Optimization of ANC configurations through spatial matching of the cavity field

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Abstract: The efficiency of Active Noise Control system in car interiors is highly dependent on the spatial matching of the primary and secondary field at all passengers. Insuring an efficient global control in a vehicle requires that the modal properties of the cavities are considered when defining the loudspeakers and control microphone positions. An optimization process for spatial matching within the relevant frequency range is presented. The process starts with the characterization of the primary acoustic field in the vehicle. As the secondary field can be deduced from the transfer functions between loudspeakers and microphones, the optimal configuration is determined by minimizing the squared sum of the primary and secondary field at listener positions. A specific tool developed to automatize the process is presented. Finally, the prospect of performing the optimization using simulations of primary and secondary fields will be discussed.

Keywords: Active noise control, Optimization, Spatial matching.

1. Introduction

The use of Active Noise Cancellation (ANC) systems in cars has recently increased, leaving the high-end segment and entering the lower segment. Electrification has also made these systems attractive due to the potential weight gains. There is then an incentive to be able to optimize and predict the performance of an ANC system in vehicles.

The efficiency of Active Noise Control system in car interiors is often related to the performance of the adaptive filters implemented on the system's DSP. The algorithm is indeed an important part of the system and insures the temporal matching between the primary field (engine or road noise) and the secondary field produced by the loudspeaker. However, an efficient control for all passengers puts the additional requirement of spatially matching the primary and secondary field at all passenger positions leading to a robust global control in the vehicle cavity.

This paper presents an optimization process specifically developed for ANC system installed in automotive. The process is inspired from the strategy developed for the definition of ANC system in commercial airplanes where spatial matching is instrumental to the success of the installation due to the size of the cavity [1].

The concept of spatial matching is first described. The optimization process, relying on a characterization of the cavity response and the operative sound field, is then presented. A validation of the process and an example of the performance increase related to the optimization of the ANC configuration for optimal matching is discussed. Finally, on-going developments for configuration optimization on simulated cavity response are discussed.

2. Spatial matching in ANC application in cavity

Active Noise Control (ANC) uses the principle of superposition to cancel the primary (unwanted) noise with a secondary acoustic field generated by an electroacoustic or electromechanical actuator. In most applications dealing with a variable primary noise, the generation of the secondary acoustic field requires an adaptive process programmed on a DSP ensuring a robust phase and amplitude matching of the secondary field at one or several control microphones. As the quality of the control is highly dependent on this temporal matching, many publications and reviews consider the benefits and limitations of suitable adaptive filtering algorithms [2].

In the case of active control in a 3-dimentional cavity where listeners are potentially located at different positions inside the cavity, spatial matching at all listening positions is required. Two approaches are

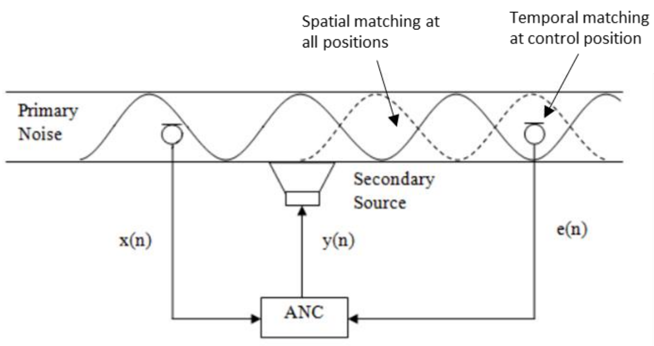

Figure 1 : Schematic of an ANC configuration with temporal matching at control microphone and spatial matching achieved in the volume of the tube.

available: a local control approach using multiple independent systems at driver and passengers' positions or a global control approach, i.e. a single ANC system controlling simultaneously several microphones and loudspeakers. The second approach is usually considered beneficial due to the complexity and cost related to the multiple systems required for local control.

Spatial matching in a global ANC configuration means that the position and the shapes of the primary and secondary field coincide within the region where control is desired. The more complex the original field, the more difficult it is to generate a matching shape. The more secondary sources are used, the better the match and therefore the better the reduction of the primary noise. Defining the optimal number and positions of control microphones and loudspeaker – within the constraints of a car installation- to fulfill spatial matching is the optimization problem at stake for achieving high performance ANC in a vehicle.

