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Low-Cycle Thermal Fatigue and High-Cycle Vibration Fatigue Life Estimation of a Diesel Engine Exhaust Manifold

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Abstract

This paper aims at estimating the low-cycle and high-cycle fatigue life of a turbocharged Diesel engine exhaust manifold. First, a decoupled thermo-structural Finite Element analysis has been performed to investigate low-cycle fatigue phenomena due to the thermal loadings applied to the exhaust manifold. High/low temperature cycles causes stress-strain hysteresis loops in the manifold material whose related dissipated energy can be directly correlated to low-cycle thermal fatigue. Afterwards, a dynamic harmonic analysis has been performed aiming at investigating the existence of high-cycle fatigue phenomena due to vibrational loading applied to the exhaust manifold during the duty cycle. Three direction acceleration experimental loadings have been applied to the model. An ad-hoc methodology has been developed to superimpose thermo-structural results to dynamic harmonic analysis results. In particular, quasi-static thermo-structural results have been employed to identify the mean stress values of vibration fatigue cycles, while alternate stress values have been derived from harmonic analysis. Different combinations of frequencies and phases of the acceleration input signals have been considered to create different high-cycle fatigue loadings. Each cyclic load case has been processed employing the multiaxial Dang Van fatigue criterion.

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Keywords: fatigue; exhaust manifold; thermal stresses; cracks; frequency response analysis

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1. Introduction

In the last decades, internal combustion engine design has constantly evolved in order to satisfy pressing demands for the increasing of both fuel conversion efficiency and specific power output. New materials and innovative design/manufacturing methodologies/technologies have been introduced aiming at engine downsizing and pollutant emissions and fuel consumption reduction. As a consequence of the above targets, last generation engines are expected to undergo increased average thermal and mechanical loads over smaller and lighter components. The engine optimization process has therefore to be focused on the weight minimization, keeping durability and strength performance unchanged.

Exhaust manifolds are crucial components in internal combustion engines. They are usually manufactured with complex geometries, which represent a trade-off between minimal weight and dimensions and maximal thermo-fluid-dynamic performance.

Damage mechanisms due to thermal loading are universally recognized to play an important role for exhaust manifolds durability [1,2]. Moreover, with the adoption of downsizing and turbocharging as engine design guidelines, other failure mechanisms have arisen, such as vibrational oscillations, marginally considered in the pertinent literature until nowadays [3,4]. On one hand, thermal loadings are directly correlated with low-cycle fatigue phenomena, while, on the other hand, vibrational loading are related to high-cycle fatigue cracks.

During the first design stage, Finite Element analyses constitute an important and useful tool to analyse and optimize exhaust manifold geometries. The adoption of numerical procedures allows cost, time and number of experimental tests to be reduced, before the definite approval of the manifold design.

In this contribution, both thermal loading and vibrational loadings effects are investigated via non-linear Finite Element simulations, on the fatigue strength of a four cylinder turbocharged diesel engine for automotive applications.

The paper is organized as follows. First, the whole modeling strategy is described. Then the results of thermal analysis are presented. These are superposed to the mechanical loads acting on the exhaust manifold in order to evaluate stress and strain distributions via non-linear Finite Element simulations. Both quasi-static and dynamic harmonic analysis are proposed. Finally, thermo-mechanical quasi-static Finite Element forecasts are employed to estimate low-cycle fatigue life while mechanical stresses due to the vibrational loadings are processed to evaluated high-cycle fatigue safety factors. Results show the methodology to be a useful tool to be employed to detect possible critical points in the first stage of the design process of exhaust manifolds.

2. Modelling strategy

The numerical analyses are performed using the commercial Finite Element software MSC.Marc2013.1 Ad hoc modelling strategies have been developed for both low-cycle and high-cycle fatigue estimation.

2.1. Low-cycle fatigue

A first set of simulations consists in decoupled thermal and mechanical quasi-static Finite Element analyses. Only the exhaust manifold, the engine head and the turbine have been discretized, see Figure 1(a). Modelling the engine block as a rigid surface has been considered not to substantially affect the results.

