Experimental and Numerical Study of Wind Noise Caused by Cowl Area on Volvo XC60

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Abstract

The paper presents a detailed experimental and numerical study of aerodynamically produced noise which occurs due to turbulent structures created by the cowl cavity and side mirror. The study aims to answer the question about how much turbulence in the cowl area contributes to the overall wind noise level on Volvo cars. Measurements were carried out at the Volvo wind tunnel on a Volvo XC60. Configurations considered were: rear view mirror On/Off with the cowl cavity open/closed. The results discussed in this paper include intensity probe measurements in the flow as well as standard measurements in the car. The experimental results are compared to numerical data, which are presented as isocontours of λ_2 criterion and pressure fluctuations.

1 Introduction

Aerodynamic noise produced by a running car represents a discomfort for both travellers and pedestrians. Thus, certain regulations for exterior noise limitation have been imposed on car manufacturers. Although there are no regulations for interior noise, customer expectations and demands are increasing. A vast scientific work has been carried out on the subject of aerodynamic noise generated by air flow around the car. Studies of wind noise generated by A-pillar and side mirror can be found in the literature [1,2,3,4,5,6,7,8,9].

Another area which is situated close to the A-pillar and mirror is the cowl area which often has a cavity shape and might cause an increased wind noise level. The depth and width of the cowl is depending on the A-pillar concept. In the so-called "Floating" A-pillar concept (such as Volvo XC60), the cowl area tends to be bigger than in "Planted" A-pillar concept (such as Volvo V70). In order to give input for styling at early stages of the project and to enable early target prediction, the study was carried out on the current Volvo XC60.

In this article we are discussing the importance of the cowl area and methods which can be used for studying wind noise generated by this cavity. In this investigation experimental and numerical methods were combined together in order to increase understanding of the phenomenon and to give input to new projects about the importance of the cowl shape.

2 Experimental Setup

Exterior and interior wind noise measurements were conducted on the Volvo XC60 production car at the Volvo wind tunnel. The car was tested at fully taped condition with all seals and splits taped in order to have a so called "flush surface" and eliminate interior leakages. Wipers were removed. The grill and spoiler area was closed in order to have the same configurations in both numerical and experimental parts. The car was fixed to the floor; non-rotating wheel condition was used.

Closed grill was chosen for the simulation of the condition when the grill shutter is closed. In this case more air is going above the car which represents the "worst case" when the cowl cavity noise is expected to be more noticeable and therefore measurable.

To measure a small noise contribution in Volvo's wind tunnel is a challenge. The tunnel is mostly used for aerodynamical and thermodynamical testing. It has slotted walls made of steel and has a reduced test section with acoustical treatment which does little to reduce reflections. It makes it difficult to measure small wind noise contributions inside the car.

Configurations considered in this study are listed in Table1 and presented in Figure1. Configurations with rear view mirror mounted were investigated with the cowl open (Configuration1) and the cowl closed (Configuration2), which can be seen in Figure1(a) and (b).

In order to measure cowl noise contribution it was decided to consider configurations with the side mirror removed on the left hand side (LHS) as illustrated in Figure1(c) and (d). The purpose was to remove the large sound source generated by the side mirror and distinguish the cowl noise. For these configurations, the side mirror was replaced by a flush surface of sail triangle which was specially made and allowed to keep all sealings and isolation material in their original place.

The closed cowl cavity configurations (see Figure1(b) and (d)) were modelled by extended surface which was aligned with the hood curvature and was covering the cowl cavity. The aim was to create a surface which would keep the flow attached to the hood and help to reduce or eliminate the separation bubble which might occur in front of the windscreen. It would allow to differentiate the contribution of cowl cavity noise from the overall wind noise.

Configuration	Cowl	Mirror	Volvo XC60 Fully Taped
Configuration1	Open	On	cowl open , with mirrors
Configuration2	Closed	On	cowl closed, with mirrors
Configuration3	Open	Off	cowl open , without LHS mirror
Configuration4	Closed	Off	cowl closed, without LHS mirror

Table1. Configurations tested during the study on fully taped Volvo XC60.

Figure1: Fully taped XC60 in the test section of Volvo wind tunnel. Mirror On: Configuration1 (a) cowl open, Configuration2 (b) cowl closed. Mirror Off: Configuration3 (c) cowl open, Configuration4 (d) cowl closed.

3 Wind Noise Measurements

Two methods were used for measurements of the wind noise generated in the cowl area of the car: external sound sources measurements and standard measurements inside the car.

