Modeling the vibrations in a catalytic converter for diesel engine

Nestor Martinez[1], Miguel Amado[1], and Martha P. Guerrero[2]

[1]Katcon Global, [2]Universidad Autónoma de Nuevo León

Abstract: *This paper describes the use of the commercial code, Abaqus, to model the modal frequencies (vibrations) and the noise (acoustic wave propagation) in a catalytic converter used for diesel engine. A three dimensional model in CDF is used to first obtain the temperature distribution and the heat transfer coefficients, this information is then used to model the thermo mechanical performance of the converter in order to obtain the vibrations and the noise under real operation conditions. The methodology for the construction of the model in the context of Abaqus is described, the system includes the manifold and the exhaust tube which greatly contribute to the total vibration of the system, however focus is made on the converter and its design, comparisons are made varying the thickness of selected components of the converter, the main objective of the work is to evaluate the performance of converter in order to fulfill the new standards on noise. Overall, the use of 3D modeling is feasible.*

Keywords: Design Optimization, Thermal Stress, Vibration, Coupled Analysis, Catalytic Converters.

1. Introduction

The catalytic converter is a device installed in the exhaust system. This consists normally of a ceramics honeycomb that diminishes the tolerable levels of the harmful elements of exhaust gases of an automobile. The catalytic converter locks up a substrate with the greater possible relation of surface to volume, which is impregnated with an emulsion that incorporates the catalytic material consisting of precious metals like platinum (Pt), Rhodian (Rh) and palladium (PS) in different mixtures and proportions [3].

During the 50's, the problem of pollution increased, along with the population density and the amount of automobiles. It was recognized that the automobile was one of the main contributors to the problem, by the 60's the norms for the control of emissions were beginning to be executed. The Introduction of the catalytic converters in the exhaust systems took place at the end of the 70's in EUA. In this period only the reduction of hydrocarbons (HC) and the carbon monoxide (CO) emissions were treated. Years later, the three way catalytic converter was developed, called this way for treating effectively the harmful gases expelled in the engine as hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx) and transforming these harmful gases, in inert gases to the environment as (N_2), (CO_2) and (H_2O). A key for the successful commercial introduction of the three way catalytic converters occurred in 1981with the development of an oxygen sensor. During the following decades, the norms of emissions were adopted worldwide. [5]. In 1960 the automobiles produced normally 100 grams of CO, HC and NOx by one mile. Nowadays it is only 2 grams by each crossed mile [5].

The difference between catalytic converters for gasoline or diesel engine is governed by the type of fuel that makes the combustion in the motor of the automobile. The catalytic converter of three way is used for the gasoline motor, while in the diesel engines the diesel converter of oxidation is apply to reduce to the HC and the CO and afterwards the diesel particle filter is used to eliminate the NOx. However, at the present time the automotive industry is replacing diesel converter of oxidation for a combination of catalytic converters of three way and diesel particle filter due to its better performance.

2. Function of the catalytic converter.

A catalytic converter consist mainly of a ceramic honeycomb filter, which is protected by components such a shells, thermal barriers, insulators and cones; and is attached to the manifold and the engine by supports and flange (Figure 1).

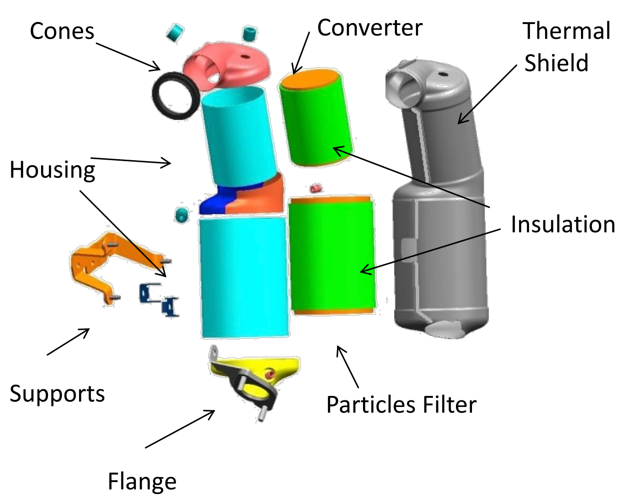


Figure 1 Components of a catalytic converter.

The main function of the catalytic converter is to reduce the toxicity of exhaust gases generated by the combustion process. Other functions and constrains are required by car manufacturers, such as the control of noise from the exhaust pipe, the amount of the emissions after treatment, the reliability of achieving heat transfer, which is limited to the surrounding components that can be damaged by temperature and gas leaks that can create discomfort to passengers or pedestrians [7].

