Aerodynamic Noise Sources Reduction of a Sedan Car via Surface Modifications using Wind Tunnel Experiments

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Abstract

NVH in passenger vehicles is a major concern for automotive manufacturers to meet the comfort standards. In this regard, this research aims to investigate the external aerodynamics of the IKCO DENA+ car, which contributes to annoying cabin noise. In this research, the sources of aerodynamic noises were identified using wind tunnel tests on a 2/5 scaled model. Smoke flow visualization of the flow around the car to identify aerodynamic noise sources has been conducted. The results obtained from visualization showed that six factors were identified as sources of aeroacoustics noise, including 1.the distance between the side mirror and the body, 2.the form of the side mirror, 3.the rear passenger quarter window, 4.the shark antenna, 5.car handles, and 6.design feature on the rear door of the car. Then, within the next steps, the surface modification solutions regarding the identified noise sources were tested. In addition, Measurements using hot wire anemometry and pressure sensors were performed at different velocities of 18 to 118.8 km/h. The results showed that surface modification related to quarter window led to a reduction in flow disturbances and noise levels on the car's rear door glass significantly. Furthermore, modifying the side mirror of the car has considerably improved the aerodynamic within the area of the front door glass. Consequently, these modifications reduced pressure disturbances by 9% and 5%, respectively.

Keywords: Aeroacoustics; NVH; Sedan Cars; Wind Tunnel Testing; Smoke Flow Visualization

1. Introduction

Today, with the development of technology in the automotive industry and cars have become essential in daily life, design constraints on vehicle interiors and exteriors that are related to the comfort and convenience of the passengers have become stricter. One of the most critical standards that cars must pass during the design phase is the amount of annoying noise in the cabin (NVH Standard). The noise inside the cabin can have various sources; the following factors can be mentioned as the primary noise producers: 1. engine and related parts, 2. vehicle structure with different frequency modes, 3. road and wheels interaction, 4. environmental factors and most importantly, 5. aeroacoustics noise caused by external airflow and air movement path are created.

The topic of aeroacoustics and the study of noise produced by airflow is one of the emerging fields in the automotive industry. Several studies have been conducted on the importance of aeroacoustics noises [1-3]. Mira company has studied aeroacoustics noises and the effect of car body design on them [4-6]. According to Harris's research [7], annoying noise in the cabin can be related to three parameters of car velocity, air velocity in different places and the amount of car acoustic sealing. Romberg [8] from the Chrysler Group divided the total noise produced by the car into three categories: aerodynamic noise, aspiration noise and residual noise. The source of aerodynamic noise is external airflow, vortices and turbulence around the vehicle; while the aspiration noise can be created for three reasons: 1. Penetration of the sound of pressure disturbances from the channels into the cabin, 2. Penetration of the pressure disturbances of the flow into the cabin resulting in production of noise in the cabin, and 3. Penetration of the airflow into the cabin which produces the noise. The residual noises are other types of sounds generated in the car which were mentioned at the beginning [9]. At velocities of more than 100 km/h, which is related to the car’s driving on highways, the dominant sound in the car is in response to the aerodynamic noises [10, 11]. According to the first researches from the beginning of the 60s and 70s, the aerodynamic noise of the car is divided into three main categories: [5, 10]

1. Broadband Wind Rush Noise: This sound is caused by the movement of air and the acceleration of particles on the car’s body.

2. Tonal noise: The cause of this noise is the presence of sharp surfaces and gaps in the car body.

3. Resonance noise: It is caused by open windows and sunroof.

Also, researchers have shown that the car's general shape does not significantly affect the produced noise. Still, the air rotation in the A-Pillar of the vehicle can substantially affect the made noise [1].

Aerodynamic noise reduction technology has been developed in aerospace engineering and aircraft design, while the area of automobile engineering is still in the initial stages of development. Methods of noise reduction in the construction of silent birds [12], reduction of noise produced by airfoils [13, 14], reduction of noise of wind turbines [15, 16] and reduction of noise produced by various types of rotors [17, 18] are some of the studies carried out in the field of aerospace engineering in the area of aerodynamic noise reduction. Some papers have been performed for the purpose of noise reduction in the car cabin. Lu jon [19] in his paper proposed the modification of glass materials and the use of acoustic laminated glass, which, in addition to conducting an experimental test on the Volvo S80 car model, showed that the use of acoustic glass reduces wind noise between 1 and 5 dB in the frequency range of 1 to 6. kHz results. This issue can also be seen in Piper's research [20]. Also, in line with the use of a modification of sealing tapes, a study has been published by Kang et al. [21] and at the same time, Rao [22] investigated the application of viscoelastic damping materials for noise and vibration control in automotive structures. The study demonstrated that such materials can effectively dissipate vibrational energy and reduce structure-borne noise within the vehicle cabin. It is worthwhile to mention that active flow control methods have also been used in cabin sound reduction, where a secondary energy source is used to reduce noise and airflow control [23].

Considering that there are different sources of noise in the car, researchers do not recommend using road tests in this field because the secondary noises of the road, engine and body can also cause errors in the tests. As a result, to investigate the noises caused by the airflow, using of the wind tunnel, which focuses only on the airflow around the car is feasible. In this regard, Jen et al. [24] from Ford Company used wind tunnel tests to identify noise sources. Also, experimental investigations to identify aerodynamic phenomena were proposed by Sumitani from Toyota [25]. This research showed that pressure waves and perturbations that result in sound production are related to aerodynamic flow phenomena directly.

