

Improvements of the Beamforming Technique in Pininfarina Full Scale Wind Tunnel by using a 3D Scanning System

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ABSTRACT

Acoustic comfort is a key selling point leading vehicle manufacturers to invest money and resources in research activity. As a consequence the localization of internal and external noise sources of the vehicle is becoming more and more important.

The "Beamforming" technique is a well-known method, based on an array of microphones, suitable to identify the external noise sources of a road vehicle. This technique is able to localize the noise sources by estimating the amplitudes of plane, or spherical, waves incident toward the array. For many different reasons, such as the unknown position in the space of the noise sources, the processing time, the algorithm simplicity and so on, the investigation is generally made only on a virtual plane (planar Beamforming) and not in the full three-dimensional space. As a consequence the results accuracy, especially in terms of Sound Pressure Level (SPL) is not entirely satisfactory.

Based on these considerations, Pininfarina started a research program to improve the "Beamforming" technique by surveying the three-dimensional geometry of the full scale vehicle placed in the wind tunnel test section. This approach allows for a direct investigation of the noise sources on the 3D model, improving the source detection.

The details of the 3D scanning system are described together with its application. Moreover, are presented three experiments that show, with respect to the Planar "Beamforming" (PBF) technique, the improvements of the SPL values of the noise sources detected focusing the microphones array on the surveyed 3D geometry.

INTRODUCTION

Since 2005, to investigate the external noise sources of vehicles in the full scale wind tunnel, the Aerodynamics and Aeroacoustics Research Center, replaced the Acoustic Mirror System (operating since 1996 [1-2]) with a "Beamforming" system. With respect to the acoustic

mirror the main advantages of the "Beamforming" are the great reduction of acquisition time, the better spatial resolution and the possibility to explore the time-dependent behavior of the acoustic field [1 – 5].

This technique is based on microphones array and allows for the identification of the noise sources in a virtual plane close to the vehicle and parallel to the plane where the array of microphones lies.

The wind tunnel is equipped with two microphones arrays. The first one consists of 78 microphones and is located on the ceiling of the test section (4 m from the ground), while the second one consists of 66 microphones and it is placed on the side wall of the test section (see Fig. 1).



Fig. 1: Microphone Arrays in the full scale Wind Tunnel.

The basic principles of the "Beamforming" and the improvements on the analysis were presented in a number of previous works by different authors; the "Cross Spectral Imaging Function" is the analysis algorithm used in this work [7]. A possible way to improve the results of the technique, in terms of SPL accuracy, is to focus the investigation directly on the

three dimensional model. With this method, it is possible to keep into account, for example, the different height of the vehicle's components (i.e. bumper, A-pillar, rear view mirror, radio antenna, wipers, etc.) and therefore the different distance between the sources and the acquiring array of microphones. By knowing the correct position of these possible noise sources, the microphones array can be locally focalized in that points thus achieving more accurate results in terms of SPL level and localization. The experiments described in the following paragraphs show how a better focalization of the array of microphones increases the level of SPL of the detected noise sources, especially those far away from the conventional bi-dimensional focalization plane. As a consequence, the knowledge of the correct geometry of the tested model gets very important.

Many companies developed systems to survey the three-dimensional geometry of bluff bodies, based on laser scanning or other optical systems. The first method is generally very accurate but it requires long acquisition time and it is not very suitable to be installed in a full scale automotive wind tunnel for many practical reasons. An optical system, fully integrated in the full scale Wind Tunnel, has been developed in order to reduce the measurement time of the vehicle geometry in a flawless workflow.

As mentioned before, the Wind Tunnel is endowed with two arrays of microphones to investigate the noise sources of the top and one side of the vehicle. Therefore, in order to survey the 3D-geometry of the tested model, two different scans are necessary to get the height over ground and the width of the vehicle along the longitudinal direction (X axes). For the sake of clarity, only the top scanning system will be considered in the following sections. Obviously the theory, application and results are easily translated to the side scanning system.

