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Study and Design Frontal Area of a Car to Curtail Aerodynamic Noise

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Abstract:** In this field of comparative research study, comparison of two car model, a standard car and an optimized car with respect to aerodynamic analysis/aeroacoustics analysis with the help of CFD software Ansys 2019 R2 version is taken in consideration to compare the results and get to know if the optimized car model has reduction in the generation of aerodynamic noise when it travels at four different speeds (30 m/s, 40 m/s, 50m/s and 60m/s). For carried out aeroacoustics/aerodynamic noise analysis two main model are used turbulence model and an acoustics model. For turbulence model and K-epsilon model is used as it is widely used for getting turbulence generation and for acoustics model a Broadband noise model is used to generate the results through numerical simulation and data sources. First a standard sedan car is modelled in Onshape CAD tool and aeroacoustics analysis is carried out on this standard sedan car to get to know the source of aerodynamic noise. From the standard car results made changes in the sedan car geometry like giving fillets to point/sharp edges of wheel arcs, front bumper, hood-line, fender and start of roofline from A-pillar, providing under-flush, optimizing A-pillar beam and optimizing outside rear view mirror and making them fully camera integrated mirror to reduce wake. After optimizing standard geometry carried out aerodynamic analysis with the same four different speed given for standard car (30 m/s, 40m/s, 50m/s and 60 m/s). Generated contour plots and isosurface from CFX for flow characteristics and acoustic sound source with various model like Proudman's acoustic power level in Db, Curle surface acoustic power level in decibels (dB) and also, Lilley S total noise source to show the sources of noise and how many decibels of noise is generated from those sources. Maximum of 100 decibels of noise is generated from the front bumper and a minimum of 80 decibels were monitored in the results process after comparing the results with standard car which has noise nearly 120 decibels with high fluctuations of turbulence kinetic energy and decrease in its pressure level.

***Keyword:** Aeroacoustics, Aerodynamic noise, Aeolin sound, Fluid dynamics, NVH (noise, vibration and harshness) and CFD (computational fluid dynamics).*

I. INTRODUCTION

Aerodynamic noise is the noise generated due to the change in the pressure of air when flowing around any moving vehicle which is moving at a relative speed of the air. This change in pressure occurs due to the turbulent flow of the air around the vehicle body and the wind flowing around vehicle body is always turbulent due to its shape and other various conditions like environment. In early days the main source which created aerodynamic noise was a cooling fan as there was not much of good bumper designing in early days. An generation of aerodynamic noise is not dominant in lower speed conditions due to dominance of tyre noise, once the speed is above 80 Km/hr the aerodynamic noise comes in play which can be heard and this generated noise keeps on dominating as the vehicle's speed keeps on increasing the frequency at which this noise is dominant is about 330Hz to 900Hz which can be heard by humans and the noise generated due to this turbulence of air can be disturbing for a long period of a time.

A. Background

As discussed above aerodynamic noise or vehicle acoustics was not considered or had a view which currently is as in early ages most of the noise was produced by the engine, wheels, transmission system and other mechanical aspects that were used before like brakes. According to various studies it is being told that transportation has the high influence in noise generation which affects humans to some extent. From the study by WHO (world health organisation) it is stated that due to environmental noise 43,000 hospital admissions and 10,000 premature deaths takes place every year due to coronary heart disease. For reduction in aerodynamic noise most of the concentration is given to the outside rear view mirror and the A-pillar/windshield beams which are the main sources for aerodynamic noise inside the vehicle's cabin. Regarding, frontal area of car there's not much of a research on the internet as it is far from the cabin and due to presence of various acoustic shields and firewall the noise is reduced to some extent but in case of the new evaluation of transportation by electric vehicles (EVs) there is a need of attention to the frontal area of vehicle for aerodynamic noise reduction as an electric vehicles generates very less noise from its motor and after reaching a particular speed noise come to play in electric vehicles which is less than an IC engine vehicle and needs attention.

Aeroacoustic is a new field of study in automotive sector then in the 1950's when there was interest in research of the aeroacoustics started on the aerospace industries. Due to limitations of study material for aeroacoustics like analysis software and a wind tunnel testing for aeroacoustics there's lot more research to be done on aeroacoustics. Computational Aeroacoustics (CAA) from various software has recently developed to do a proper quality mesh and analysis related to aeroacoustics.

II. STUDY AREA/THEORY RELATED TO FIELD OF RESEARCH

Brief knowledge on the underlying theory for this comparative research study with main focus on aeroacoustics/aerodynamic noise is given below;

1) *Fluid dynamics*: In engineering and physics, fluid dynamic is subdiscipline of the fluid mechanics which is the study of flow of various fluids like liquids and gases. Aeroacoustics/aerodynamic noise is one of the subdiscipline of fluid mechanics. So, the study of fluid in various conditions is a fluid dynamic. Related to aeroacoustics there is turbulence which comes under the study of fluid dynamics.
2) *Turbulence*: Turbulent flow is a behaviour of fluid where it has no direction or particular pattern of flow in it instead flows abruptly due to drastic change in fluid's pressure and fluid's flow velocity. The thing with the turbulence is even after studying, doing a very wide and deep research on it is very difficult or impossible to predict a turbulence flow because most of the time it changes its pattern even if same case related to turbulence needs to be studied. Though there are few characteristics to define turbulent flow they are irregularity, diffusive, three-dimensional and dissipative. [1]

Commonly used turbulence model for aeroacoustics analysis are

a) K-epsilon
b) Reynolds-averaged Navier stokes (RANS) and Unsteady Reynolds-averaged Navier stokes.
c) Detached eddy simulation (DES) and Delayed detached eddy simulation (DDES)
d) Large eddy simulation (LES)
e) Dynamic Smogorinsky Lilly model (DSLM) and Smogorinsky Lilly model– LES sub model

3) *Computational fluid dynamic (CFD)*: Computational fluid dynamics is a part of fluid mechanics which is widely used in various software which is used to analyze various problems related to fluid flow with the help of numerical analysis and data structure. These fluid dynamics is a virtual way of testing any fluid flow by saving time and money and is widely used for research and testing processes. A CFD analysis is also used for verifying the practical generated results.

A. Acoustics

1) *What is acoustics?:* Acoustics is a branch of physics which deals with various mechanical waves which are generated due to vibration, sound/noise, ultrasonic sound and infrasound in any mediums like gas, liquid and solids. Each and every objects and living beings in the universe vibrate at a particular frequency which ranges from very wide range therefore it can be said that each and every has acoustics involved due to the vibration but human can hear it only if it is audible within human hearing frequency range which is 20 Hz to 20 kHz. [2]

Types of acoustics: Acoustics can be divided in four main division

a) Engineering
b) Earth science
c) Life science
d) Arts

2) What is acoustics in automobile engineering?: In automotive engineering acoustics is subdivided in NVH (noise, vibration and harshness) in which generation of noise and vibration from various sources of the vehicle are refined to control the harshness due to them by three different ways reducing it from the source, isolating the source or isolating the cabin and absorbing/suppressing the source of NVH.

