

# Flow Induced Vibration Integrated Design of Exhaust Manifold System for Dual Valve Engine

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**ABSTRACT:** Exhaust piping design includes the consideration of exhaust gas flow pressure, gas temperature and the vibration caused by the turbulent flow in the pipe. Since the exhaust piping system is mounted with vehicle chassis it will transfer the flow induced vibration to the other parts of the vehicle and cause relative loading, which increase stress in parts and reduce the life time of the same. Also the manufacturing of exhaust piping is a complex process; it should be designed to meet all the necessary critical factors particularly to overcome flow induced vibration. Flow induced vibration causes failure to the exhaust piping system as well as increase loading for the other parts of the vehicle. Since the manufacturing also complex and critical for exhaust piping system it should be designed to meet all the critical function requirements. It is manufactured through hydro forming method. Many literature reviews provide the importance of the flow induced vibration in designs involving flow of fluid, also it emphasis the necessity of integrating the flow induced vibration in the design phase itself. So it is potentially a worthy research work to understand and detail the process of flow induced vibration analysis integrated design of exhaust piping system. This research work proposes design of exhaust manifold system for single cylinder engine, which is integrated with analysis systems (FEA) to find out the fundamental or resonance frequencies, which will serve as the critical point of design which concerns with flow induced vibration. After arriving principle geometric parameters the design is evaluated for actual working condition using FEA/CFD tools, the results of the analysis suggests the improvement required for the design if the system attains excitation through flow induced vibration.

**KEYWORDS:** vibration, exhausts gas flow.

## I. LITERATURE REVIEW

### **Experimental Investigation of Flow-induced Vibration Interference between Two Circular Cylinders.**

This paper presents experimental results concerning flow-induced oscillations of circular cylinders arranged in tandem. The interference phenomenon on VIV is investigated by conducting experiments in which the upstream cylinder is maintained fixed and the downstream one is mounted on the elastic base. The results for an isolated cylinder are in accordance with other measurements found in the literature.

### **Flow-Induced Vibrations of a Rotating Cylinder**

The flow-induced vibrations of a circular cylinder free to oscillate in the cross-flow direction and subjected to a forced rotation about its axis, are analysed by means of two- and three-dimensional numerical simulations. The impact of the symmetry breaking caused by the forced rotation on the vortex-induced vibration (VIV) mechanisms is investigated for a Reynolds number equal to 100. The cylinder is found to oscillate freely up to a rotation rate (ratio between the cylinder surface and inflow velocities) close to 4. Under forced rotation, the vibration amplitude exhibits a bell-shaped evolution as a function of the reduced velocity (inverse of the oscillator natural frequency) and reaches 1:9 diameters.

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## Numerical Investigation of a Laminar Pulsating Flow in a Rectangular Duct

A pulsating laminar flow of a viscous, incompressible liquid in a rectangular duct has been studied. The motion is induced under an imposed pulsating pressure difference. The problem is solved numerically. Different flow regimes are characterized by a non-dimensional parameter based on the frequency ( $\nu$ ) of the imposed pressure gradient oscillations and the width of the duct ( $h$ ).

## II. PROBLEM DESCRIPTION

Flow induced vibration causes failure to the exhaust piping system as well as increase loading for the other parts of the vehicle.

Since the manufacturing also complex and critical for exhaust piping system it should be designed to meet all the critical function requirements. It is manufactured through hydro forming method.

Many literature reviews provide the importance of the flow induced vibration in designs involving flow of fluid, also it emphasis the necessity of integrating the flow induced vibration in the design phase itself.

So it is potentially a worthy research work to understand and detail the process of flow induced vibration analysis integrated design of exhaust piping system.

## PROPOSED SOLUTION

This research work proposes design of exhaust manifold system for dual valve engine, which is integrated with Finite Element Analysis (FEA) to find out the fundamental or resonance frequencies, which will serve as the critical point of design which concerns with flow induced vibration.

After arriving principle geometric parameters the design is evaluated for actual working condition using FEA/CFD tools, the results of the analysis suggests the improvement required for the design if the system attains excitation through flow induced vibration

## III. METHODOLOGY

<b>Design of Exhaust Piping System</b>
<b>CAD modelling and Finding Critical Frequencies</b>
<b>Flow Simulation (CFD)</b>
<b>Flow Induced Vibration Analysis</b>
<b>Design Evaluation and Enhancement</b>
<b>Result and Discussion</b>
<b>Reporting</b>

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## IV. NEW DESIGN AND FIV SIMULATION OF EXHAUST PIPE

### Exhaust Pipe Configuration Model and Details

The following figure shows the required exhaust pipe configuration in 3D space as spine of the exhaust pipe where the cross section runs to form the required model.



