International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 4, Issue 8, August 2015)

The Impact of Coupled Fluid Structural Interactive Analysis on Flow Uniformity of Catalytic Converter

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***Abstract*— Fluid structural interaction is a crucial factor in the design of exhaust manifold. Typically, validating the system without considering the effects of oscillatory interactions is time consuming and inconclusive when confronted with reality boundary conditions. Experience has shown that often the most significant source of error in flow analyses is associated within specified boundary conditions.**

Thus, the solution comes in unique way of using seamless integration of thermal and dynamic loads with specified boundary conditions and will convey computational results closer to the real scenario. As a consequence, velocity concentrated regions due to displacement are aggregated more in front face of substrate when coupled with dynamic loading, leading to fatigue. Failure originated using this approach is evidently discussed and compared with experimental results. The uniformity index generated by the coupled analyses proves to be critical in concerning the durability issues of hot end system.

***Keywords*— FSI, substrate, erosion, coupled analysis, FEA, CFD, thermal coupling, dynamic analysis, displacement, uniformity index.**

I. INTRODUCTION

Vibration levels are critical objective in automobile exhaust system design. Exhaust manifold mounted on the cylinder head of an engine produces certain vibrations causing disturbance in exhaust gas flow. It is therefore important for analyst to predict, describe and assess the flow changes due to vibrations on exhaust manifold during product development. Exhaust manifold also plays an important role in the performance of an engine system. Particularly, the efficiencies of emission and fuel consumption are closely related to exhaust manifold. The exhaust manifold is under dynamic loads produced by engine excitation, which could lead to non-uniform flow. Non-uniform flow causes uneven heat distribution in the catalyst. Thus, the catalyst heats up slower in zones with a lower flow velocity and as a result the light-off is delayed. The pollutants entering these zones pass the catalyst unconverted and the overall emission conversion efficiency is decreased. Significant contributions have been made by Julia Windmann, Steffen Tischer and co-authors [1 & 2].

There paper reveals unequivocally the negative influence of a velocity maldistribution in front face of the catalytic converter on conversion efficiency. Additional to the effect on emission conversion efficiency, non-uniform flow is also one of the important parameter that determines durability of catalytic converter internals such as catalyst and support mat.

Non-uniform exhaust gas flow also causes high pressure drop along the catalytic converter which can also be counted as one of the root cause to increase exhaust system backpressure that is definitely not beneficial for vehicle performance and fuel economy. Micheal G. Campbell and Edward P. Martin investigation on failure modes of catalyst pointed out mechanical durability of ceramic catalyst as the prime factor affecting total catalyst durability [3 & 4]. Failure modes include fragmentation of the catalyst, loosening of the catalyst from the shell and telescoping of catalyst layers. Also thermal stresses resulting from radial and axial temperature gradients as one cause of ceramic catalyst factures.

II. EXPERIMENTAL RESULTS

The substrate discussed in this paper failed in the engine test is shown in figure 1. It was a challenge for virtual validation group to simulate the failure and resolve the concern.

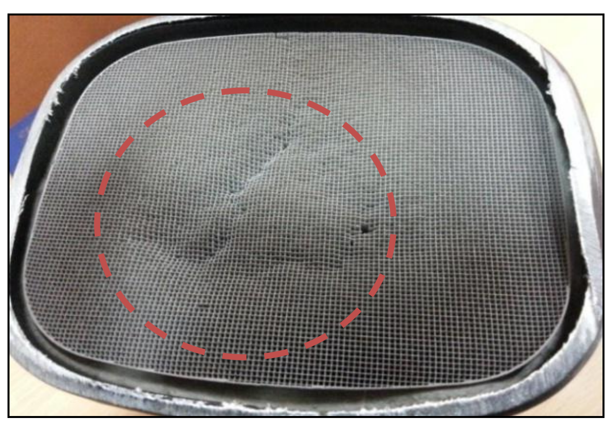

Figure 1.Erosion observed in front face of substrate

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At present, for uniformity analysis in CFD only the fluid region was taken into consideration, no structural constraints were incorporated. However, in real time both thermal as well as mechanical load will act on the solid region causing displacement and thermal deformation to catalytic converter. Exchange of codes is used which combines the thermal and structural boundary condition to analyze flow through displaced catalytic converter [5]. This simulating methodology can determine the fullest utilization of catalyst under actual loading condition. If uniformity divergence caused due to displacement is high then it will direct to non-uniform flow leading various tribulations to entire exhaust system.