3.1 Exterior wind noise measurements

The method for exterior wind noise measurements used during this work is based on the intensity probe. Wind noise intensity was measured by the probe with two parallel mounted microphones placed in the flow close to the point of interest. Both microphones have nose cones mounted on the top in order to keep the flow attached. The probe was mounted on the stand with a magnetic foot which was placed on the floor of the wind tunnel. Position of the probe was adjusted in such a way that the flow is parallel to the microphones' cylinders. The setup was designed with the aim to produce as little disturbance as possible around the area of interest.

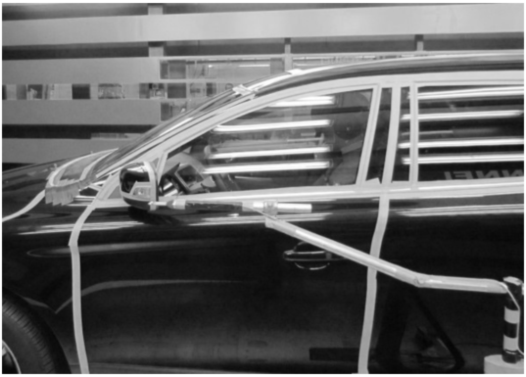

Figure2: Intensity probe at Position1.

This approach allows to measure the local intensity of wind generated noise. Spectral resolution of the probe is from 500 Hz up to 8 kHz. Brüel & Kjær [10] software and hardware was used for sound intensity measurements.

Exterior measurements were performed sequentially with one intensity probe in two different positions. The first probe position was close to the side mirror (see Figure2), called the mirror position (Position1). This position allows measuring the intensity of the sound source created by the rear view mirror. The second position was close to the cowl, called the cowl position (Position2, see Figure1d). By removing the mirror it was possible to place the probe microphones in that position and measure the sound source created by the cowl area.

The main purpose of the exterior wind noise measurements is to get reference values for upcoming projects which have clay cars available at the early stages. Interior sound measurements are difficult to perform on clay cars; however exterior measurements can be done. Successful optimization performed on the clay car can be implemented in early project phase and improve product quality at no cost.

3.2 Interior wind noise measurements.

The Interior wind noise was measured with an artificial head placed in the driver position. Head Acoustics [11] software and hardware was used for measuring and post-processing of signals. During interior wind noise measurements, the intensity probe was removed from the test section in order to avoid interference effects.

4 Experimental results

In Figure3 results of the measurement with the intensity probe at the Position2 (mirror Off) are presented for a velocity of 130km/h. The results of the probe measurements are presented as Constant Percentage Bandwidth (CPB) spectra. A difference in sound intensity level between Configuration3 with open cowl and Configuration4 with closed cowl can be observed on a broad range of frequencies. Intensity of the sound source generated by the closed cowl is lower then the intensity of the open cowl cavity. The biggest difference has a value of around 4dB which can be found at 600Hz.

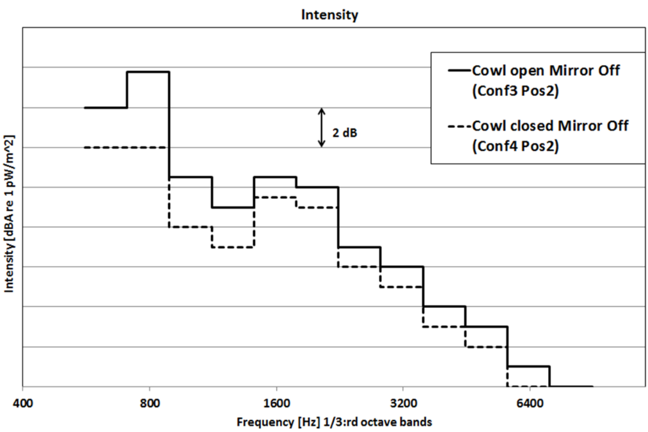

Figure3: CPB spectra for measurements with intensity probe at Position2 on the Volvo XC60 without the mirror. Configuration3: cowl open, Configuration4: cowl closed.

Results of measurements of the same configurations inside the car are presented in Figure4 as 3rd Octave spectra. The trend of decreased sound pressure level by 2 or 3dB can be observed between 600Hz and 3200Hz. It results in a difference of Articulation Index between Configuration3 and Configuration4 of: ΔAI% = 2,4% for front left outer ear (FLOE). It is interesting to notice that ΔAI% for front left inner ear (FLIE) was smaller: ΔAI= 1,7%.

