ACOUSTIC SYNTHESIS OF AN AUTOMOTIVE HVAC

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SUMMARY

The acoustic synthesis is a design and/or diagnosis approach used to analyze and predict the acoustic behavior of a complex system. Based on the requirements in terms of time spent, accuracy and outcomes, an acoustic synthesis is performed on an automotive HVAC – which a fan is the main source – considering operating conditions. The synthesis is developed in order to propose an approach which considers the integration effects and some interaction effects.

INTRODUCTION

The emergence of hybrid or electric engine and the improvement of internal combustion engines have caused a significant change in the automotive acoustic field. Thus the specifications of the automotive suppliers are now more demanding regarding the noise produced. The Heating, Ventilation and Air-Conditioning system, named HVAC subsequently, is one of the most important car equipment in charge of the passenger comfort in terms of temperature and humidity.

Therefore, the HVAC – whose main source is a fan – is the support of an acoustic synthesis performed in order to determine the noise sources and theirs transfer paths and to predict the acoustic situation in a preset reception point.

In this paper, a preliminary acoustic synthesis performed on a simplified HVAC has established a first reference and identified the components accountable for the noise produced. Their integration in a complex environment and the interaction between them are treated. A method is proposed and implemented in order to provide acoustic data used in the context of sound synthesis and psychoacoustics. Once the prediction done, one may use the acoustic synthesis as a pre-conception tool to comply the noise requirements.

The project CEVAS, founded by French authorities, deals with the different aspects of this topic.

PRINCIPLE

An acoustic synthesis ([1] and [2]) allows the partition of the mechanical system into various sub-structures – also called in the following sections “blocks” – that are either moving or motionless. The active sub-structures are the sources responsible for the noise production. The passive blocks stand for the transfer paths from the sources location to the reception points. The link between the two kinds of blocks has to be considered on many aspects such as the physical variables and the frequency refinement.

The transfer path of a mechanical system may be various:

- Air borne: The noise produced is directly propagated through the acoustic environment. The noise is either due to an active component or due to the interaction between an incident excitation on a passive one – such as an incident vortex on a plate.
- Structure borne: An active component, most of the time a rotating device, transmits vibrations across the mechanical support which is the excitation of vibro-acoustic transmission.
- Liquid borne: This noise appears frequently in the case of fluids excited in a confined environment such as plumbing pipes. The noise may be an excitation for a noise whose origin is structure borne.

An acoustic synthesis takes into account these three modes of propagation of oscillating energy.

Several methods and tools are used in order to successively characterize these blocks. The tools may have different origins such as computation, experimental data and analytical laws. One can fulfill the study of the same block by means of different methods.

An acoustic synthesis may be performed considering different environments:

- In a free-field radiation environment (block alone).
- In the system environment (integration effects): the influence of system’s boundaries on a block is determined.
- In an interactive environment (interaction effects): a block is characterized taking into account the influence of the other sub-structures.

Once the block or the assembly of some blocks is established, one may use it in a different acoustic synthesis in a coherent manner. Therefore, the blocks have to be characterized in the most generic way.

The acoustic synthesis relies on the creation of a Vibro-Acoustic Scheme (Figure 1), noted VAS, in which one has to incorporate the identified blocks – active and passive –, the methods and tools available for their characterization and the kind of output data such as a Sound Power Level or a psychoacoustic criterion as loudness.

