DESIGN MODIFICATION AND ANALYSIS OF ENGINE EXHAUST MANIFOLD

S.B.Borole[1], Dr. G.V.Shah[2]

[1]*borole.shreyash@gmail.com*
[2]*gvscfd@gmail.com*
Mechanical Engineering Department, P.V.P.I.T. Bavdhan, Pune University, Pune, Maharashtra, India

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Abstract - *This study focuses on the development of a reliable approach to predict failure of exhaust system fitting and on the removal of structural weaknesses through the optimization of design. The task with this project was to find a new solution concept for the connection of pipes into flanges in manifolds. The concept that uses today for their manifolds is based on welding the pipes into place in the flange. The product development model that is used in this project is written by Fredy Olsson. For this project have the parts "Principal construction" and" Primary construction" been used.*

The Objective is to present experimentation, modeling and analysis of exhaust system fitting weldless by using FEA. Modeling is done using PRO/Engineer Creo. Analysis is carried out by using ANSYS. The optimization of cast and fabricated manifolds (single or dual wall design) requires different techniques, due to the production restrictions. The locations where failures occur, on both the exhaust manifolds (cast or fabricated) and exhaust manifold gaskets, are predicted with high degree of accuracy.

From the study it is seen that the different solution concept is result from this work. All of the solution concepts contain end shaped pipes that provides the sealing area against the engine. The main difference between them is that the flange is designed in different ways. Different techniques are needed for the optimization of cast and fabricated manifolds, because of production restrictions. This problem is already been addressed and a procedure has been implemented.

The manual and automatic optimization methods have distinct advantages and disadvantages. A cost effective solution is delivered by a combined methodology, which also results in a failure-free exhaust manifold design.

Key Words: Development Project, Manifold, Flange, Pipe, End Shaping, Weldless FEA

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1. INTRODUCTION

Noise & vibrations are major responsible factors towards human comfort level. To enhance the human comfort, it is very necessary to reduce noise & vibration level due to fitting of exhaust system, where noise and vibrations are more due to weld connections [6].The welding process is expensive due to high technology welding robots and time consumption. The pipe and flange are exposed to large thermal stresses while welding [4]. This stresses weakens the materials, produces the defects, which can take shape of small pieces of material, weld spatter, may loose and end up destroying the catalytic converter [5]. Other defects can occur in the welding seam and they must be repaired manually. However, the manifold should not be manufactured by casting, because the high temperatures in present combustion engines demand more expensive and high quality materials that causes problem when casting [7] [2]. The goal in the development of exhaust system fitting is to analyze several solutions weldless. The solutions that are subject for further development are prepared during the primary construction with for example CAD. Different solution concepts are result from this thesis work. All of the solution concepts contain end shaped pipes that provides the sealing area against the engine. The main difference between them is that the flange is designed in different ways.

1.1 Failure Modes of Exhaust Systems

Failures of exhaust manifolds are mainly caused by the extreme temperature gradients the part has to withstand. A secondary cause for failures is the dynamic excitation of the exhaust subsystem, especially if not negligible masses of attached parts like turbocharger or close-coupled-catalyst are driven into resonance. Typical structural failure modes are manifold cracking and leakage. Those are related to the design and boundary conditions if a proper material choice was done initially. Understanding the root cause of a failure is the most challenging part on the way to a solution.

Understanding Failures

TMF Cracking – An initial thermal loading of exhaust manifolds can cause the material to exceed the yield stress in large areas of the exhaust t manifold. Cyclic temperature loading causes a few areas to exhibit local cyclic plastic straining of the material, which may cause a crack initiation. Depending on the location of the high loaded areas, individual design parameters need to be considered in order to find a target-oriented optimization strategy. It becomes obvious that a detailed knowledge of the system behavior is needed, in order to interpret results correctly.

Leakage – Besides cracking of exhaust manifold systems, the leakage problem is very often also related to *cyclic plastification of exhaust manifolds. Once leakage occurs, a partial destruction of the gasket and the flange occurs, which may lead to an ensuing manifold crack due to a changed force flow in the exhaust manifold. Also here a detailed knowledge of the influencing parameters like bolt pretension, friction between adjacent parts and nonlinear gasket behavior is needed to get an initial understanding of the problem.*

High Cycle Fatigue – High cycle fatigue (HCF) problems at the exhaust manifold are caused by dynamic excitation. This kind of problem is not discovered very often, and is mainly related to unfavorable bracket design [3].

2. OPTIMIZATION AN PRODUCT DEVELOMENT OF EXHAUST SYSTEM

2.1 Solution Concept-

Several suggestions to solve the problem have been found after brainstorming and solution search. The collection of concurrent manufacturer's products has also been examined. Information about working up materials and motorcycle repair manuals has been searched for in libraries.

The solutions are divided into two groups, one were the connection of the pipe has been analyzed. The other group contains some different types of flanges. The second group is to be subject for a short evaluation where the best flange for the solution is to be chosen [5].

Pipe Connection

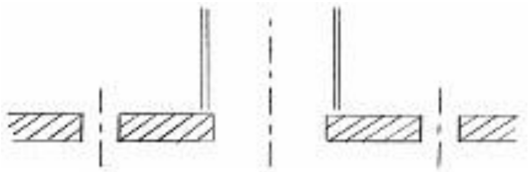
In this chapter a search for principal solutions that are fulfill the criterions for the product take place.