3) *NVH:* Noise, vibration and harshness are generated from the various sources like uneven road surface, engine, transmission, intake and exhaust system, radiator fan, suspension system and many other reasons. This unnecessarily generated noise, vibration and harshness makes directly impact on the chassis as, chassis is a base of any vehicle on which each and every component are mounted to make a system. This unnecessary noise, vibration and harshness causes the chassis to vibrate at a certain frequency generating pesky squeaks, rattles and buzzes. This transfers noise, vibration and harshness to other system and creates an uncomfortable situation to the driver and passenger in the vehicle's cabin.
4) *Main reason of NVH are*
a) Aerodynamic noise b. Mechanical system c. Electrical system
5) *Aeroacoustics/aerodynamic Noise:* Aeroacoustics can be defined as the generation of noise in a fluid flow. Aeroacoustics noise comes under Aeolian/Eolian sound which means sound generated by the air flowing over or through any object.
6) *Importance of Aeroacoustics:* Aerodynamic noise is an issue which cannot be eliminated completely but can be reduced to some extent. This aerodynamic noise cannot be heard from the vehicle which are at slow speed like city driving as other sounds like engine and powertrain sounds are dominant during less speed condition and also due to less speed the air flow is less. Once the vehicle attains 80 Km/h or more than that aerodynamic noise comes to play which can be heard by the driver and passenger of the vehicle, aerodynamic noise in case of electric car differs as the noise can be heard easily and even at lower speeds as the motor creates very less noise and therefore, aerodynamic noise plays major role in electric vehicles than compared to I.C engine vehicle. This generated noise after crossing a particular speed can be very uneasy and disturbing for the passenger and driver if travelling for a long distance. Any vehicle is not fully aerodynamic as it contains some or the other areas or regions of bluff leading to create turbulences when air is flowing around vehicle due to sudden flow separation which in terms increase air pressure at the particular area and therefore generating a whooshing noise. And the parts or region of a body is not design always considering aerodynamics but sometimes it focusing on other tasks more important than in terms of its aerodynamics. Source of a whooshing noise that can be heard from the vehicle's cabin is vehicle's A-pillar, gaps and cavities, windshield and the seals of vehicle doors and windshield. The noise generated by the air flow should be very less that it should not interrupt as a communication barrier in case of people communicating in cabin, also while listening to any music inside the vehicle and any horns or emergency situations like sirens coming from any other emergency vehicle.
7) *Reasons of aeroacoustics/aerodynamic noise on frontal area of car*
a) *Over-flush and Gap:* Due to presence of over flush and gap turbulence in air flow is generated increasing turbulence kinetic energy thereby generated aerodynamic noise due to wide fluctuations in turbulence of air. To avoid aerodynamic noise under-flush with less gap is recommended to curtail aerodynamic noise.
b) *Pointy/sharp Edges:* Any point and sharp edges present in the area or surface where the air directly hits needs to be provided with fillets with optimum radius.
c) *Wake:* Due to presence of sudden wake pressure fluctuates drastically generating turbulence and eventually aerodynamic noise.
d) *Rough Surface:* When the air or fluid flows through rough surface its flow breaks and starts to become turbulent which increase turbulence kinetic energy and eventually aerodynamic noise.

8) Side effects of aeroacoustics/how does its effect?: Aerodynamic noise affects human very badly if the noise generation of the flow is between the range where the human feels irritating or stressful which can be studied through psychoacoustics.
9) Psychoacoustics: Psychoacoustics is a branch of scientific study to understand sound perception and audiology.

Table 1. Natural Frequency Of Human Body

Sr. no	Body part	Frequency (Hz)
1	Head (axial)	Approx. 25
2	Shoulder	4-5
3	Chest	Approx. 60
4	Spine	10-12
5	Stomach	4-8
6	Forearms	16-30
7	Palms	50-200
8	Legs	Approx. 2

A human can hear from range 20 Hz to 20Khz, with the help of limits of perceptions one can get to know how the human gets affected by various generated noise.

III. LITERATURE REVIEW

A. Literature Review

Nurul Muiz Murad (2008), the research paper tells about the aeroacoustics of a car due to the aerodynamic flow around the A-pillar of the body. An computational fluid dynamics is applied to a car body under certain boundary conditions and different radii of windshield is altered during the computational process to get to know which type of design and angle is good for the windshield also during analysis some yaw angles like 5 degree, 10 degree and 15 degree are applied to replicate crosswind flow that is generated during turning a car at a high speed and how much aerodynamic noise is created during these conditions. Also, in the analysis which region of A-pillar is making most of the noise is identified and the sharp edges are eliminated from simplified car design to get a view of analysis during analysis how doing minor changes in vehicle body and some regions around A-pillar affects the generations of aerodynamic noise. [3]

Nicholas Oettle (2018) et al., this paper tells that how aerodynamic noise can influence the safety and comfort of the passenger and driver in the car and also how important it is to look after this generated aerodynamic noise when vehicle at a relative speed. Also, psychoacoustics of human beings is spoken in this paper and up till what extent humans are comfortable with the noise that is generated due to aerodynamic flow around the vehicle.

Also, in early days there was no focus on exterior body to limit the aerodynamic noise only the seals of the vehicle use to be considered to supress the noise generation of aerodynamic noise. [4]

CHEN Xin (2012) et al., in this paper computational fluid dynamics simulation method is used by making a surface model of the car and providing boundary conditions to simulate the whole process and get to know in which part of the model car is the aerodynamics noise is more.

By this analysis also get to know from which interior regions of car is the noise is being heard by the people sitting in the car's cabin compartment.

After analysis the results said that the noise source that can be hear from car interior's front dash panel, front fender and also front doors of the car due to presence of cavity between the body and the door. Making changes in the in the car model after getting to know the source of aerodynamic noise by, making changes in the current designing and any future vehicle the generated results is very useful.[5]

IV. METHODOLOGY

1) *Research On Automotive Aeroacoustics:* Did a thorough research on aeroacoustics/aerodynamic noise around automobile bodies and how various manufacturer uses different techniques to keep the noise under control. During the research noted down all the techniques used to reduce or supress aerodynamic noise according to the various sources of the noise generation. Also, did research on psychoacoustics to get to know how this generated noise disturbs the cabin members and how much decibels should be this noise in the range to give maximum comfort to the vehicle's cabin members.
2) *CAD Modelling A Standard Car Model According To Automobile Standards:* Made a CAD model of a standard car in Onshape online CAD modelling tool to create a geometry for acoustics analysis on the made standard car geometry. Made a model considering sedan type vehicle according to the automotive standards of India. The CAD geometry of standard car is made only till B-pillar as the research focuses only on frontal area of car and also considered half model to reduce the overall time for meshing and analysis. The following CAD geometry has a length of 2103 mm from front bumper till the B-pillar, width of 1804 mm and a height of 1469 mm which falls under sedan category standards of India as mentioned above.
3) *Optimized CAD Geometry:* Did a Broad band noise analysis on the standard car geometry in Ansys to find out the places which needs to be optimized and reduce the source of noise. Following are the changes that are made from standard car ; mirrors of the standard car are optimized and made it fully camera controlled mirror which is the upcoming technology in automotive industry to reduce the overall protrusion area which will reduce the bluff and will eventually reduce wake thereby reducing turbulence flow and finally reduction in the aerodynamic noise. Frontal bumper, grille, hood, windshield gap, door gap, A-pillar, headlight corners and wheel arches are optimized giving under-flush, minimizing the gaps, eliminating point region by providing fillet and keeping the surface smooth to make sure the air flows as smooth as possible. In the below figure left column is standard car CAD geometry and the right side is the optimized car CAD geometry and the green arrows and yellow boundary regions shows which portion of the car is optimized.