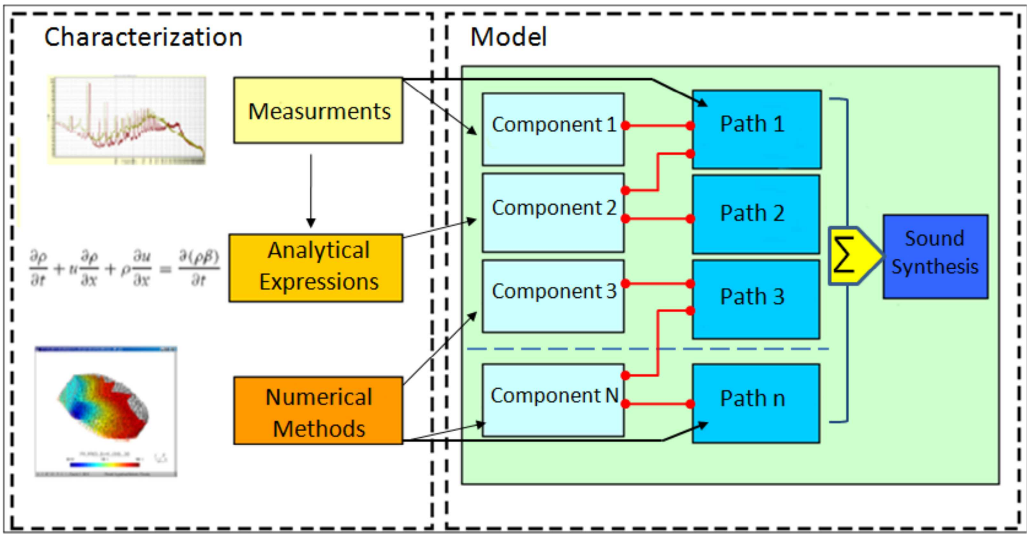

Figure 1: Standard VAS

An acoustic synthesis is carried out following the steps presented on the Figure 2.

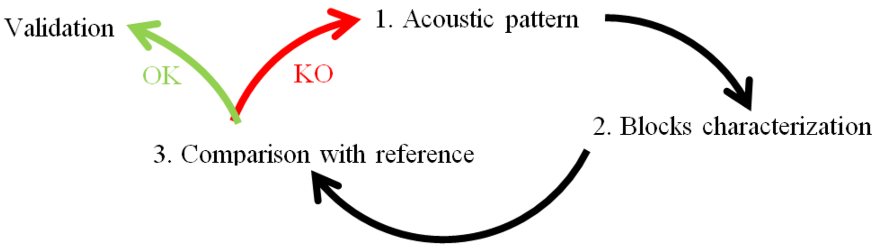

Figure 2: Steps followed during an acoustic synthesis

First of all, the VAS of the mechanical system is done. This step requires identifying the noise sources and transfer paths. The VAS is either exhaustive – every part of the mechanical system are taken into account – or simplified (some sources are considered negligible).

The second step consists in the determination of the acoustic behavior of every block. One has to choose among the available methods by ensuring that the characterization complies with the VAS.

The acoustic prediction is finally compared to a target result (experimental data or psycho-acoustic requirement). A correction of the VAS may be done if the acoustic prediction gives unsatisfactory results. This correction leads to perform once again the second step.

APPLICATION CASE

The system studied is an automotive HVAC presented in the Figure 3. An automotive ventilation system is a heating or cooling air system based on flow circulation (colored arrows).

The noise origins are various and listed below by decreasing importance:

- Aero-acoustic noise: A fan placed upstream is in charge of the air flow circulation. The air flow noise created is propagated through the cabin car. Moreover, the interaction between the air flow and the other components – mainly flaps – causes turbulences and thus an additional noise source.
- Harmonic noise: Contrary to the aero-acoustic noise – which is a broadband noise –, a tonal noise may appear due the mandatory rotation of the fan in order to create the air flow. The harmonic noise emerged at specific frequencies such as the blade passage frequency and its harmonics.
- Vibro-acoustic noise: The fan rotation and the HVAC boundaries create vibration source that may be perceivable through the HVAC in quiet conditions (low flow rate combined with low fan's rotation speed).