This research focuses on investigating and reducing the noise inside the IKCO DENA+ car cabin. Previous road tests and costumers' complaint show that an annoying noise of this vehicle starts from velocity of 80 km/h. It is also indicated that aerodynamic sources are responsible for this kind of noise in this car. In this study, with the help of wind tunnel tests on 2/5 model, the origins of aerodynamic noise are identified to test the solutions suitable for noise reduction. Visualization of the flow field around the car for aerodynamic phenomena and identification of noise sources were carried out with the help of smoke and green laser. It should be mentioned that all measurements were performed using hot wire anemometry and pressure sensors within a wide range of velocities from 18, 36, 54, 72, 90, 108 and 118.8 km/h for the purpose of noise reduction related to front and rear passengers. The innovation of this research is identification of aerodynamic phenomena occurring around the car and the modification of the car body in the wind tunnel tests to reduce the sources of disturbances and noise in the cabin. Unlike numerical simulations that rely on modeling assumptions, the experimental methodology provides direct and reliable observation of flow structures and aerodynamic phenomena. In contrast to road tests, the controlled wind tunnel environment eliminates interference from secondary noise sources such as engine and road interaction, allowing accurate identification of aeroacoustics sources. Furthermore, the combined use of flow visualization and quantitative measurements enables both qualitative understanding and quantitative evaluation of aerodynamic noise-generating mechanisms. This integrated approach facilitates the identification of multiple noise sources simultaneously and allows the effectiveness of practical geometric modifications to be systematically assessed.

2. Experimental Setup and Methodology

This research is conducted experimentally using wind tunnel experiments. Different measurement techniques were used to measure and compare the results in different case studies; all the tests were performed in a specific procedure which will be described.

2.1. Model and Experimental Setup

In this study, the scaled model of a 2/5 IKCO DENA+ car was used. This Model was prepared using plastic injection on the clay model of the vehicle in the product development and research center of Irankhodro company (IKCO) and has all the details of the real car. Pictures of this model in the wind tunnel can be seen in Fig. 1.

Fig. 1 Images of models 2/5 of the IKCO DENA+ car inside the wind tunnel

All the experiments were carried out in the subsonic wind tunnel of the Aerospace Engineering department at Amirkabir University of Technology. This wind tunnel is an open circuit type, and its test section dimensions are 1×1×2 m^3. Due to the use of a nozzle with a contraction ratio of 9:1, three layers of screens with different mesh and a standard honeycomb, the intensity of disturbances in the test section of this wind tunnel is less than 0.1%, which makes it possible to perform low-velocity tests and capture aerodynamic phenomena. A box of differential pressure sensors consisting of 80 differential Honeywell pressure sensors (HSCDD025MDNN5) with the maximum range of 5 mbar and full-scale accuracy of 0.25% were used for static pressure (P_S) measurements and pressure disturbances (P'). To calculate the velocity of the free stream, a pitot-static tube connected to a digital micromanometer made by KIMO company and model MP120 was used, which can measure the velocity with an accuracy of 0.1 m/s. The smoke generator and a green laser was also used to visualize airflow and phenomena around the car. The schematic of the test setup is shown in Fig. 2, which shows the arrangement of the model and measurement techniques used during the tests. Also, to compare the results in different test cases, all the experiments have been done in a specific procedure.

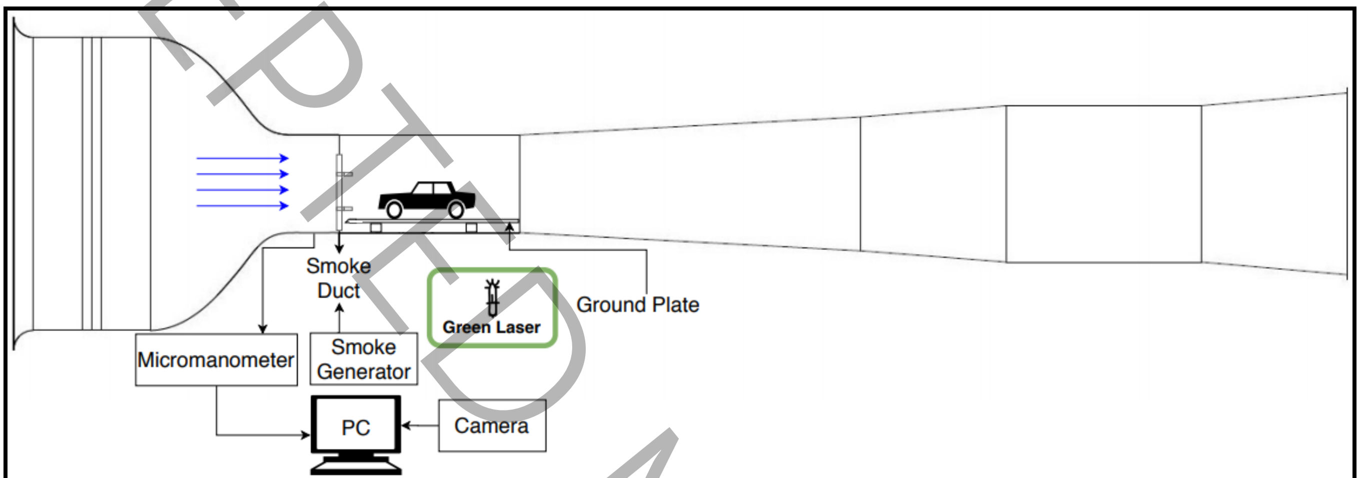


Fig. 2 Schematic of the test setup in wind tunnel

2.2. Test Procedure

To compare the results of different test cases and evaluate the effect of each component, all the tests and analyses of the results have been done according to a specific procedure. All the wind tunnel tests were conducted at velocities of 5, 10, 15, 20, 25, 30 and 33 m/s, equivalent to 18, 36, 54, 72, 90, 108 and 118.8 km/h. The test procedure is as follows, first, an offset value of the sensors was measured and documented before setting up the wind tunnel, and second the free stream velocity was increased. At each specific rate, the flow is given a time limit of 30 seconds to be uniform and finally, data collection is performed for 30 seconds with a frequency of 5 kHz. Thus, the process of conducting the research was as follows: first, the flow was visualized using smoke and laser techniques, and critical aerodynamic phenomena around the car as well as potential areas were identified and then geometry modifications were applied to these areas. The effect of each modification on velocity fluctuations and pressure disturbances on the front and rear passenger windows were measured and compared.

3. Results and Discussion

The results obtained from wind tunnel experiments using smoke flow visualization technique will be described within the subsequent sections.