Solution 1

The pipe has larger diameter than the hole in the flange, see Figure 1 below. The pipe is squeezed into the hole and stays in the hole only because of the tension between the pipe and the flange.

Solution 2

Figure 1: Solution 1



The pipe is connected to the flange with some kind of sealing material. The flange is designed with an edge in the hole; see figure 2 below, the pipe rests on this edge. The sealing material is placed between the pipe and the inside of the hole.

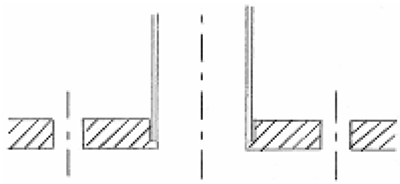


Figure 2: Solution 2

Solution 3

This pipe is connected to the flange with a screw thread, see Figure 3 below. The pipe and the flange are threaded.

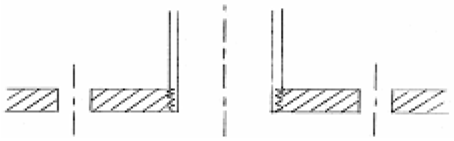


Figure 3: Solution 3

Solution 4

The hole in the flange is shaped as a cone. The pipe is passed through the flange before its end shaped also as a cone, see Figure 4 below. It is important that the end of the pipe stays a few millimeters outside the flange; this enables a tension between pipe and flange when it's mounted.

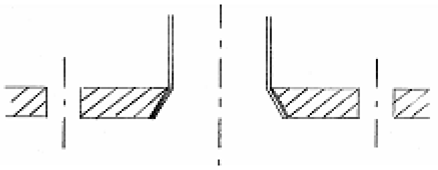


Figure 4: Solution 4

Solution 5

This solution is similar to solution 4, except that the pipe is end shaped to follow the edge of the flange see Figure 5 below. The sealing area is moved to the pipe end between the flange and the Engine

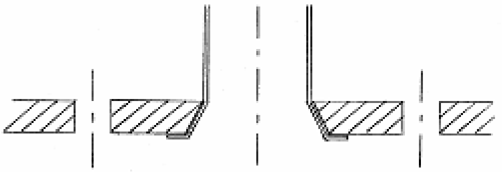


Figure 5: Solution 5

Solution 6

This solution is similar to solution 5, except for the cone shape see Figure 6 below. Solutions like this have been done in test series before at Extencore Solution Exhaust System AB, but in slightly different design of the flange.

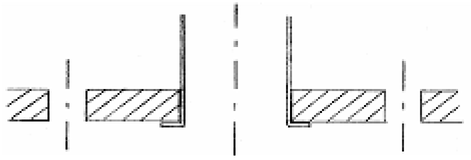


Figure 6: Solution 6

Solution 7

This solution is similar to solution 6, except that the sealing area is moved into the flange that is formed to fit the pipe end see Figure 7 below.

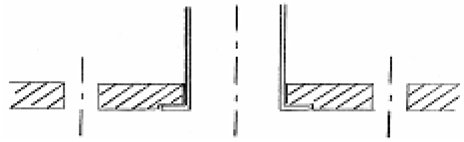


Figure 7: Solution 7

Solution 8

This solution has a two-step end shape and the flange is designed so that the pipe fits into the hole see Figure 8 below. It is important that the end of the pipe stays a few millimeters outside the flange; this enables a tension between pipe and flange when it's mounted.

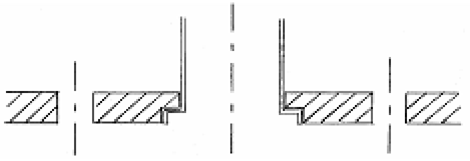


Figure 8: Solution 8

Flanges Connection

In this article different ways to arrange the flange will be presented.

Flange 1

Separate flanges for each pipe, see Figure 9 below. This structure permits movement due to thermal expansion.

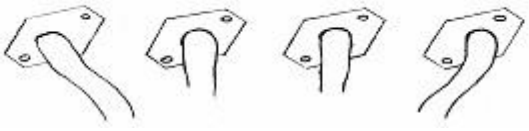


Figure 9: Separate Flange

Flange 2

This flange consists of only one piece, see Figure 10 below. Flanges like this are most common today. This design does not permit thermal expansion as the others.

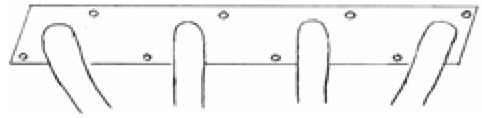


Figure 10: Whole Flange

Flange 3

This flange consists of one piece, but permits thermal expansion because of the weak points between the pipes sees figure 11 below.

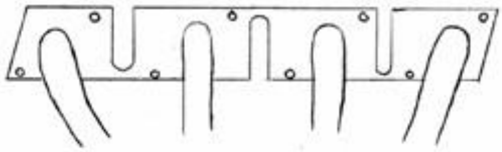


Figure 11: Slotted Flange

Table 1: Direct Grouping Method, Solution Judgment against Demands [1]

No.	Solutio	TD	ED	Pass
1	The pipe is squeezed into the flange.	0	2	No
2	Connection with sealing material.	0	2	No
3	The pipe and the flange are threaded.	1	2	No
4	The pipe and flange are shaped as a cone.	2	2	Yes
5	The pipe is shaped as a cone and follows the flange.	2	2	Yes
6	A small end shape on the pipe.	2	2	Yes
7	A small end shape on the pipe that fits a track in the flange.	2	2	Yes
8	A two-step end shape that fits into the flange.	2	2	Yes

2.3 Concept Evaluation

The evaluation of the concepts must take place in several steps, were the bad concepts is eliminated one by one. Finally the best concepts are remaining. The first and last steps in the concept evaluation are done by evaluating the concepts against the criterions with methods from Fredy Olsson's book "Principkonstruktion"by" [5].