This optimization problem requires the knowledge of the primary sound field. This paper will consider the specific case of engine noise; however, a similar process is beneficial for other noise sources such as road noise. Figure 2 shows the primary field related to the engine order 2 in a test car of the compact SUV type. The operational field shapes are shown at frequencies where the contribution of the order 2 to the overall level is high. These field shapes are the ones that need to be match by the secondary field shapes.

The optimization problem can be understood using a 2-Dimentional analogy as shown in figure 3. For a given frequency, or RPM, spatial matching requires an ANC configuration capable of reproducing similar field shapes as the primary field. Two conditions are

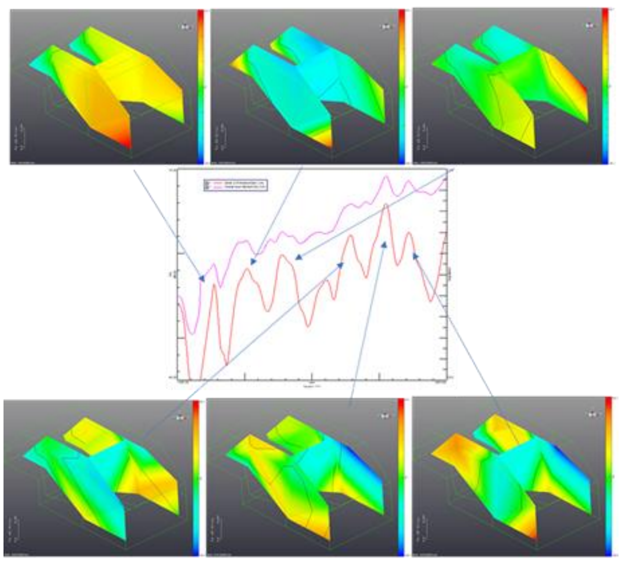

Figure 2: Primary field related to the engine order 2 in the test car

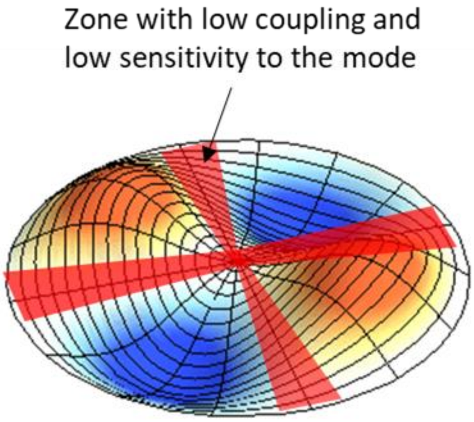

Figure 3: Zones of low coupling and low sensitivity for a 2-dimentional mode.

required: 1) all or most of loudspeakers are positioned in zones that couple well with the field shape. The nodes of the operational field shape should be avoided. 2) all or most of the control microphones should be positioned in zones of high sensitivity to the field for the adaptive filter to quickly converge. In other words, the nodes of the field should be avoided for both loudspeakers and microphones. This condition should be fulfilled for all the field shapes excited within the frequency range of operation for an ANC system, typically [20-400 Hz].

3. Optimization process

The optimization process for the definition of the optimal positions of microphones and loudspeakers relies on the definition of a superset of control microphones and loudspeaker positions. This superset is used throughout the 2 steps of the process: 1) Characterization of primary field and transfer function necessary for secondary field calculation and 2) Optimization. The optimization problem can be defined as finding a subset of microphones and loudspeakers among the superset leading to the best matching of the secondary and primary fields.

3.1 Characterization

Figure 4 shows a typical superset defined for the characterization of the primary field. The vehicle is instrumented with, in this case, 26 microphones at potential control positions and 6 monitor microphones. The position of the microphones is chosen for giving a good representation of the field shapes and includes a large number of positions that could physically be used in the final configuration. In addition, monitor microphones at listening positions