3.1. Flow Visualization and Aerodynamic Phenomena Identification

As was previously mentioned, the smoke visualization technique is used to observe the physics of flow around a scaled car model and to identify areas susceptible to the production of aerodynamic noises. The results obtained from flow visualization showed that the antenna areas, rear passenger quarter window, the distance between the side mirror and the car body, the aerodynamic form of the mirrors and handles, and the feature of the external surfaces of the rear doors are possible sources of aero noise. Fig. 3 shows the flow captured between the mirror and the car body over a specific time. It is worthwhile to mention that during these experiments, the smoke outlet pipe was placed between the mirror and the car body; also, the inflow represented the flow interaction between the mirror and the body. According to this figure, at first, due to the presence of the mirror base, a relatively large vortex was formed, which moved along the length of the car towards the front door glass as time passed. When this vortex reached its largest dimensions, it hit the end of the glass. Therefore, this phenomenon can be the main source of annoying noise for the front passengers and driver. Also, Fig. 4 shows the picture of the flow behind the side mirror of the car model. In this case, the smoke pipe was located in the middle of the mirror; therefore, the flow line corresponding to the center of the mirror was illustrated. The captured pictures showed that the flow behind the mirror is highly turbulent, and a large number of eddies are observed within the wake of the mirror as a bluff body.

Furthermore, Fig. 5 shows the picture related to the visualization of flow in the rear door quarter glass area. Presence of a forward-facing step in the airflow resulted in a vortical flow at the rear quarter glass and the triangular-shaped area. Thus, it can be concluded that presence of the vortex with a small magnitude and in turn a high frequency caused vibration of the glass in this area. In the following, flow visualization of the car handle area is also illustrated in Fig. 6. According to this picture, it can be seen that the cavity area under the handle caused the flow to be trapped in it and the eddies to shed behind it. Also, despite the fact that the handle is far from the body of the car, vortex shedding continued towards the end of the vehicle.