Primary Evaluation – Demands

The criterions that must be fulfilled will be checked here, see Table 1. The concepts that do not fulfill all demands are not going any further than this. This evaluation step is based on knowledge and experiences from the group.

Solution Judgment – Direct Grouping Method Technical demands / Economic demands

Scale: 3 is certainly fulfill the demands

2 is probably fulfill the demands

1 is hardly fulfill the demands

0 will not fulfill the demands

Comments for Solutions that Didn't Pass

Solution 1: The pipe can't be fastened just by squeezing in the flange because of the thermal stresses which appear when the manifold gets hot. The connection would probably leak.

Solution 2: Sealing material which can stand the temperatures needed can't be found.

Solution 3: It's difficult to thread the pipe because of the thin material. This solution doesn't Work on oval pipes.

Evaluation

This evaluation has been done together. This is done through more experience of connection that may provide a satisfying solution to the problem.

Solution 4 & 5: These solutions are quite similar and are ahead in this project being handled as one. They have a good sealing area and the cone is give support for the pipe. Therefore this solution will be subject for further evaluations.

Solution 6: These solutions are also quite similar and will ahead in this project be handled as one. If there is a heel on the flange the pressure on the sealing area will be larger. Therefore this solution is subject for further evaluations

Solution 7, 8: These solutions have no benefits compared to solution 6.Therefore these solutions are not subjects for any further evaluations.

2.4 Final Evaluation – Wishes

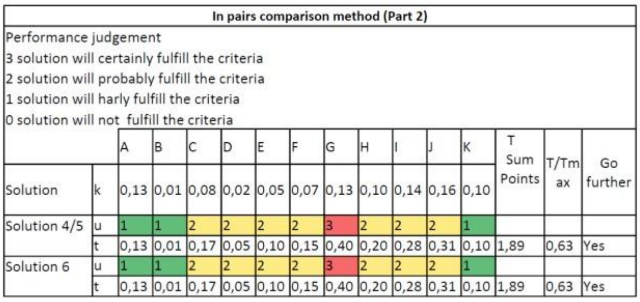
The final evaluation has been done with a method from "Principkonstruktion"by Fredy Olsson [1]. This method is called "In pair's comparison method, part 2"; see Table 2 The method is based on evaluating the solution against the wishes. Some of the wishes don't contain any boards.

For example wish C: "Contain as few parts as possible". When these kinds of criterions are evaluated the solutions are compared to each other. From this evaluation step solution 4/5 and 6 will go further.

Evaluation of Flanges

Because of the simple principal construction of the flanges they don't have to be subject for major evaluation. Therefore the flanges that are provide easy installation, easy work up and easy mounting of the pipes is preferred.

Table 2: In Pairs Comparison Method, Part 2 [1]



In pairs comparison method (Part 2)

Performance judgement
3 solution will certainly fulfill the criteria
2 solution will probably fulfill the criteria
1 solution will harly fulfill the criteria
0 solution will not fulfill the criteria

		A	B	C	D	E	F	G	H	I	J	K	T Sum Points	T/Tmax	Go further
Solution	k	0,13	0,01	0,08	0,02	0,05	0,07	0,13	0,10	0,14	0,16	0,10			
Solution 4/5	u	1	1	2	2	2	2	3	2	2	2	1			
	t	0,13	0,01	0,17	0,05	0,10	0,15	0,40	0,20	0,28	0,31	0,10	1,89	0,63	Yes
Solution 6	u	1	1	2	2	2	2	3	2	2	2	1			
	t	0,13	0,01	0,17	0,05	0,10	0,15	0,40	0,20	0,28	0,31	0,10	1,89	0,63	Yes

Flange 1: This flange is permit movement due to thermal expansion. But this thermal expansion is not a problem in today's products. The installation of the manifold is probably being difficult when there are four separated flanges. Therefore this flange is not go any further.

Flange 2: This flange has a well-known design and is permit an easy installation with few parts. The mounting of the pipes may be difficult when the pipes must be slipped through the flange before end shaping. However this flange is subject for further construction.

Flange 3: This flange is permit movement due to thermal expansion as flange 1. The work up for this flange is probably be unnecessary, when the thermal expansion is not a big problem. The flange may also be a little bit difficult to install when the flange is not stiff. The flange is not go any further.

2.5 Presentation of Aimed Concepts

The aimed concepts are based on well-known techniques considering pipe forming and flange design. This fact makes any calculations of end shaping the pipes and punching the flanges unnecessary in this phase. Two different types of end shaped pipes are presented with two different types of flanges. The solutions can be combined and each of the end shaped pipes can be used in both types of flange.

The Pipe

To fulfill the demands and wishes the solution of the pipe has to be simple and fast to manufacture. As few parts as possible is of course also preferred.

