

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 9, September 2017

Exhaust Header Designing for Formula SAE Car

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ABSTRACT: This paper emphasizes on designing and optimization of exhaust headers for FSAE car engines and it uses the art of wave dynamics to maximize wave scavenging potential during valve overlap period. The main objective of designing exhaust headers are to enhance engine breathing by minimizing backpressure at high rpm and exhaust pulse tuning to maximize wave scavenging potential during valve overlap period. The virtual engine model has been developed in Ricardo Wave Software and analysis of the performance changing factors have been done. This work studies the performance of different geometries using Ricardo Wave Build by analyzing the torque curve, power curve, port pressure as well as vol. efficiency and also their effects are discussed. Track data of Formula SAE was gathered, and according to the optimum engine running condition, the tuning goal was achieved. Structural analysis was also carried out using different materials with weight reduction being the paramount factor accounting for it.

KEYWORDS: Wave scavenging, Back pressure, Intake ramming, Virtual engine simulation, Ricardo

I. INTRODUCTION

A substantial part of engine performance is exhaust header design. This is because lengths and diameter of exhaust headers have an important impact on the performance of the engine. It is just not the bundle of some pipes which just directs the exhaust gasses, it is more than that. The design of exhaust header, as well as intake manifold, uses the principle of wave dynamics to get well optimized high-performance engine. It is based on the superposition of pressure waves at optimum timing. Here, optimum timing is defined as the valve overlap period. It is the period at which both intake and exhaust valves are open for a certain time.

Exhaustheader design is initiated in accordance with the intake manifold characteristics on basis of the performance parameters. It is designed for a specific range of rpm. One cannot get the increased torque at low end as well as high end. Racing cars are usually defined for high rpm and street cars are for low rpm band. The FSAE (Formula Society of Automobile Engineers) design goal is to develop and construct a single-seat race car for the non-professional weekend autocross racer with the best overall package of design, construction, performance and cost.

The concept of exhaust wave scavenging was briefly discussed by Gordon P.Blair et al. [6]. The work in this paper is divided into 2 stages. 1) MATLAB code development 2) Iteration in Ricardo Wave engine model. Code is developed by using wave equation from Performance Tuning in Theory and Practice by A. Graham Bell and applying wave dynamics theories.

This paper emphasizes on optimizing exhaust header design of FSAE cars to maximize the wave scavenging potential while reducing the back pressure at high rpm, and to flatten the torque curve in operating range while considering the effects of the troughs created in the torque curve during the induction ramming. A brief idea of the configuration of exhaust headers that is 4-2-1 configuration and 4-1 configuration is being discussed. Structural analysis and the study of different materials for its application is also discussed.

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II. THEORY

The exhaust pulse coming out from the exhaust port is in the form of compression waves and it moves towards the open end of the pipe and after reflecting from the open end due to sudden change in area, it changes its phase to expansion wave.[6] So, lengths of exhaust pipes are designed in a way such that superposition of different phase waves occur at the valve overlap period. Interference of these two opposite types of waves creates a vacuum force which helps in further removal of exhaust gasses. [6] The exhaust header should be tuned in such a way that it uses gas momentum and inertia to suck out the gasses out of the cylinder resulting in wave scavenging effect. For FSAE cars, we analyze particularly in mid-range torque than high-end torque. Accordingly configuration of exhaust header has to be chosen in order to get the maximum mid-range torque.[5] Back pressure is induced due to negative port pressure flowing back towards the engine. Excessive back pressure can cause harm to the engine and decreases engine performance. On the contrary, optimum backpressure is good for the engine but only at low rpm. [7] At low rpm, the high frequency pulsation is required as it keeps them intact which helps to vacuum out the residuals. But at higher rpm, the pulsation causes hindrance to the flow thus restricting it.

III. PROPOSED METHODOLOGY AND DISCUSSION

This method utilized the simulation study of the virtual engine model built for the HONDA CBR 600RR engine. The maximum time engine's operating rpm range was obtained by the data logger on the FSAE track, and this is the area on which the maximum scavenging potential has to be defined. The mathematical modeling was done by developing the MATLAB code according to the wave dynamics for the operating range. This generated the approximate lengths and diameters of the exhaust manifold. These results were later verified by doing the changes accordingly in the virtual RICARDO engine. Also, the best exhaust header configuration was chosen according to the WAVE results. Performance parameters were monitored throughout the iterations and the best result was selected. The final CAD geometry was developed according to the packaging constraints. This final cad geometry was analysed for flow analysis using the STAR-CCM+ software. Various material properties were studied for this specific purpose. The optimized results were studied and further finalized.

