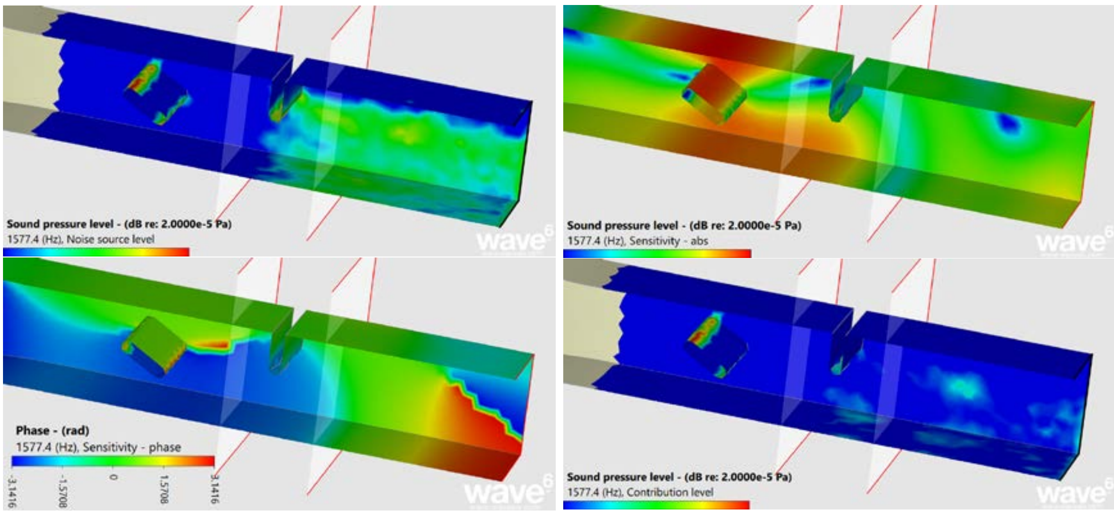

Figure 6. Source / Sensitivity / Contribution Maps at 1577Hz. Left top: Source, Right top: Sensitivity – abs, Left lower: Sensitivity - phase, Right lower: Contribution. Partition of source regions is shown by transparent surfaces.

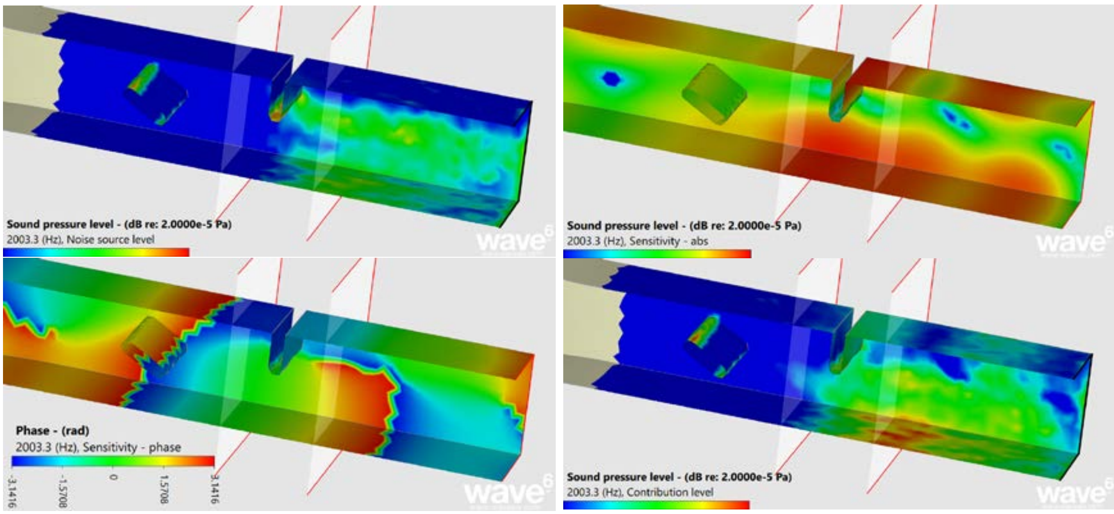

Figure 7. Source / Sensitivity / Contribution Maps at 2003Hz. Left top: Source, Right top: Sensitivity – abs, Left lower: Sensitivity - phase, Right lower: Contribution. Partition of source regions is shown by transparent surfaces.

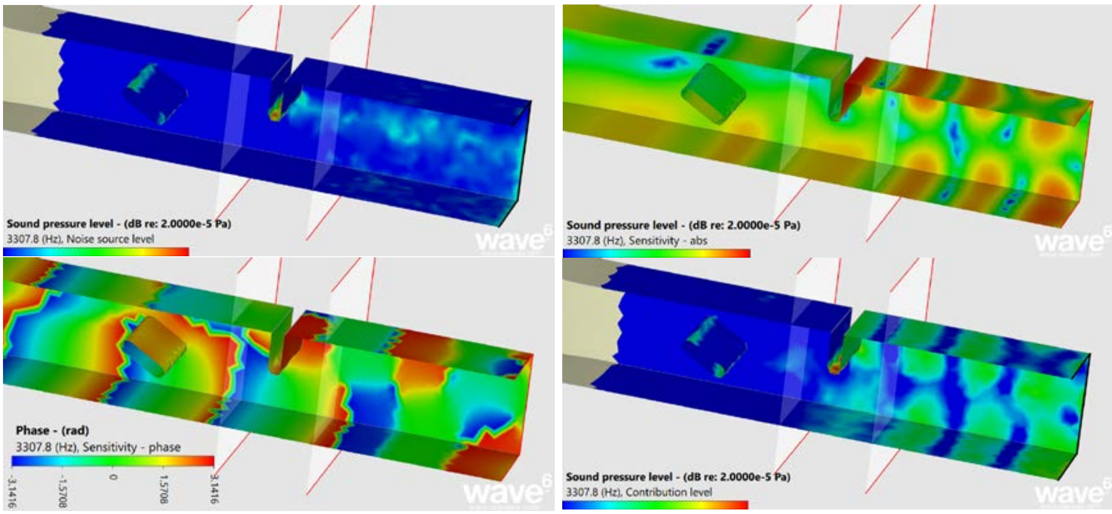

Figure 8. Source / Sensitivity / Contribution Maps at 3308Hz. Left top: Source, Right top: Sensitivity – abs, Left lower: Sensitivity - phase, Right lower: Contribution. Partition of source regions is shown by transparent surfaces.

5. CONCLUSION

In this paper, a study on acoustic propagation of flow induced duct noise was discussed. The NCAA employed here could accurately predict acoustic radiation from the duct. The NCAA only required FSP on the duct which can make the required CFD result file size much smaller than volume based acoustic analogies. This is very efficient and useful when solving system level large model. Contributions from partitioned source regions were calculated and investigated in terms of noise source and acoustic path. The investigation showed that not only noise source level but also acoustic path character (amplitude/phase) is important on the flow induced duct noise.

With above results, it can be concluded that designers have to think of acoustic path characteristic at frequency of interest in order to efficiently reduce noise from duct. At lower frequency, attention has to be paid for acoustic modeshapes of the duct and location of noise sources. As frequency goes high, one would also need to pay attention on local phase variation at region where FSP is high if interest is SPL at a point.

6. REFERENCES

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