Solution 4/Solution 5

The first solution to present is solution 4/solution 5 see Figure 12

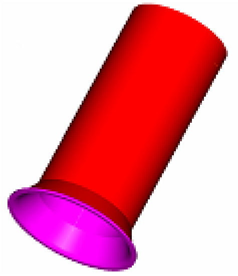


Figure 12: Solution 4/Solution 5

For stable pipe mounting the hole of the flange is formed as a cone, when end shaping the pipe same cone shape is aimed at. This makes the contact area between pipe and flange large; this hopefully secures the stability of the whole manifold.

The Figure 13 shows a large sealing area between the pipe and the engine which isn't needed to be as large. Earlier studies have shown that a circular sealing area of 1-2 mm is enough. A smaller sealing area doesn't need as big end shaping which is easier to manufacture. This solution although demands a rather big end shaping of the pipes because of the cone formed flange [2].

Solution 6

The simplicity benefits this solution. The pipe has only one end shape which is easy to perform in one step, see Figure 13 The flange connection is not be as strong as solution 4/5 due to the design of the flange (without a cone shape).

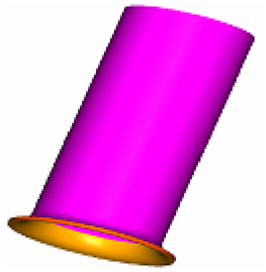


Figure 13: Solution 6

A 90 degrees end shaping is impossible to perform so a radius is inevitable on the pipe edge. Material properties define how sharp the end shape can be done without material failure. End shapes looking similar to the figure 12 above can be seen in connections between pipes and mufflers on usual car exhaust systems. The flange can be made with a heel just under the end shaping of the pipe, see Figure 14. The heel should make sure that the sealing area gets maximum pressure from the flange when it's mounted on the engine [1].

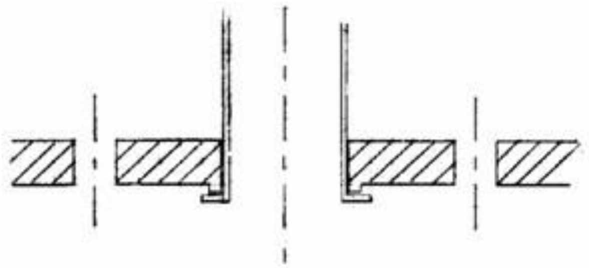


Figure 14: Sealing

The Flange

The new ideas of how to solve the design of the flange depend on maximum pressure on the pipe end. The present solution with welded pipes in the flange has an even pressure over the whole flange. The contact area between engine and flange is much bigger than the new solution. Due to this the temperature of the flange is significantly higher. The temperature rise can result in a demand for higher quality materials in the flange.

Flange 2

This flange is used in present solution and is made in one piece, see figure 15. If this type of flange is to be used in the new weld less solution it must be put into place before the end shaping of the pipes can be done. This fact demands considerably more of the end shaping machine. The flange is simply designed, technically well known and can easily be punched. The contact pressure on the pipes benefits from the stiffness of this type of flange. The Stability aspect is a big advantage for this flange [1].

Figure 15: One Piece Flange

Material

The manifold is one of the most important parts in the exhaust system of combustion engines. It acts on performances of the engine so it has to be developed and improved in its conception. The current welded manifolds are composed of three or four main parts that are the two flanges (front and rear), the pipes and sometimes the gasket that avoid leaks.

In this chapter a look for the material selection for the different parts of the manifold is take place. First a summarize of the different criterions and characteristics the parts are to stand be done. Then we are look at characteristics of different kinds of materials and alloys to choose the more suitable in the last part.

It is assumed that the flanges are not really the main purpose of that study because it is not the weakest part neither the more technical part of the manifold. Focus is on the pipes and on the gasket in a minor proportion.

Austenitic stainless steels have an excellent ductility, formability, and corrosion resistance. Strength is obtained by extensive solid solution strengthening, and the austenitic stainless steels may be cold worked to higher strengths than the ferritic stainless steels.

Furthermore, the austenitic stainless steels are not ferromagnetic. Unfortunately, the high nickel and chromium contents make the alloys expensive [8] [9]. See Table 3.

Table 3: Material Properties

Sr. No	Material Name	Young's Modulus	Poisson's Ratio	Density (×1000
1	Austenitic stainless steel	193	0.27-0.30	8

3. FINITE ELEMENT ANALYSIS

FEA is a powerful tool for improving durability performance of exhaust components, helps to explore many possible design options, reduces product development time and cost. Most cracks in durability testing originate in notches, welds or spot welds and joints. In order to achieve optimum design, virtual analytical FEA experiments are performed.

3.1 FE Model Development

The exhaust system components such as manifold flange, front pipe are made of stainless steel of various grades such as SS316, 316L and 304. The connections between flange and pipes are made similar to solution.5 see Figure 6. 1e. CAD model was checked properly for geometry clean up, mid surface extraction FE model has been developed by using pre-processing software CATIAV5. See Figure 16.