4) Exporting geometry from Onshape for CFD analysis: To download the made geometry first exported the geometry in the STEP file format, choose a STEP file format as this STEP file format is almost as the same size as the original file also the quality and dimensions of the geometry remains the same as made in the CAD tool and almost each and every software accepts and convert this STEP file very easily and in less time.

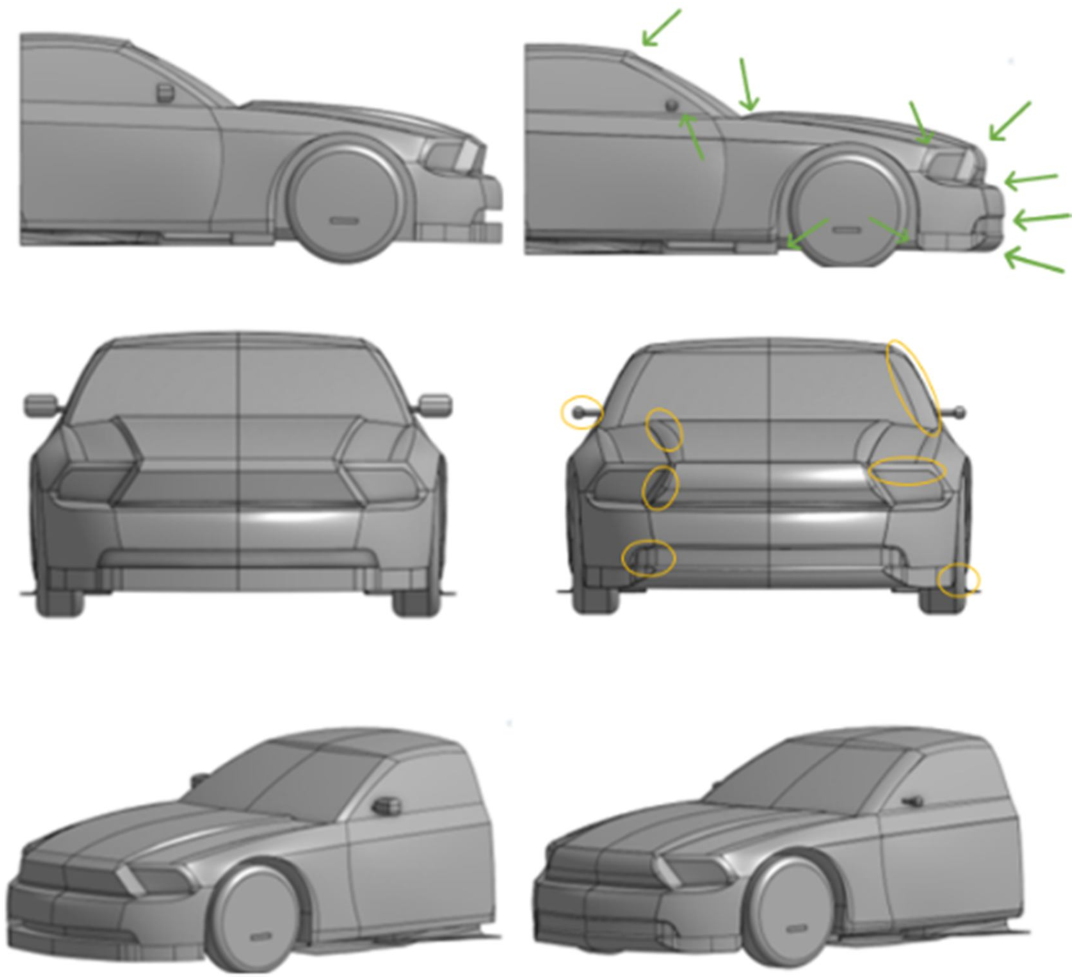

Fig. 1. Comparision of Optimized car CAD Geometry with standard car

5) Importing geometry for and creating an enclosure and providing named selection for CFD analysis (Ansys Design Modeler)
Imported the geometry in Ansys 2019 R2 version to carry out and acoustics analysis in a fluid flow(fluent) Analysis system. Provided an enclosure around the car geometry considering following calculations; (only half side car is considered in enclosure to reduce the analysis time)

For length 2103 mm > 2.1 m > $2.1 \times 10.7 = 22.4\ m$ (considering near to 10 times of the length)

For Width 1804 mm > 1.8 m > $1.8 \times 4.7 = 8.4\ m$ (considering near to 5 times the width of the car)

For height 1469 mm > 1.4 m > $1.4 \times 6 = 8.4\ m$ (considering 6 times the height of the car)

Provided named selection to the made enclosure as inlet at front of the car, outlet at back of car, slip wall to the side and upper enclosure face, base face as road and the symmetry face as symmetry

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6) *Mesh/grid Generation (Ansys Mechanical):* Generated mesh to the enclosure for CFD analysis in the Ansys Mechanical as medium size mesh with 60 mm element size, mesh size can be finer for the case but is considered as fine as possible according to the using system. Generated mesh has total 1160725 number of nodes and 6336192 number of elements.

Minimum range/value for a good quality mesh

TABLE 2
Mesh Quality: Minimum Range/Value For Various Mesh Quality

Sr no.	Type of mesh quality	Minimum range/value
1	Aspect ratio	Less than 5
2	Maximum corner angle (MCA)	±30 degrees
3	Skewness	Near to zero
4	Orthogonality quality	Near to one

7) *Settings and conditions for both standard and optimized car in Ansys Fluent: General setting:* In the general setting the solver type is selected as Pressure-based solver, this solver deals with algorithms which belongs to general class method called as projection method. In a projection method the mass of restrictions of mass conservation velocity field is obtained by solving a pressure equation. Velocity field, correcting the values and satisficing the continuity are done from the derivation of momentum equation and continuity of the pressure equation. As the equations are coupled to each other and not non-linear the following solution process involves iterations which solves the governing equations in a repetitive manner until the solution totally convergences. [12] Velocity Formulation is setting where the fluid gets defined if it has relatively constant velocity and less fluctuations or it changes its velocity and direction frequently. Absolute is used when the fluid has constant and liner direction whereas relative is used where the velocity of fluid changes frequently and has a rotating motion to it like impeller. An absolute setting is provided for this case as the fluid has constant velocity and a liner direction.[13] Time is a setting where two cases can be defined steady and transient in which steady means given setting remains same throughout the analysis and in transient a particular time is set to change the given settings for example Ffowcs analysis needs transient time. In the broad band noise case, a steady state time is provided for the analysis. [14] Gravity i.e. 9.81 is provided for the analysis in component Z with minus according to the global geometry axis.
8) Turbulence model- K-epsilon: A K-epsilon turbulence model is commonly used model for CFD analysis as it even takes less time than other turbulence model with as accurate results as possible. It is a two-equation model which includes two extra equation to represent turbulent properties of flow which allows two equation to account the history effects like convection and diffusion of a turbulent energy. As there are two transporters involved in this model the first transported variable is turbulence kinetic energy (TKE) and the second transported variable is turbulence dissipation rate (TDR). A K-epsilon turbulence model has three options in it standard, RNG (Re-Normalisation Group) and Realizable from which a realizable option is selected for this case also there's six option for Near-Wall Treatment from which Scalable Wall Functions is selected. And rest options from user defined functions like Turbulent Viscosity, Prandtl Number for both TKE and TDR are set as none. [15]– [17]