In the first section of this paper a description of this optical system will be given, while in the second section the improvements over the conventional "Beamforming" technique will be reported.

3D SCANNING SYSTEM

The three-dimensional scanning system is described in this section. After a basic overview of the mathematical concepts at the heart of the application, the system calibration technique is described. Furthermore, an analysis of the accuracy of the system is reported.

THEORY OVERVIEW

It is well understood that from one image captured by a single video camera, it is possible to get information of only two spatial dimensions. By using two cameras and processing the overlapping areas of the two captured images, it is possible to retrieve the values of the third

spatial dimension. Obviously the cameras need an appropriate calibration.

Before continuing it is necessary to define the reference systems. A point in the Wind Tunnel or "World" Reference System (WRS) is indicated by capital letters (X, Y, Z) , whereas small letters (x^i, y^i) refers to the pixel's coordinate in the image captured by the i -th Video-Camera (VC^i). A simplified scheme of the scanner is shown in Fig. 2 where, for the sake of clarity, only the YZ section of the "world" space is plotted. In this example the world coordinate X and the cameras coordinates y^i are omitted to avoid confusion.

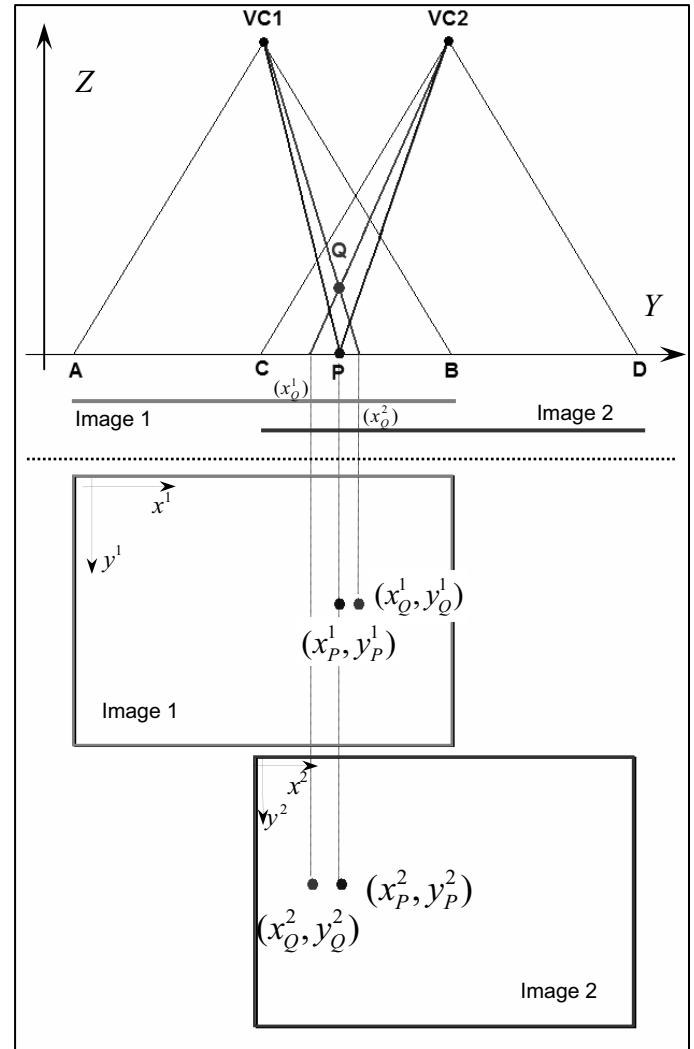


Fig.2: Simplified scheme of scanner.