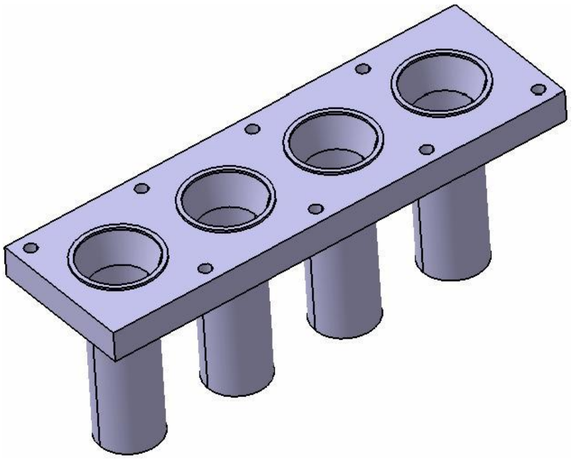


Figure 16: CAD Model of Solution 5

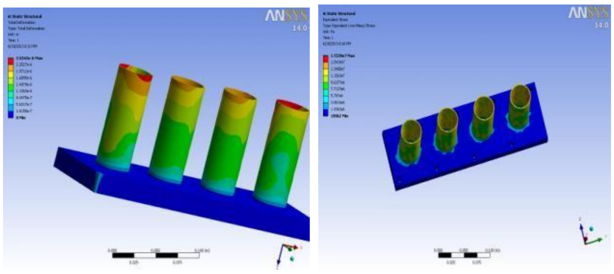
3.2 Static Analysis

In Static analysis, load is applied in normal (to the whole exhaust system pipe with the known boundary condition. The forces are to be determined along with deflection and Von-mises stresses for the applied load. The area of interest from the above analysis is that equal distribution of forces because of its pipe [10].

The Von-mises stresses, deflections are checked for its allowable limit and also forces. Here Ansys is used to apply materials, properties, loads and boundary condition.

Optimized solutions are used for static analysis in which we are finding deformation and maximum stress occurring in exhaust pipe.

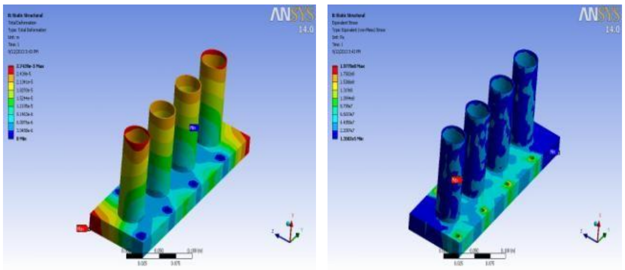
Solution 4, Flange 2



a.Deformation Plot b.Von Mises Stress Plot

Figure 17: Static Analysis of Solution 4 with Flange 2

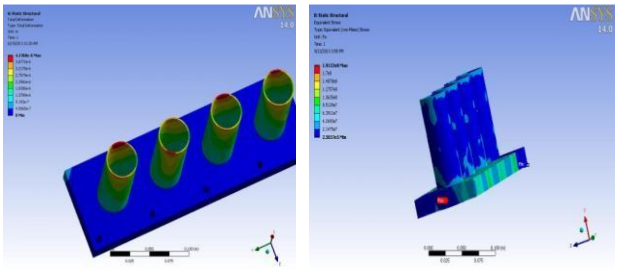
Solution 5, Flange 2



a. Deformation Plot b. Von Mises Stress Plot

Figure 18: Static Analysis of Solution 5 with Flange 2

Solution 6, Flange 2



a.Deformation Plot b. Von Mises Stress Plot

Figure 19: Static Analysis of Solution 6 with Flange 2

From Figure 17, 18 and 19 following table 4 of Von Mises Stress and Deformation of exhaust system by FEA.

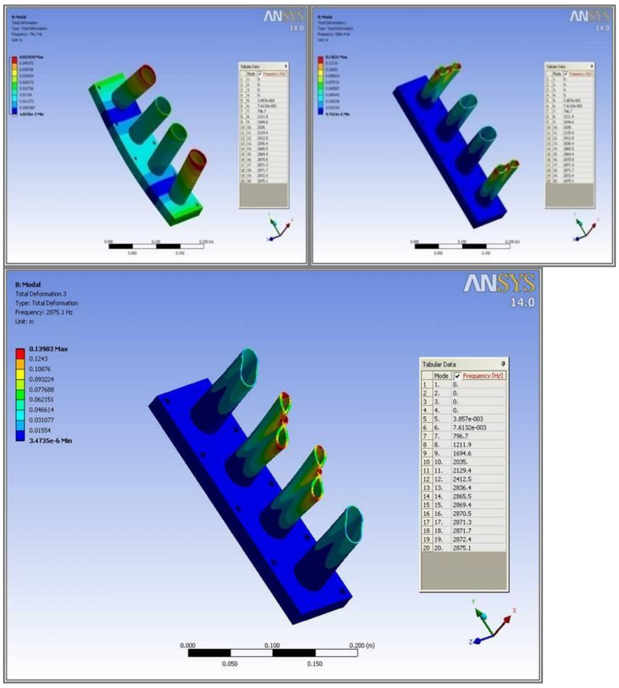
Table 4: Von-Mises Stress and Deformation of Exhaust System by FEA

Solution	Stress(MPA)	Deformation(mm)
4	173.39	0.0253
5	179.79	0.0274
6	191.22	0.0413

3.3 Model Analysis

Exhaust System Fitting Finite Element Analysis by Using Ansys: Considering 20 mode frequency