2.2. High-cycle fatigue

A second set of dynamic harmonic analysis has been developed. Other turbocharger components have been added to the model, in order to take into account the influence of the projecting masses directly connected to the exhaust manifold on the dynamic response of the system. In particular, the supercharger and the sleeve have been modeled as proper concentrated masses and moments of inertia, see Figure 1(b).

(a) (b)

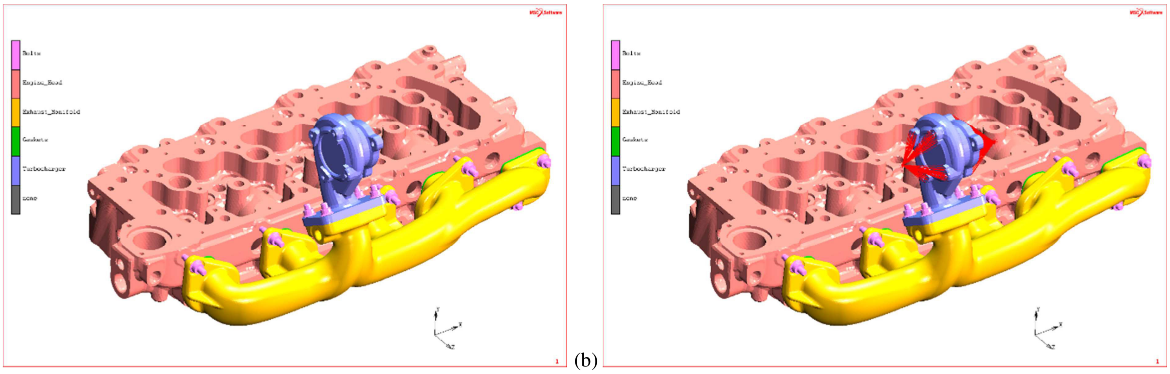


Fig. 1. (a) quasi-static Finite Element model; (b) dynamic harmonic Finite Element model.

The following sections detail the thermal and mechanical models developed.

3. Thermal analysis

3.1. Model description

A thermal model has been developed in order to evaluate the temperature distribution inside the system.

The thermal analysis is based on a previous CFD simulation of the fluid dynamic behaviour of the exhaust gases, from which gas temperatures and corresponding heat transfer coefficients are obtained. Because of the high thermal inertia of metals, the oscillations of walls temperatures due to the cyclic variation of entering heat fluxes have been considered to be negligible [5]. Therefore, gas temperatures and heat transfer coefficients have been averaged through an engine cycle before being applied on the inner surfaces of the exhaust manifold.

Specific entering heat flux, previously evaluated by a 1-D CFD simulation of the combustion process, has been applied on the engine head combustion dome. Different reference temperatures and heat transfer coefficients have been then applied on all the remaining model surfaces, i.e. engine head oil galleries and engine head and exhaust manifold external surfaces.

3.2. Results

Figure 2(a) shows the temperature distribution inside the exhaust manifold. As expected, maximum temperatures are registered in the central portion of the component, far from the turbocharger and engine head joint flanges.

(a) (b)

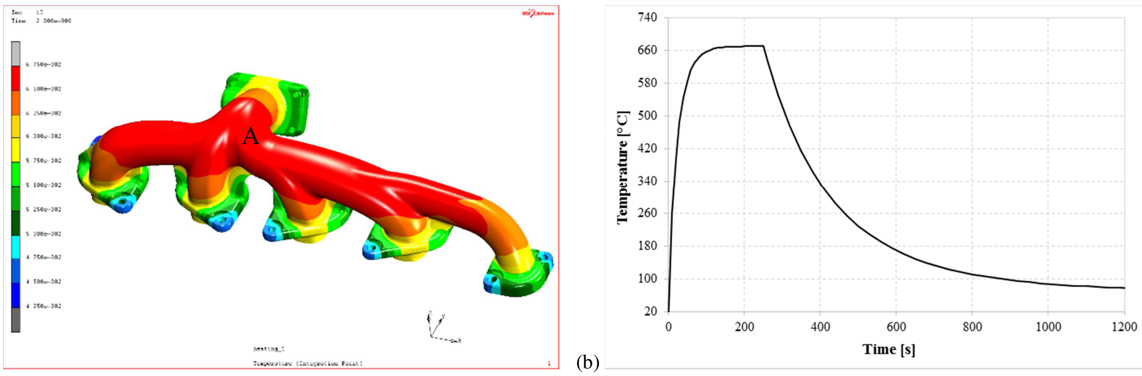


Fig. 2. (a) temperature distribution in the exhaust manifold; (b) temperature variation in point A for a single start-stop cycle.