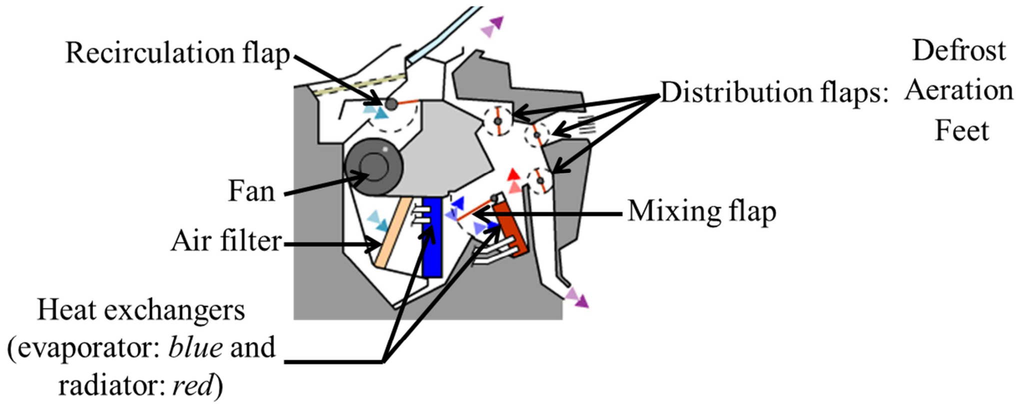

Figure 3: HVAC integrated in a vehicle

Four different components are assembled:

- The main component of the equipment is the fan responsible for the air flow rate creation and the pressure loss compensation.
- The flaps have two main objectives: a mixing flap, placed between the evaporator and the radiator, adjust the temperature requested while a distribution flap, having different opening angles, delivers flow outwardly. The recirculation flap is a particular distribution one: it is held to switch the air's origins, from the outside (fresh air) or from the inside (recycled air) of the vehicle.
- The role held by the heat exchangers (evaporator and radiator) is to deliver air whose temperature corresponds to the ventilation kind requested by the user.
- The air filter is put upstream the evaporator in order to get rid of particles contained in the air.

In the following sections, the HVAC is considered in a free-field radiation environment and not integrated in a vehicle.

The noise origin considered in the acoustic synthesis is only aero-acoustic (air flow noise). The fan's tonal noise is also studied due to its intrinsic characteristics (blade passage frequencies).

Three levels of study are performed based on the same vibro-acoustic scheme. The preliminary results are obtained using blocks characterized in a free field environment. Methods and suggestions are then proposed for the integration (second level) and interaction effects (third and last level).

Vibro-Acoustic Scheme

The HVAC's VAS is pictured on the Figure 4 has three kinds of blocks:

- The fan is the main source identified and induces the noise production of the other blocks due the flow created. This block is then central in the acoustic synthesis implementation. The fan is the starting point of the noise generation and transfer.
- The flaps are a source noise and an intrinsic transfer function at the same time.
- The noise created by the heat exchangers needs to be evaluated. The main role of the heat exchanger is the modification of the incoming flow (aeraulic) and an intrinsic transfer function (acoustic).

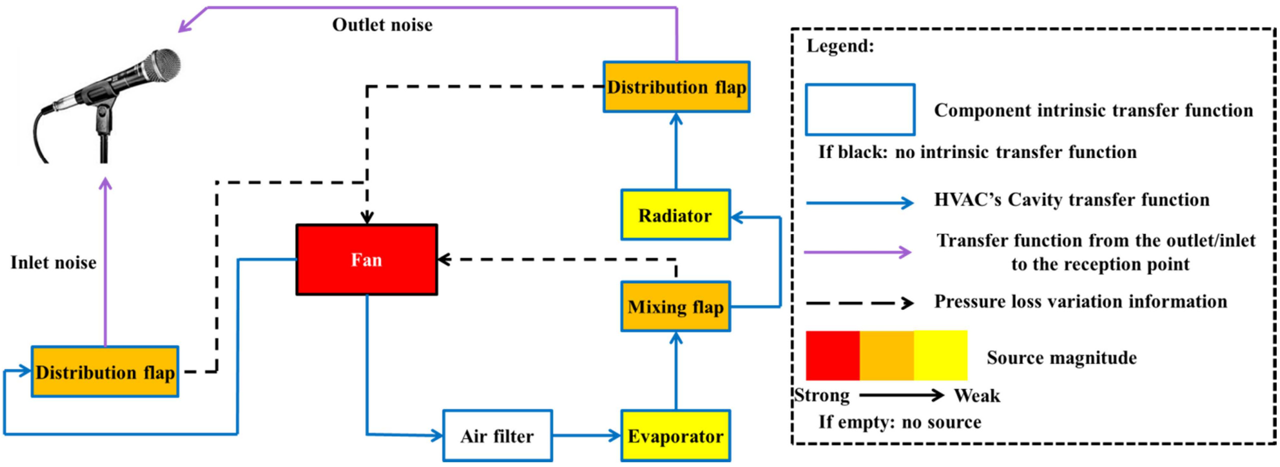

Figure 4: Operating VAS of a HVAC

One may neglect the inlet noise if the air is extracted from the outside of the vehicle.