- 1) Calculations of exhaust header lengths using MATLAB code
- 2) Iterations in Ricardo wave build
- 3) Selection Of Header Configuration based on Ricardo results
- 4) Material selection and strength analysis using ANSYS software.

Iteration motive

It has been observed that by adding 0.125 inches in diameter, peak of the torque curve shift towards higher rpm range by difference of 500-800rpm and by reducing 0.125 inches from diameter, the peak of the torque curve shift towards lower rpm by a difference of 500-800 rpm. So, different iterations have been done to optimize the performance. Similarly, by adding lengths to primary pipes, power curve tends to shift towards higher rpm and by reducing lengths, the peak of power curve shifts to lower rpm.

Material analysis:

Material selection of the exhaust header was done using ANSYS Workbench by doing a static structural analysis.[1] It also helped in determining the thickness of the exhaust header. The aim was to make a lightweight model which is able to undergo all loading conditions.

A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time.

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Material Selection Matrix:

Parameter\Material	Cast Iron	Stainless Steel	Inconel Steel	Titanium
Availability	Yes	Yes	Yes	Yes
Cost	Low	Moderate	High	High
Weight	Heavy	Heavy	Heavy	Light
Thermal Conductivity	47-80	12-45	15	15

Based on above table we can see that cast iron and stainless steel are both heavy designs as well as the thickness that the header can be manufactured with these metals is also more whereas Inconel steel and titanium can be used to make header with relatively less thickness as less as 1mm. [3] Also the thermal conductivity of these metals is lesser than that of cast iron and stainless steel; hence the header temperature remains higher as less heat is conducted. This increases the exhaust gas velocity and reduces backpressure, thus the scavenging is better in Inconel and titanium due to high temperature. But titanium is much lighter than Inconel steel so it was the best option to choose.

IV. EXPERIMENTAL RESULTS

Primary Length	Primary Diameter	Secondary Length	Secondary Diameter	Tertiary Length	Tertiary Diameter
15	0.9214	13.1667	1.2118	12	1.25
15	0.9	13.1667	1.2118	12	1.25
15	0.775	13.1667	1.2118	12	1.25
15	0.8411	19.4	1.1063	12	1.25
15.125	0.8411	19.4	1.1063	12	1.25
15	0.8822	16	1.1603	12	1.25
15	1.0072	16	1.1603	12	1.25
15	0.8822	16	1.2853	12	1.25
15	0.7572	16	1.1603	12	1.25
15	0.8822	16	1.0353	12	1.25
15	0.7874	13.1667	1.1603	12	1.25
21.875	0.7523	14.5833	0.9895	12	1.25
20.375	1.0639	16	1.3993	12	1.25
15.7	1.181	11	1.5645	12	1.25
20	1.0639	6	1.3993	12	1.25
20	0.906	6	1.3993	12	1.25

Fig.1. Iterations of Various Dimensions of Exhaust Header

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Vol. 6, Issue 9, September 2017

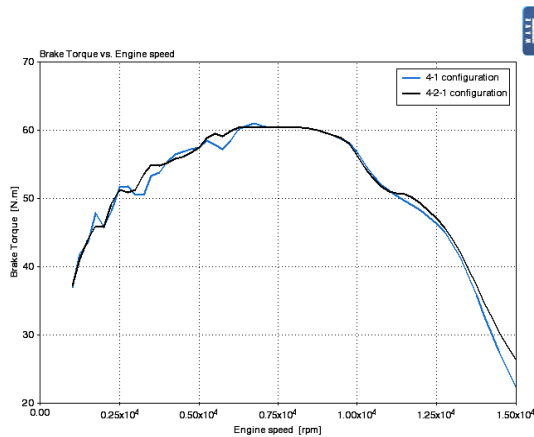


Fig.2. Engine torque vs. RPM (configuration)

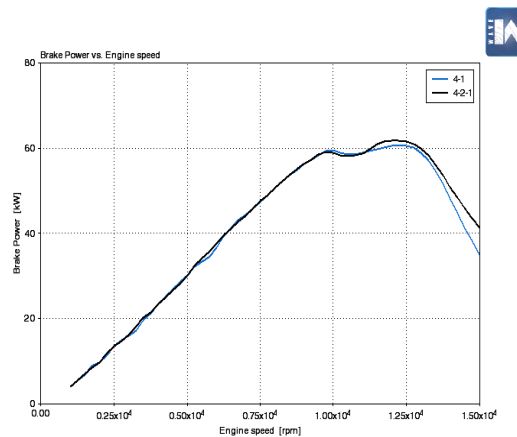


Fig.3. Engine power vs. RPM (configuration)

Fig 3 illustrates the variation in characteristic of power with respect to the configuration of a manifold. The aim was to get the peak power in between operating range of rpm with less number of trough. There should not be any frequent fluctuations in characteristic.