Spine 3d Sketch

The following coordinate data were used to develop the spine sketch which is used to form the exhaust pipe model

X	Y	Z	Section Dia. (mm)
0	300	0	75.00
0	0	-60	75.00
50	0	-60	80.00
100	0	-60	80.00
150	0	-60	80.00
200	0	-60	85.00
300	0	-60	85.00
500	0	-60	150.00
750	0	-60	150.00
1000	0	-60	150.00

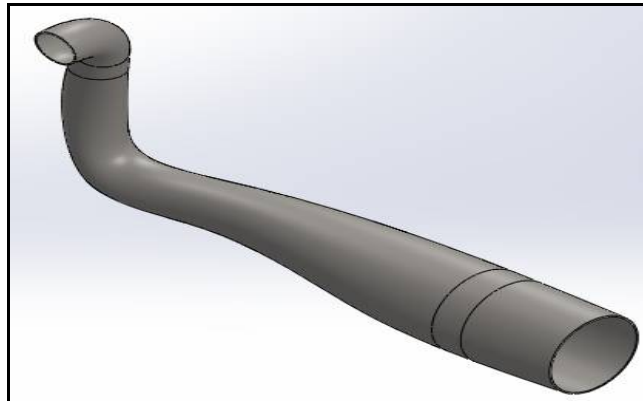
Pipe configuration Dimension

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The following figure shows the exhaust pipe model, the end to end length is 1000 mm with ground clearance to exhaust is 300 mm, the pipe is 3D configured through coordinate points and corresponding circular cross section with thickness of 2.5 mm.



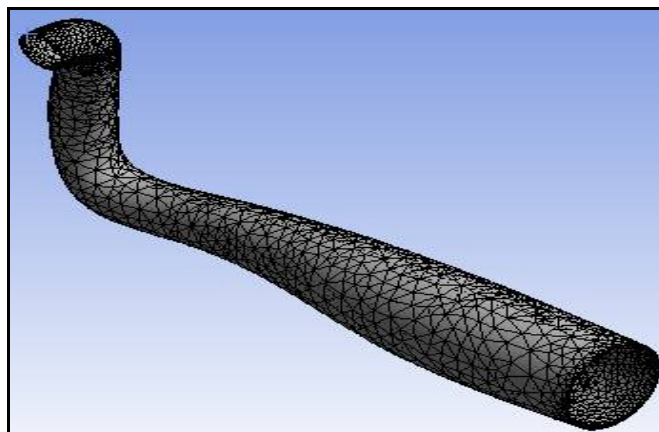
Exhaust Pipe Model

Property	Value	Units
Elastic Modulus in X	190000	N/mm <sup>2</sup>
Poisson's Ratio in XY	0.26	N/A
Shear Modulus in XY	78000	N/mm <sup>2</sup>
Mass Density	7300	Kg/m <sup>3</sup>
Tensile strength in X	448.08	N/mm <sup>2</sup>
Yield Strength	241.28	N/mm <sup>2</sup>
Thermal Expansion Coefficient in X	1.5e-005	/K
Thermal conductivity in X	38	W/(m-K)

Steel Alloy 6.3 – Cast Properties (Pipe Material)

### Modal Analysis

This section provides modal (Resonance Frequency) analysis of the exhaust pipe model, which will behave as datum for further flow induced vibration analysis. The following figure shows the meshed model of the pipe.