The input data – considered as variables – are the flow rate requested by the user and the modes of ventilation (HFF: *Hot Feet Fresh air*, CVAR: *Cold Vent Air Recycled mode*, HDF: *Hot Defrost Fresh air* and CVAF: *Cold Vent Air Fresh air*) translating the fan's pressure rise and the flaps' positions.

One may consider the pressure loss compensated by the fan as a sum of two parts:

- a structural one due to the cavity in which the components are integrated and due to the motionless components (air filter and heat exchangers).
- and a variable one due the different flaps' positions. These variable positions are due to the different modes of ventilation.

In this study, the fan's operating points investigated are limited between the two extreme flow rate-pressure loss curves of the HVAC.

The acoustic data at the reception point, considered as the output of the acoustic synthesis, is the Sound Pressure Level (SPL) at a predefined position.

Preliminary results

A first acoustic synthesis has been performed on a simplified HVAC during the thesis of A. Al-Mezzawi [3]. The VAS is described in the Figure 5 with the same legend of the previous one:

- The fan noise has been characterized using the ASHRAE empiric law [4]. The flow rate and the rotational speed are considered as input data.
- The transfer functions of the ducts are fulfilled analytically as a transmission loss.
- The heat transfer block (noise and transfer function) is completed using experimental data [5].
- The flap noise is predicted thanks to the Oldham and Waddington reference [6]. One may vary the value of the flap opening and thus the pressure loss.
- The value estimated is the Sound Power Level (SWL) at the outlet of the simplified HVAC.

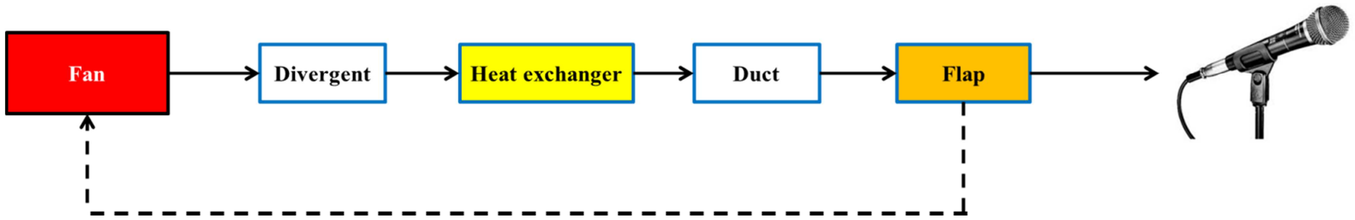

Figure 5: VAS of the simplified HVAC

The first version of the acoustic synthesis provides preliminary results plotted in APPENDIX A:

- The flaps' noise source is considered as weaker as the fan's one.
- One may note that the participation of the heat exchanger is indirectly linked to the flap's opening. The noise produced by the heat exchanger is linked with the incident flow homogeneity. The inhomogeneous flow produces high ventilation speed that represents a significant noise source in the high frequencies domain.
- Therefore, one may obtain a satisfactory acoustic prediction to rank the sources.

Nonetheless, the comparison with reference (Figure 2, step 3) is not accurate when the input data are modified. The result of this acoustic synthesis gives a good prediction only if the flap opening is close to 90° (flap fully opened).

Also, the integration and interaction effects are not taken into account. For instance, the ASHRAE law doesn't consider the acoustic cavity of the HVAC while the Oldham reference predicts the noise in the case of a flap placed in a straight duct.

Complete acoustic synthesis

Integration effects

In order to take into account the integration effects represented by the HVAC cavity transfer function (blue line in Figure 4), a method have been carried out based on M. Legros paper [7].

The components are modeled into a source term representing its intrinsic ability to produce a noise and a attenuation term translating its intrinsic capacitance to lessen the sound.