Transport equation for realizable K-epsilon model [18]

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \epsilon}{\partial x_j}\right] + G_k + G_b - \rho\epsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_j}(\rho \epsilon k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + \rho C_1 S_\epsilon - \rho C_2 \frac{\epsilon^2}{K + \sqrt{v\epsilon}} + C_{1\epsilon}\frac{\epsilon}{k}C_{3\epsilon}G_b + S_\epsilon$$

Equation 1 Turbulence model: K-epsilon transport equation

Where, $\rho = Density\ of\ fluid$

$k = Turbulence$

$G_k = Generation\ of\ turbulence\ kinetic\ energy\ due\ to\ mean\ velocity\ gradient$

$G_b = Generation\ of\ turbulence\ kinetice\ energy\ due\ to\ buoyancy$

$Y_M =\ contribution\ of\ the\ fluctuating\ dilatation\ in\ compressible\ turbulence\ to\ the$

$overall\ dissipation\ rate$

$C_1, C_{1\epsilon} \& C_{3\epsilon} = Constant$

σ_ϵ & σ_k = $Prandtl\ number\ for\ k\ and\ \epsilon, respectively$

S_k & S_ϵ = $User\ defined\ source\ terms$

9) *Scalable wall function for K-epsilon with equation[19]:* Acoustics Model-Broadband noise: For practical application where the turbulence is created over and object the noise does not have any distinct tone to it but in fact the sound energy continuously changes due to distribution of frequencies at a very broad range and thus in such cases a broadband noise model can be used to check the aeroacoustics through or over any object with and also, in conjunction and semi-empirical correlations and Lighthill's acoustics analogy can be used to shed a light on the source of generated aeroacoustics with the help of broadband noise model. And therefore, to study on the aerodynamic noise generation on a frontal area of a car, broadband noise model is used with Far-Field Density of 1.225 Kg/m^3 , Far-Field Sound Speed of 340 m/s, reference acoustics power as 1e-12, number of realization as 50 and number of Fourier modes as 50.[20]

Broadband Noise equations

For Proudman's Acoustic Power per unit volume[21]

$P_A = c\rho_o \left(\frac{u^3}{l}\right)\left(\frac{u^5}{a_0^5}\right)$ ... ... $(\boldsymbol{Equation\ 1})$ Equation 2 Acoustic model: Proudman's Acoustic power unit per volume equation

Where,

$c = constant$

$\rho_o = fluid\ density$

$a_0 = Speed\ of\ sound$

$l = Turbulent\ lenght\ scales$

$u = Turbulent\ velocity$

For Turbulent velocity

$u^2 = \frac{2}{3}k$ ... ... $(\boldsymbol{Equation\ 2})$ Equation 3 Acoustic model: Turbulent velocity equation

Where,

$k = Turbulence\ kinetic\ energy$

For Acoustic power in Decibels (dB)

$L_P = 10\log\left(\frac{P_A}{P_{ref}}\right)$ ... ... $(\boldsymbol{Equation\ 3})$ Equation 4 Acoustic model: Acoustic power in Decibels (dB) equation

Where,

$P_{ref} = Reference\ acoustic\ power\ (P_{ref} = 10^{-12}\ W)$

10) Material type and type of fluid with cell zone conditions: Choose material type as fluid and the fluid as air for the domain with a constant density of 1.225 Kg/m^3 and a constant velocity of 1.78e-5 $Kg/m-$s.

11) Boundary conditions: There are in total seven boundary conditions applied for this particular case namely inlet, outlet, slip_walls (side walls), road (moving wall/base face), symmetry, Vehicle and interior-solid. To study the noise generation from frontal area of a car 4 analysis on standard car with 4 different speed 30, 40, 50 and 60 m/s, and 4 analysis with 4 different speed on the optimized car to compare the results and get to know how much noise has been curtailed after providing smooth surface, under-flush, fillets, etc.

a) *Velocity Inlet:* Choose the inlet face as velocity inlet and for both standard and optimized car I have considered 4 each speed in total 8 analysis with four different speeds. Setting in the velocity inlet are, velocity specification method as Magnitude, Normal to Boundary, reference frame as Absolute, supersonic/initial gauge pressure as 0 and Velocity magnitude as 50 m/s according to the shown image. Turbulence settings as follow specification method as Intensity and Viscosity Ratio, Turbulent intensity as 5% ad turbulent viscosity ratio as 10.

b) *Pressure Outlet:* Gave the default settings to the pressure outlet boundary conditions.

c) *Road/Moving Wall:* Provided a moving wall with translation direction to the road or the base face of the enclosure with the same velocity as given in the velocity inlet boundary condition.

d) *Slip_walls/Side walls:* Gave the side walls i.e. upper and side face of the enclosure as slip walls with 0 specified shear and a standard roughness model with roughness constant as 0.5.

e) *Vehicle:* Gave the vehicle faces as the vehicle with a no slip boundary condtions with standar roughness model with a 0.5 roughness constant.

12) *Solution methods-Scheme/algorithm:* For algorithm a coupled scheme is selected which consist of pressure-velocity coupling for an aeroacoustics analysis

Coupled algorithm scheme equation

In a momentum equation the pressure gradient for component k is of the form

$$\sum_f p_f A_k = -\sum_j a^{ukp} pj$$

For any i th cell the discretised form of momentum equation for component $u_k$is defined as

$$\sum_j aij^{u_k u_k} ukj + \sum_j aij^{u_k p} pj = b_i^{u_k}$$

The balances flux is replaced by using a flux expression equation resulting in discretised form

$$\sum_k \sum_j aij^{p u_k} ukj + \sum_j aij^{pp} pj = b_i^p$$

The overall system of equations after being transformed to the δ −form, is presented as

$$\sum_j [A]_{ij} \vec{x_j} = \vec{B_i}$$

Influence of the cell i on the cell j is form

$$A_{ij} = \begin{bmatrix} a_{ij}^{pp} & a_{ij}^{pu} & a_{ij}^{pv} & a_{ij}^{pw} \\ a_{ij}^{up} & a_{ij}^{uu} & a_{ij}^{uv} & a_{ij}^{uw} \\ a_{ij}^{vp} & a_{ij}^{vu} & a_{ij}^{vv} & a_{ij}^{vw} \\ a_{ij}^{wp} & a_{ij}^{wu} & a_{ij}^{wv} & a_{ij}^{ww} \end{bmatrix}$$

The unknown and residual vectors have the form [22]

$$\vec{X_j} = \begin{bmatrix} p_i^l \\ u_i^l \\ v_i^l \\ w_i^l \end{bmatrix} \text{ and } \vec{B_i} = \begin{bmatrix} -r_i^p \\ -r_i^u \\ -r_i^v \\ -r_i^w \end{bmatrix}$$ Equation 5 Coupled algorithm scheme equation

13) *Spatial Discretization:* Gradient: Least Squares cell based [23]

$(\nabla\emptyset)c0 \times \Delta r_i = (\emptyset ci - \emptyset c0)$ Equation 6 Solution method: spatial discretization, gradient with Least Squares cell based

In spatial discretization the pressure is applied with a second order scheme as the second order gives very accurate results and even the mesh generation is applicable to use a second order pressure. Also, momentum, turbulence kinetic energy (TKE) and turbulence dissipation rate (TDR) has a second order upwind scheme setting to get accurate TKE and TDR calculation in the final results. A pseudo transient type of solution control is selected for further solution control settings.