4. Thermo-mechanical quasi-static Finite Element model

4.1. Model description

The first mechanical model considers the effects of subsequent applications and removals of the temperature distribution. Bolt tightening for both exhaust manifold and engine head, and exhaust manifold and turbine assembly have been taken into account. Elasto-plastic material behaviour has been considered in order to investigate if some point of the exhaust manifold undergo a plastic hysteresis cycle.

The material employed for the exhaust manifold manufacturing is the SiMo cast iron EN-GJS-XSiMo 4.05. Temperature dependent stress-strain curves have been taken from experimental results of [6]. In particular, the Chaboche [7,8] stress-strain relationship has been used to fit stress-strain curves, based on the non-linear kinematic hardening rule expressed by:

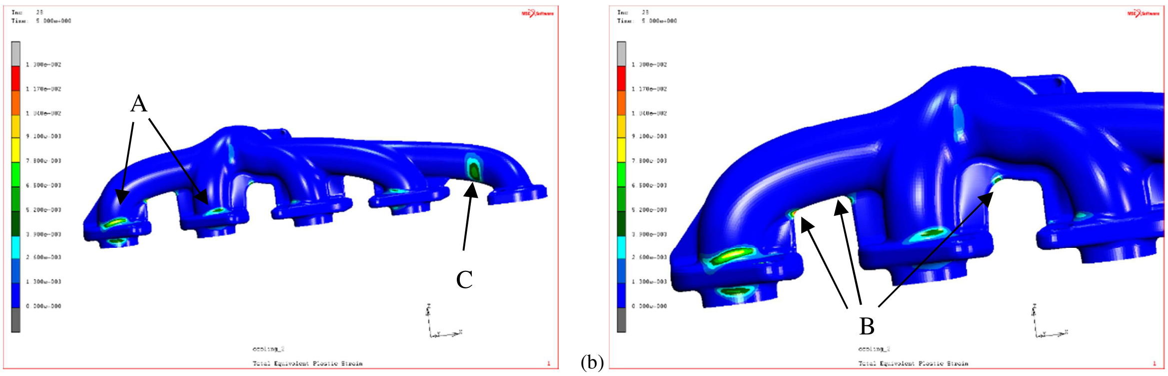
$$X(\varepsilon_p) = \alpha \frac{K}{\gamma} - \left(X_0 - \alpha \frac{K}{\gamma} \right) \exp^{-\alpha\gamma(\varepsilon_0 - \varepsilon_p)} \tag{1}$$

where α = sign(σ – X), K and γ are experimentally calibrated material properties depending on temperature and ε_p is the local plastic strain.

Temperature dependent values of the Young modulus have been also employed.

4.2. Results

Figures 3 shows the Equivalent Plastic Strain distribution in the exhaust manifold, computed after the application of the thermal cycle evaluated by the previously presented thermal analysis. Large areas where plasticity occurs are detected. In particular, possible critical points are flanges fillets (A), fillets of the ribs connecting flanges and pipes (B) and the bend at the end of the Exhaust Gas Recirculation (EGR) pipe (C).



(a) (b)

Fig. 3. Exhaust manifold areas undergoing plasticity.

5. Dynamic harmonic Finite Element model

5.1. Model description

The second mechanical model aims at evaluating the vibrational response of the structure. In particular, the first step of this analysis is the same as the one employed in the previously presented quasi-static model, i.e. bolt tightening and temperature distribution application. Following, a modal analysis has been performed to extract the first three exhaust system natural frequencies. Then, three different harmonic acceleration loads have been applied to the rigid surface mimicking the engine block, each in a range of frequencies covering the first three natural frequencies of the system, see Table 1.