The points lying in the cones defined by $[VC^1, A, B]$ and $[VC^2, C, D]$ are framed respectively by the video cameras VC^1 and VC^2 . The point P , located in the overlapping segment CB , has "world" coordinates $(Y_p, 0)$ and pixel coordinates (x_p^1) and (x_p^2) in the images captured by cameras VC^1 and VC^2 . Point Q is

located at the same Y position with different Z value. It has pixel's coordinates (x_q^1) , (x_q^2) where $x_p^1 \neq x_q^1$ and $x_p^2 \neq x_q^2$. This example, suggests that, by making simple geometrical considerations it is possible to derive a relationship between a unique point in the "world" reference system and a couple of pixel's coordinates.

Nonetheless, a pure geometrical approach is not entirely satisfactory since the accuracy of the results suffers from perspective errors due to video cameras optics defects and camera limitations. A different approach has to be adopted.

Fig. 2 illustrates that all the "world" points lying along the line passing through the Q point have coordinate (x_q^1) in the camera 1 image. To identify the unique Y_Q it is necessary to fix the Z_Q value. This suggest that the "world" coordinate Y_Q is function of (x_q^1) and Z_Q .

By applying these considerations to the 3D-space, for every generic i -th camera it is possible to write the following equations:

$$\begin{aligned} X &= f_x^i(x^i, y^i, Z); \\ Y &= f_y^i(x^i, y^i, Z). \end{aligned} \quad (1)$$

The functions f_x^i and f_y^i can be approximated by polynomials:

$$\begin{aligned} X &= \sum_j a_j^i (x^i)^p (y^i)^q Z^r \\ Y &= \sum_j b_j^i (x^i)^p (y^i)^q Z^r \end{aligned} \quad (2)$$

where $p + q + r = R$, with R the order of the polynomial, and $r=0,1$. The coefficients $\{a_j^i\}$ and $\{b_j^i\}$ for the camera i are computed with the calibration process, as described in detail in the next section. The calibration coefficients take into account all the optical properties and defects of the system.

As an example, let us consider the case where $R = 3$; Eq. (2) can be written as:

$$\begin{aligned} X &= a_0^i + a_1^i x^i + a_2^i y^i + a_3^i Z + \\ & a_4^i (x^i)^2 + a_5^i x^i y^i + a_6^i (y^i)^2 + a_7^i x^i Z + a_8^i y^i Z + \\ & a_9^i (x^i)^3 + a_{10}^i (x^i)^2 y^i + a_{11}^i x^i (y^i)^2 + a_{12}^i (y^i)^3 + \\ & a_{13}^i (x^i)^2 Z + a_{14}^i x^i y^i Z + a_{15}^i (y^i)^2 Z, \end{aligned} \quad (3)$$

$$\begin{aligned} Y &= b_0^i + b_1^i x^i + b_2^i y^i + b_3^i Z + \\ & b_4^i (x^i)^2 + b_5^i x^i y^i + b_6^i (y^i)^2 + b_7^i x^i Z + b_8^i y^i Z + \\ & b_9^i (x^i)^3 + b_{10}^i (x^i)^2 y^i + b_{11}^i x^i (y^i)^2 + b_{12}^i (y^i)^3 + \\ & b_{13}^i (x^i)^2 Z + b_{14}^i x^i y^i Z + b_{15}^i (y^i)^2 Z. \end{aligned}$$

Considering the overlapped image between VC¹ and VC², re-arranging the equations (3) for each camera it is possible to write the following linear system whose solution corresponds to the coordinate (X, Y, Z) of a particle's vehicle with the pixel's coordinate (x^1, y^1) , (x^2, y^2) :

$$\begin{bmatrix} 1 & 0 & A_1 \\ 0 & 1 & B_1 \\ 1 & 0 & A_2 \\ 0 & 1 & B_2 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} C_1 \\ D_1 \\ C_2 \\ D_2 \end{bmatrix}, \quad (4)$$