In [7], the method is applied on a fan represented only by a source term. If one wants to consider the two intrinsic terms in order to apply the method in the case of the flaps and heat exchangers, the experimental data has to be extracted from a dedicated test bench, as presented in details by S. Bennouna [8] and H. Trabelsi [5].

Once the components' intrinsic terms are determined based on experimental data, one may propagated these in a complex acoustic environment. The propagation is calculated using the finite-elements method which takes into account the acoustic response of the HVAC's cavity.

The HVAC's boundaries may change if one considers the input data. Therefore, one has to model as many cavities as ventilation modes:

- HFF: Feet flap opened; defrost, aeration and recirculation flaps close the cavity.
- HDF: Defrost flap opened; aeration, feet and recirculation flaps close the cavity.
- CVAF: Aeration flap opened; defrost, feet and recirculation flaps close the cavity.
- CVAR: Aeration and recirculation flaps opened; defrost and feet flaps close the cavity.

The HVAC is modeled by a cavity in which each component is depicted by its volume occupied. The ventilation system is then modeled by a sum of volume representing every component identified as noise sources or intrinsic transfer function. For the same ventilation mode, one has to compute as many propagation – or transfer path – as noise sources identified.

The final result is given following the Figure 6 by resuming the simplified geometry of Figure 3. For each component, the source term, represented by a force per unit volume noted f, is propagated through the HVAC's cavity in which the components' attenuation term noted α is added.

The noise participation of the component noted i, considering the mode ventilation noted X, is obtained with the equation (1):

$$\mathrm{SPL}_i{}^X = \mathrm{Source}_i * \mathrm{Transfer\ path}_i{}^X . \qquad (1)$$

The acoustic participation of each component is summed to get the total noise prediction:

$$\mathrm{SPL}_{total}{}^X = \sum_i \mathrm{SPL}_i{}^X . \qquad (2)$$

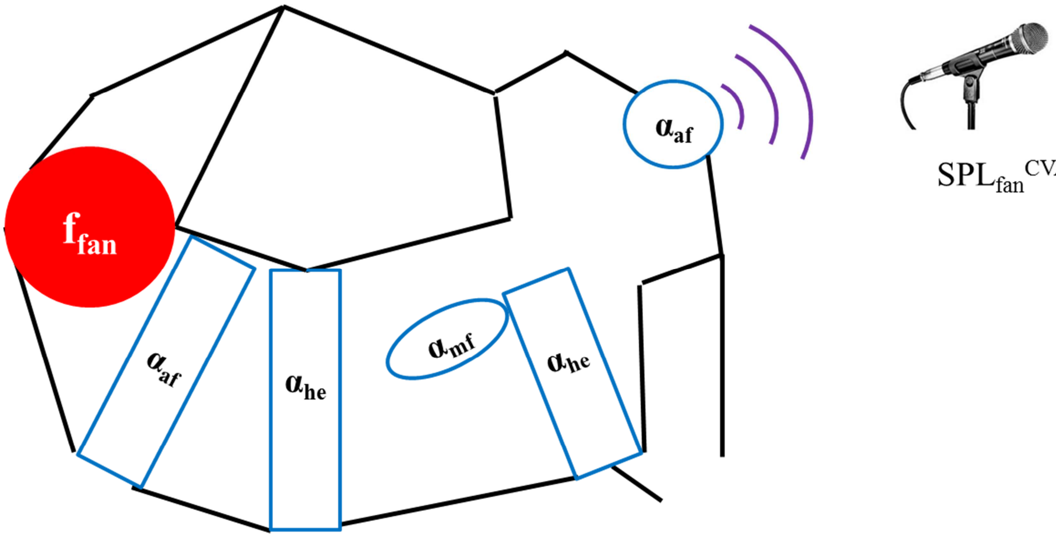

Figure 6: Computation of the fan noise integrated in the HVAC cavity considering the CVAF ventilation mode

Once the calculation of the different propagations is made (N components multiplied by X ventilation modes), the noise prediction is straightforward based on the two equations of the Figure 6. Only the experimental data quantifying the intrinsic terms vary in the acoustic prediction (f and α).