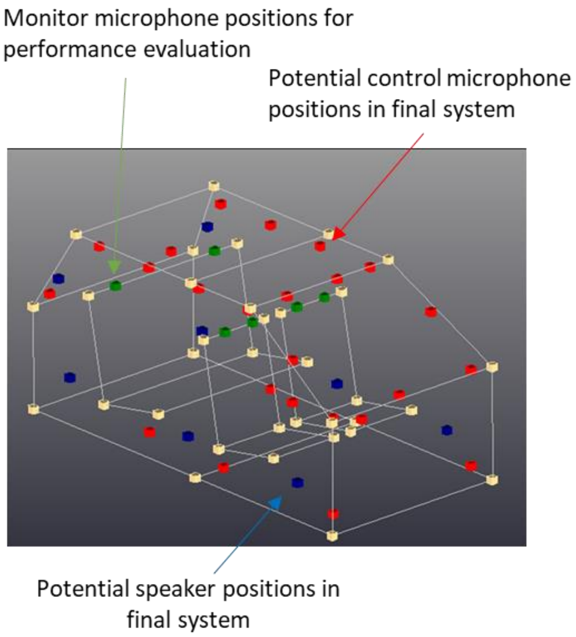

Figure 4: Superset used for optimization.

are included in the set. First, operational measurements are performed for run-ups and some chosen stationary runs (idle and constant speed) allowing a full record of the primary field. Secondly, a measurement of all FRFs between the pre-defined potential loudspeaker positions and all microphones is performed using a calibrated loudspeaker. These FRF are used in the next step to compute the secondary fields related to a defined subset of control microphones and loudspeakers.

3.2 Optimization methodology

The search space consists of all combinations of loudspeaker and control microphone positions available from the measurements. The cost function, defined below, is sequentially evaluated over all points of the search space that meet the requested criteria in terms of number of loudspeaker and control microphones. The optimum configuration leading to the smallest cost function is identified. Constraints given by the practicality of the configuration are integrated by setting some of the positions (such as loudspeakers) as obligatory. The optimization is then performed only over the "optional" positions. For example, if the loudspeakers of the existing audio system are to be used, they can be defined as "fixed" and the optimization can determine if and which additional loudspeakers would improve the system. The total number of configurations to search through is then:

$$N = \sum_{j\in\Lambda}\binom{L}{j}\sum_{k\in\Gamma}\binom{C}{k} = \sum_{j\in\Lambda}\frac{L!}{j!(L-j)!}\sum_{k\in\Gamma}\frac{C!}{k!(C-k)!} \quad [1]$$

where L is the number of optional loudspeaker positions, C the number of optional control microphone positions, Λ the ensemble containing the numbers of loudspeakers to look for, Γ the ensemble containing the number of controls to look for. For example, when looking for a 4X6 configurations (4 loudspeakers and 6 controls) among 10 loudspeaker positions and 19 control positions, there are 5697720 configurations to test. A specific software designed for this optimization typically needs a few minutes to scan the search space.

The cost function is defined as the squared pressure of the controlled field at frequencies corresponding to selected engine orders, averaged over weighted selected monitors, averaged over the recorded time of the load case for a specified rpm range." Mathematically, it can be expressed as:

$$\phi = \langle \sum_{monitors}\left(w_m {x_d}^2_{m,engine\ orders}\right)\rangle_{rpm\in[rpm_{min},rpm_{max}]} \quad [2]$$

where $\mathbf{x_d}$ refers to the controlled field, defined as $\mathbf{x_d} = \mathbf{x_0} + \mathbf{x_s}$, where $\mathbf{x_0}$ is the primary field and $\mathbf{x_s}$ the secondary field. w_m are weighting factors used to set an optional preference on given monitor positions.

The controlled field is estimated from the optimal force distribution in the loudspeakers $\mathbf{F_d}$ by $\mathbf{x_d} = \mathbf{x_0} + \mathbf{FRF_0}\,\mathbf{F_d}$, where $\mathbf{FRF_0}$ is a matrix containing the transfer functions between the loudspeakers and the microphones**.** The error signal, ***e***, in the control microphones, i.e. the remaining part of the noise after the primary field is cancelled out by the ANC system, can be written:

$$\mathbf{e} = \mathbf{x_0} + \mathbf{FRF_0}\,\mathbf{F_d} \quad [3]$$

Assuming no limitation in the force vector $\mathbf{F_d}$, a Least Mean Square (LMS) solution minimizing the error signal $\mathbf{e}$ can be found as:

$$\mathbf{F_d} = -\mathbf{FRF_0^+}\mathbf{x_0} \quad [4]$$

where $\mathbf{FRF_0^+}$ is the pseudo-inverse of $\mathbf{FRF_0}$**.** This solution represents the maximum least-mean square control at the control microphone locations that can physically be achieved with the given configuration. In other words, the configuration that has the lowest cost function is the one that can generate a sound field with the best spatial matching with the primary sound field.