where

$$\begin{aligned} A_i &= -a_3^i - a_7^i x^i - a_8^i y^i - a_{13}^i (x^i)^2 - a_{14}^i x^i y^i - a_{15}^i (y^i)^2 \\ B_i &= -b_3^i - b_7^i x^i - b_8^i y^i - b_{13}^i (x^i)^2 - b_{14}^i x^i y^i - b_{15}^i (y^i)^2 \end{aligned}$$

$$\begin{aligned} C_i &= a_0^i + a_1^i x^i + a_2^i y^i + a_4^i (x^i)^2 + a_5^i x^i y^i + a_6^i (y^i)^2 + \\ & a_9^i (x^i)^3 + a_{10}^i (x^i)^2 y^i + a_{11}^i x^i (y^i)^2 + a_{12}^i (y^i)^3; \end{aligned}$$

$$\begin{aligned} D_i &= b_0^i + b_1^i x^i + b_2^i y^i + b_4^i (x^i)^2 + b_5^i x^i y^i + b_6^i (y^i)^2 + \\ & b_9^i (x^i)^3 + b_{10}^i (x^i)^2 y^i + b_{11}^i x^i (y^i)^2 + b_{12}^i (y^i)^3 \end{aligned}$$

and $i=1,2$.

In order to detect the same vehicle detail in both the images acquired by the cameras 1 and 2, a cross correlation of the portion of the image 1 centered on pixel coordinates (x^1, y^1) with image 2 is performed.

The maximum value of the cross correlation map corresponds to the identification of the vehicle detail on camera 2 and gives the pixel's coordinate (x^2, y^2) . At this stage, the pixel's coordinates of vehicle detail are known, and can be substituted in (4) to retrieve (X, Y, Z) .

SYSTEM CALIBRATION

As seen in the previous section, the calibration is a crucial step of the whole process. The purpose is to

compute the coefficients $\{a_j^i\}$ and $\{b_j^i\}$ of Eq. (2) approximating at best the map between the N known couples of points with coordinates (X_k, Y_k, Z_k) and (x_k^i, y_k^i) with $k=1, \dots, N$.

The first step is to map known points in the “world” (wind tunnel) reference system to known pixel's coordinates. To accomplish this operation, an extended calibration panel has been built (Fig. 3) with markers distributed on a regular grid. The panel is further mounted on a traversing system to move it along all the possible directions in the test section.

The calibration of the generic i -th video camera, is performed by aligning the center of the plane with the center of the image and by acquiring images of the calibration panel at different Z values. Processing the images captured by the video camera, the pixel's coordinate (x_k^i, y_k^i) of each dot can be associated to the correspondent point (X_k, Y_k, Z_k) in the WRS.

The solutions of the two following minimization problems are the coefficients $\{a_j^i\}_{j=1}^{15}$ and $\{b_j^i\}_{j=1}^{15}$:

$$\min_{a_1^i, \dots, a_{15}^i} \sum_{k=1}^N (X_k - f_x^i(x_k, y_k, Z_k))^2, \quad (5)$$

$$\min_{b_1^i, \dots, b_{15}^i} \sum_{k=1}^N (Y_k - f_y^i(x_k, y_k, Z_k))^2$$

where f_x^i and f_y^i are approximated as in (3).

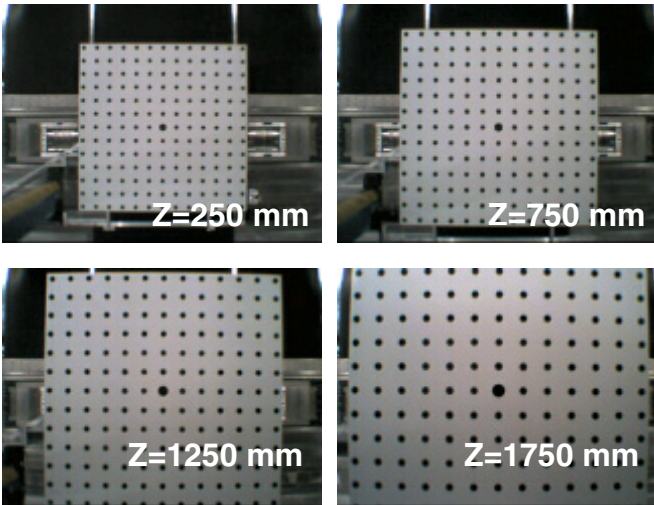


Fig. 3: Calibration panel's images, at different Z values, acquired by the video camera.