Interaction effects

The interaction effects between two close components – such as the flaps – are more complex to consider because they have various origins and depends on the HVAC's geometry or on the components' relative position. The association of the air flow and a geometric singularity creates turbulences that are additional sources for a component placed downstream [9].

Therefore, the study of these effects is far more specific than the previous ones. One can't reproduce the prediction approach without a comprehensive study of the geometry.

To keep the method taking into account the integration effects, one of the solutions is to modify the source term on:

- The zone of turbulence impact: the specifications of the added load have to be done relying on a CFD calculus (Computational Fluid Dynamics) or a PIV measure [10] (Particule Image Velocimetry). The incident vortex created by the geometric singularities represents a load fluctuation on the flaps' surface (for instance) which is propagated using the Amiet model [11], [12].
- Two close components can be assembled to form a group of sources and intrinsic transfer functions.

IMPLEMENTATION AND INDUSTRIAL USE

The acoustic synthesis is then implemented in order to provide an interactive tool for industrial purposes. Based on the output data of the block's characterization, the implementation of the acoustic synthesis may reproduce the VAS to deliver a Human-Computer Interaction (HCI).

Through the HCI, the user may choose the input data of the acoustic synthesis (flow rate and ventilation modes) and also change the data of each block. For instance, if the user wants to study the effect of the fan choice on the acoustic prediction, it is possible to vary the block's data. Therefore, a database characterizing different kinds of fan is suitable to fulfill the corresponding block in the VAS.

The virtual prototyping is then one of the most interesting advantages of the acoustic synthesis. Also, the output data may be the starting point of further psycho-acoustic study.

PSYCHO-ACOUSTICS AND SOUND QUALITY

Prior to the psycho-acoustic study, one has to build a sound signal from the output spectrum of the acoustic synthesis in order to get an audio sample of the acoustic prediction which is appropriate during virtual prototyping. This procedure, called noise synthesis, is explained in the paper of A. Minard [13].

The acoustic synthesis is a prediction tool and also a pre-conception instrument in the case of an analysis of the output data. A psycho-acoustic study is especially suitable as an HVAC is directly in relation to the passenger vehicle.

The psycho-acoustic approach used to evaluate the sound quality is set to determine adescriptors related to the sound properties. Then, using a variety of methods, an acceptance law states whether the product is going to be perceived by the user.

Several descriptors have been set up to objectively characterize a sound. These descriptors – mainly defined by Zwicker and Fastl [14] – identify and classify the sound characteristics (not exhaustive):

- linked to signal characterization:
    - Loudness: depends on the noise level but also on the frequency and duration of the sound. Loudness is measured in Sone or Phon, units based on a sensory level.
    - Tonality: indicator judging the pitch of a sound periodically.
    - Sharpness: indicator to judge the perception of noise as acute.
    - Roughness: rapid temporal modulations (~ 70 Hz)
    - Fluctuation Strength: slow temporal fluctuations slow (~ 4 Hz).
    - Speech Interference Level, SIL.
- characterization related to the listening:
    - Subjective Duration perceived by the jury listening to the sound.
    - Sensory pleasantness.

A listening jury has to establish the relationship between the sound characteristics and the physical properties and determine the sound quality of the signal.

The methods used are either direct – the sounds are judged through semantic scales corresponding to the signal descriptors [15] – or multidimensional: the hearing of paired sounds are correlate with the psychoacoustic descriptors [16].

In the case of the HVAC, the first laws of sound quality have been published ([17] and [19]). They are strongly related to noise generated by the fan.

CONCLUSION

An acoustic synthesis provides a prediction tool which can be applied as soon as the conception phase of a system. The methods and tools required employ all the knowledge of the acoustic domains.

A preliminary study based on experimental data and analytical law was able to rank noise sources. A method for a thorough synthesis has been settled in order to take into account the integration and interaction effects.

One of the advantages of an acoustic synthesis is the fast virtual prototyping made possible by the data preparation of every block. The acoustic synthesis is a suitable tool for an industrial use.

The output data of the acoustic synthesis are the starting data of a psycho-acoustic study which furnishes a preview of the sound quality to the HVAC designer.