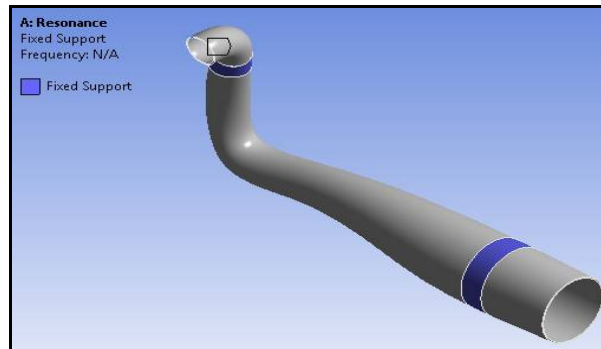
Meshed Model

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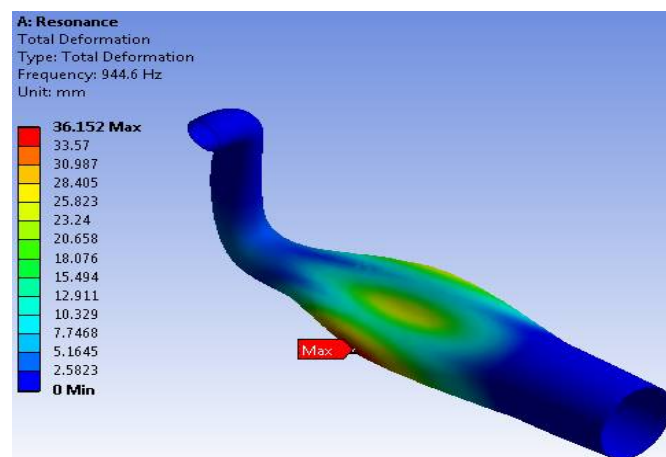
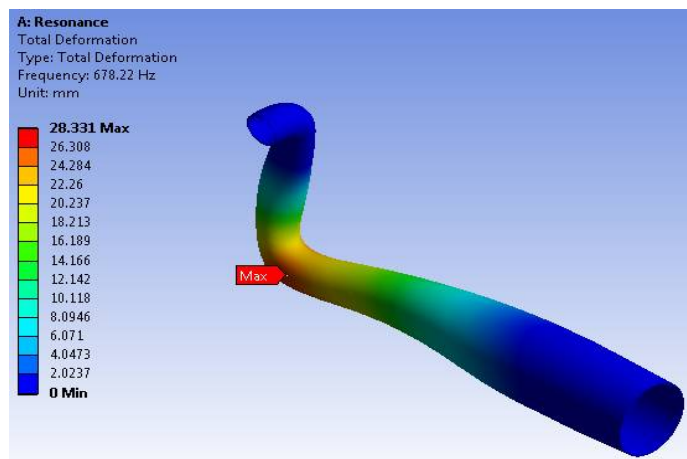
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The modal contains 41271 nodes and 19632 elements which are made up of Solid 138 elements (3D Tetra). The following figure shows the boundary condition for the analysis.



Boundary Condition (Fixed DOF)

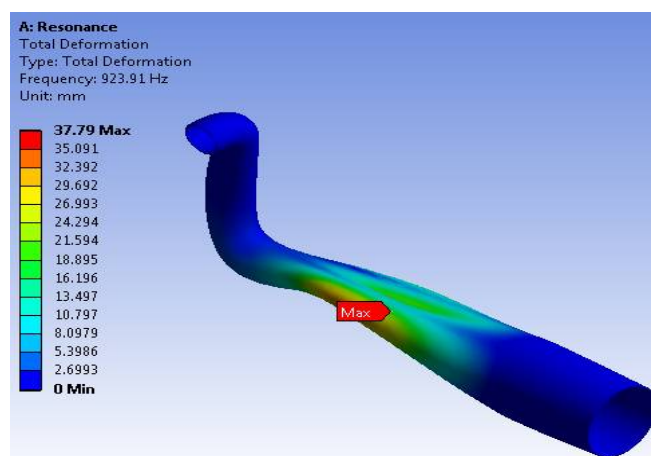
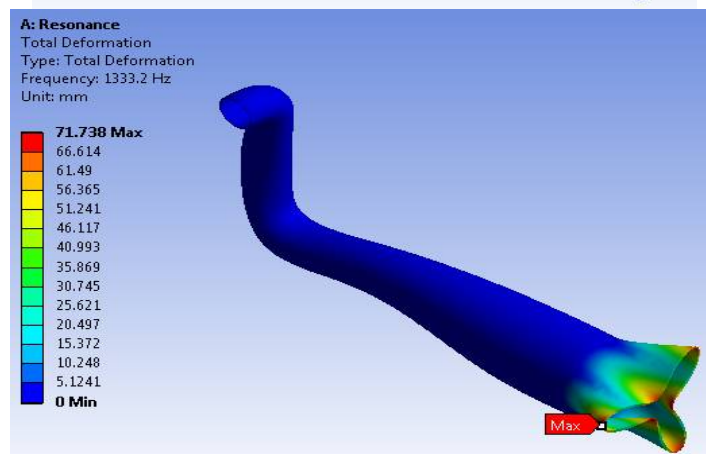
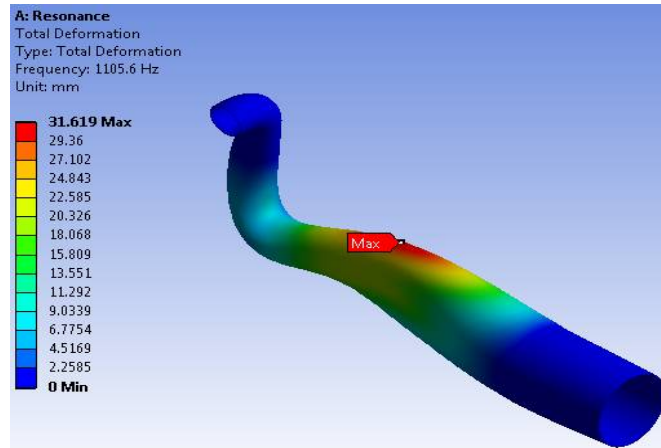
The following figure shows the modal analysis results in terms of resonance frequencies, these are critical frequencies where the forced/harmonic/random vibrations should not reach these points of critical/resonance frequency.