Solution 4, Flange 2, Mod-7, 15, 20



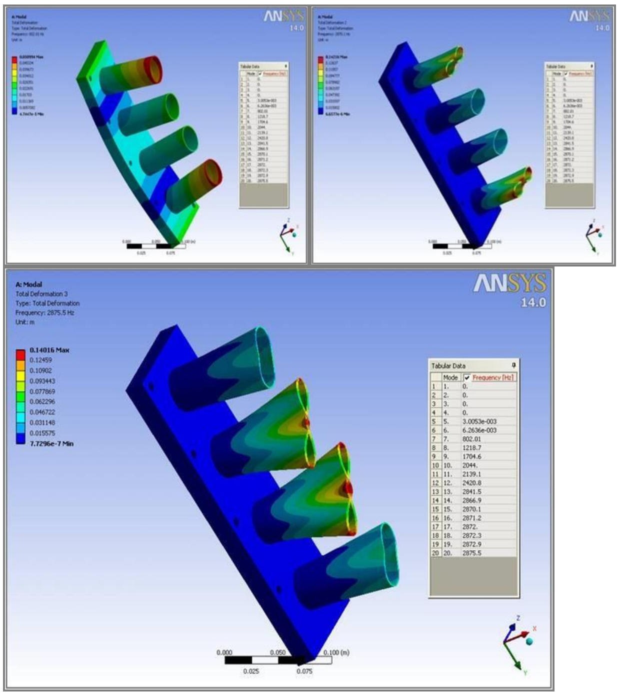
B: Modal
Total Deformation 3
Type: Total Deformation
Frequency: 2875.1 Hz
Unit: m

Tabular Data

	Mode	Frequency [Hz]
1	1.	0.
2	2.	0.
3	3.	0.
4	4.	0.
5	5.	3.857e-003
6	6.	7.6132e-003
7	7.	796.7
8	8.	1211.9
9	9.	1694.6
10	10.	2035.
11	11.	2129.4
12	12.	2412.5
13	13.	2836.4
14	14.	2865.5
15	15.	2869.4
16	16.	2870.5
17	17.	2871.3
18	18.	2871.7
19	19.	2872.4
20	20.	2875.1

Figure 20: Model Analysis of Solution 4 with Flange 2

Solution 5, Flange 2, Mod-7, 15, 20



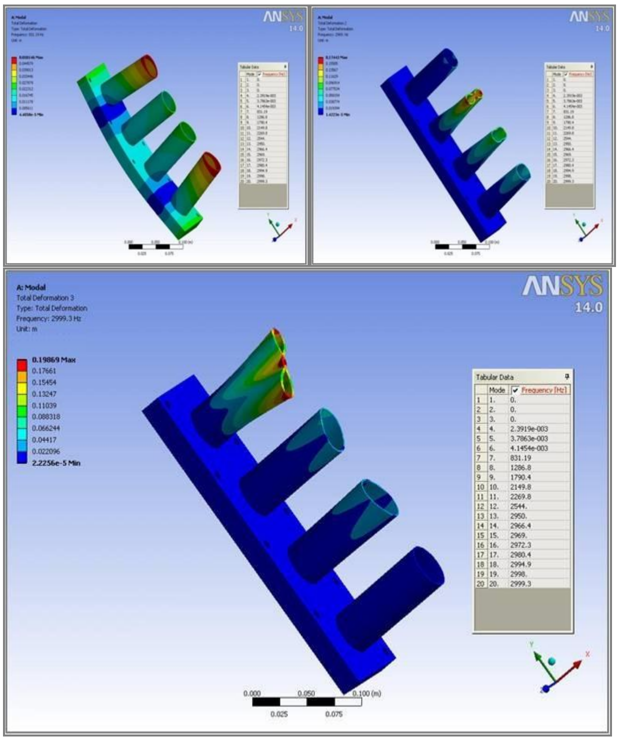
A: Modal
Total Deformation 3
Type: Total Deformation
Frequency: 2875.5 Hz
Unit: m

Tabular Data

	Mode	Frequency [Hz]
1	1.	0.
2	2.	0.
3	3.	0.
4	4.	0.
5	5.	3.0053e-003
6	6.	6.2636e-003
7	7.	802.01
8	8.	1218.7
9	9.	1704.6
10	10.	2044.
11	11.	2139.1
12	12.	2420.8
13	13.	2841.5
14	14.	2866.9
15	15.	2870.1
16	16.	2871.2
17	17.	2872.
18	18.	2872.3
19	19.	2872.9
20	20.	2875.5

Figure 21: Model Analysis of Solution 5 with Flange 2

Solution 6, Flange 2, Mod-7, 15, 20



A: Modal
Total Deformation 3
Type: Total Deformation
Frequency: 2999.3 Hz
Unit: m

Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	0.
2	2.	0.
3	3.	0.
4	4.	2.3919e-003
5	5.	3.7863e-003
6	6.	4.1454e-003
7	7.	831.19
8	8.	1286.8
9	9.	1790.4
10	10.	2149.8
11	11.	2269.8
12	12.	2544.
13	13.	2950.
14	14.	2966.4
15	15.	2969.
16	16.	2972.3
17	17.	2980.4
18	18.	2994.9
19	19.	2998.
20	20.	2999.3

Figure 22: Model Analysis of Solution 6 with Flange 2

4. EXPERIMENTATION OF EXHAUST SYSTEM COMPONENT

Manufactured exhaust system component is selected for the experiment. For free analysis the component is hanged by using string. Accelerometer is mounted on flange end by general observation. Ensured the FFT connections for the ready signal. Impact hammer is used for manually excite the structure so that it produce signals. These signals excite the system with varying amplitudes & phases, averages are then collected. The following figure shows the experimental setup. The setup is designed in order to get natural frequency at free -free vibrations. The current setup has negligible structural vibrations.