Practically, the algorithm used to search for the best configuration of "optional" microphones and loudspeakers is shown in figure 5. The search for maximized control at monitor position is performed over the search space. The performance of the selected set can be calculated and visualized over the all frequency or rpm range allowing for a prediction of

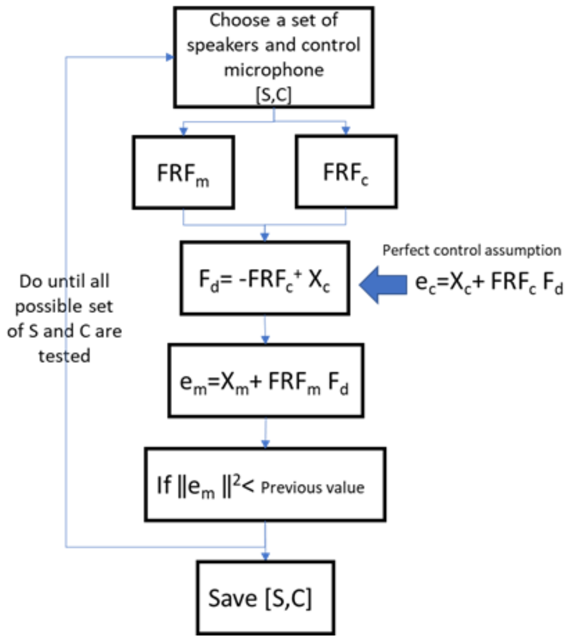

Figure 5: Optimization algorithm for optimization of the ANC configuration.

the noise reduction at monitor positions physically achievable with the selected configuration.

3.3 Results and validation

The optimization process provides several outputs:

- The acoustic pressure at all monitor microphones for the order considered as a function of rpm.
- The overall level at all monitor microphones as a function of frequency or rpm.
- The driving level at all loudspeakers required to achieve the maximal damping.

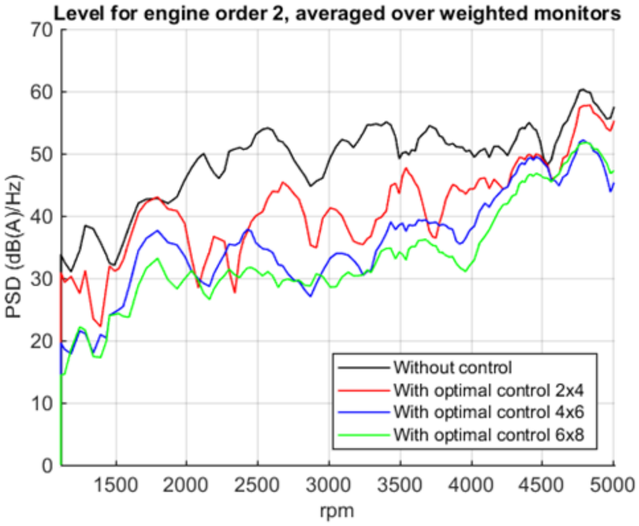

Figure 6: Comparison of performance for different configuration. 2x4 relates to 2 loudspeakers and 4 control microphones configuration.

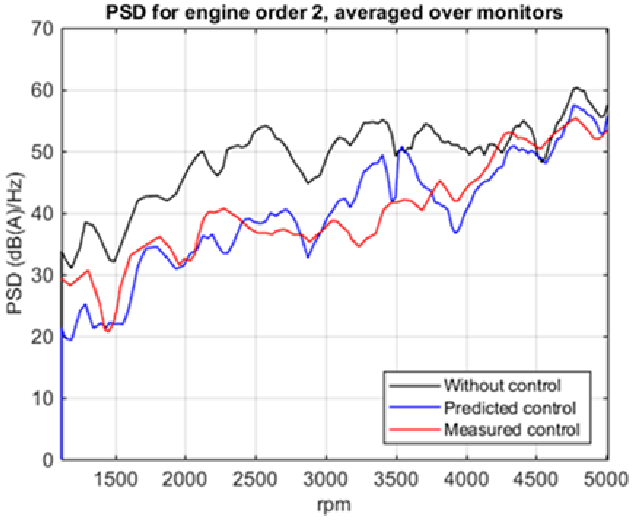

Figure 7: Comparison of predicted and measured control

Figure 6 shows typical results of an optimization showing the predicted performance of three different configurations from a simple 2 loudspeaker x 4 microphones to larger 4x6 and 6x8 configurations, in agreement with the intuitive idea that that a larger number of secondary sources allows for better performances.