DESCRIPTION OF THE SYSTEM

The top scanner of the full scale Wind Tunnel consists of 5 video cameras placed on the upper arm of the main traversing system (TG). The video cameras are aligned along the Y direction of the wind tunnel and are located

in fixed position starting from $Y=-1$ m to $Y=1$ m with a distance of 0.5 m.

During the scanning, the TG is moved only in the X direction with step of 0.5 m. At each X position, five images of the vehicle are acquired by the video camera. Currently, the captured photos have a resolution of 640 x 480 pixels.

After the scan is complete, in order to investigate the geometry of the vehicle, the acquired images by the first video camera are processed with the images captured by the second one; the images of the second video camera are processed with the third one and so on.

In order to get better results during the cross-correlation phase some image projectors are located on the same arm as the cameras, projecting static pictures on the vehicle surface. In fig 4 some examples of images acquired during the scan are shown.

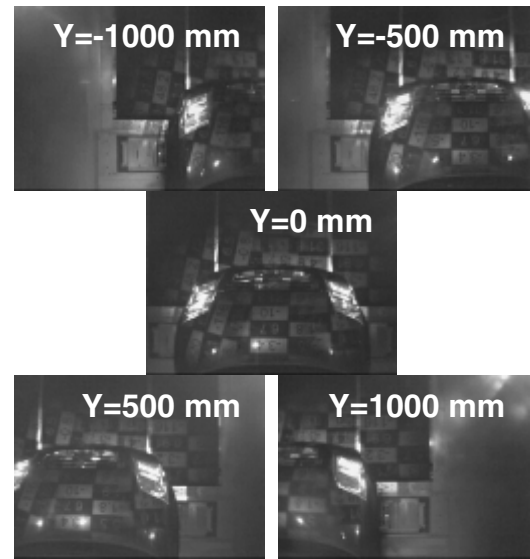


Fig. 4: Example of the image acquired by the 5 video cameras.

ANALYSIS OF THE SYSTEM'S ACCURACY

To assess the accuracy of the described process, a 3D scan of the SAE model with wheels has been performed. This model has a simple and well known geometry. It is possible to compute the RMS error for each absolute coordinate as follow:

$$RMS_Z = \sqrt{\frac{\sum_{k=1}^N \left(\frac{\hat{Z}_k - Z_k}{\hat{Z}_k} \right)^2}{N}} \cdot 100; \quad (5)$$

where $\hat{Z}_k$, Z_k correspond respectively to the nominal and computed values. Analogous formulas can be written for RMS_X and RMS_Y .

Table1 reports the accuracy of the system, as just defined:

RMS_x	$< 0.5\%$
RMS_y	$< 0.5\%$
RMS_z	$< 4\%$

Table 1: Accuracy of the top scanner

These errors can be drastically reduced increasing the resolution of the video cameras.

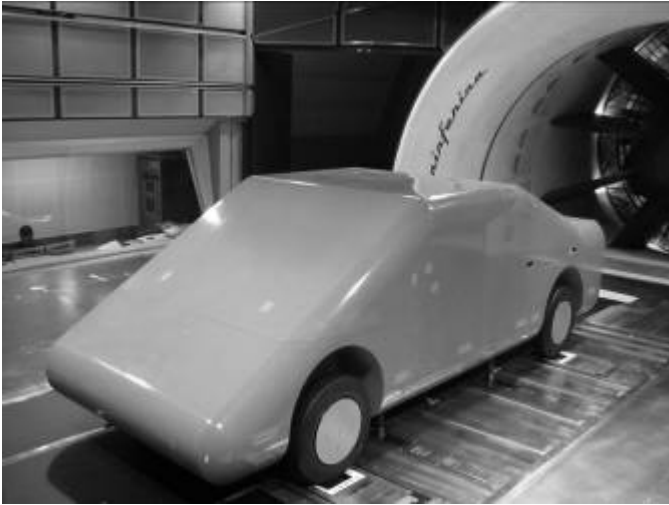


Fig. 5: SAE model with wheels.