III. Catalytic Converter Model

Computational model to solve for thermal flow field and associated dynamic thermal stress field is shown in figure 2 along with the material data of each component shown in table 1.

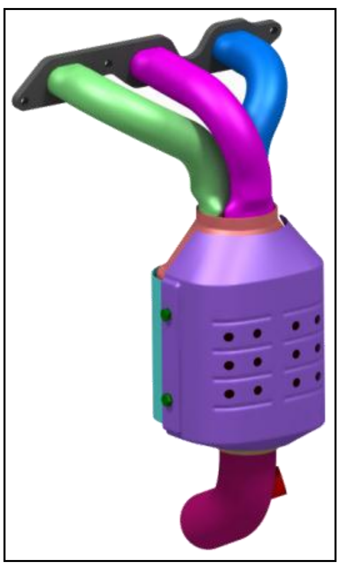

Figure 2. 3D CAD Model

TABLE I
Material Properties

S No	Component	Material
1	Inlet flange	Mild Steel
2	Mounting brackets lh & rh	
3	Weld nut (outlet flange)	
4	Runner	Stainless Steel
5	Inlet cone	
6	Converter shell	
7	Outlet cone	
8	Outlet pipe	
9	Outlet flange (sheet metal)	
11	Heat shield	
12	Shell bracket lh	
13	Shell bracket rh	
14	Heat shield bracket- front	

IV. Loads & Boundary Conditions

A. CFD

CFD geometry of the element is made as polyhedral mesh, with a refined prism layer mesh near the wall. Internal flow field are compressible Navier-Stokes equation, High Reynolds number k-ε turbulence model is used in the CFD model with standard wall functions for near-wall treatment. Constant density is used for solid region.

Table II
Cfd Boundary Conditions

Domain	Type	Value
Inlet	Mass Flow Rate Temp	100 kg/hr, 850°C
Outlet	Pressure Outlet	325 mbar
Cell Density	Ceramic	600/4
Dimension	Length*breadth*height	183.4x143.8x120 mm
Porosity	Porous Media	Porosity = 0.8136 $\alpha = 2.23\ kg/m^4$ $\beta = 1840.34\ kg/m^3\text{-}s$

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B. FEA

For FEA model, mesh is created using Hypermesh pre-processor. Inlet flange bolt holes, engine mounting bolt holes are constrained in all dof (Ux, Uy, Uz, Rx, Ry, Rz = 0). To avoid leak surface to surface contact has been defined between manifold outer flange face and engine block mounting face**.**

V. Coupling Methodology

The flow and temperature field is solved using Star CCM+ v9.04 (a CFD system) and resulting film local heat transfer coefficient and reference temperature is interpolated to the corresponding surface mesh generated for coupled dynamic analysis. Then applies a simple boundary condition that consists of mechanical constraints, reference temperatures and local heat transfer coefficients on the surface of catalytic converter in FEA, The temperature distribution of the surface is recalculated and the coupled dynamic analysis is done using Abaqus v6.10-1 (FEA system). Then the displacements from the coupled dynamic analysis are interpolated back to CFD model to analyze flow through displaced catalytic converter body.