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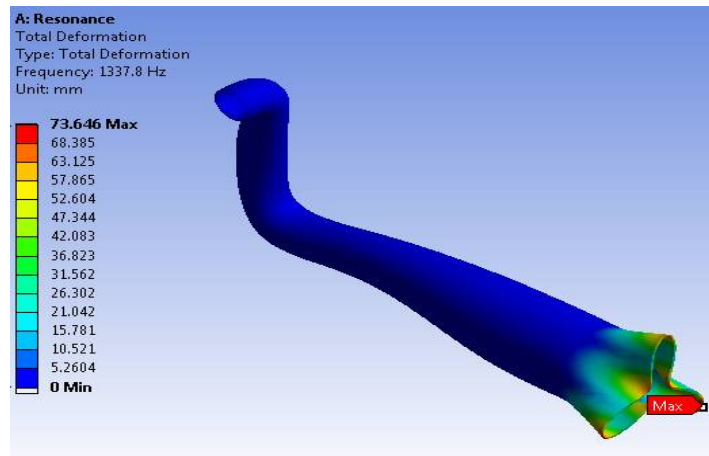
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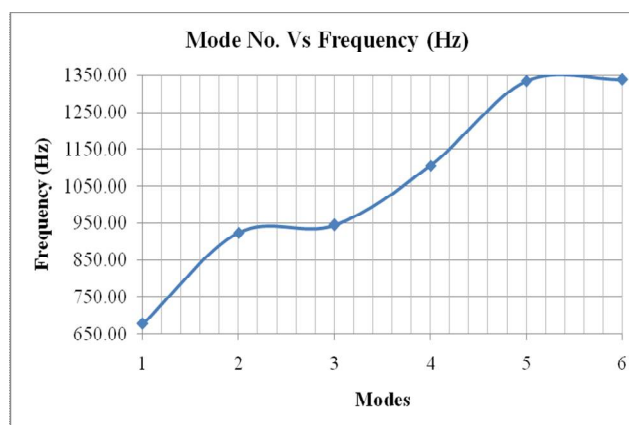
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Modal Analysis Results without Flow Effect  
(1 – 6 Modes)

The following table provides the critical / resonance frequency results.  
Mode Vs Frequency

Mode No.	Frequency (Hz)
1	678.22
2	923.91
3	944.60
4	1105.60
5	1333.20
6	1337.80



Mode Vs Frequency

The resonance frequency is increasing for every mode, which are horizontal and vertical bending, torsional bending, axial stretch bending, etc, Solver will impose possible support model to generate the Eigen value (Frequency).

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### 6.3 Flow Analysis

The flow analysis delivers pressure and velocity on the pipe, ANSYS-Fluent is a commercial CFD used worldwide and it is used here to analysis the exhaust gas flow in the exhaust pipe. The inlet mass flow is arrived from engine dimensions, the Engine Specification and Mass Flow Calculation are as follows

Max. Engine Output	=19.8 @ 5250 Rpm
Max. Torque	=28 Nm @ 4000Rpm
Capacity	=351.25 cc
Bore	=70 mm
Stroke	=91.2 mm
Volume Flow Rate / Cylinder / Cycle	
=Per Engine Cc (351.15)	
=Bore Area X Stroke Length m <sup>3</sup>	
=0.00384845 x 0.0912	
= 351 cc	

For every 2 RPM of the engine delivers one exhaust so,

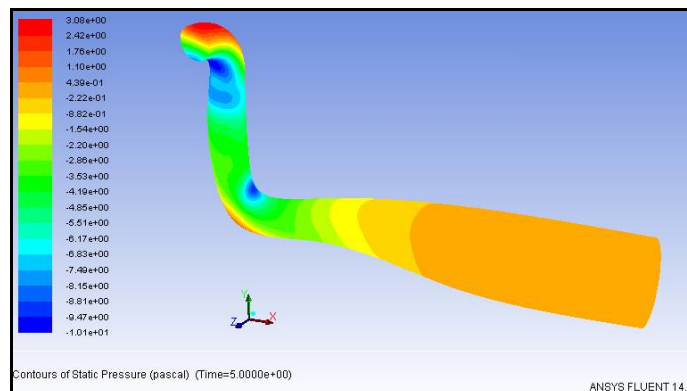
At Max. Engine Output (Per Cylinder)	
= Cc/Cylinder * 4500 / 2	
= (351.25 * 4500)/2	
= 790087.5 Cc / Cylinder	
= 0.79 m <sup>3</sup> /min	
= 0.0131 m <sup>3</sup> /s	