The results of the performance prediction were also compared to the actual obtained reduction in a specific case shown in figure 7. It should be noted that the predicted control does not consider the properties of the ANC adaptive filter, and particularly the effect of convergence speed of the filter. Anyhow, it can be seen on figure 6 that the predicted and measured control for similar microphones and loudspeaker configurations shows a good agreement in most regimes. The slight discrepancy around 3500 rpm is related to the fact that the measured and predicted run-ups were performed at different times and in different conditions.

4. Example of optimization

The optimisation of an existing installation was performed using the spatial optimization process. A vehicle with an ANC installation showing low performance was characterized and an optimization was performed. Figure 8 shows the predicted performance of the original installation. This prediction is in line with the measured results (not available).

The first task was to optimize the microphone positions with the same loudspeaker configuration. After optimization better performances

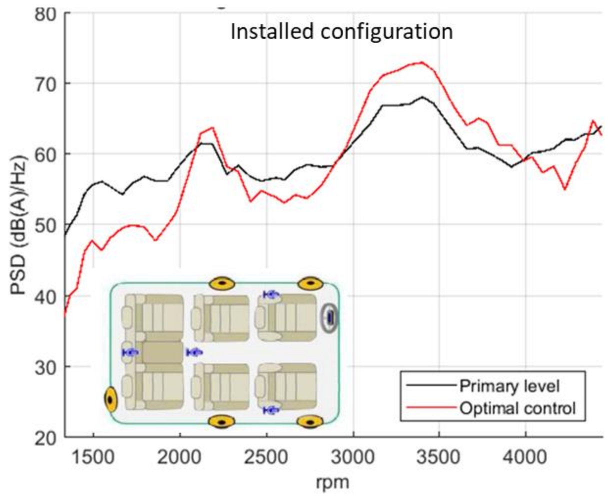

Figure 8: Performance prediction of the original installation

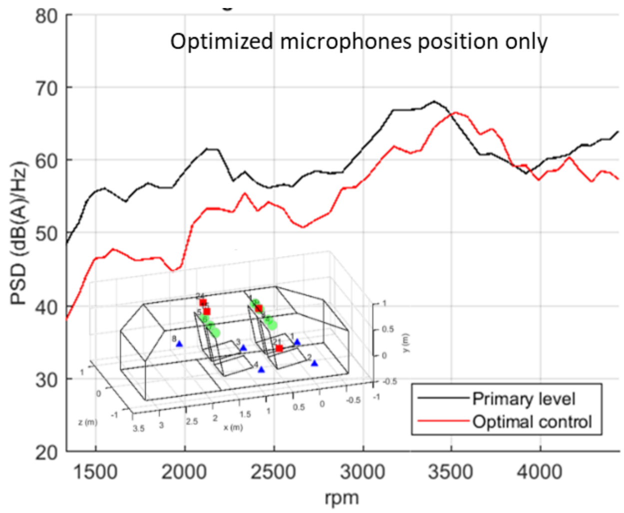

Figure 9: Optimization using the same number of loudspeakers and microphones.

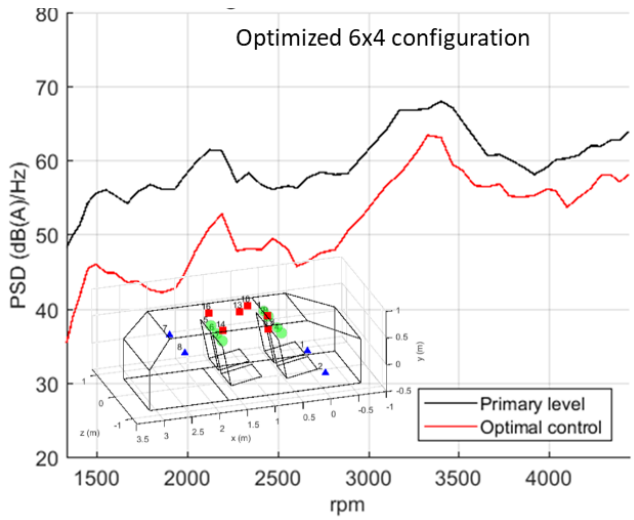

Figure 10: Optimization for low cost installation.