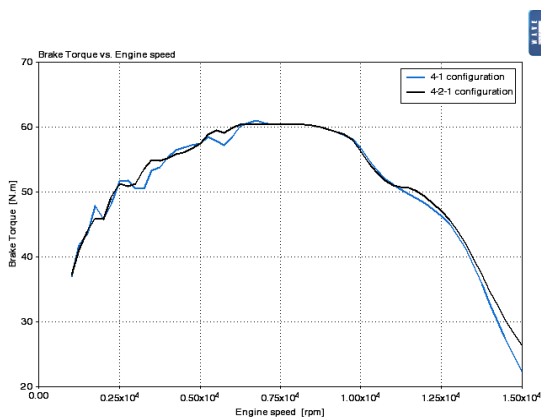


Fig.4. Torque vs. RPM (different geometries)

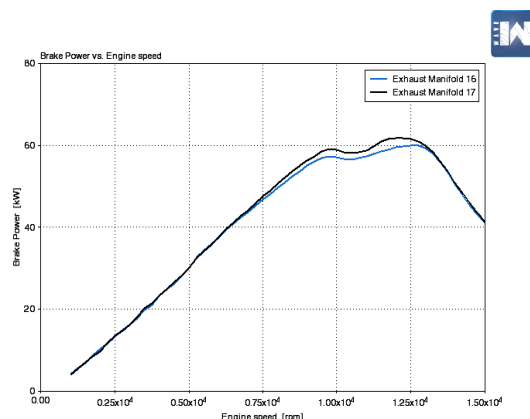


Fig.5. Power vs. RPM

Fig 4 illustrates the variation in brake torque characteristic with respect to the configuration of a manifold. By keeping the final lengths and diameters of primary, secondary and tertiary tubes same, [2] two different configurations has been made. Selection of header configuration has been made considering flat torque at mid-range and peak torque at mid-range. Also, it has been observed that 4-2-1 configuration has broader torque curve than 4-1 configuration. Therefore, 4-2-1 header configuration has been chosen as per our requirement.

Figure 5 indicates the slight rise in peak power over the RPM range on variation of the exhaust header length

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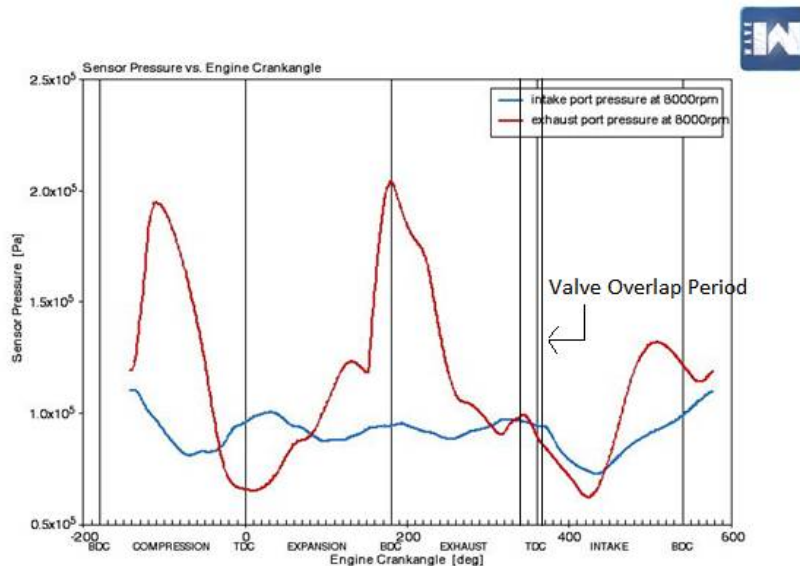


Fig.6. Port pressure vs. Crank Angle

By monitoring the port pressure at particular rpm, we can analyse the change in the behaviour of an engine due to change of exhaust manifolds. At high rpm, due to increased tight pulsation formation, back pressure increases. Figure 1 illustrates the variation of intake port pressure and exhaust port pressure with changing crank angle at 6000rpm. The valve overlap period for CBR600RR is 21° BTDC and 5° ATDC. Intake pressure is always greater than exhaust pressure at valve overlap period. We can conclude that at 6000 rpm, there will not be any reverse scavenging due to change in pressure. This ensures minimum back pressure at 6000rpm.