Mass Flow Rate/Cyl= 0.016113 Kg/s

The following are the Flow Boundary Conditions

Inlet	=Mass Flow Rate	=0.016113 Kg/ s
Outlet	=Environment Pressure	=101325 pa
Inlet Gas Temperature	=	=250°C

The temperature of the exhaust gas is depends on the combustion process, for CI engine the combustion temperature will be around 500 - 600°C, the outlet temperature will be around 170 - 250°C, as the gas move out the pipe the temperature gets down to 100 and less, this is at the full throttle, depends upon the ambient temperature the outlet temperature will be varied, the grade and air-fuel mixture also changes the temperature of the exhaust gas. Since the material is high temperature alloy steel, it can withstand more than 900°C easily. In simulation the temperature is taken as 250°C. The following figures shows flow analysis results, these results then transferred to FIV analysis to verify against resonance frequencies. The effect of flow pressure is transferred to the exhaust pipe wall which continuously experiences the pressure and temperature of the exhaust gas, the stress induced in the pipe is the effect of the both above. So, it is recommended to have a high temperature steel and the same is taken for the analysis.



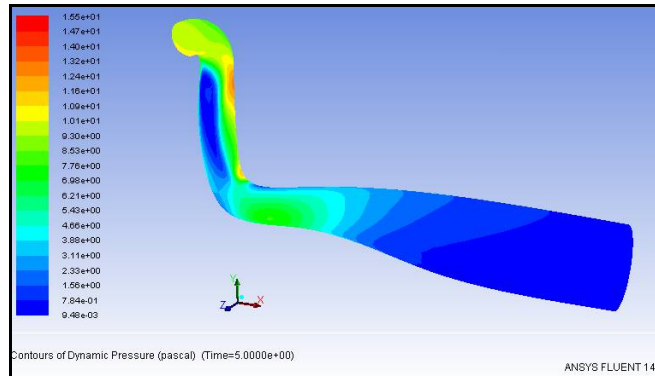
Static Pressure plot



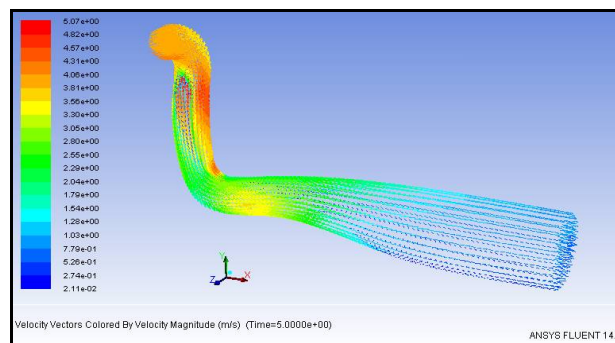
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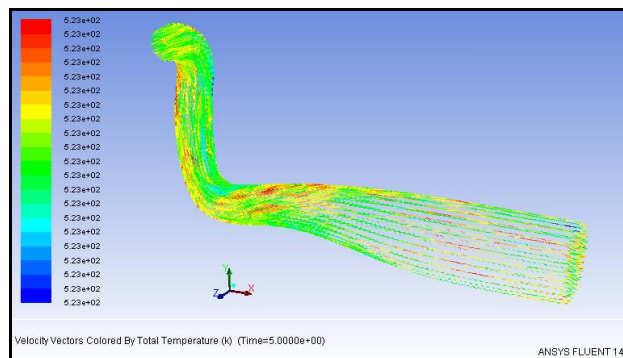
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Dynamic Pressure Plot



Velocity Plot



Temperature Plot

## Flow Induced Vibration Analysis

The FIV is a major part in design of flow components, in this case hot exhaust gas flows out at a higher velocity and creates thermal and mechanical stress through pressure on the exhaust pipe walls, basic design covers pressure based design with consideration on temperature only, but the flow creates a vibration which is important and should be identified in the design stage itself to avoid failure due to flow induced vibration, this section provides the setup and results of the flow induced vibration of the exhaust pipe model. Ansys provides comprehensive coupling for performing multiple domain analysis, in this research work, flow analysis is coupled with structural to capture the hot gas pressure exerted on the walls and then transferred to modal analysis to find out flow induced frequency, which will be compared against excitation frequency to verify the design.