Only the Young modulus temperature dependence has been taken into account, while non-linear material behavior has been neglected. This peculiarity is essential because the dynamic harmonic analysis, performed after a non-linear preload state, freezes the obtained stiffness matrix considering the local tangent to the stress-strain curve, relative to the preload analysis results. Therefore, if plasticity occurs in some areas, local stiffness employed for vibrational analysis could result artificially too low, considering that elastic shakedown usually occurs in elasto-plastic systems under dynamic cyclic loadings [9].

Table 1. Acceleration loading applied to the dynamic harmonic model.

Acceleration Direction	Amplitude	Frequency Range
Longitudinal acceleration	0.65 g	100-400 Hz
Vertical acceleration	0.50 g	100-400 Hz
Transversal acceleration	0.55 g	100-400 Hz

5.2. Results

Figure 4 shows the three natural modes corresponding to the three natural frequencies of Table 2. As expected, natural modes mainly involve the projecting masses of the turbocharger system.

(a) (b) (c)

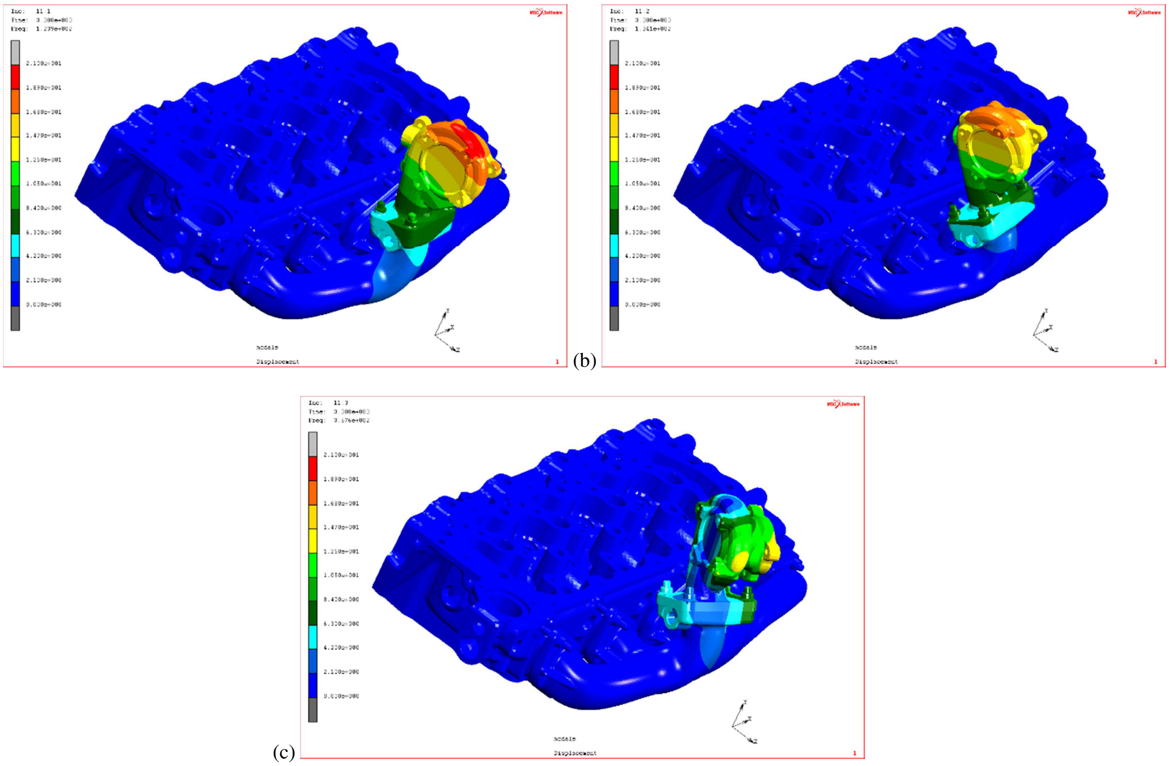


Fig. 4. (a) first natural mode; (b) second natural mode; (c) third natural mode.

Table 2. Natural frequencies of modal analysis.