Results of exterior intensity probe measurements at Position1 on the car with the mirror On are presented in Figure5 for Configurations 1 and 2.

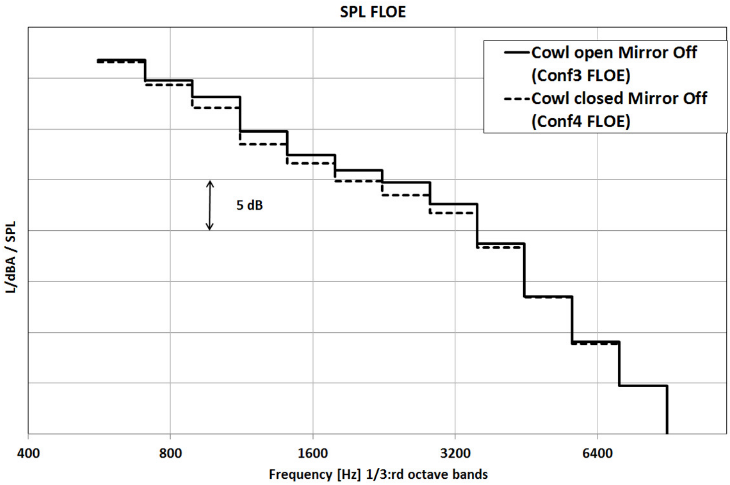

Figure4. 3rd Octave spectra of sound pressure level measured inside the car at FLOE position on Volvo XC60 without the mirror. Configuration3: cowl open, Configuration4: cowl closed.

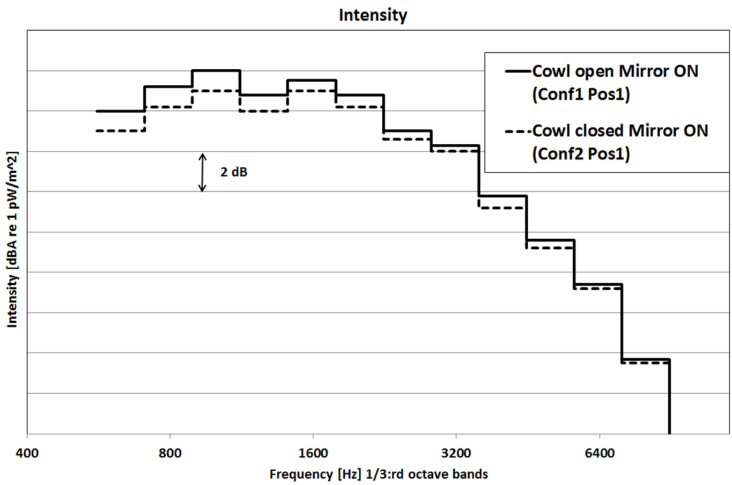

Figure5: CPB spectra for measurements with intensity probe at the Position1 on Volvo XC60 with mirror On. Configuration1: cowl open, Configuration2: cowl closed.

The difference between configurations is mostly noticeable at lower frequencies. It indicates that the influence of the cowl on the flow around the side mirror is rather small. But never the less an improvement of 1dB can be found when the cowl is closed. When the side mirror is the dominating sound source close to the side window, the sound pressure level (SPL) measured at FLOE is mostly influenced by that source. The difference in Articulation Index measured inside the car for Configuration1 and Configuration2 does not exceed 1,3%. Partly this issue can be attributed to the fact that, with mirror On, the wind noise level in the car is elevated and the smaller influence of the cowl cavity is hard to detect. At the same time, it is expected that the mirrors gets better in new coming products due to optimization work on the shape of the mirror house and foot. In this case the cowl cavity noise will be more noticeable if this area is not optimised.

The difference between configurations which is measured inside the car is more pronounced between configurations mirror On/Off, and is about: $\Delta AI\% = 3,5\%$.

The results of the measurements were used for development of the all new Volvo XC90. The cowl cavity was minimized as much as concept choices made early allowed. Together with optimized mirrors, the result on the all new Volvo XC90 model was good and on target.

5 Numerical setup

For the numerical investigation, the geometry of a full scale Volvo XC60 was considered herein, together with a simplified version of the wind tunnel used in the experiment. Configurations used for calculations are listed in Table1 and illustrated in Figure6.

Due to practical reasons, only half of the car was used in the numerical setup together with a symmetry plane. Similar to the experimental setup, the wheels are not rotating, the ground is fixed and a stream of air is passing over the car at 140 km/h.