The gathering of the three works (acoustic synthesis, noise synthesis, sound quality assessment) for industrial purposes and virtual prototyping is the global objective of the CEVAS project.

ACKNOWLEDGEMENTS

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APPENDIX A

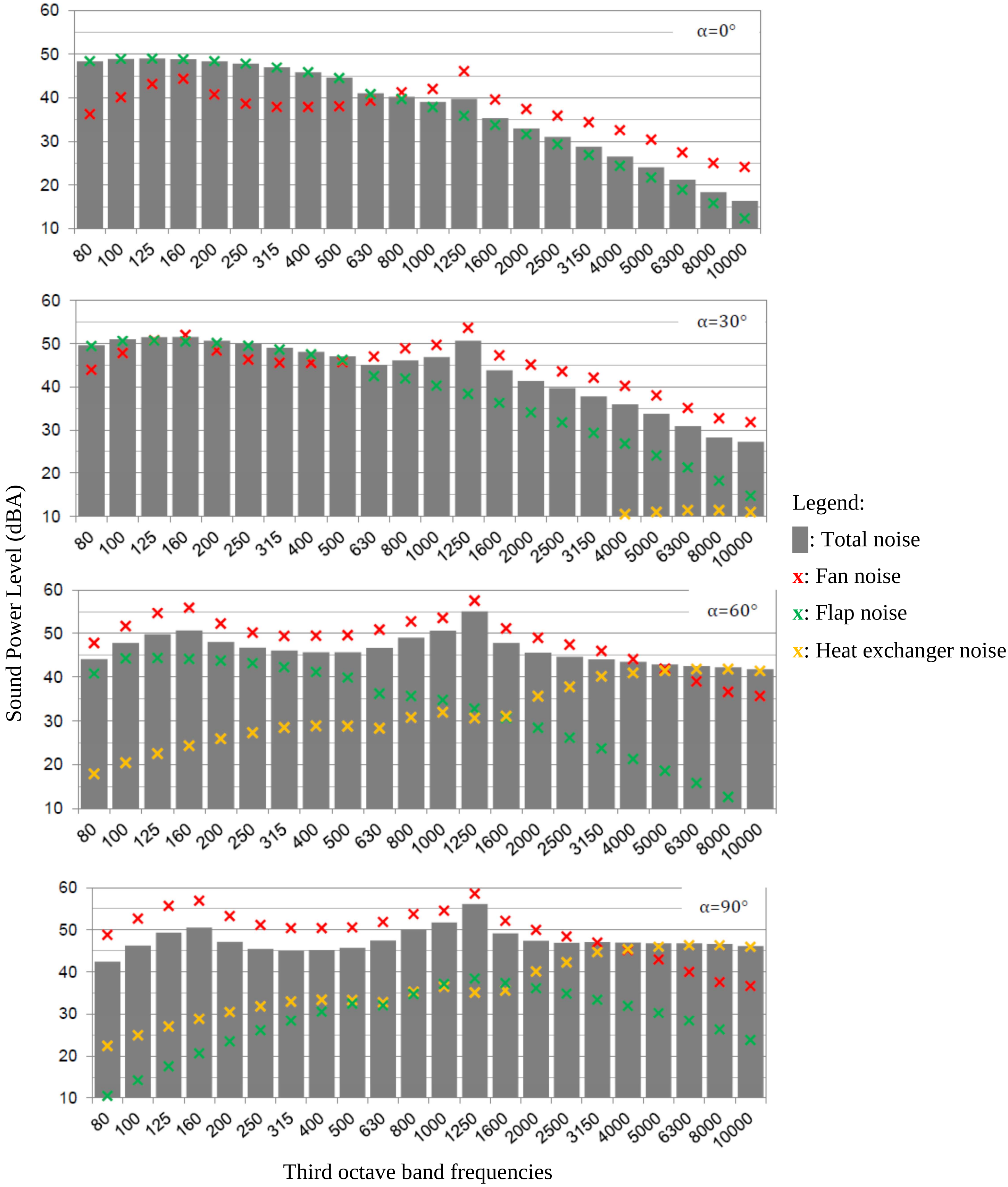

Figure A: Acoustic prediction for different values of flap opening (90°:open, 0°:close)