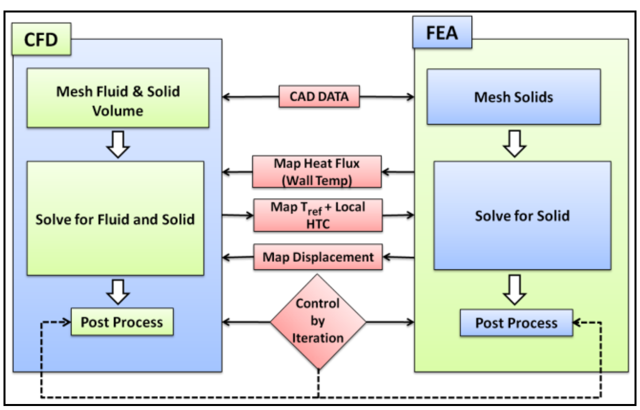

Figure 3. Coupling Process Flow

VI. Thermal Coupling

STAR-CCM+ passes local heat transfer coefficients and reference temperatures to Abaqus and Abaqus supplies the wall temperature to STAR-CCM+. In Abaqus terminology, the heat transfer coefficient is referred to as film coefficient and the reference temperature is referred to as sink temperature Exchange of data between two codes are done for enough times so that a converged solution is reached. Figure 4 shows the coupled temperature results from CFD to FEA.

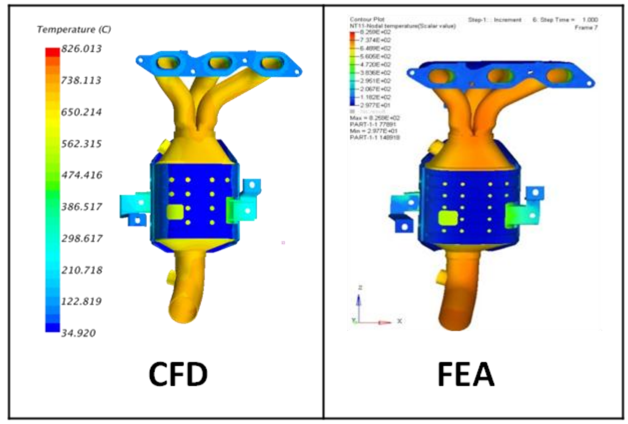

Figure 4.Coupled Temperature Results

VII. Dynamic Analysis

As investigated maximum temperature load predicted from thermal analysis taken as an input for dynamic analysis including thermal and mechanical constraints are applied to the model with dynamic loads.

To determine the stress and displacement levels for an engine rocking or roll angle of ± 4 degrees is considered with respect to the time domain. Loading curve is applied along the engine roll axis as per roll co-ordinates. The boundary condition applied at the roll axis midpoint is constrained in all DOF. Rajadurai et al [7] in his previous paper explained in detail about influence of coupled analysis for a Hot End Exhaust System Validation.

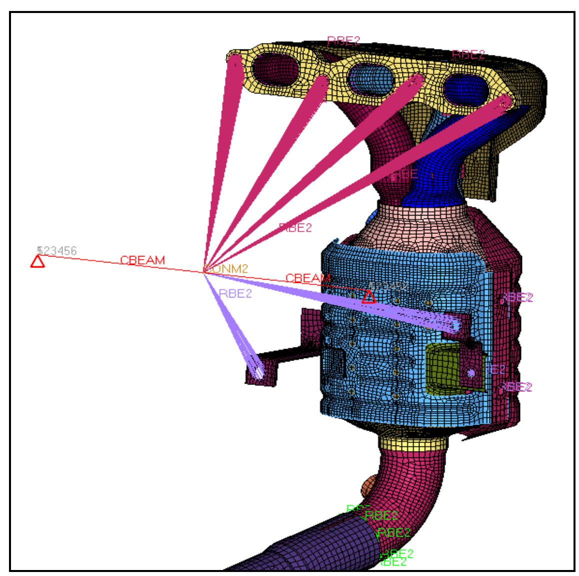

Figure 5. FE Model with applied Boundary Conditions

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A. Assumptions

- Engine roll axis has been modelled with beam elements CBEAM by considering cross sections as solid circle of diameter 10 mm and the high elastic modulus is defined for material in order to simulate the rigid element behaviour RBE2.
- Local co-ordinate system has been created on end node of roll axis, and the applied rocking angle load is defined at the mid node. Y-axis as roll axis is assigned for the applied load as well as engine C.G.
- Structural damping of 0.02(2%) is considered.
- Element described as per pre-processor tool. It is converted as .inp file when export by changing correct abaqus translation.