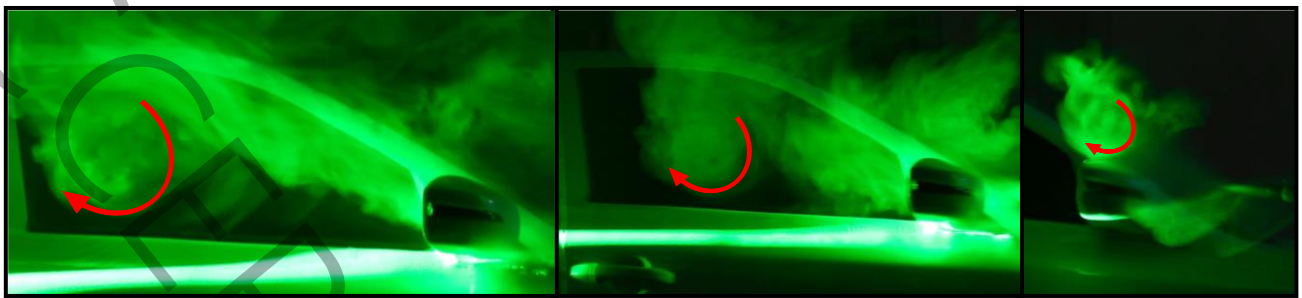


Fig. 3 Visualization of the flow between side mirror and car body

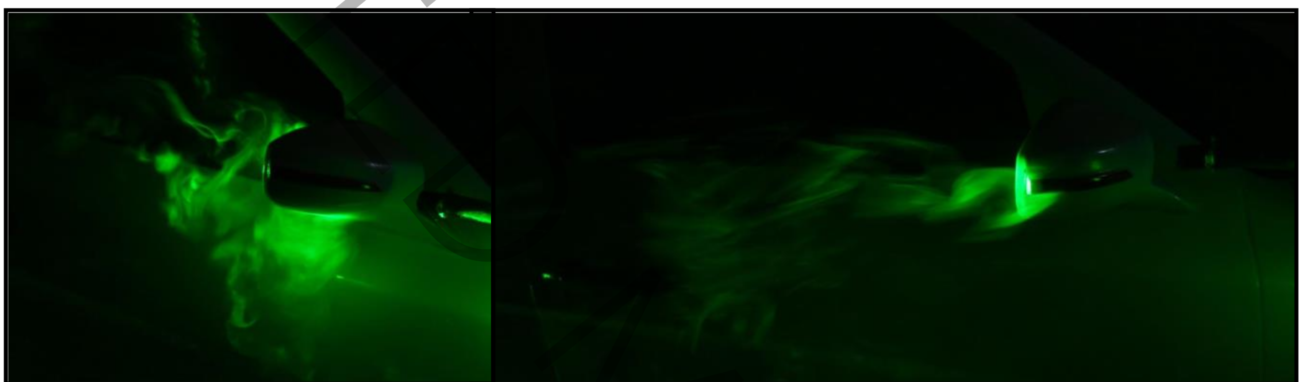


Fig. 4 Visualization of the flow behind the side mirror of the car

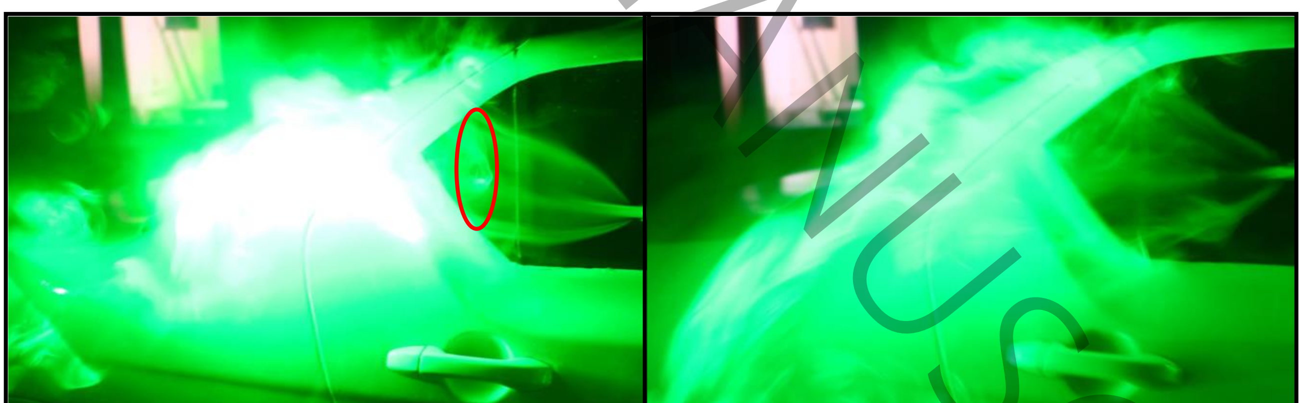


Fig. 5 Visualization of the flow passing through the rear door quarter glass

Fig. 6 Visualization of the flow passing through car handles

Generally, the shark antenna of IKCO DENA+ car is slightly bigger than the one mounted on the previous version of this car model, and its location is also moved toward the end of the vehicle. Fig. 7 shows the visualization of the flow field around the shark antenna. A large antenna in front of the flow caused a large area of vortical flow around the car. The presence of shark antenna is similar to a small wing, which is fixed from one side to the car body. For this reason, it is possible for wing tip vortices and induced flows at the tip of the antenna to be created, specifically under conditions, such as stormy weather and flexuous roads. For aeronautical applications, these vortices can be controlled using winglets; however, installing a winglet in this form of antenna for road vehicle applications is not possible due to styling appearance restrictions; thus, the production of these vortices is uncontrollable. In addition, the shedding of this vortex in the wake of the car model caused a secondary vortex to be created on the rear glass. It should be mentioned that this vortex has small dimensions, and because it forms precisely in the middle of the rear window, it can cause annoying noise for the rear passengers of the car. Also, the trail caused by the large dimensions of this antenna, which consists of mixing flows, affects a wide airflow area and creates an annoying sound.

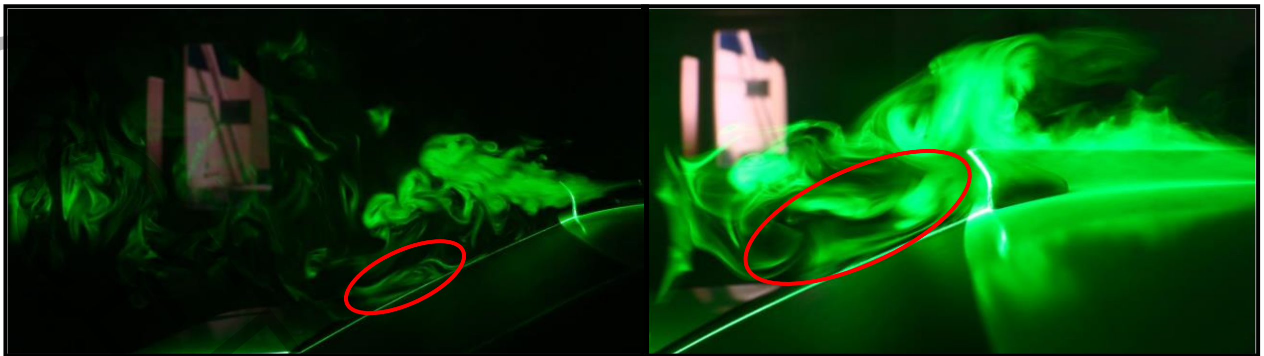


Fig. 7 Visualization of the flow passing through the car shark antenna area

Fig. 8 illustrates the visualization of airflow within the depression area of the design feature of the car body along with its door can be seen. According to this picture, which is taken in different time frames, it can be observed that first, when the flow reached this depression, it expands and moves toward three directions, including car wheel, ground and the upper area of the car. Also, very high turbulence area was created when the air reached this area of the car body. As is shown in next picture, the flow moves toward the ground, collides with it; then, disappeared. On the other hand, the flow moved towards the rear quarter windows. Furthermore, the flow hitting the wheels were directed to the ground and the vehicle wake flow, in addition to applying drag force to the wheel. The following pictures show that the airflow moving toward the glass is trapped in the quarter window that results in a vortical flow. Admittedly, due to the fact that the smoke flow in these series of pictures is only placed on the door, it is difficult to understand that whether this vortex is due to the existence of the step on the quarter window itself or it was created directly from the door design feature. However, the design of the body helps directing the flow towards the windows and trapping the air in the vortex flow. In the end, the flow completely passes over the car body and enters the wake of the car, which can in turn, be the cause of drag force for the car.