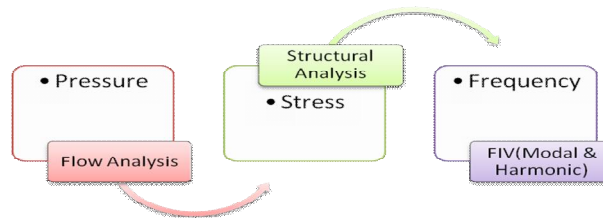
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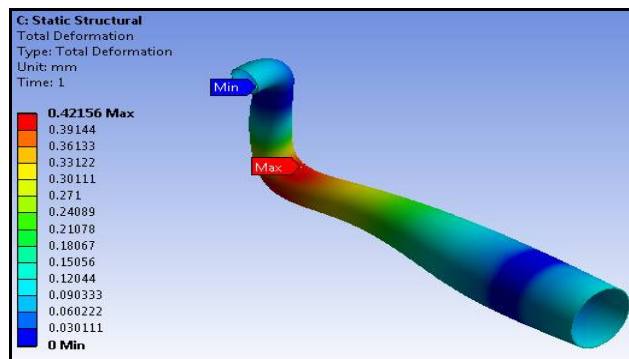
## Simulation Work Flow

The following figure shows the simulation work flow

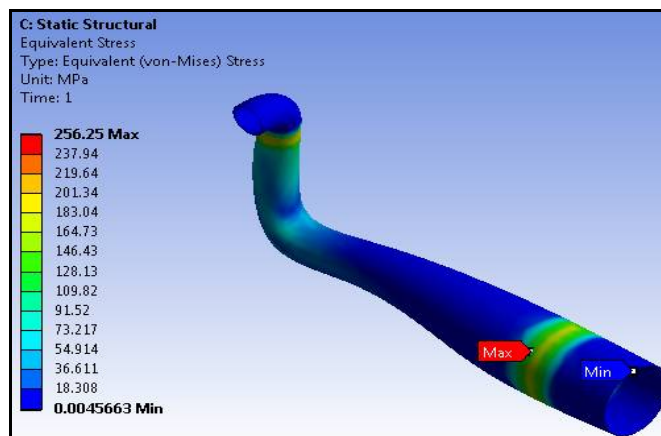


## Simulation Work flow

The coupled domain analysis scheme shows the flow simulation results in the form of pressure is transferred to structural model where the stress on the walls were found and transferred to Modal analysis to find out excitation frequency due to flow pressure. The results will be compared against the resonance frequency to ensure the safety of design due to flow induced vibration; if changes are required then the design is modified to proceed for further verification. This method eases out the verification of design due to FIV, where the existing method prefers finding out the dimensions of the exhaust system based on flow pressure and temperature only. The following figure shows the FIV results. The following figure shows the structural deformation and stress due to flow pressure in the exhaust pipe



Deformation



vonMises Stress

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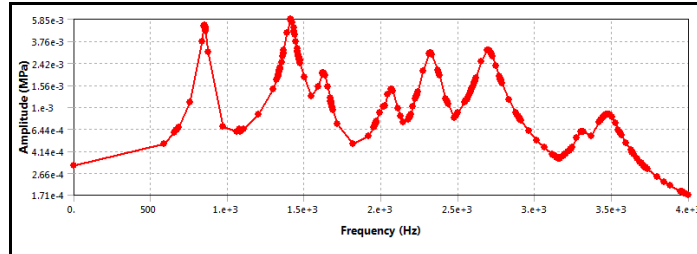
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The following table shows the flow induced vibration frequencies and natural frequencies of the exhaust pipe model, the FIV frequencies must not be coincide with the natural frequency to ensure the safety of the design, a 10% ceiling from natural frequency is best practice for safer design.

Mode No.	Resonance (Hz)	FIV(Hz)
1	678.22	666.07
2	923.91	846.95
3	944.60	854.51
4	1105.60	1082.4
5	1333.20	1327.2
6	1337.80	1341.5

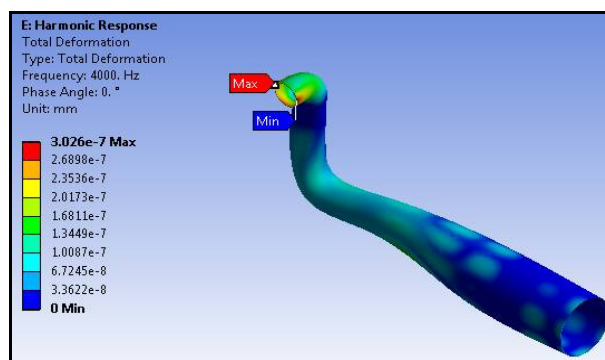
Natural Frequency Vs FIV

From the results the FIV ensures the non-coincidence of frequency, but it is necessary to verify with forced vibration frequencies through harmonic analysis and find out the frequency coincidences, it is presented in the following tables and figures.