B. Loading Conditions

Dynamic transient load is applied w.r.t temperature. Stress and displacement contours are plotted. Since surface stress is not a major concern for flow uniformity disturbance, displacements are mapped to the CFD model.

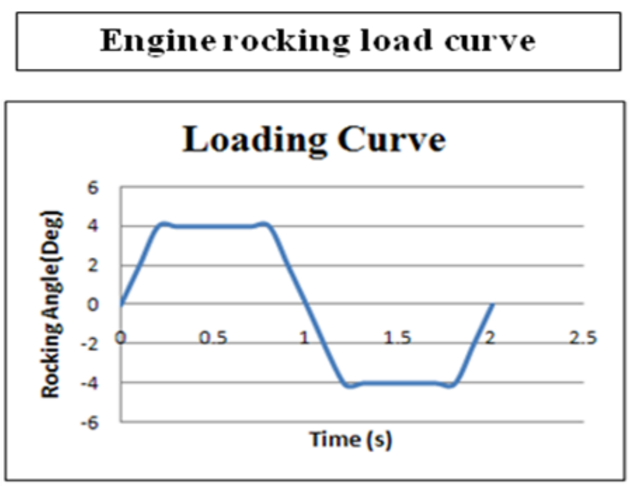


Figure 6. Engine rocking loading curve of ±0.0698 radian for 0-2 seconds

Thermal loads are applied using thermal stress output .odb file called in the sequence. Non-linear material properties are applied w.r.t temperature for all stainless steel materials. Figure 8 shows that modulus of elasticity is decreasing with increase in temperature, it is interpreted in analysis.

As a worst case scenario this analysis is done to map maximum displacement to CFD to achieve better results in flow uniformity through deformed bodies.

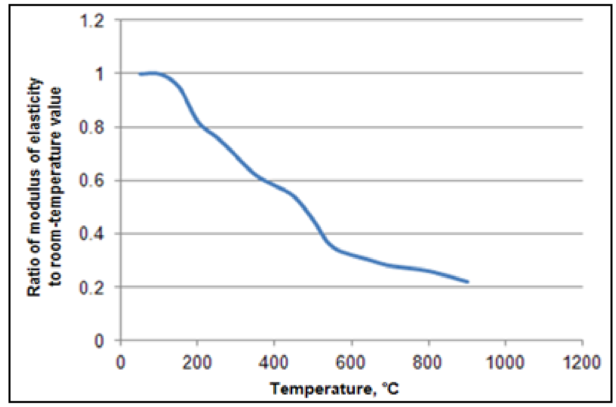
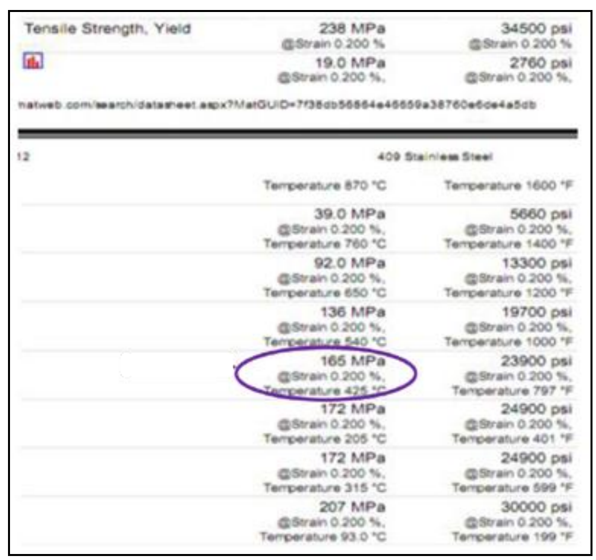


Figure 7. Graph for non-linearity of elastic modulus w.r.t Temperature

Below image represents the stress levels of stainless steel material for different temperatures.