Static Structural Analysis

The Static Structural Analysis was done for the geometry:

Mesh Statistics:

Nodes: 72156

Elements: 379004

Loading conditions as follows:

Pressure in Primary: 1.2×10^5 pa

Pressure in Secondary: 1.1×10^5 pa

Temperature: 650° C

Fixed supports at:

- 1) Flange in the Primary
- 2) Primary with Engine Connection
- 3) Tertiary with Muffler Connection

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Vol. 6, Issue 9, September 2017

These conditions were obtained by using RICARDO Wavebuild 1-D Engine Simulation Model.

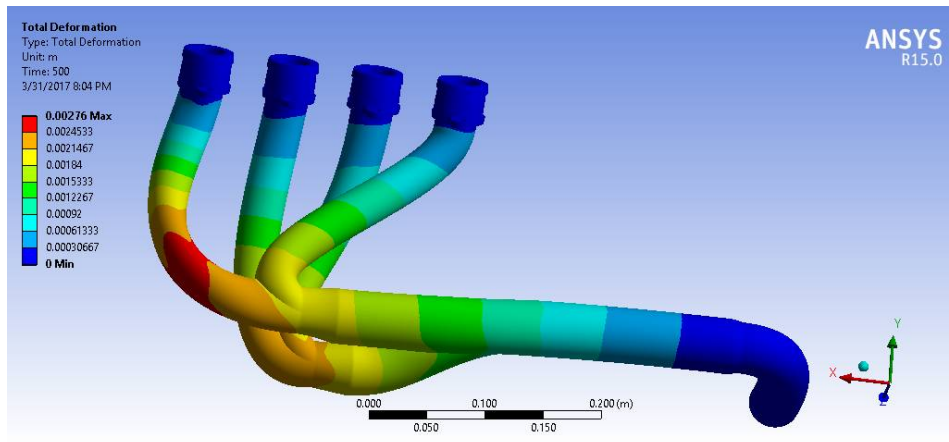


Fig.7. Maximum Deformation was seen on a primary runner which has the maximum bend angle. But the magnitude of deformation is very less. So it won't affect the manifold much.

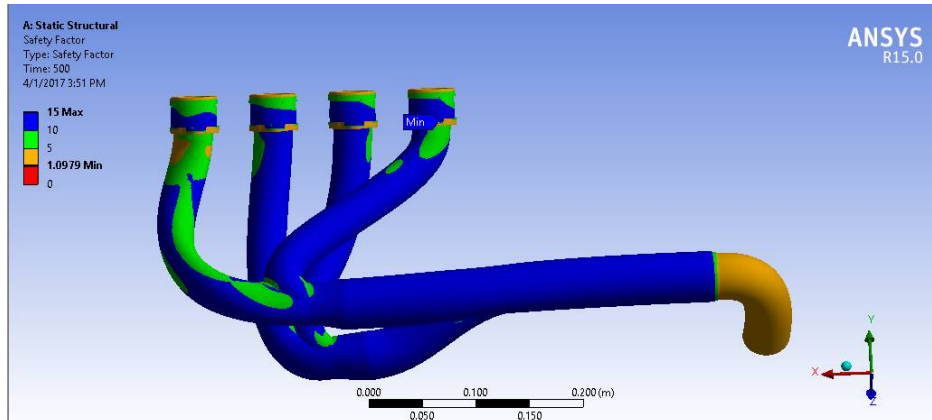


Fig.8. The minimum factor of safety is around 1 which occurred at the flange of mounting.