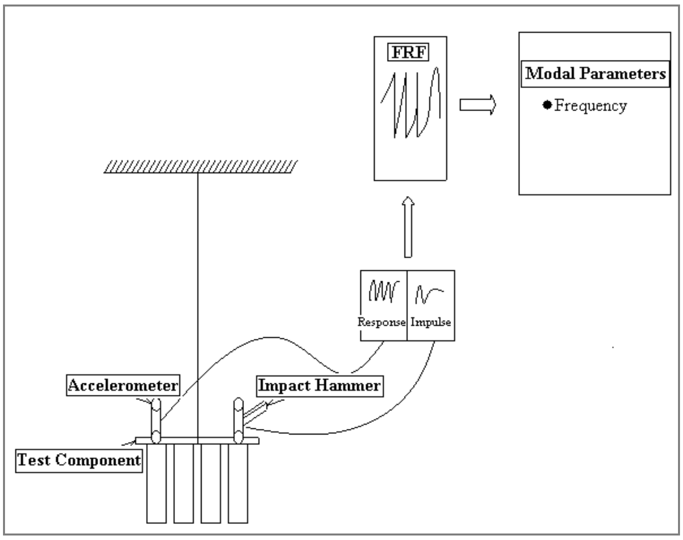


Figure 23: Schematic Diagram of Experimental Setup

Figure 24: Actual testing photo-1

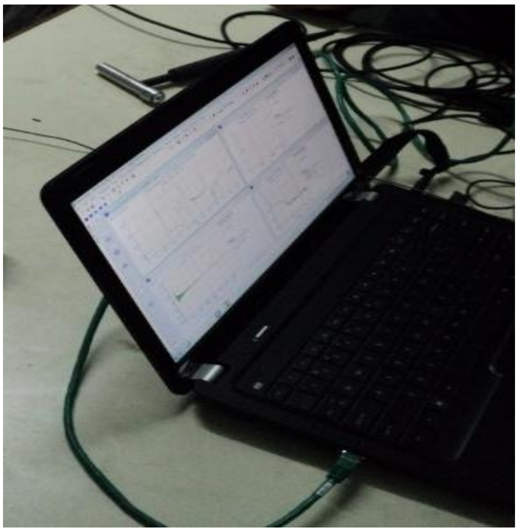


Figure 25: Actual testing photo-2

5. RESULTS AND DISCUSSIONS

5.1 Stress Analysis Result & Discussions

- Exhaust system design is important for exhaust attribute performance. Ideally, the system should be designed as a straight exhaust system, which is lower cost, less weight, less back pressure, power loss and better NVH performance.
- From Static analysis, it has been noted that equal distribution of forces on pipe front and rear occurred which is our area of interest for the applied load in normal direction. The maximum Von-mises stresses and deformations are occurred in optimized solutions are as shown in Table 4.
- By graphical representation see below Figure 26 and figure 27. We can made decision in solution 4 for exhaust system fitting-weldless induces less stress and deformation compare to other optimised solution i.e. solution 5 and solution 6.

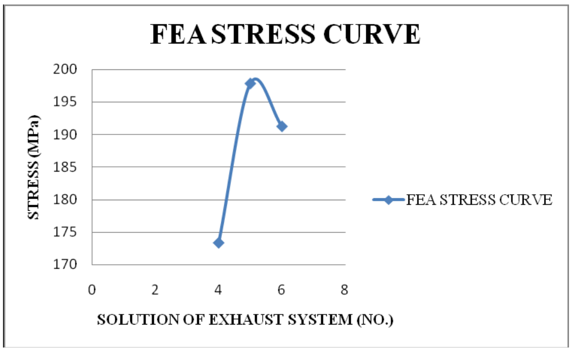


Figure 26: Stress vs Solution

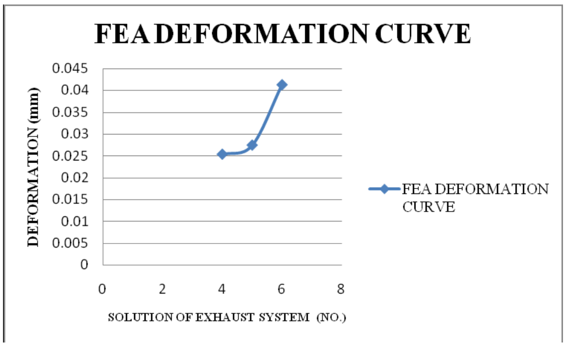


Figure 27: Deformation vs Solution

5.2 Model Analysis Result & Discussions

Exhaust system modes are critical for exhaust dynamic analysis. Normal mode analysis should be performed to make sure that the frequencies of exhaust system does not line up with power train. Engine rated speed = 6000 rpm

$$\text{Natural Frequency} = \frac{\text{Max.Engine rpm} * \text{Number of cylinder}}{120}$$

Natural Frequency = 4000/60* 4/2= 133.33Hz

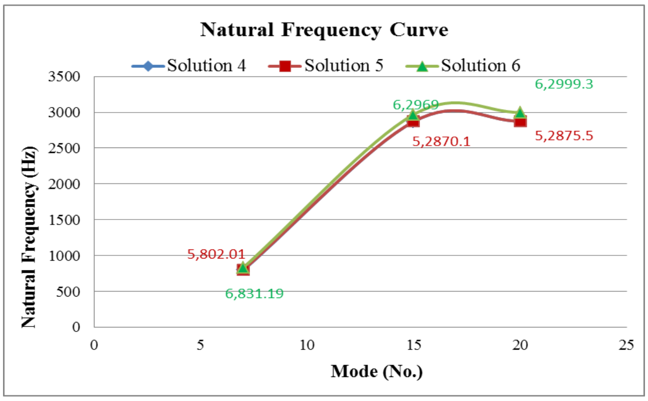


Figure 28: Natural Frequency (Hz) Vs Mode (No.)