Tensile Strength, Yield	238 MPa @Strain 0.200 %	34500 psi @Strain 0.200 %
	19.0 MPa @Strain 0.200 %,	2760 psi @Strain 0.200 %,

natweb.com/search/datasheet.aspx?MatGUID=7f38db56864e46659a38760e6de4a5db

12 409 Stainless Steel

	Temperature 870 °C	Temperature 1600 °F
	39.0 MPa @Strain 0.200 %, Temperature 760 °C	5660 psi @Strain 0.200 %, Temperature 1400 °F
	92.0 MPa @Strain 0.200 %, Temperature 650 °C	13300 psi @Strain 0.200 %, Temperature 1200 °F
	136 MPa @Strain 0.200 %, Temperature 540 °C	19700 psi @Strain 0.200 %, Temperature 1000 °F
	165 MPa @Strain 0.200 %, Temperature 425 °C	23900 psi @Strain 0.200 %, Temperature 797 °F
	172 MPa @Strain 0.200 %, Temperature 205 °C	24900 psi @Strain 0.200 %, Temperature 401 °F
	172 MPa @Strain 0.200 %, Temperature 315 °C	24900 psi @Strain 0.200 %, Temperature 599 °F
	207 MPa @Strain 0.200 %, Temperature 93.0 °C	30000 psi @Strain 0.200 %, Temperature 199 °F

Figure 8. Non-linear material property of SUS 409 w.r.t Temperature

C. Displacement Plots

Displacement Plot at time 1.0 sec with peak displacement of 3.821 mm occurring at manifold runner pipe. These displacements are coupled back to CFD to analyze flow through deformed bodies. Figure 9 shows coupled displacement results from FEA to CFD.

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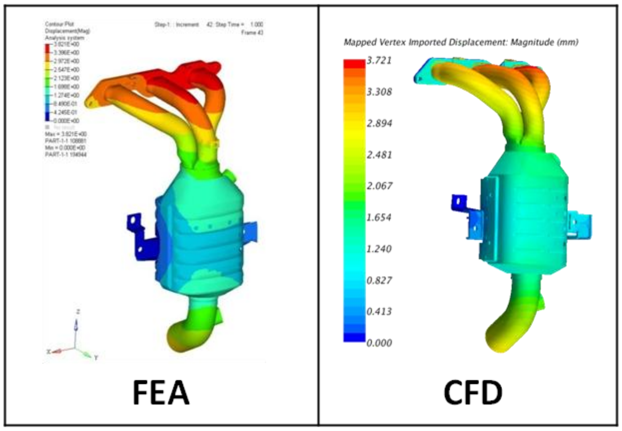

Figure 9.Coupled Displacement Results

VIII. Failure Correlation With Test

- A good correlation is obtained for the failure as observed in the test.
- Displacement plot shows the maximum displacement of 3.821 mm occurred in 1.0 sec at exhaust manifold.
- Integrated maximum displacement results occurred at 1.0 sec is taken to solve flow through displaced catalytic converter.
- It is observed that Uniformity index before displacement is 0.93 and after displacement the uniformity value decreases to 0.81.
- The high velocity region is at the middle junction of three exhaust ports and the region is discontinuous as shown in fig. 11