14) *Solution Control:* For solution control under Pseudo Transient Set the pressure as 0.5, Momentum as 0.6, density as 1, body forces as 1, Turbulence Kinetic Energy (TKE) with Turbulence Dissipation Rate (TDR) as 0.7 and Turbulence viscosity as 1.
15) *Hybrid Initialization:* Run a hybrid initialization with the 10 number of iterations with an averaged turbulence setting
16) *Run Calculations:* For the case 1200 number of iterations were given to carry out analysis. This iterations number is given according to Hybrid initialization information and also, considering time and system that is being used.

V. RESULTS AND DISCUSSION

Results section is divided into two main parts namely Flow characteristics and Acoustic sound source to get a better view of the source noise generation and due to which phenomenon aerodynamics noise generation takes place when a vehicle has a speed above 80 km/hr. At four various speed 30m/s, 40m/s, 50 m/s and 60m/s named as A, B, C and D as standard car and A-, B-, C- and D- as optimized car, analysis is carried out to study aerodynamics noise generation from standard car and from the results optimizing standard car and comparing both of them to validate the reduction of the aerodynamic noise.

Results are generated from the CFX, CFD post in Ansys 2019 R2 with the help of various contour plots, creating a plane in ZX-plot and also use of iso-surface to get to know motion of the air when it goes over any object at a given particular speed.

Table 3

Generated Result with Global Legend Range

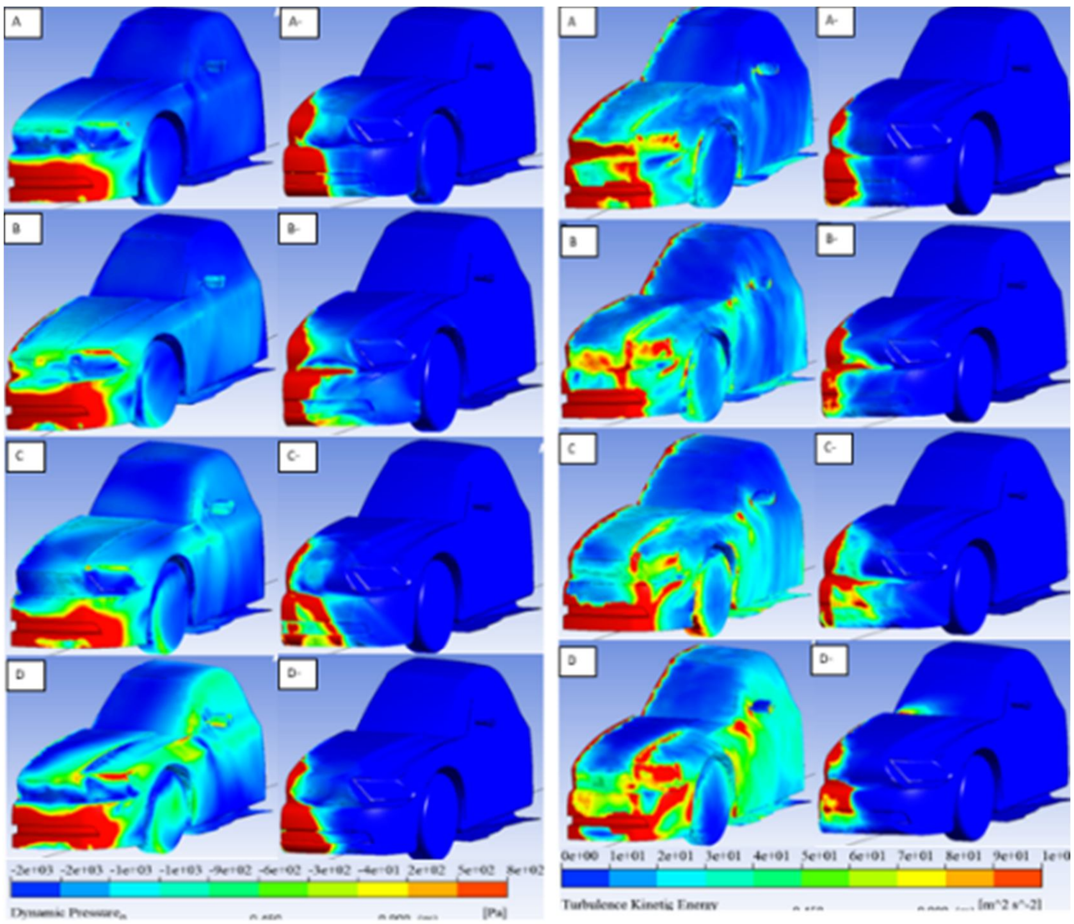
Sr no.	Type of result	Name of result	Legend value of the result (global range)
1	Contour plot	Dynamic pressure (flow characteristics)	-2e+03 – 8e+3
2	Contour plot	Turbulence kinetic energy (flow characteristics)	0 – 1e+2
3	Isosurface	Turbulence kinetic energy (flow characteristics)	2e-11 – 4.1e+13
4	Contour plot	Proudman's Acoutics power level in Db (acoustic sound source)	7e+1 – 1e+2
5	Contour plot	Curle Surface acoutics power level in Db	8e+1 – 1e+2
6	Isosurface	Proudman's Acoutics power level in Db (acoustic sound source)	0 – 568.231
7	Contour plot	Lilley S totoal noise source (acoustic sound source)	0 – 2e+18
8	Isosurface	Lilley S totoal noise source (acoustic sound source)	0 – 2e+18

NOTE: Due to some error, an extra enclosure area of 0.6mm is given from the symmetry side resulting in high pressure and eddies near symmetry edge also, no windshield wiper is used in both standard and optimized sedan car geometries.

A. Flow Characteristics

In flow caracterisctics there are two main phenomenon which are considered and calculated namely Dynamic pressure and Turbulence kinetic energy (TKE) as these are the two main elements which genrates aerodynamic noise.

1) *Dynamic Pressure Contour Plot*: "Dynamic pressure can be defined as the kinetic energy per unit volume of fluid, it comes from one of the terms of from Bernoulli's equation which is derived from conservation of energy when a fluid is in motion" and according to the Bernoulli's equation, as said the generated pressure of the fluid increases as the speed of the object decreases and the vice-versa as pressure of the fluid decreases, speed of object increases [24]. From the dynamic pressure contour plot it can be seen that the pressure of the air decreasing as the speed of the vehicle is increasing in the areas where there is presence of sudden wake like mirror, hood, windows, door panel and over-flush region like bumper design du to which curtailment in the air's pressure as can be seen in the cyan colour of dynamic pressure contour plot. Due to providing a camera integrated mirror instead of standard, wake is reduced to very great extent also providing under-flush to the bumper and re-designing A-pillar has cut-off fluctuations in air pressure.