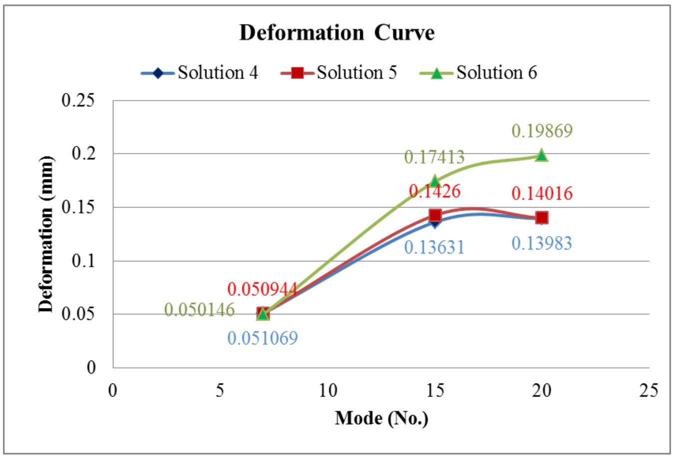


Figure 29: Deformations (mm) Vs Mode (No.)

Table 5 Comparison of the Natural Frequencies (Modal Analysis)

	Natural Frequency (Hz)		
	Mode 7	Mode 15	Mode 20
Solution 4	796.6	2869.4	2875.1
Solution 5	802.01	2870.1	2875.5
Solution 6	831.19	2969.0	2999.3

Table 6 Comparison of the Deformation (Modal Analysis)

	Deformation (mm)		
	Mode 7	Mode 15	Mode 20
Solution 4	0.051069	0.13631	0.13983
Solution 5	0.050944	0.1426	0.14016
Solution 6	0.050146	0.17413	0.19869

From above graphs & tables, it is found that Solution 5 is feasible solution. So results of solution 5 from modal analysis are taken for the experimental validation on FFT.

5.3 Experimental Outcomes

Experimental work is carried out on FFT to find out natural frequency of exhaust component. These results are used to compare with outcomes of FEA.

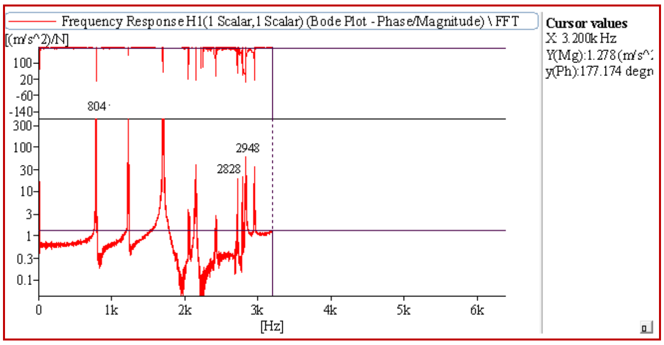


Figure 30: Frequency response

From frequency response curve, following results are found

Table 7 Experimental Frequency

Mode 7	Mode 15	Mode 20
804 Hz	2828Hz	2948 Hz

5.4 Validation of Experimental results with FEA

Following table validate results for solution 5 –

Table 8 Percentage frequency difference

Mode No.	Experimental Frequency (Hz)	FEA Frequency (Hz)	Frequency difference (%)
Mode 7	804	802	0.5
Mode 15	2828	2870	1.5
Mode 20	2948	2876	2.5

6. CONCLUSIONS

A further development of the three solutions is necessary to assure their total fulfilment of the criterions and technical function. There are strong believes that the solutions are perform the task perfectly. In static analysis it has been seen that the concept that chosen for experimental is safe.

For assembled system the agreement between theoretical and experimental natural frequencies was within approximately 2.5% for first 20 modes. This type of finite element model is therefore probably sufficient also for most others exhaust system of similar type.

To achieve reliable models both theoretical and experimental modal analysis should be performed so that finite element and test model can be compared and successfully improved. Free-free boundary condition is recommended for this model. At an early stage of product development process the boundary conditions that exhaust system will have under operation are not always known. By using free-free boundary condition it is still possible to develop FE models of exhaust system or part of it, which corresponds well with measurements.

The result includes the systematic study of straight exhaust system with the known engine conditions, loads and boundary conditions. It will give the general guidelines such as modal analysis is to be performed in the initial stage of the project by considering the boundary condition only at the manifold flange where it is connected to engine and checked for nodal and anti-nodal points from mode shape animation. The nodal points are to be considered as preliminary hanger locations for the exhaust system. Also same modal analysis is used to check for resonance by comparing modal frequency with engine frequency from rated speed. It has been observed from Modal analysis that modal frequency has been compared with engine excitation frequency and resonance won't occur.

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