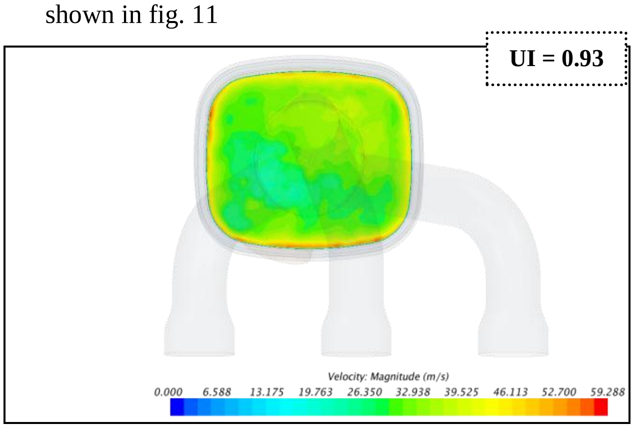

Figure 10.Substrate front face gas uniformity before integrating displacement

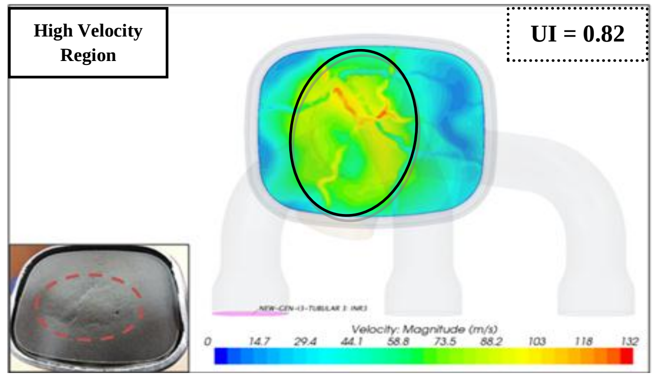

Figure 11.Substrate front face gas uniformity after integrating displacement

IX. Conclusion

Validating the system without considering the effect of fluid and structural interactions resulted inconclusive. Using the approach of coupled analysis, simulation captured well the high velocity pattern at the failure location. To highlight the thermal and dynamic loading factors in product development cycle; we have done this analysis which will help to reduce the failure occurrences due to non-uniform flow in catalyst. This methodology further implied in the design optimization of manifold profile. Prediction of boundary and loading conditions for FSI analysis is also given to easily understand the methodology done.

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Abbreviations

FSI	Fluid Structural Interaction
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
FE	Finite Element
HTC	Heat Transfer Coefficient
DOF	Degrees of Freedom
CG	Center of Gravity

AUTHOR'S PROFILE

[1]**Mylaudy Dr. S Rajadurai**, born in Mylaudy, Kanyakumari District, Tamil Nadu, India, received his Ph.D. in Chemistry from IIT Chennai in 1979. He has devoted nearly 35 years to scientific innovation, pioneering theory and application through the 20th century, and expanding strides of advancement into the 21st century. By authoring hundreds of published papers and reports and creating several patents, his research on solid oxide solutions, free radicals, catalyst structure sensitivity, and catalytic converter and exhaust system design has revolutionized the field of chemistry and automobile industry.

Dr. Rajadurai had various leadership position such has the Director of Research at Cummins Engine Company, Director of Advanced Development at Tenneco Automotive, Director of Emissions at ArvinMeritor, Vice-President of ACS Industries and since 2009 he is the Head of R&D Sharda Motor Industries Ltd.

He was a panelist of the Scientists and Technologists of Indian Origin, New Delhi 2004. He is a Fellow of the Society of Automotive Engineers. He was the UNESCO representative of India on low-cost analytical studies (1983-85). He is a Life Member of the North American Catalysis Society, North American Photo Chemical Society, Catalysis Society of India, Instrumental Society of India, Bangladesh Chemical Society and Indian Chemical Society.

[2]**Suraj Sukumaran** is a Sr. Engineer at Sharda Motor, R&D, Chennai. During his academic year, he was awarded in merit list for achieving 44th rank among 2407 students in Mechanical Engineering department from Anna University, Chennai. He has been involved in simulating Flow Thermal analysis in CFD for automobile exhaust system of passenger cars and off road vehicles. His area is mainly on flow & heat transfer simulation including uniformity index, velocity index, pressure drop, HEGO index, conjugate heat transfer analysis and chemical modeling. He is currently working on methodologies and strategies in CFD analysis for better optimization of exhaust system development. He is also involved in various advanced development research like SCR, DPF, CO_2& NH_3.

[3]**Sundaravadivelu. M** holds a Bachelor degree in Automobile Engineering from SRM University, Chennai. He has been involved in performing finite element modeling and analysis including Modal, Static, Dynamic, Fatigue, and Thermal.

During his career, Mainly, He concentrates in coupling Analysis with CFD by utilizing commercially available FEA software's. Also he focused in development of new CAE capabilities, methodologies and expertise by staying aware to trends in the computational technology fields. He manages Hyundai projects by understanding customer needs and processes to ensure relevant and innovative technology development. He presented papers in conferences like SIAT (SAE), Altair technology etc. Also he published many papers in international journals such as SAE, IJETER, IJRDET.