Number of Natural Frequencies	Frequency
First Natural Frequency	123.9 Hz
Second Natural Frequency	134.1 Hz
Third Natural Frequency	357.6 Hz

Figures 5 and 6 present the most interesting results of the dynamic harmonic analysis. In particular, the highest stress values are registered when a transversal acceleration is applied to the model with a frequency equal to the first natural frequency, see Fig. 5, and for a longitudinal acceleration applied with a frequency equal to the second natural frequency, see Fig. 6. In fact, in such situations, the direction of the acceleration signals directly excites the modes corresponding to the considered natural frequencies.

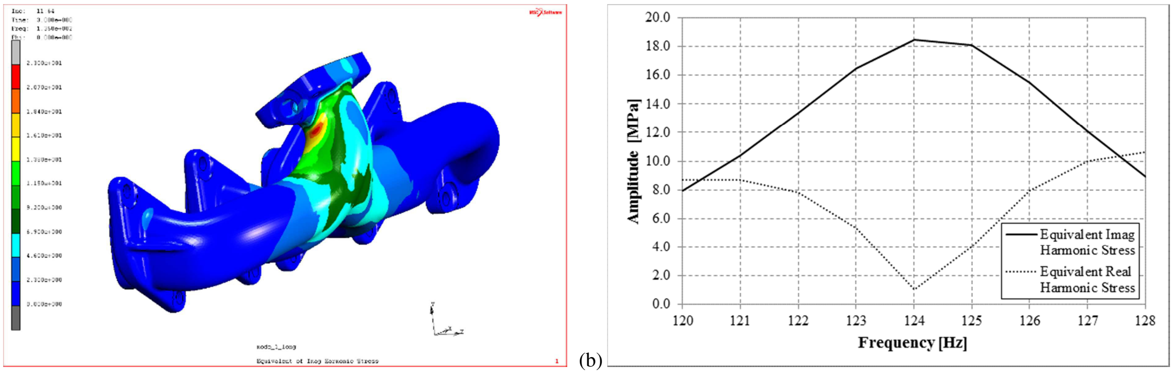
(a)


Fig. 5. (a) Equivalent Imaginary Harmonic Stress distribution for a transversal acceleration; (b) Equivalent Imaginary and Real Harmonic Stresses as a function of the transversal acceleration frequency in the most critical point of the exhaust manifold.

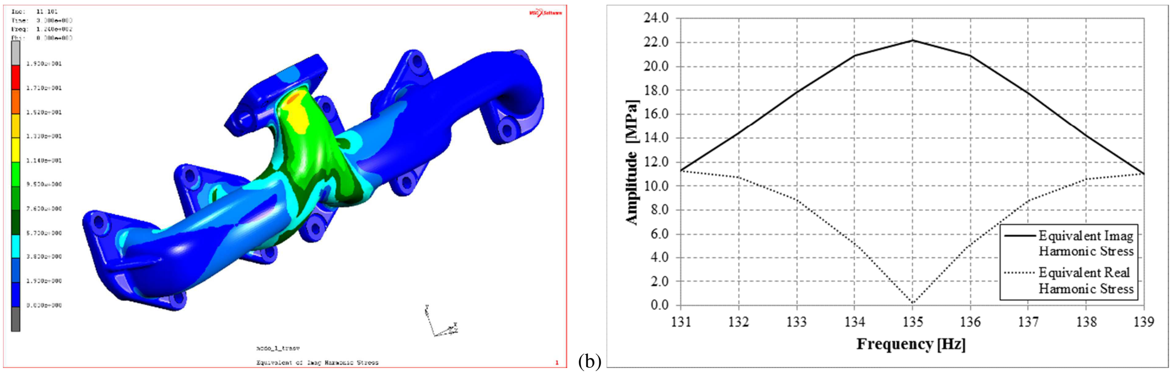
(a)


Fig. 6. (a) Equivalent Imaginary Harmonic Stress distribution for a longitudinal acceleration; (b) Equivalent Imaginary and Real Harmonic Stresses as a function of the longitudinal acceleration frequency in the most critical point of the exhaust manifold.