Flow characteristics Contour plot: Comparison of standard car for Dynamic pressure with optimized car

Flow characteristics Contour plot: Comparison of standard car for Turbulence kinetic energy with optimized car

Fig. 2. Dynamic pressure and Turbulence kinetic energy contour plot

Dynamic pressure/velocity pressure in fluid dynamics is defined by

$q = \frac{1}{2}\rho u^2$ Equation 7 Compressible fluid dynamics, dynamic pressure equation

Also, the dynamic pressure can be written as

$q = M^2 \frac{1}{2}\gamma\rho$ Equation 8 Dynamic pressure equation

Where,

$q = dynamic\ pressure, M = Mach\ number$

$\rho = Fluid\ mass\ density, u = flow\ speed, \gamma = Ratio\ of\ specidfic\ heat$

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2) *Turbulence Kinetic Energy Contour Plot:* Turbulence kinetic energy is the phenomenon which comes under fluid dynamics in which kinetic energy per kg per unit mass is associated with the presence of eddies in turbulent flow.[25] Turbulence kinetic energy takes place due to sudden fluctuations of pressure and also sudden change in velocity of the fluid. In below figure of TKE contour plot A, B, C and D is a standard car with four different speed and A-, B-, C-and D- is the optimized car with four different speed 30m/s, 40 m/s, 50m/s and 60m/s respectively. From the figure for standard car it can be seen as speed of vehicle increases, turbulence kinetic energy also gets increased (red contour plot as maximum turbulence kinetic energy) in the area where there are pointy region, over-flush and even sudden wake due to which there is sudden change in the pressure at those region causing disturbance in the velocity of air. In case of optimized car, the turbulence kinetic energy is increasing but it is less compared to the standard car as fillets, under-flush and wake of the mirror is reduced in a very great extent than the standard car model. 0 is the least legend value and 100 m^2/s^2 is the maximum (showing as red in the contour plot) where the turbulence kinetic energy is at max which is 100 pa or little bit more than that.

This turbulence kinetic energy is calculated as half the sum variances from the velocity components

$k = \frac{1}{2}\left(\overline{u^1}\right)^2 + \left(\overline{v^1}\right)^2 + \left(\overline{w^1}\right)^2$ *Equation 9 Turbulence kinetic energy equation*

Where, u, v *and* w = velocity component

Further, for transport equation of turbulence kinetic energy and to acquire boundary conditions for Reynolds stresses a different equation is used for a k-epsilon standard model.

3) *Turbulent kinetic energy iso-Surface:* Below figure is the iso-surface generated by the turbulence kinetic energy at 4 different speeds. Legend value for turbulence kinetic energy is 2.e-11 m^2/s^2 as minimum value and maximum value as 4.1e+13 m^2/s^2 which is according to the global range.

Transport equation for Turbulence kinetic energy

$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \frac{1}{2}(P_{ii} + G_{ii}) - \rho\epsilon(1 + 2M_t^2) + S_k$ *Equation 10 Transport equation for Turbulence kinetic energy*

As discussed above how turbulence kinetic energy increases with the increase in speed same can be seen through iso-surface. In standard vehicle maximum turbulence kinetic energy is generated near mirror, headlight, wheel arch and hood which gradually is affecting bumper as the speed increases but in the case of optimized car turbulence kinetic energy is less in those areas with the same global range legend due to optimized design.

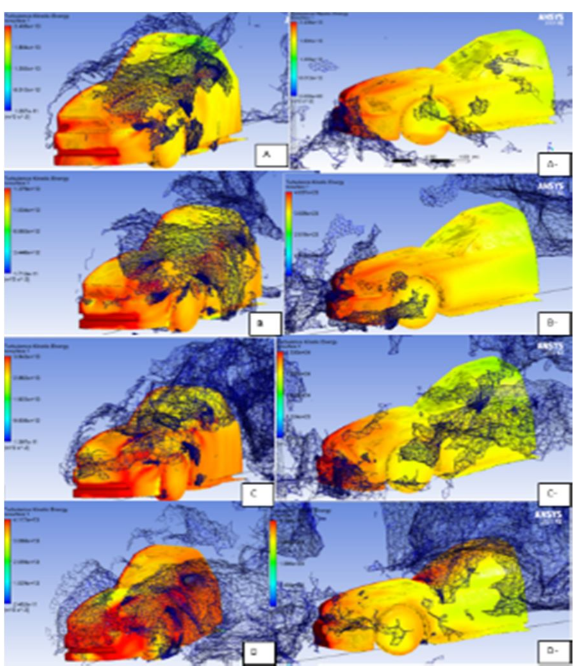
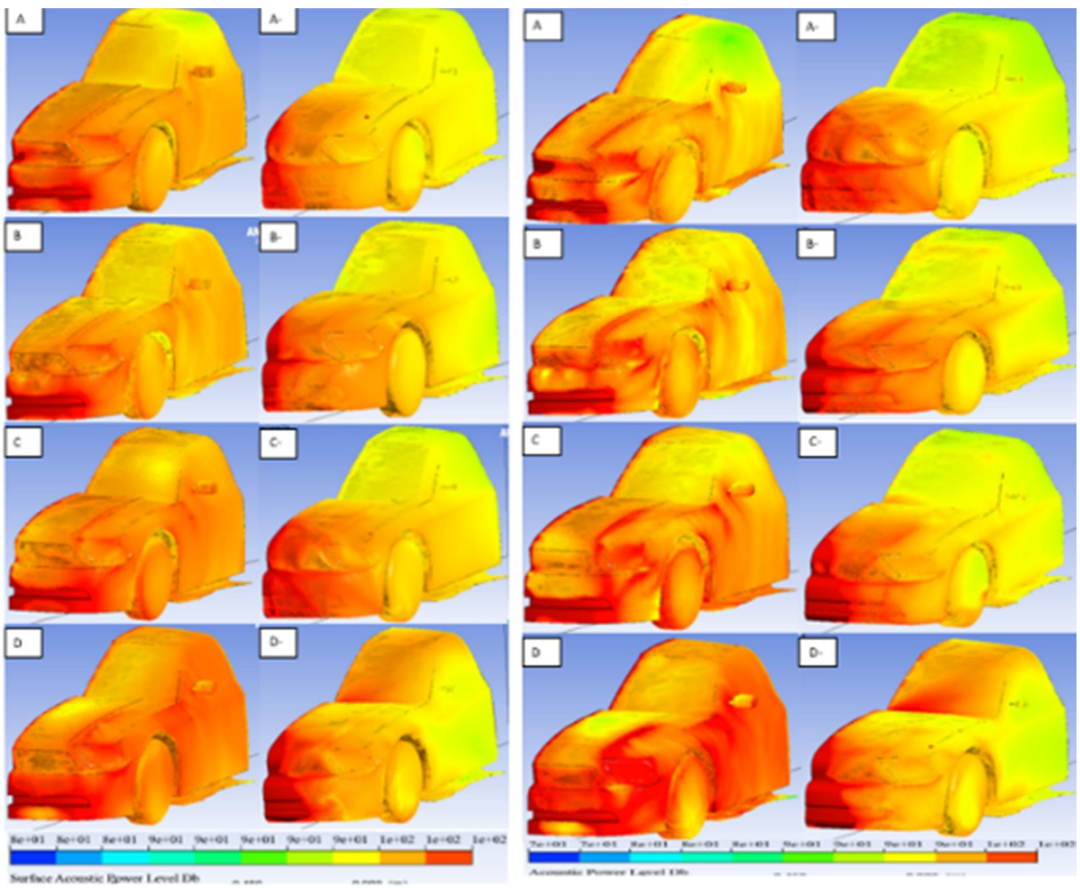


Fig. 3. Turbulence kinetic energy Iso-surface

B. Acoustic Sound Source

In this section, results and discussion are presented due to flow characteristics how noise is generated due to their presence when the car is in motion.