The main differences between numerical model and experimental setup are listed in Table2.

Traditionally, the first step in computing a flow field is to initialize the domain with the best possible solution. In the current case, the field was initialized with the solution obtained from solving a potential equation for velocities.

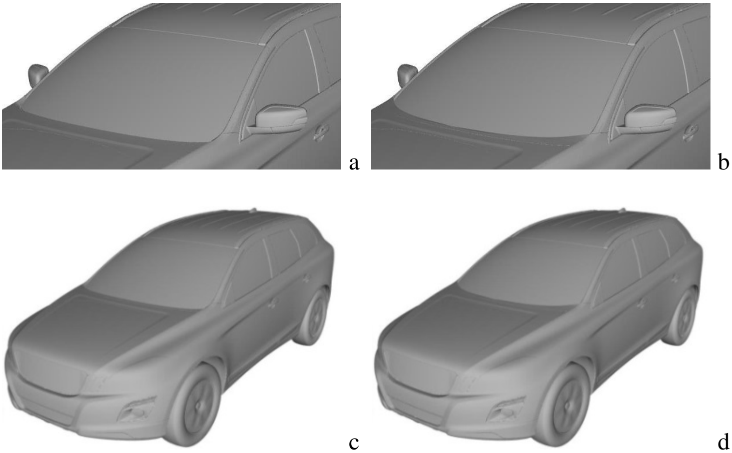

Figure6: Numerical model of Volvo XC60. Mirror On: Configuration1 (a) cowl open, Configuration2 (b) cowl closed. Mirror Off: Configuration3 (c) cowl open, Configuration4 (d) cowl closed.

Car	Numerical model	Experimental setup
Underbody	Flat, simplified	Real
Wheels and rims	Covered rims, simplified	Real
Cowl cavity	Hood extension not connected to wind screen	Plastic surface connected to wind screen

Table2. Main differences between numerical model and experimental setup.

This solution was used as a starting point for a complete Reynolds Averaged Navier Stokes (RANS) computation. The newly obtained solution was used again as a starting point for a transient calculation within the Large Eddy Simulation (LES) framework. An important assumption considered herein is incompressibility, which is a common practice for fluids flowing at low Mach numbers ($M < 0.3$). The boundary conditions are the velocity inlet (140 km/h at inlet), pressure outlet (gauge pressure $p = 0$ Pa at outlet), wall (0 km/h at walls and ground), and symmetry. Moreover, the discretization schemes are first order upwind for turbulence equations (k-ε), second order upwind for momentum, and second order for pressure. In the RANS calculation, the widely used k-ε realizable, turbulence model is applied as closure for the averaged equations system. Although LES solves part of the turbulence spectrum, one still needs to model turbulent structures which are smaller than the filter width. In the current approach, a Smagorinsky subgridscale model was considered.

This approach [12] allows identifying the main flow structures and pressure fluctuations on the surface of the car. The method is considered to be a good tool for identifying the problem and comparing configurations. There is a common belief: less turbulence generates less wind noise.

6 Numerical results

Results of the calculations are presented in Figure7 as isocontours of λ_2 criterion [14], which illustrates the flow structures around the car. The A-pillar sheds several coherent structures which are developing streamwise along the side window. Another rather large structure is seen at the cowl area, extending and over flowing the A-pillar. Two more counter rotating vortices are present along the windscreen from plenum to the roof, but they are thought to be numerical artefacts of the symmetry boundary condition applied on half of the car.