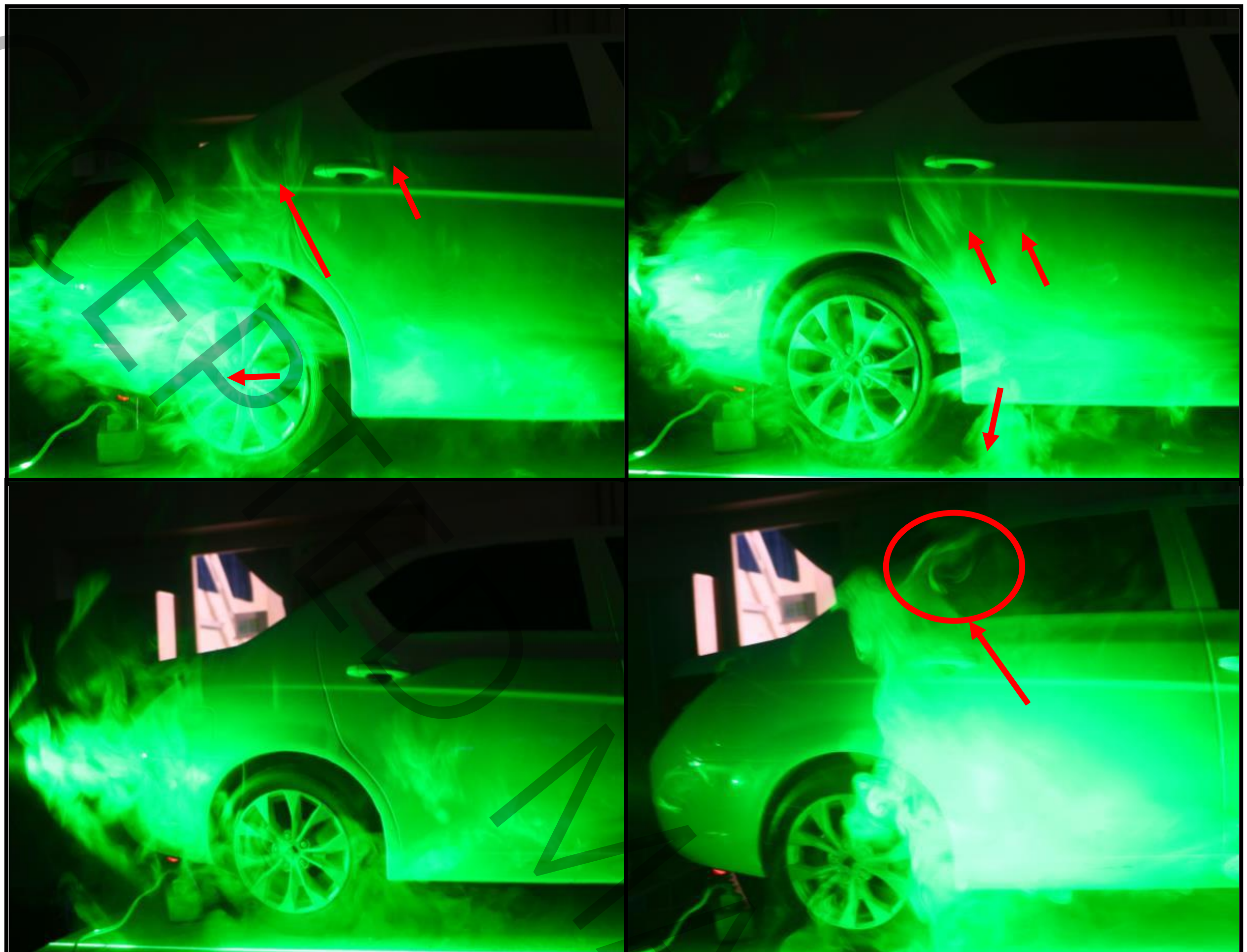


Fig. 8 Visualization of the flow passing through the rear door of the car

3.2. Measurement of Aerodynamic Noises

According to the methodology explained in the previous sections, the results obtained from wind tunnel tests regarding noise measurements will be described within the subsequent paragraphs. The process of analyzing the results of this part is as follows; first, susceptible areas for noise the production were identified in each test case, second, geometric modifications were made on these areas, third, by measuring the intensity of flow turbulence and pressure disturbances on the rear and front glass, the effectiveness of modifications to each case is specified. As stated before, smoke visualization was used to observe the physics of airflow around the car and identify areas responsible for the production of aerodynamic noises. In this section, the results of the flow visualization in the wind tunnel tests showed that production of aeroacoustics noise is in response to parameters, such as: 1.

Distance between the side-mirror and the body, 2. The aerodynamic form of the side-mirror shape, 3. Rear passenger quarter window, 4. Shark antenna, 5. Car handles, and 6. Design or depression on the surface of the rear door of the car. According to these results, geometrical modifications were made to the geometry of the car model as illustrated in Fig. 9. These modifications include: (i) reducing the gap between the side mirror and the vehicle body to minimize flow separation and vortex formation; (ii) redesigning the side mirror geometry to streamline the flow and weaken wake turbulence; (iii) covering or smoothing the rear quarter window to eliminate the forward-facing step responsible for vortex generation; (iv) modifying the door handle shape to reduce flow trapping and vortex shedding; (v) refining the rear door surface indentation to prevent flow redirection toward the window; and (vi) removing the shark antenna to eliminate its associated vortical wake. Each of these modifications was designed based on the flow visualization results to target specific noise-generating regions and improve the overall aerodynamic behavior of the vehicle.