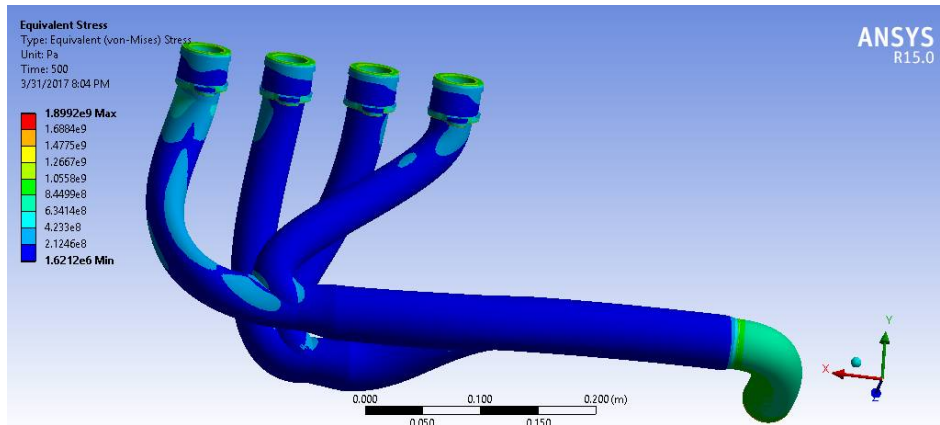


Fig.9. The value of equivalent stress is fairly low on the entire geometry.

Equivalent stress (also called *von Mises stress*) is often used in design work because it allows any arbitrary three-dimensional stress state to be represented as a single positive stress value.

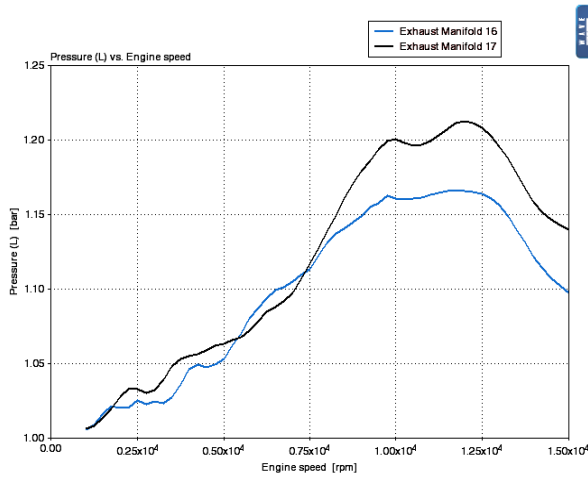


Fig.10. Back pressure vs. RPM

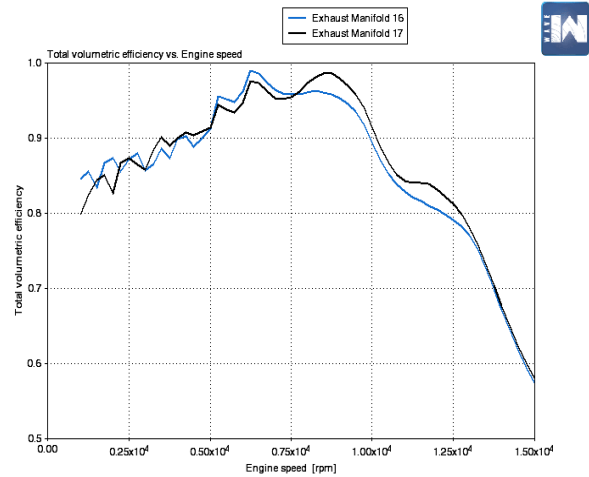


Fig.11. Volumetric efficiency vs. rpm

Figure 10 illustrates the variation in back pressure with respect to engine speed. Every engine has a threshold limit of back pressure above which it limits the performance of an engine. Many iterations have been done to minimize back pressure at the higher end and maintaining minimal back pressure at lower ends as discussed above.

V. CONCLUSION

The aim of this paper depicts the factors deciding the exhaust manifold design. The design criteria was achieved by using the RICARDO software, the strength analysis and the material selection was carried out using the ANSYS results. The different configurations of the muffler were studied to achieve the desirable results. The main aim of this paper was to achieve the right balance between the backpressure, so that it would aid the scavenging process to in-hand increase the volumetric efficiency of the engine.

The aim of this work was to design an exhaust manifold aiding the performance. The report analyses different configurations of manifold build and justifies the best design while considering the performance parameters. Tools like mathematical modelling in MATLAB, integrated tuning effects were studied in the RICARDO WAVE etc. which came

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Vol. 6, Issue 9, September 2017

in handy in optimizing parameters. The engine performance was fine-tuned according to the Formula SAE track. The demonstrated design study of exhaust header depicts.

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