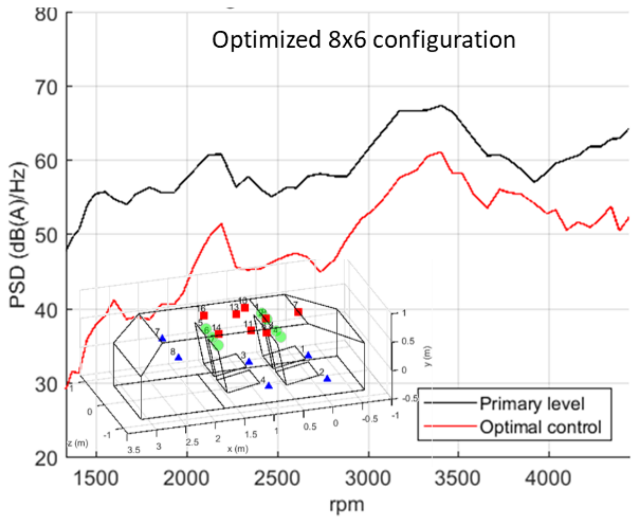

Figure 11: Optimization for premium installation

are observed at low and mid rpm as shown in figure 9 showing that the process can improve the performance of configurations “intuitively” set with microphones close to the listener. Further, a low-cost system using only 4 speakers and 6 microphones was optimized, solving the low performance at high RPMs as seen in figure 10. Finally, a premium system with six loudspeakers was designed increasing the performance at low and high rpm, as shown in figure 11. The performance prediction as a function of the system complexity allows to optimize the final configuration with respect of final costs of the installation.

5. Future work: Optimization from design data?

The presented process relies on the generation of experimental data obtained through a characterization of the car. It is of interest to predict the performance of an ANC configuration at the design phase. If the secondary field can be deduced from FRF issued from a modal base determined from FEM based simulations (figure 12), the prediction or estimation of the primary field is the main challenge. Two approaches are considered. Firstly, an investigation of the performance of an optimization based only the selected dominant modes using an excitability criterion will be performed. Secondly, the possibility to use a system of equivalent boundary conditions for the excitation of the cavity extracted from similar models will be evaluated.

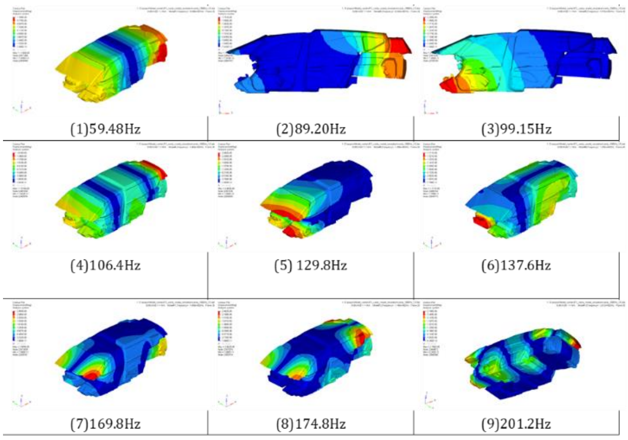

Figure 12: Modal base calculated from FEM

7. Conclusion

The performance of an Active Noise Control system in a vehicle are highly related to the quality of the spatial matching between the primary noise field and the secondary field produced by the system in the cavity. “Intuitive” configurations were microphones are positioned near the listener positions are sometimes performing poorly as they do not take into account the response of the cavity. A process for optimization of the configuration has been developed and validated. The process allows to optimize the loudspeaker and microphone positions in the cockpit and to predict the performance of the ANC system with sufficient accuracy to enable system design decisions. These are confirmed in a later stage through ANC adaptive algorithm simulations, prototyping and measurements in the final installation.

7. References

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