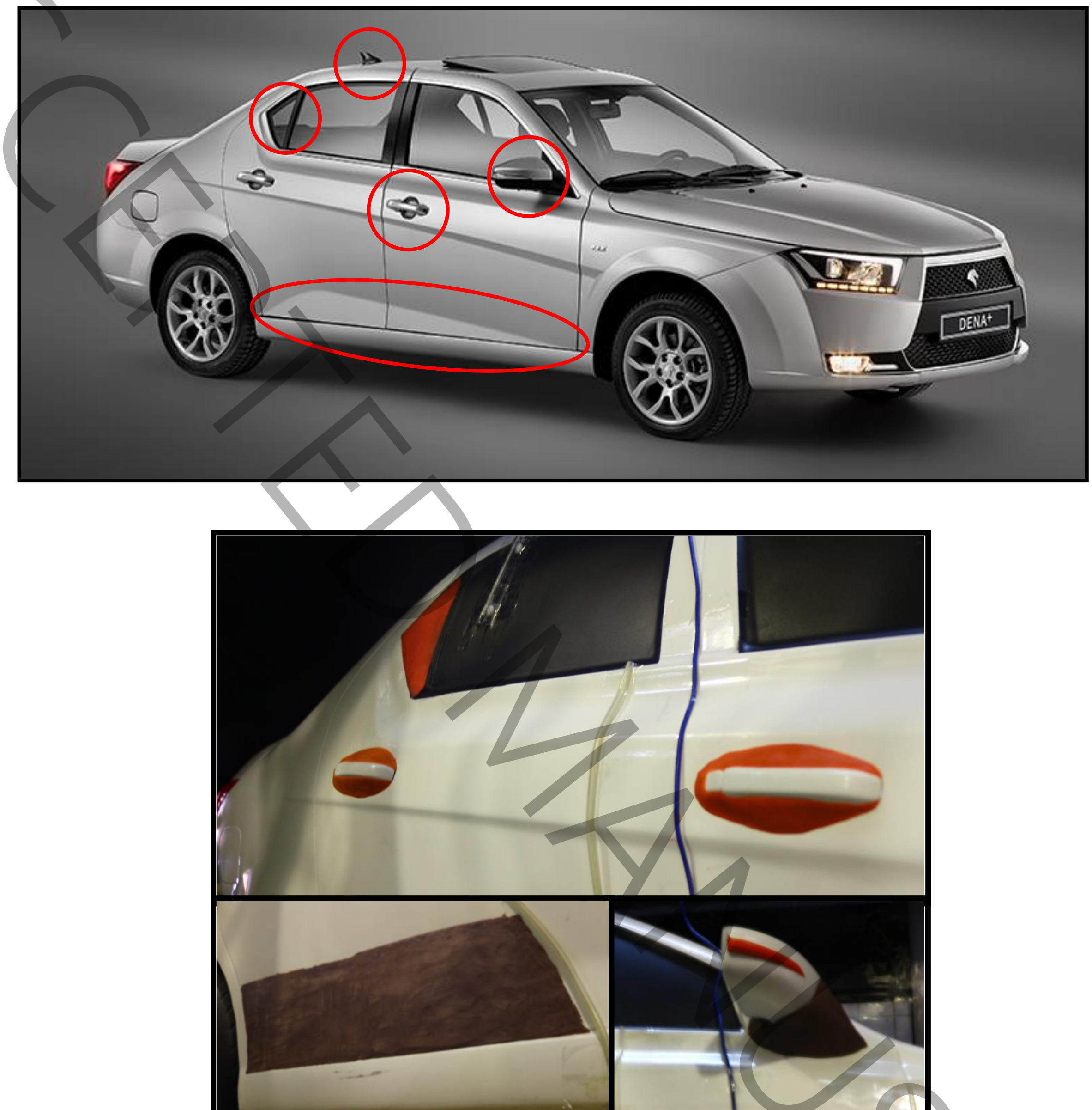


Fig. 9 Picture of the IKCO DENA+ (Aero noise sources) and modified car body prototypes

The modifications made to the body were according to the results obtained from the wind tunnel tests, including, changes in the shape of the handles, the distance between the mirror and the body, correction of the indentation of the rear door of the car, and the covering of the quarter window of the rear passenger glass. Also, the complete removal of the antenna was one of the test samples. Table 1 shows the car models, which were investigated experimentally through wind tunnel testing. It is worthwhile to mention that due to the way the antenna is connected to the model body and the possibility of its detachment during the wind tunnel tests, this component was omitted in all experiments except for the real model test. Therefore, the effect of removing the antenna should be considered in all experiments.

Table 1 Wind tunnel test models based on geometrical modifications

Wind Tunnel Model Name	Geometrical Modifications
A	Real car model
B	Modification of the side mirror + Removal of the antenna
C	Modification of the quarter window of the passenger window + Removal of the antenna
D	Modification of car handles + Removal of the antenna
E	Modification of the rear door feature + Removal of the antenna
F	Removal the antenna
G	Combined modification of quarter window and handles + Removal of the antenna.

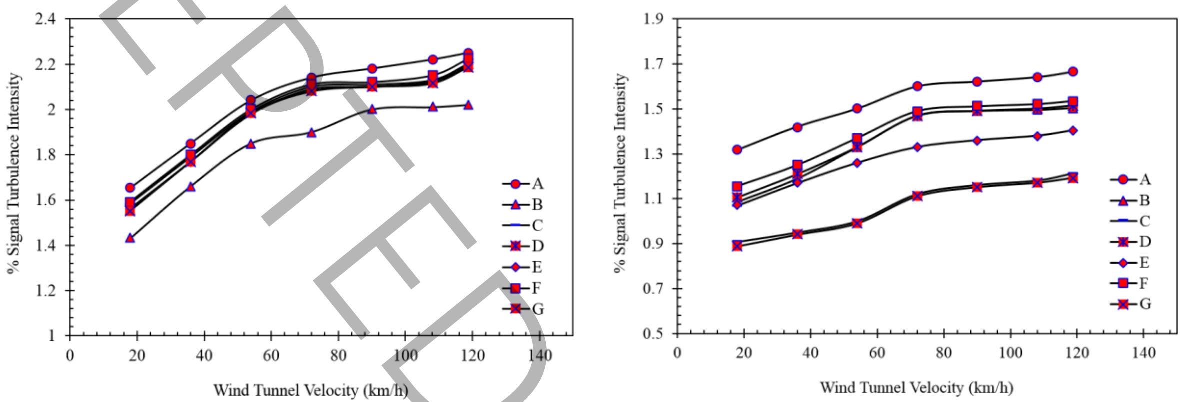
3.3. Turbulence Intensity

As explained in the previous sections, two different hot wire probes were used to measure the effectiveness of the body modifications on flow over the rear and front windows of the car. The turbulence intensity parameter was used to measure the variable behaviors of airflow in these areas. The method of calculating this parameter is shown in Eq.1.

$$\%TI = \frac{\sqrt{\overline{(U(t) - U_{avg})^2}}}{U_{avg}} \times 100 \qquad \text{Eq.1}$$

In this equation, TI represents the turbulence intensity expressed as a percentage, U(t) is the instantaneous velocity as a function of time in m/s, and U_{avg} is the mean velocity calculated over the measurement time interval in m/s. As indicated before, the velocity measurements were performed using hot-wire anemometry at selected locations near the front and rear side windows of the vehicle model, where significant flow disturbances were expected. At each measurement point, data were acquired over a time interval of 30 seconds with a sampling frequency of 5 kHz, resulting in a sufficient number of samples to ensure statistical convergence.

Fig. 10(a) shows the turbulence intensity on the rear passenger glass under different velocities. In this graph, it can be observed that by increasing velocity, the turbulence intensity on the glass represents an increasing behavior which has also been seen in previous studies [10]. Therefore, for velocities higher than 100 km/h, the main source of noise in the car is aerodynamic noise. This issue is independent of the car's shape and highly depends on the nature of the airflow turbulence and the flow passing through the car body. Due to the stagnation point in front of the vehicle and the rotation created in the A-Pillar area, the increase in velocity strengthens these factors. Modifying the car body caused the turbulence intensity to be lower than the original model in all test cases. Because the antenna was removed in all test models, Maximum turbulence intensity after the original model is related to the model in which only the antenna was removed and no geometric modifications were applied. For other tests, in addition to removing the antenna, a modification was made to the body. Test model D is the second model representing the most turbulence intensity, which shows that the modification of the handles did not have much effect on the intensity of rear window disturbances. This can be resulted from the fact that the handle vortices are located in the longitudinal direction of the car and fall behind the car, which can lead to an increase in drag. Modifying the design on the door or sample E has also a significant effect which is more effective than removing the antenna, while the modification of the quarter window has the most significant impact on reducing the intensity of disturbances in such a way that an average of 25% reduction in the intensity of disturbances is observed at all velocities. The intensity of disturbances related to the flow on the front door glass at different velocities is shown in Fig. 10(b). Similar to the previous figure, the increasing trend of disturbance intensity with increasing velocity can be seen in all samples. In this case, the rate of increment is higher than the rear window, which is aligned with the previous explanation about the main factors having influence on the aero-noise in the car. The main factors are the stagnation point in front of the car and the flow rotation within the A-Pillar area. This figure shows that the highest disturbance intensity is related to the unmodified model. Other samples have a negligible effect on the front door glass flow disturbances, while the modification of the side mirror has a very significant impact on the reduction of the font side glass disturbances. Thus, an average of 12% reduction in flow disturbances can be observed at all velocities. Fig. 11 shows the turbulence intensity on the rear door and front door glass of the car at a velocity of 118.8 km/h, the velocity at which the maximum annoying noise was reported for the IKCO DENA+ car by costumers. As the previous graphs showed, most flow disturbances are also related to this velocity. This figure shows that the level of flow disturbances on the front side glass is higher than that of the rear window due to the stagnation point and flow rotations in the A-Pillar of the vehicle. Also, the effect of body modification is evident at this velocity. It can be seen that the most significant reduction of disturbances in the front side glass is related to sample B, where the distance between the car's side mirror and the body is modified. Also, the significant effect of changing the quarter window on reducing disturbances in the rear glass is observed.