The basic chemical reactions that take place in the catalytic converter are the oxidation of the CO and HC to obtain CO_2 (Eqs. 1-3), and the reduction of the NOx to achieve N_2 and H_2O (Eqs. 4-6), as described in the following equations:

Oxidation:

$$C_yH_n + \left(1 + \frac{n}{4}\right) O_2 \rightarrow yCO_2 + \frac{n}{2} H_2O \quad (1)$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \quad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (3)$$

Reduction:

$$NO(or\ NO_2) + CO \rightarrow \frac{1}{2} N_2 + CO_2 \quad (4)$$

$$NO(or\ NO_2) + H_2 \rightarrow \frac{1}{2} N_2 + H_2O \quad (5)$$

$$\left(2 + \frac{n}{2}\right) NO(or\ NO_2) + C_yH_n \rightarrow \left(1 + \frac{n}{4}\right) N_2 + yCO_2 + \frac{n}{2} H_2O \quad (6)$$

There are some important mechanical and thermal aspects to assure the catalytic converter performance. It is critical to understand the different modes of heat transfer involved in and around the exhaust system to be able to improve the design of components. The high temperatures reached by the catalytic converter must be controlled to obtain an appropriate temperature distribution in these components to avoid any car damage or reduce the passengers' comfort. The main constrain to obtain a good temperature distribution is that several components surrounding the catalytic converter or diesel particulate filter are difficult to protect because they are located in the chamber engine and the available space is very limited [7]. A high-quality design and a proper material selection are the key to prevent early damage in the catalytic converter components.

Thermo-mechanical stresses in the system are caused by thermal cycles or thermal shocks. Internal thermal shock could be caused by sudden temperature changes in the exhaust gases produced during the car acceleration or deceleration; while the external thermal shock can be caused by water which can be found when driving on wet roads. In both cases the high temperature gradients can cause thermal fatigue in the components Also, at high temperatures the exhaust system components could experience degradation by corrosion as they reach up to 1000 ° C [7].

The mechanical aspects that influence the catalytic converter performance are related to the vibrations and noise produced by the engine. The vibrations from the engine and road profile stimulate the exhaust system. For example, if the resonance frequencies produced by the loads applied are not properly absorbed; they can cause damage or excessive noise in the exhaust system. Moreover, even without resonance, the exhaust system could fail due to its working conditions under high cycle fatigue. The stress in the supports of the catalytic converter must be correctly distributed to avoid the nucleation of cracks that could lead to an early fracture.

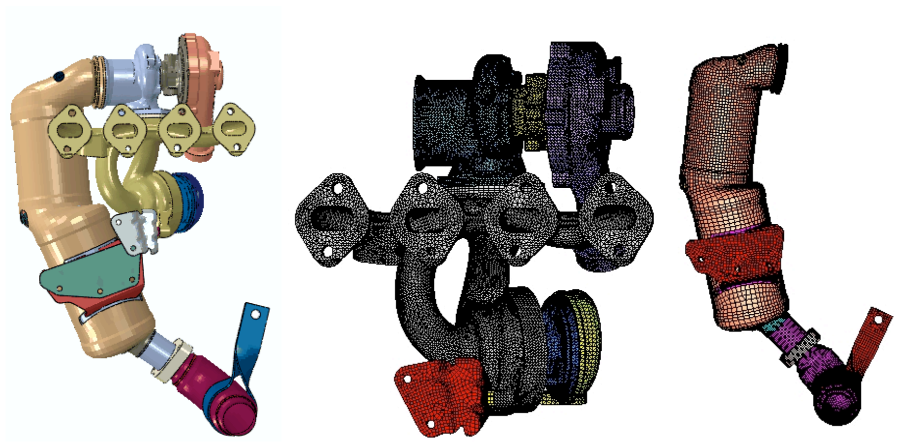
3. Model Preparation

A full 3D model was created; the sequence of modeling was as follows:

1. The geometries were imported from different sources, assembled and meshed.
2. A modal analysis was run.
3. A thermal analysis using output from CFD on the same geometry was run.
4. A hot modal analysis was run.

3.1 Geometry and Meshing

Geometries are imported and assembled in NX, after healing the geometry; this is exported to Hypermesh, where all meshing takes place, also the materials properties are added in this step, Figure 1.



(a) (b) (c)

Figure 2. Geometry a) Assembled, b) Mesh for Maniful, c) Mesh for the converter, tubes and cones.

3.2 Boundary Conditions

In order to obtain the frequencies of the assembling a step of frequency is set up in Abaqus CAE, only the supports and gas collector are restricted in all degrees of freedom, the rest of the geometry is free to move.
For the thermal analysis a heat transfer step was created at steady state. The conditions of convection and conduction and radiation were imposed, table 1 presents this information. Additionally the gas temperature (gas collector and turbine) was set at 750°C, gas temperature 700°C and converter and particules filter for diesel 700°C.