In Fig 5 a picture of the model used to compute the system accuracy is shown, while in fig. 6 the result of the model's top side 3D scan is reported.

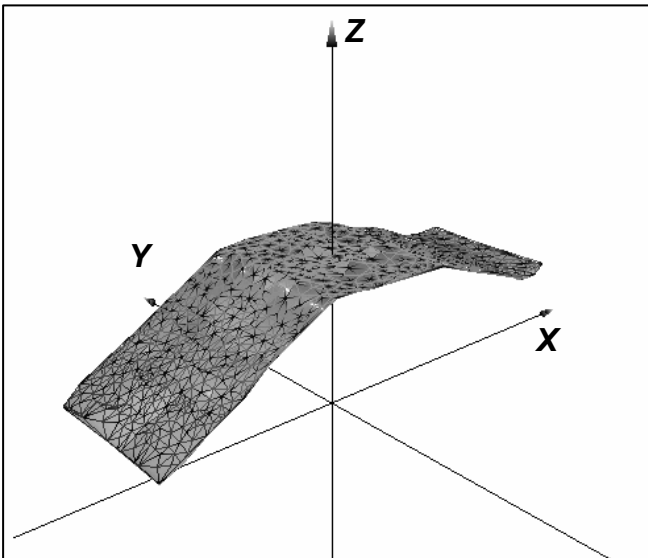


Fig. 6: Top scansions result of the SAE model with wheels.

IMPROVEMENTS OF THE BEAMFORMING TECHNIQUE

As mentioned in the introduction, the Beamforming is a technique to detect the noise sources located in the space. The source location is performed by estimating the amplitudes of plane (or spherical) waves incident toward the array from a set of points in the space. Since the position of all the potential noise sources in the three dimensional space is unknown, the points are chosen to be on a two dimensional plane. This is the so called Planar Beamforming (PBF).

The experiments performed in the full scale wind tunnel hereafter described, highlight the improvement reached by focusing the microphones array in the points of the three-dimensional geometry of the vehicle, with respect to the results obtained with the PBF.

The basic principle of the Beamforming is the coherent sum of all the pressure signals measured by each single microphone, i.e. the "delay and sum" principle. The time delay of each signal is proportional to the distance between the microphone and the point chosen for the investigation. In this way all the waves originating from the given point are aligned in time and summed in a coherent way. Signals arriving from other directions will not be aligned before the summation, and therefore they will not be coherently added. The "delay and sum" scheme allows to the microphones array to have a directional sensitivity. The implementation of this basic principle is beyond the scope of this paper.

These considerations focus on the importance of a correct array focalization. In the following, a description of the experiments and a comparison of the results obtained with the PBF and the 3D Beamforming is presented.

EXPERIMENTS

All the investigations have been performed on the same wind tunnel test car (Citroen C2), see Fig. 7. To highlight the errors due to a wrong focalization of the array of microphones, in the first two experiments two Reference noise Sources (RS) have been placed at different heights on the car body. Looking at the results it is possible to notice that the PBF allows getting correct results only for the sources located close to the focus plane. The errors of the SPL computed for the other sources are remarkable and increase especially at high frequencies. In the third experiment the reference sources have been removed, and the aeroacoustic noise arising from the car has been measured at a wind velocity of 140 km/h.

In Fig. 7 and fig. 8 the tested car and the surveyed geometry of the top of the car are shown respectively.