(b) (a)

Fig. 10 Turbulence Intensity of flow disturbances on the rear door glass (a) and front door glass (b) under different flow velocities

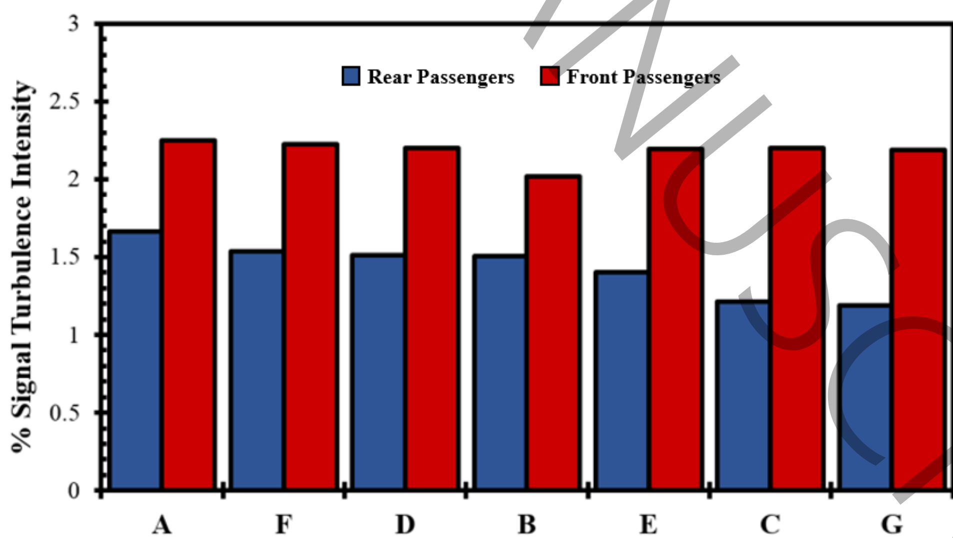


Fig. 11 The turbulence intensity value on the rear and front door glass of the car at a velocity of 118.8 km/h

3.4. Static Pressure Disturbances

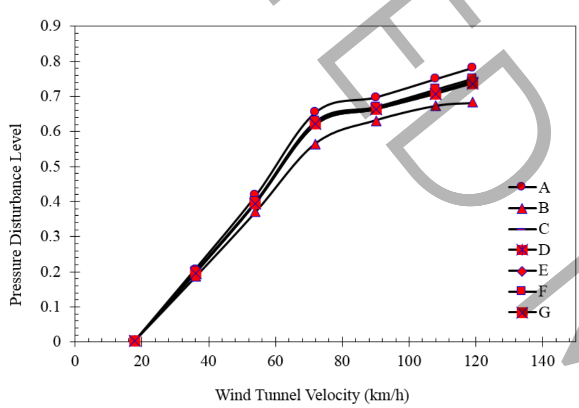
As was previously mentioned, static pressure measurement was also carried out for the purpose of getting further insight into the flow behavior and aerodynamic phenomena. In this regard, the pressure disturbances indicating the difference between static and mean pressure values (Eq.2) are presented for different test cases at different velocities.

$$P' = P(t) - P_{avg} \qquad \text{(Eq.2)}$$

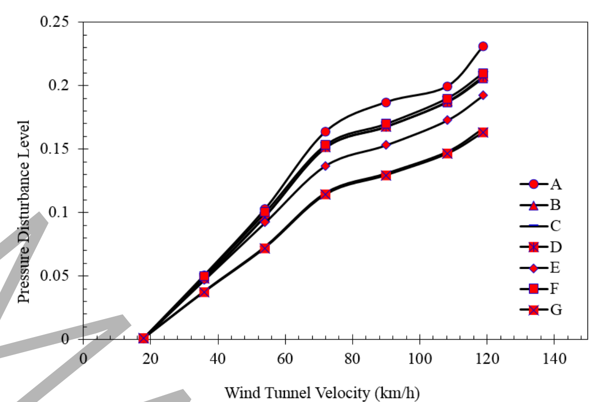
In Eq.2, P' represents the instantaneous pressure disturbance, P(t) is the instantaneous static pressure signal, an P_{avg} is the time-averaged static pressure calculated over the measurement interval. Static pressure was measured using differential pressure sensors at selected locations on the front and rear side-window regions of the vehicle model. For each test case and free-stream velocity, pressure data were recorded for 30 s with a sampling frequency of 5 kHz. The mean pressure was obtained by averaging the instantaneous pressure signal over this time interval. The pressure disturbance was then calculated by subtracting the mean pressure from the instantaneous pressure signal. This procedure was applied at the measurement points located near the front and rear side windows, where flow visualization indicated strong flow separation, vortex formation, and unsteady flow behavior.