6. Fatigue analysis

6.1. Low-cycle fatigue results

Elasto-plastic mechanical analysis has shown some areas where plasticity occurs, which can be considered as possible indicators of low-cycle fatigue phenomena, see Fig. 3. To estimate the low-cycle fatigue life of the exhaust manifold, an energetic criterion [10] has been employed. In fact, the fatigue life of a material is strongly correlated to the dissipated energy per cycle [11]:

$$\Delta W_s = \int_t^{t+T} \sigma d\varepsilon_p \tag{2}$$

where σ is the local stress tensor and ε_p is the local plastic strain tensor.
In particular, the criterion is expressed by the relationship:

$$\Delta W_s \cdot N^{\beta} = C \tag{3}$$

where N is the number of cycles at which crack is expected to propagate and β and C are experimental material constants [12].
Figure 7 shows the distribution of the dissipated energy in the exhaust manifold when a single thermal start-stop cycle is considered. Highest amounts of energy are dissipated at the fillets of the ribs connecting flanges and pipes (A) and at the bend at the end of the EGR pipe (B).

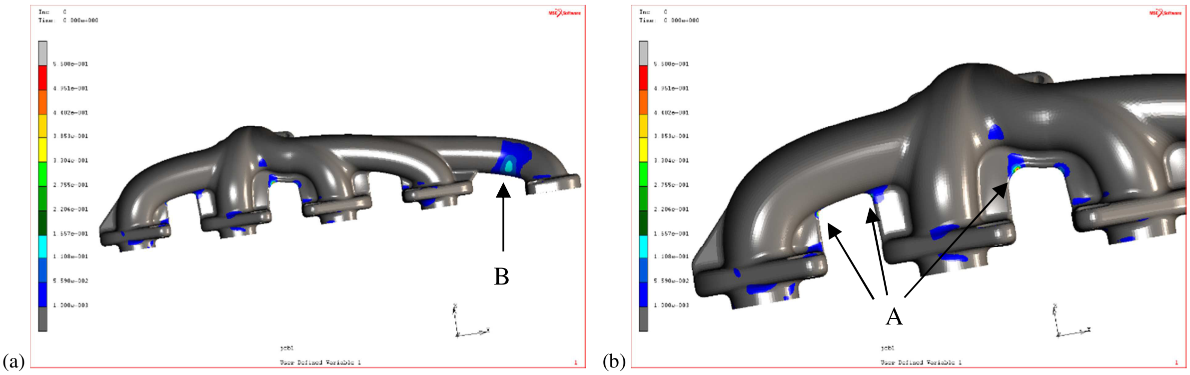


Fig. 7. Dissipated energy for a single thermal cycle.

6.2. High cycle fatigue results

The results of the dynamic harmonic analysis have been processed with the stress-based multiaxial Dang Van fatigue criterion [13,14]. In particular, vibrational stresses have been superposed to the stress distribution obtained by the elasto-plastic simulation where bolt tightening and temperature distribution application have been considered. An ad-hoc processing procedure has been developed to create high-cycle fatigue stress histories. In particular, stress tensor results, obtained by dynamic harmonic analysis, have been combined considering all possible phase and frequency configurations, aiming at processing all possible load cases.
Figure 7 shows the Dang Van safety factor distribution, where the worst combination is considered of the single stress tensors evaluated by the dynamic harmonic analysis. Most critical areas are located at the flange fillets (A), at the fillets of the ribs connecting flanges and pipes (B) and at the bend near the flange connecting the manifold to the turbocharger (C).

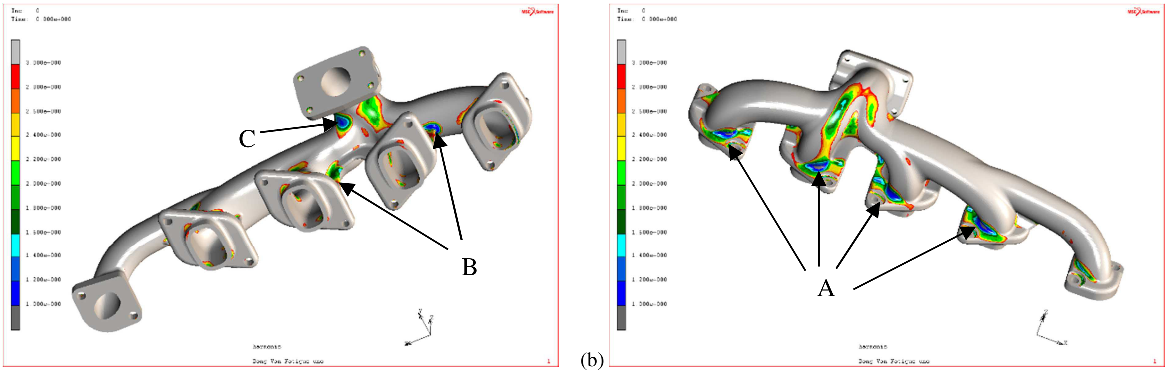


Fig. 8. Dang Van safety factor distribution.