Frequency Response under Flow Pressure

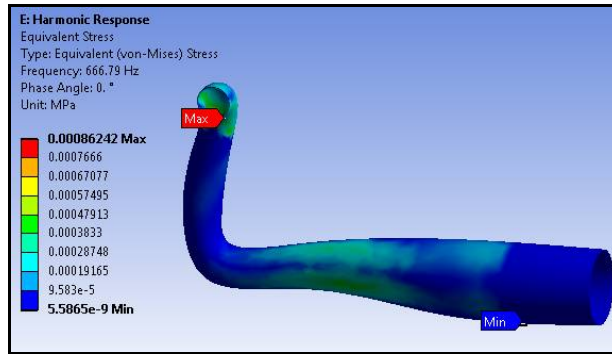
The figure show that the peak stress is happening at 1411.9 Hz and the value is 5.85e-3 Mega Pascal, which is very much lower than yield which ensures the safety of the exhaust pipe under flow pressure.



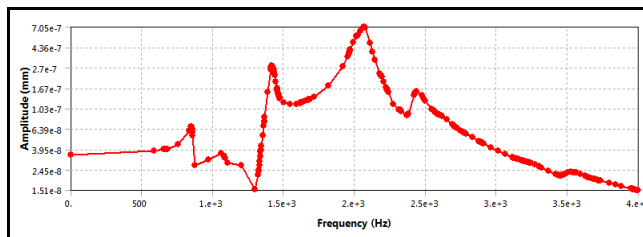
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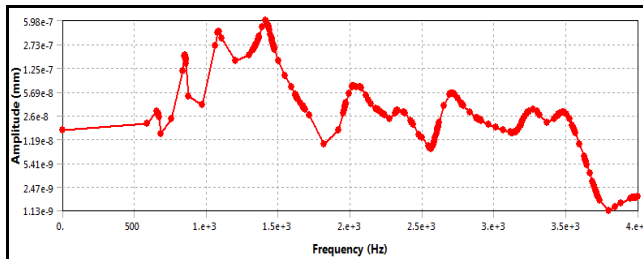
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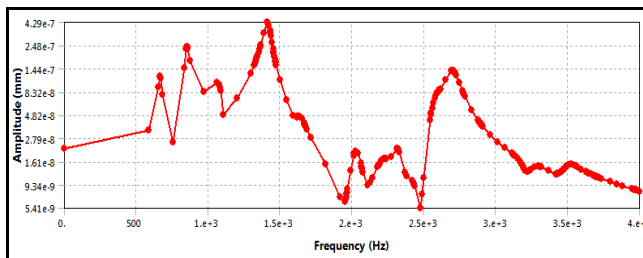
Deformation & vonMises Stress  
(Harmonic Response)