Analyzing these graphs is of vital importance due to the fact that the sound is a pressure wave; thus, these graphs can also represent a sound level. The level of pressure disturbances on the rear glass at different velocities is shown in Fig. 12 (a). Static pressure disturbances represent an increasing trend by increasing velocity, which proves that the effects of aerodynamic noise increase with increasing velocity to the point that at velocities more than 100 km/h, the dominant car noise became aeroacoustics noise. It can also be seen in this diagram that the removal of the antenna and the indentation of the door has almost the same effect. On the other hand, the modification of the handle and mirror does not have a significant impact on the pressure disturbance level of the rear window. It is worth mentioning that the modification of the quarter window causes the static pressure disturbances to decrease by 9%. The most significant effects were observed at the highest test velocity, showing that aerodynamic modifications can reduce noise from aerodynamic. Fig. 12 (b) shows the intensity of pressure disturbances on the front side glass at different velocities. This graph also shows the increasing trend of disturbances with velocity increment, representing the sound level. Also, by comparing the graphs related to various test models, it is concluded that the various modifications do not have noticeable effects on the front glass, and only the change of the side mirror caused a 5%

decrease in the intensity of the pressure disturbances of the front glass at the highest velocity. Variations in pressure disturbances on the rear and front glass of car passengers in different test cases at a velocity of 118.8 km/h are shown in Fig. 13. In this diagram, it is clear that the level of pressure disturbances equivalent to the level of sound produced on the front side glass is much higher than the rear side glass. For this reason, the effects of body changes on the front side glass are minimal, and only the modification of the mirror is able to have a significant impact, which is not far from expected considering the proximity of the mirror to the front side glass. In the case of the rear door window, it can be seen that the modification of rear quarter glass, removing back step, represented the most significant effect on reducing the sound level.



(b)



(a)

Fig. 12 the level of flow pressure disturbances on the rear door glass (a) and front door glass (b) at different velocities

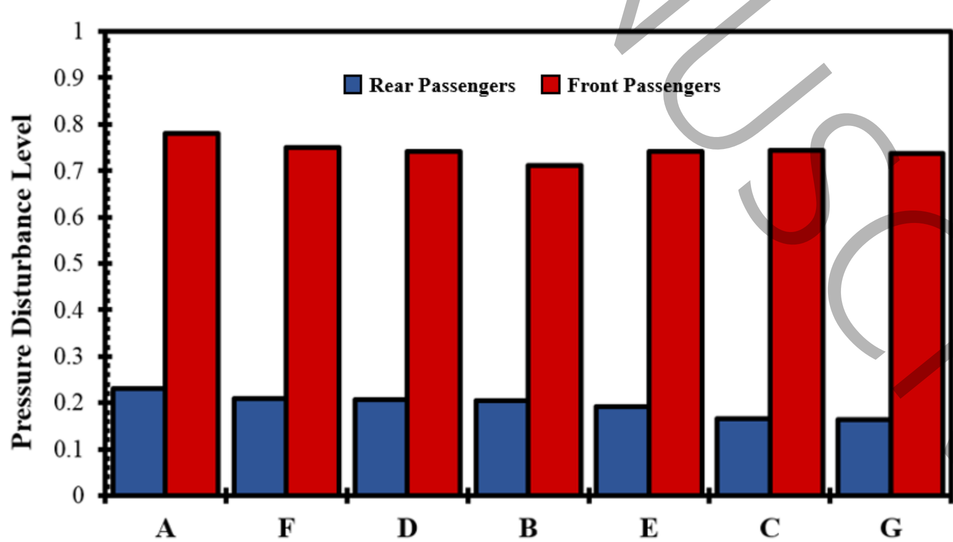


Fig. 13 The intensity level of pressure disturbances on the rear and front glass of the car at a velocity of 118.8 km/h

4. Conclusion

In this research, the flow field passing through the external surface of a scaled car model was studied experimentally from aerodynamic point of view for the purpose of noise reduction inside the passenger's cabin of IKCO DENA+ vehicle. To be specific, sources of aerodynamic noise were identified through wind tunnel testing for a 2/5 scaled vehicle model to help evaluation of noise reduction solutions. In addition, capturing the flow phenomena occurring in the flow field around the car model for identification of noise sources was conducted by the help of smoke flow visualization and green laser visualization techniques. The results obtained from these flow visualization tests showed that aeroacoustics noise generation can be in response to six parameters, including: 1. The distance between side mirror and car body, 2. Aerodynamic shape of side mirror, 3. Rear quarter window, 4. Shark antenna, 5. Car handles, 6. The design feature on the rear door of the car. As previously mentioned, the main focus of this research was studying and finding solutions for diminishing the noise inside the IKCO DENA+ car cabin. In this research, the possible sources for aerodynamic noise generation were identified through wind tunnel testing for a $\frac{2}{5}$ scaled car model; furthermore, the recommended solutions for reduction of generated noise were evaluated through experimental tests. This study was carried out using hot wire anemometry and surface-pressure measurement techniques within a broad range of velocities ranging from 18, 36, 54, 72, 90, 108 and 118.8 km/h. aerodynamic areas around the car were determined by applying flow visualization technique; then, geometrical modifications were applied to these areas. The modifications were made so that six test models were studied in comparison with the original car model. It was observed that the level of air disturbances and produced noise increased by increment of the velocity, which proved the fact that by increment of the car velocity, the dominant noise source is aeroacoustics noise. In general, the level of pressure disturbances and the intensity of flow disturbances on the front door glass were much higher than on the rear door glass, which showed that the two primary sources of car noise production were the front stagnation point and the rotation of the flow in the A-Pillar area. Also, the results of the hotwire anemometry and pressure sensors showed that the modification of the rear quarter window reduced the flow disturbances and sound level on the car's rear side window significantly. Removing the antenna and modifying the design of the car's rear door were the second-best solutions for noise reduction. Additionally, changing the car's side mirror resulted in improving the aeroacoustic performance of the car. Future work may focus on extending the present experimental study through high-fidelity numerical simulations, such as computational fluid dynamics (CFD), to provide deeper insight into the complex flow structures and aeroacoustics mechanisms. In addition, full-scale vehicle testing under real driving conditions could be conducted to validate the wind tunnel results. Further investigations may also explore optimized design modifications using parametric studies and machine learning techniques to achieve more effective noise reduction. Moreover, the combined effects of aerodynamic modifications and acoustic insulation strategies could be examined to enhance overall cabin comfort.

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