1) *Proudman's Acoustic power level Db contour plot*: With the help of Proudman's formula (Equation 2) acoustic power level Db contour plot is generated. As seen in the flow characteristics at which point dynamic pressure is developed due to sudden colliding region with wake which further influences generation of turbulence kinetic energy and this TKE generations is at a very wide range of fluctuations as seen in the iso-surface of TKE which provokes the noise generation as can be seen through Proudman's acoustic power level Db contour plot, main sources of aerodynamic noise seen on the standard car is bumper's over-flush region, hood line, headlight edges, wheel arch, fender and side view mirrors. To curtail aerodynamic noise small changes like smooth transition, under-flush, wake reduction is provided to the optimized car and due to these minor changes there is a very drastic difference in the aerodynamic noise generation as can be seen through optimized car A-, B-, C- and D- contour plot with the comparison of standard car A, B. C and D. By this optimization there is a decrease in the noise which decreases the noise level in the cabin compartment of the car which helps to maintain psychoacoustic range for the passengers inside the cabin and have calm and peaceful journey.



Acoustic sound source: Comparison of standard car for Curle surface acoustic power level in Db with optimized car

Acoustic sound source: Comparison of standard car for Proudman's acoustic power level with optimized car

Fig. 4. Curle surface acoustic power level in Db and Proudman's acoustic power level in Db contour plot

Curle noise source power (Surface acoustic power level in Db): A Curle noise source model is rewritten form Lighthill's analogy equation which is for jet engine where there is no presence of boundary interferences from any boundaries. Curle has considered a rigid surface with source term by taking dipoles from the surfaces into account.

$\rho^{`}(x,t) = \frac{1}{4\pi a_0^2}\frac{\partial}{\partial_{x_i}}\int \frac{p_i\left(y,t-\frac{|X-Y|}{a_o}\right)}{|X-Y|}dS(y)$ *Equation 11 Curle surface integral equation*[26]

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After simplifiying curle surface integreal eqaution we get surface acoustic power (SAP) equation in Db

$SAP(Db) = 10\log(\frac{SAP}{P_{ref}})$ *Equation 12 Surface acoustic power (SAP) level in Db equation*

Generated surface acoustic power level in Db is almost same as the acoustic power level. Generation of noise model on the surface level of car is from bumper, hood, fender, windshield and side view mirror which can be easily seen in the standard car surface acoustics power contour plot (A, B, C and D) and the surface noise from fender, side view mirror and windshield has decreased in a good rate as can be seen in the optimized car contour plot. Max generated noise is at the bumper which is 100 Db and the least is near windows, door and roof which is at 90 Db.

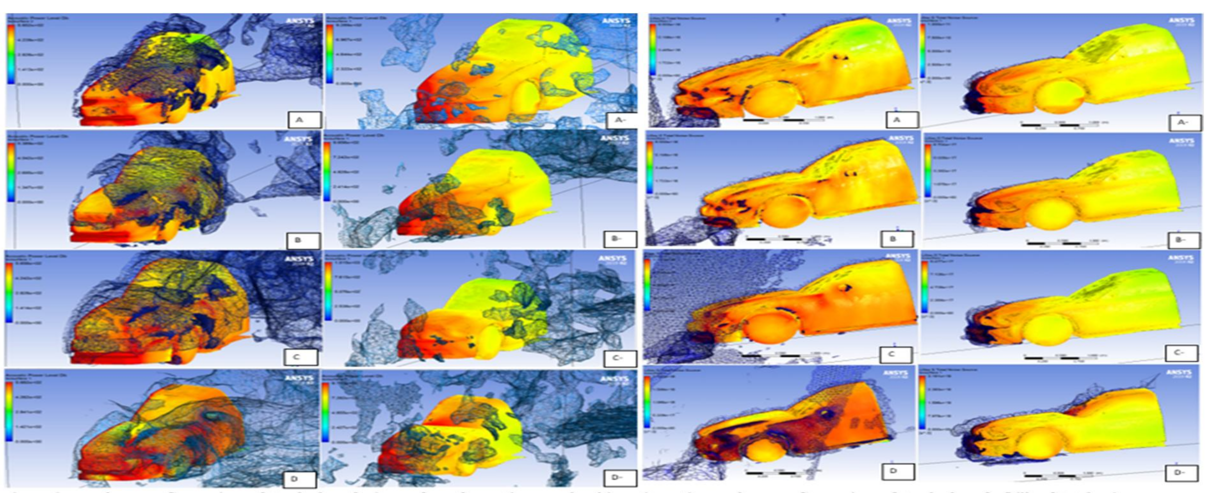
2) *Proudman's Acoustic Power Level In Db Iso-Surface:* After observing iso-surface for acoustic power level in Db as mentioned earlier it can be seen that noise is produced due presence of turbulence kinetic energy mainly at hood, bumper, fender, windshield, wheel arch and outside rear-view mirror. As the speed of the car increases all the noise generation mentioned above generates more noise due to increase in turbulence of wind at a very broad range as it can be seen in a standard car contour plot (A, B, C and D). It can be seen from contour plot the noise is reduced at surface level but with the help of iso-surface it can be seen how exactly it is decreasing and helping to curtail aerodynamic noise after observing optimized contour plot (A-, B-, C- and D-). Legend value for generated iso-surface of acoustic power level in Db is 568.231 Db as max value and 0 as the minimum value.

Lilley S is another source model for generation of postprocessing in a fluent. A Lilley S noise source is computed from the sources generated from Turbulent shear flow around an object or through an object. So, the generated contour plot is combination of shear noise and self-noise which is the sub part of Lilley S total noise source.

$S = -2\frac{\partial u_k}{\partial x_i}\frac{\partial u_j}{\partial x_k}\frac{\partial u_i}{\partial x_j} - 2\frac{\partial u'_k}{\partial x_i}\frac{\partial u'_j}{\partial x_k}\frac{\partial u'_i}{\partial x_j} - 6\frac{\partial U_k}{\partial x_i}\frac{\partial U_j}{\partial x_k}\frac{\partial u'_i}{\partial x_j} - 6\frac{\partial u'_k}{\partial x_i}\frac{\partial u'_j}{\partial x_k}\frac{\partial U_i}{\partial x_j}$ Equation 13 Lilley S total noise source equation

Where, $-2\frac{\partial u'_k}{\partial x_i}\frac{\partial u'_j}{\partial x_k}\frac{\partial u'_i}{\partial x_j} = Self - noise\ terms$

$-6\frac{\partial U_k}{\partial x_i}\frac{\partial U_j}{\partial x_k}\frac{\partial u'_i}{\partial x_j} - 6\frac{\partial u'_k}{\partial x_i}\frac{\partial u'_j}{\partial x_k}\frac{\partial U_i}{\partial x_j} = Shear - noise\ terms$



Acoustic sound source: Comparison of standard car for iso-surface of acoustic power level in Db with Optimized car

Acoustic sound source: Comparison of standard car for Lilley S total noise source contours with optimized car

Fig. 5. Acoustic power level in Db and Lilley S total noise source Iso-surface

After observing Lilley S total noise source contour plot, it can be seen which surface area of car produces self-noise and shear-noise and a total noise is shown in the form of contour plot. Areas which undergoes shear-noise and self-noise is hood line, bumper over-flush design, headlight edges, wheel arch edges, fender near starting of A-pillar and on the edges of outside rear view mirror which can be seen through standard car contour plot (A, B, C and D) and after optimizing the car and eliminating sharp edges and providing under-flush there is a decrease in the Lilley S total noise source due to reduction of both self-noise and shear-noise to some extent as can be seen on the optimized contour plot (A-, B-. C- and D-). Max legend value is 2e+18 s^-3 with minimum value as 0 according to global range.