Table 1. Boundary conditions for the thermal analysis.

	Convection		*Radiation*	
PLACE	Reference Temperature °C	Convection coefficient (mw/mm^2k)	Reference Temperature °C	Emissivity
Thermal shield	80	0.05	80	0.8
Supports	80	0.05	80	0.8
Tubes	60	0.05	60	0.8
Gas collector	100	0.05	100	0.67

A variety of materials are used for the different components of the assembly, the table 2 show the number and type of element used.

Table 2. Material for each part of the assembly and number and type of elements used.

Part	*Material*	*Number of elements*	*Element type*
Converter	Cordierite	11020	C3D8I
Particles filter	Silicon carbide	12716	C3D8I
Insolation of converter	3M INTERAM 1600HTE	2500	C3D8I
Insolation of the Particles filter	3M INTERAM1600HTE	5400	C3D8I
Converter shield	AISI 409	1450	C3D8I
Particles filter shield	AISI 409	2040	C3D8I
Entry Cone	AISI 409	1207	S3,S4
Middle cone	AISI 409	974	S3,S4
Exit cone	AISI 409	1179	S3,S4
Insolation of the thermal shield	3M INTERAM 1600HTE	10273	S3,S4
Thermal shield	AISI 409	6550	S3,S4
Exhaust tube	AISI 409	7263	S3,S4,C3D8I

Supports	cast iron	3303	C3D6,C3D8I
Collector	cast iron	128463	C3D4
Turbins	ggg-simo51	237466	C3D4,CED8I

3.3 Materials' properties

As mention before, in the present simulation different type of materials such as ceramics, metals and composite materials are used. The physical and mechanical properties were obtained either from the providers, handbooks or directly by measurements in laboratory, for the hot modal the thermal expansion coefficient of each material was included. Table 3 gives some of the properties used in the model, for all metals dependence of elasticity respect to temperature was taken into account, also for the plastic behavior, for the other materials only a fixed value at room temperature for all properties was used.

Table 3. Some materials' properties.

	Silicon Carbide	*3M INTERAM 1600HT*	*Cordierite*	*Cast Iron*	*AISI 409*
Thermal conductivity (W/m°K)	3.4	0.13	0.46	25	27
Density (Ton/cm^2)	6.88E-10	1.00E-09	4.68E-10	6.85E-09	7.80E-09
Elasticity (Mpa)	10343	18	9000	172500	206153
Thermal expansion (1/°C)	4.50E-06	2.90E-05	7.60E-07	1.35E-05	1.35E-05

3.4 Frequency

For the frequency the Eigensolver used was Lanczos and only the first 10 values were calculated and acoustic - structural coupling was used. The matrix storage was symmetric for the equation solver and the Eigen vectors were normalized by displacement. The model was run using a 2 CPUs and the ram was of 8 Gb.

4. Results

Table 4 presents the results for the cold and hot modal analysis, the comparison made corresponds to the same shape modes in both cases. Figures 3 and 4 the temperature distribution, the results from CFD were input into to the model as a file, the information consisted of the temperatures and heat transfer coefficients at some nodes. In all cases for the hot modal the values are lower, since most of the materials yield when increasing the temperature, this is reflected in the results as the elastic an plastic behavior dependent on temperature was used, for the other properties as density and thermal conductivity values at 100°C were used.

The geometrical shape changed very little as the insolating materials used in the converter have low thermal expansion and the outside parts are made of different metals, though there was a shape change, this is not considerable because the maximum temperature register was 450°C.

Table 4. Cold and hot modal results.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Cold modal	156.95	233.83	254.68	267.45	323.84	341.36	398.35	448.46
Hot modal	131.55	174.10	186.34	210.02	234.87	271.25	318.73	353.24

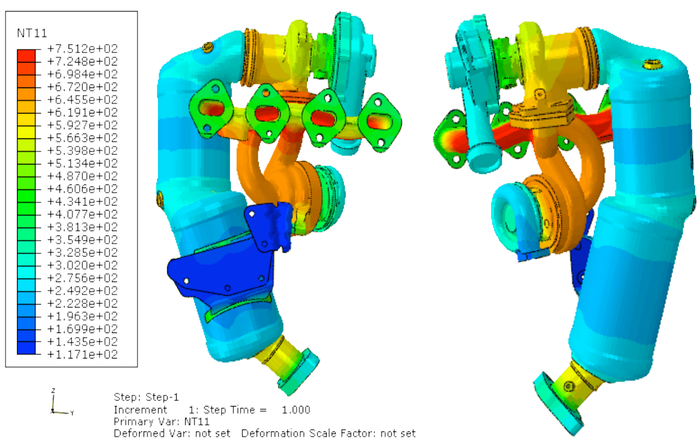


Figure 3. Thermal distribution.