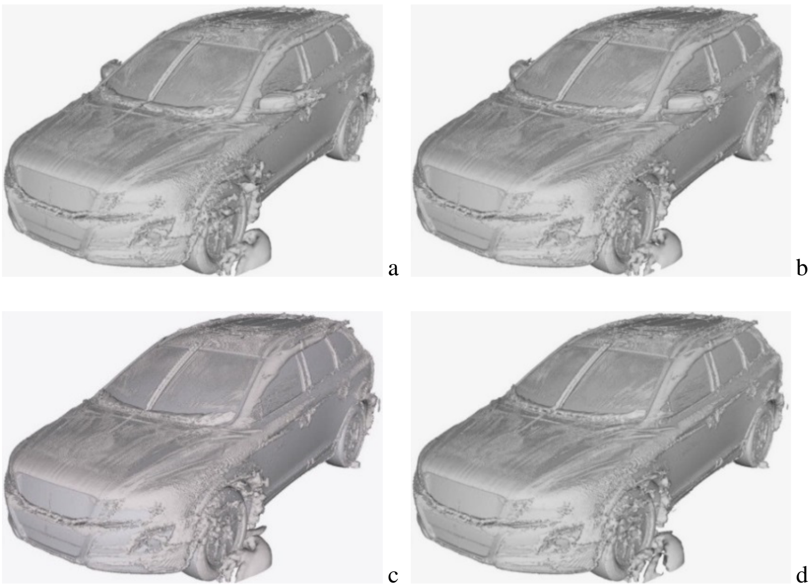

Figure7: Isocontours of λ_2 on Volvo XC60. Mirror On: Configuration1 (a) cowl open, Configuration2 (b) cowl closed. Mirror Off: Configuration3 (c) cowl open, Configuration4 (d) cowl closed.

As it was mentioned above, the closed cowl cavity configurations were considered in order to reduce or eliminate the separation bubble on the wind screen. The numerical results show that it was possible to decrease the separation bubble, but not to eliminate it. Moreover, if the hood extension which represents the cover for the cowl cavity is created wrong, it will increase the separation bubble on the front screen and create increased pressure fluctuations on the surface of the car, thus more noise.

Figure8 shows normalized pressure fluctuations (p_{rms}) which are dominant on wind screen, A-pillar and side window. The comparison between configurations with open and closed cowl shows a decreased level of pressure fluctuations on the area of A-pillar, side window and mirror foot. At the same time, an increase of pressure fluctuations can be observed on the wind screen. In total, the value of pressure fluctuations decreases on the surface of the car if the cowl is closed.

Another phenomenon can be observed for configurations with mirror On/Off. When the mirror is removed, the A-pillar vortex is changing its position and strength (see Figure8(b) and (d)). It appears to move down from A-pillar and causes an increase of pressure fluctuations on the side window.

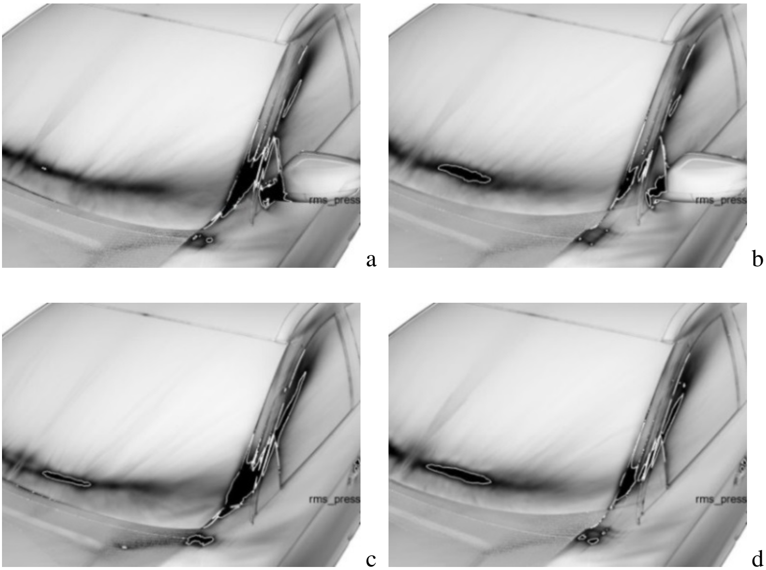

Figure8: Pressure fluctuations (p_{rms}) on Volvo XC60. Mirror On: Configuration1 (a) cowl open, Configuration2 (b) cowl closed. Mirror Off: Configuration3 (c) cowl open, Configuration4 (d) cowl closed.

The observation that the A-pillar vortex is changing its position and strength raises some questions regarding the difference between the noise generated by the side mirror and the noise generated by A-pillar vortex on the side window when the mirror is removed [13].

7 Conclusions

An experimental and numerical study of wind noise generated by open cowl cavity was carried out. Exterior intensity sound measurement were performed on a Volvo XC60 with side mirrors and with mirrors removed as well as with the cowl cavity open and closed. Interior measurements were carried out for all configurations.

It was shown that the cowl cavity is an important wind noise source and it can contribute to overall noise level inside the compartment. Improvement around 2% Articulation Index can be achieved.

Configurations of interest were modelled numerically. The shift of flow around the car was illustrated and proven to have good similarity with experiment. Pressure RMS and illustration of vortex core can be recommended for future development.

For the development on early stages of the project, it is recommended to perform optimization of the cowl area with side mirrors removed. Measurements with intensity probe at the cowl position are recommended.

The method was successfully implemented for the development of the all new Volvo XC90 model.

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