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3) *Lilley S total Noise Source Iso-Surface:* With the help of Lilley S total noise iso-surface it can be observed how the air is acting on the car and creating the noise source also, through the observation it can also be seen which area has maximum noise source and which has noise source has little amount of noise source. This iso-surface is generated through same method with the help of self-noise and shear-noise hence, the iso-surface of Lilley S total noise shows very few regions of the results where there is shear-noise and self-noise generation over a car. From the Lilley S total noise iso-surface it can be seen as the speed of the car increases noise source keeps on increasing by showing more number of iso-surface as can be seen in the below figure, for standard car for iso-surface (A, B, C and D) as discussed above regions like hood-line, fender, over-flush bumper, headlight edges, wheel arcs and outside rear view mirror has high noise source and in the same figure for optimized car (A-, B-, C- and D-) the noise level has reduced compared to the standard car to a very great extent but even in optimized car the noise surface source area increase as the speed increases. Legend value for Lilley S total noise source iso-surface is same as contour plot which is 2e+18 as maximum and 0 as minimum which is according to the global range.

C. Validation of results with the help of XY scatter plot

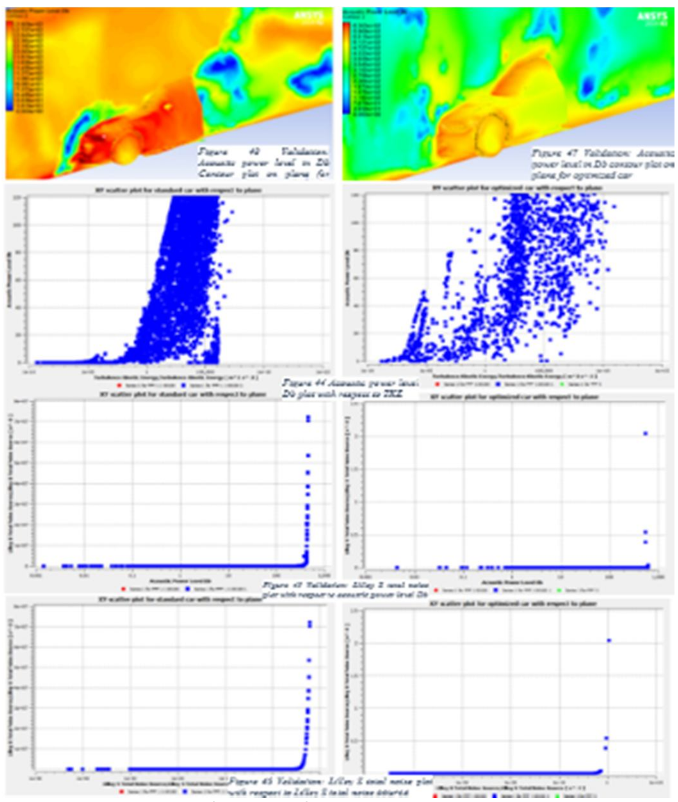

Fig. 6. Validation of results for Optimized car with standard car

1) *XY Scatter plot Explanation for Validation:* Generated XY scatter graphs are according to the plane which is created at a distance of 500 mm from the symmetry plane and an acoustic power level in Db contour plot is generated on the created plane as can be seen in the figure. From the generated XY scatter plot with respect to the created plane at 500mm distance the results can be validated as the scatter plot shows the change in the noise level of the optimized car can be seen with the comparison of a standard car. In XY scatter plot for Acoustic power level with respect to TKE it can be seen that generation of turbulence kinetic energy is decreased resulting in curtailing the aerodynamic noise generation. From second XY scatter plot which is Lilley S total noise source with respect to acoustic power level in Db it shows decrease of Lilley S total noise source as well as decrease in acoustics power level Db by this XY scatter plot it can be seen both self-noise and shear-noise has decreased in the optimized car due to provision of optimized design elements like smooth transition, under-flush and reducing OVRM size. Form the last XY scatter plot Lilley S noise source with respect to Lilley S total noise source and comparing standard car XY scatter plot with optimized car scatter plot it can be seen there's a decrease in noise sources from both self-noise source and shear-noise source of Lilley.

D. Residual Plot

Residual plot of optimized car at 50 m/s: As can be seen from the residual plot at 50 m/s after running 1200 number of iterations the results can be seen converging and all the main parameters from flow field K, epsilon, continuity, X, Y and Z velocity and also energy has converged to less than 10e-6 indicating that the results obtained from the 60mm mesh size geometry is as approximate as possible and also making it realistic generated results values. Also, all the other speed values for optimized sedan car has converged to almost 1e-6 which are also as accurate as possible and realistic as well.

VI. CONCLUSION

The comparative research study shows on which surface or on which design element of the standard vehicle aerodynamic noise is generated and how does this generated noise can affect on the human health. To study the sources of noise on standard vehicle an aeroacoustics analysis with the help of broadband noise acoustic model with K-epsilon turbulence model is carried out and through acoustic models Proudman's acoustic power level in Db, Lilley S total noise source and Curle surface acoustic power level in Db. Sources of the noise generation after carrying out analysis on standard car are Bumper's over-flush design, pointy/sharp edges on the frontal area of car, hood-line with sharp edges, point wheel arcs, door panel line, A-pillar with point edges, in appropriate angle joint between windshield with roof and big and high wake producing mirrors. This aerodynamic noise source is reduced which are seen through contour plot from 100 Db to near 80 Db of noise is reduced by controlling flow characteristics like pressure and turbulence kinetic energy (TKE) which are the main reason of aerodynamic noise generation due to their very broad range of fluctuations after passing over the mentioned surface and design elements. Through XY scatter plot of Proudman's acoustics power level Db, Lilley S total noise source and turbulence kinetic energy an validation can be given that there is a reduction in aerodynamic noise to a very great extent due to reduction in turbulence kinetic energy of air which decreased the aerodynamic noise nearly from 100 Db to 80 Db and also, there is reduction in Lilley's self- noise and Lilley's shear noise due to reduction in pressure fluctuations. Hence, it can be concluded that the aerodynamic noise produced by standard car is reduced to some level helping to maintain the psychoacoustics range inside the cabin and helping the driver and passenger with much calmer and comfort level.

A. Future Scope

An aerodynamic noise can be reduced more by studying in depth of various flow characteristics like pressure, turbulence and velocity in a practical environment instead of virtual simulations like a special wind tunnel for aeroacoustics to get to know how really change in pressure and turbulence takes place with different velocities and how does it provokes in generation of aerodynamic noise from various sources. Though an aerodynamic noise cannot be eliminated completely but it can be reduced to some extent and studied for its source generation to insulate the cabin in those particular section or area to maintain the psychoacoustic range.

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