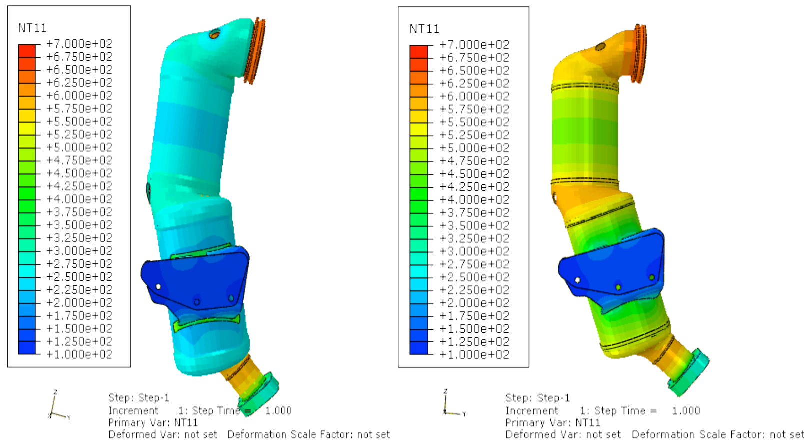


Figure 4. Thermal distribution.

5. Conclusions and future work

Due to the hardware and software solutions available it was possible to process a complete 3D model of a catalytic converter set. Also the work has presented the results from a modal analysis under cold and hot conditions and the thermal distribution considering a prior thermal distribution caused by the function of the engine was achieved. This is the first step on improving or optimizing the design of converters and exhaust systems. For further applications, the thermomechanical analysis should me obtained.

6. References

1. Automobile exhaust catalyst .Ronald M. Heck, Robert J. Farrauto.2001
2. Experimental evaluation of DOC light-off using secondary fuel injection. Argun yetkin,adam kotrba,tim garder,Jeremy popovick.2007
3. Simulación de un convertidor catalítico automotor. Martínez S. Olga. Valencia Venezuela 2005
4. Engineering fundamentals of the internal combustion engine. Second edition. willard W. Pulkrabek. 2004
5. Structural Analysis of an Exhaust System for Heavy Trucks.Mr N. Vasconcellos, Mr F. dos Anjos and Mr M. Argentino, debis humaitá IT Services Latin America, Brazil

6. NOx storage-reduction catalysts for gasoline engines. Masahiko Takeuchi and Shin'ichi Matsumoto.2004
7. Exhaust hot end flow thermal management. Said Zidat.luxemburgo2009
8. Palladium emissions in the environment.Fathi Zereini,Friedrich Alt. 2006
9. Modal analysis on an exhaust manifold to define a catalyst fe-model. Henrik ekholm,bjon zettervall.sweden 2008
10. ciencia e ingeniería d elos materiales.donald r. askelan.tercera edicion1998
11. Ferritic Stainless Steel for Automotive Exhaust Systems-High Heat-Resistant Ferritic Stainless Steel with High Formability for Automotive Exhaust Manifolds. MIYAZAKI Atsushi, HIRASAWA Junichiro, FURUKIMI Osamu.2004
12. Effect of temperature on high cycle fatigue behavior in 18Cr–2Mo ferritic stainless steel Y. Uematsu, M. Akita, M. Nakajima, K. Tokaji.2007
13. ASM Handbook, Volume 1, Properties and Selection: Irons,Steels, and High Performance Alloys.01 septiembre 2005
14. CF8C-plus: a new cast stainless steel for high- temperature diesel exhaust components. P.J. Maziasz, and J.P Shingledecker.2005
15. Ceramic materials-science and engineering. C. Barry Carter. M. Grant Norton.2007
16. Mechanical and thermal behaviour of cordierite–zirconia composites. F.A. Costa Oliveiraa, J. Cruz Fernandes.2001
17. The theory of composites. Graeme W. Milton.2004
18. Evaluation of thermal shock resistance of cordierite honeycombs. Rathindra Nath, C.D. Madhusoodana, P.K. Panda and Kiyoshi Okada. India 2002
19. Ceramic honeycomb filters and catalysts. Pronob Bardhan.1997
20. Modelling the Thermal Operation in a Catalytic Converter of an Automobile's Exhaust. O.D. Makinde. 2008
21. A.M Law, W. D. Kelton, "Simulation modeling and analysis", McGraw Hill, 1991.
22. Acoustic Analysis of Small Engine Catalytic Converters. Jüri Lavrentjev and Hans Rämmal.2010
23. Siemund, S., Schweich, D. (1996) "Three way monolitic converter: Simulation versus experiments." Chem.Eng. Sci. Vol. 51, No 15, 3709.

7. Acknowledgements

The authors acknowledge the financial support provided by the Consejo Nacional de Ciencia y Tecnología (CONACYT), México.