Deformation in X Direction



Deformation in Y Direction

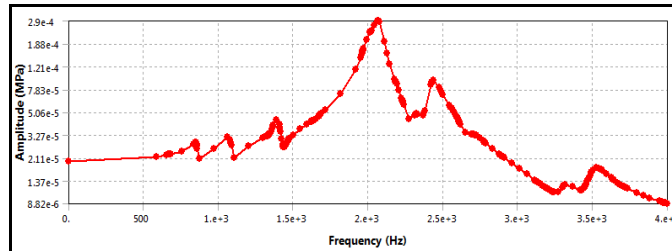


Deformation in Z Direction

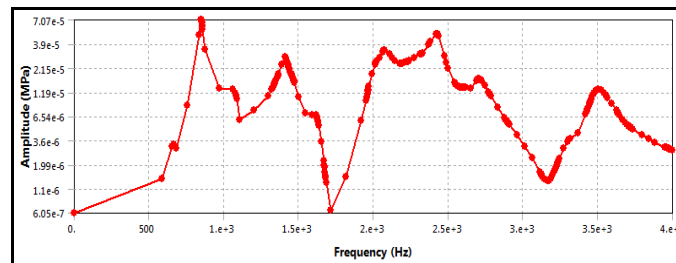
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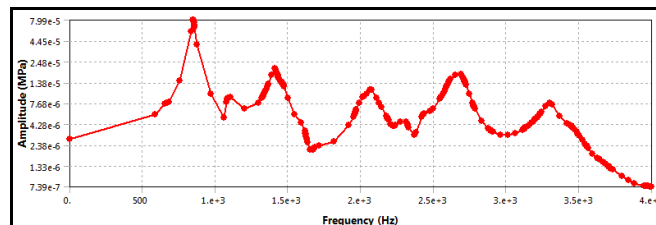
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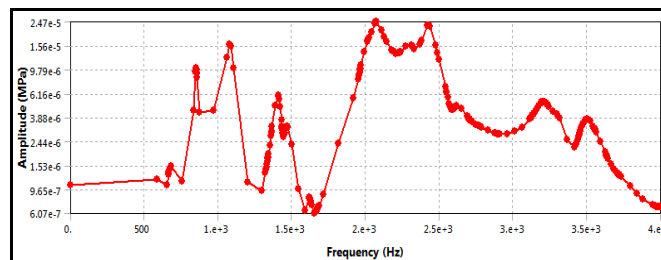
Normal Stress in X Direction



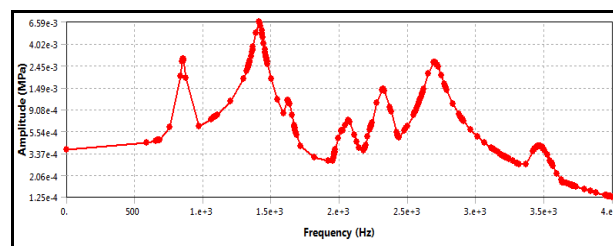
Normal Stress in Y Direction



Normal Stress in Z Direction



Shear in XY Plane

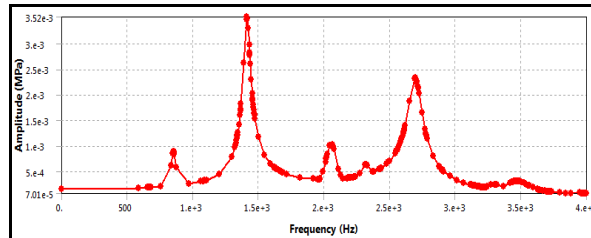


Shear in YZ Plane

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Shear in XZ Plane

The deformation in the model in all principle directions are very less, since the flow pressure is very low the induced normal stresses, shear stresses and vonMises stress are very low and well within the yield limit of the exhaust pipe and ensures the safety of the design.

Name	Value	Frequency (Hz)
Deformation – X	7.0541e-007 mm	2067.1
Deformation – Y	5.9787e-007 mm	1411.4
Deformation – Z	4.2918e-007 mm	1411.4
Normal Stress – X	2.9026e-004 Mpa	2067.1
Normal Stress – Y	7.0669e-005 MPa	849.39
Normal Stress – Z	7.9895e-005 MPa	849.39
Shear in XY	2.4739e-005 MPa	2073.8
Shear YZ	6.5906e-003 MPa	1411.4
Shear XZ	3.5199e-003 MPa	1412.5

## V. CONCLUSION & FURTHER PROCEEDINGS

Many literature reviews provide the importance of the flow induced vibration in designs involving flow of fluid, also it emphasizes the necessity of integrating the flow induced vibration in the design phase itself. So it is potentially a worthy research work to understand and detail the process of flow induced vibration analysis integrated design of exhaust piping system. This research work proposes design of exhaust manifold system for multi cylinder engine, which is integrated with analysis systems (FEA) to find out the fundamental or resonance frequencies, which will serve as the critical point of design which concerns with flow induced vibration.

The results show that the flow induced vibration frequencies are higher than the natural frequencies and the followed harmonic simulation also confirmed that the induced stress in all principle directions (X,Y,Z & Z) are well within the safe limit, the shear stress in all three planes also fall within safe limit. The vonMises also very minimal and ensures the design safety. An independent test was also conducted to identify the peak pressure resonance in harmonic and their results are presented in the appendix for further references. The project successfully concludes that the inclusion of flow induced vibration in exhaust pipe design enables the designed and manufactured to go ahead with their design in higher confidence, since the flow resonance is critical in operation which has no part in design, it is important to integrate flow induced vibration in the design stage itself to ensure the safety of the design in actual operating condition.

Further proceedings from this research can be moved to experimental investigation through measurement of vibration through data acquisition system, which can be digitalized through scientific computing tool and then taken for random vibration analysis, which details the flow effect in the design with deep insight.

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