7. Conclusion

The present paper proposes a numerical methodology for the low-cycle and high-cycle fatigue life estimation of a turbocharged Diesel engine exhaust manifold. Two different sets of simulations have been presented.

Decoupled thermo-structural Finite Element analysis has been employed to estimate low-cycle thermal fatigue phenomena. Several areas in which plasticity occurs have been detected and they have been directly related to low-cycle fatigue through the adoption of an energy based criterion.

Purposely developed dynamic harmonic modelling strategy has been developed with the aim of evaluating high-cycle fatigue phenomena due to vibrational loadings. Results reveal that vibrational loadings cannot be neglected for correctly estimating the fatigue life of exhaust manifolds in which auxiliary components are directly supported by the manifold, as in the case of the turbocharged engine addressed in this contribution.

References

[1] A. Benoit, M.H. Maitournam, L. Rémy, F. Oger, Cyclic behaviour of structures under thermomechanical loadings: application to exhaust manifolds, Int. J. Fatigue 38 (2012) 65–74.
[2] E. Charkaluk, A. Bignonnet, A. Constantinescu, K. Dang Van, Fatigue design of structures under thermomechanical loadings, Fatigue Fract. Eng. M. 25(12) (2002) 1199–1206.
[3] G. Belingardi, S. Leonti, Modal analysis in the design of an automotive exhaust pipe, Int. J. Vehicle Des. 8(4/5/6) (1987) 475–487.
[4] K. Wolff, M. Hüser, Computer aided development of exhaust system durability, Global Powertrain Congress, 1998, Detroit, MI.
[5] S. Fontanesi, M. Giacopini, Multiphase CFD-CHT optimization of the cooling jacket and FEM analysis of the engine head of a V6 diesel engine. Appl. Therm. Eng. 52(2) (2013) 293–303.
[6] Z. Jing, Prediction of failure of cast iron with dynamic loading and high temperature, Mat. Sci. Eng. A-Struct. 566 (2013) 71–81.
[7] J.L. Chaboche, Time-Independent constitutive theory for cyclic plasticity, Int. J. Plasticity 2 (1986) 149–188.
[8] J.L. Chaboche, Constitutive equations for cyclic plasticity and cyclic viscoplasicity. Int. J. Plasticity 5 (1989) 247–302.
[9] H.S. Ho, Shakedown in elastic-plastic systems under dynamic loadings, J. Appl. Mech. 39(2), (1972) 416–421.
[10] R.P. Skelton, Energy criteria for high temperature low cycle fatigue, Mater. Sci. Technol. 7 (1991) 427–439.
[11] E. Charkaluk, A. Bignonnet, A. Constantinescu, K. Dang Van, Fatigue design of structures under thermomechanical loadings, Fatig. Fract. Eng. Mater. Struct. 25 (12) (2002) 1199–1206.
[12] E. Charkaluk, A. Constantinescu, Energetic approach in thermomechanical fatigue for silicon molybdenum cast-iron, Mat. High Temp. 17(3) (2000) 373–380.
[13] K. Dang Van, G. Cailletaud, J.F. Flavenot, A. Le Douaron, A. H.P. Lieurade, Criterion for high-cycle fatigue failure under multiaxial loading, in: M.W. Brown, K.J. Miller (Eds.), Biaxial and Multiaxial Fatigue, EGF 3, Mechanical Engineering Publications, London, 1989, pp. 459–478.
[14] K. Dang Van, B. Griveau, O. Message, On a new multiaxial fatigue limit criterion: theory and application, in: M.W. Brown, K.J. Miller (Eds.), Biaxial and Multiaxial Fatigue, EGF 3, Mechanical Engineering Publications, London, 1989, pp. 479–496.