Design and Optimization of Engine Block Using Gravity Analysis

B. Indrakanth, S. Udaya Bhaskar, CH. Ashok Kumar, and N. Srinivasa Rajneesh

Abstract The engine blocks used in automotive are subjected to dynamic forces, which creates an imbalance force on it. To avoid the impact of unbalanced forces, dynamic analysis helps in reducing the stresses induced. Component mode synthesis method is used for gravity analysis using the finite element method. After meshing of the engine block, refinement of the element size is studied for optimum results to reduce the induced stresses. Dynamic analysis of the engine block is carried out to study the frequency response. Aluminum alloy 2024 and stainless steel materials have been used for the engine block to analyze, and the results are compared for an optimum design and shape of the engine block. By using the CMS method, optimum size of the engine block is obtained. The frequency model analysis has been done on the optimized size of engine blocks.

Keywords Aircraft engine block · Gravity analysis · CMS · Optimization

1 Introduction

CMS method is used for analyzing large problems for discretization into finalizing structure. By this method, optimization of the size of a given component can be done by different modifications. Many researchers have been using this technique for design considerations of various components. For the dynamic analysis, CMS technique is used for determining the eigen properties. The finite element model is reduced by CMS technique to reduce the static deformation.

An assembly model for the engine aircraft has been considered. The attention has been paid to the outer profile of the engine block. Further an assembly for the engine of a model aircraft has been considered to find out the stress which should not exceed the permissible stress limits for the material. Here the component used is examined and compared according to their performance, stress, displacement, weight

B. Indrakanth (✉) · S. Udaya Bhaskar · CH. Ashok Kumar · N. Srinivasa Rajneesh
Department of Mechanical Engineering, Malla Reddy Engineering College (Autonomous), Hyderabad, Telangana 500100, India
e-mail: birru.indrakanth@mrec.ac.in

P. K. Chaurasiya et al. (eds.), *Technology Innovation in Mechanical Engineering*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-16-7909-4_95

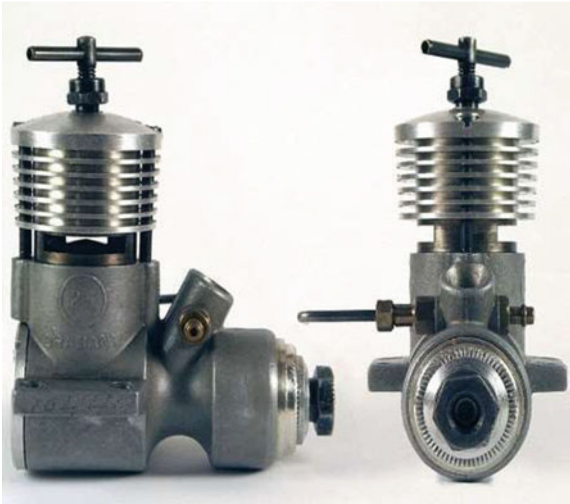


Fig. 1 Aircraft engine block

of stainless steel and aluminum alloy 2024.The task involves a rigid-body analysis. The goal is to start with the given shape and check if changes in shape can reduce stresses, while the second assignment makes use of the capability of RADIOSS to mix both forms of analysis that is motion body dynamics (MBD) analysis and the gravity analysis using components mode synthesis (CMS) (Fig. 1).

2 Literature Review

(Henderson et al. [1]) Aircraft design with environmental consideration has been done, and with the help of generic algorithm technique, aircraft framework was analyzed. (Chaietal [2]) Center of gravity position of aircraft was estimated. Position of center of gravity is achieved by two different methods. These two methods will give center of gravity position with considerable range. (Daniel Bohnke et al. [3]) Conceptual design method is used to design aircraft with environmental aspects, i.e., airframe and central body. (Tao et al. [4]) Marine engine design optimization is done with vibration isolation. This optimization is achieved by sequential programming technique. (Giordano Camicia et al. [5]) Grain refinement of cylinder head is achieved by gravity die casting method. For analyzing the microstructure changes, image analysis technique is used. An error has been identified for structural model by using CMS method when compared to exact solution [6]. The results obtained from the CMS technique were very much near to the analysis Rayleigh–Ritz method and subspace iterations [7]. In order to decrease the error using subspace iteration method, AMLS technique was considered which obtained reliable results [8]. For enhanced measurement of error which were near to exact error were defected for upper bonds on errors using CMS and subspace iteration. For improved techniques to obtain frequencies and mode shapes, Lanczos transformation was employed to obtain solutions with error bonds in comparison with subspace.

3 Methodology

Craig–Bampton method uses CMS technique for determining approximate eigen values and eigen vectors for large continuum FEM problems. The governing equations for the engine block are developed by using FEM. The dynamic equilibrium equations for the engine block are written in terms of mass matrix M, stiffness matrix K, force matrix F and displacement vector x (Table 1) (Fig. 2).

Dynamic response of the spacecraft is given by

$$M\ddot{X} + KX = F$$

$$\begin{bmatrix} M_{NN} & M_{NI} \\ M_{NI}^{T} & M_{II} \end{bmatrix} \begin{bmatrix} \ddot{X}_N \\ \ddot{X}_I \end{bmatrix} + \begin{bmatrix} K_{NN} & K_{NI} \\ K_{NI}^{T} & K_{II} \end{bmatrix} \begin{bmatrix} \ddot{X}_N \\ \ddot{X}_I \end{bmatrix} = \begin{bmatrix} F_N \\ F_1 \end{bmatrix}$$

Table 1 Comparison between material properties of aluminum alloy 2024 and stainless steel

Physical Properties	Aluminum alloy 2024	Stainless steel
Density	$3.1e^{-9}$ ton/mm^3	$9.01e^{-9}$ton/mm^3
Mechanical properties		
Hardness, Brinell	120	80
Hardness, Rockwell A	46.8	58
Hardness, Rockwell B	75	130
Hardness, Vickers	137	82
Ultimate tensile strength	586 MPa	3000 MPa
Elongation at break	100%	88%
Modulus of elasticity	73100 MPa	210000 MPa
Bearing yield strength	441 MPa	262 MPa
Poisson’s ratio	0.33	0.3
Fatigue strength	138 MPa	1070 MPa
Machinability	70%	65%
Shear modulus	28,000 MPa	86,500 MPa
Shear strength	283 MPa	597 MPa

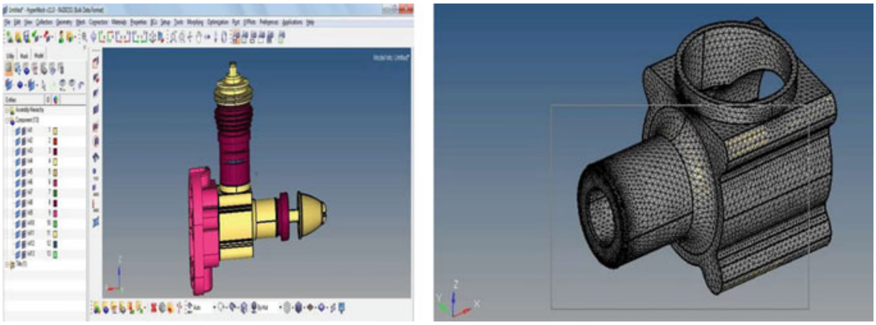


Fig. 2 Imported aircraft engine model in hypermesh through IGES

$$\overline{X} = \begin{bmatrix} X_N \\ X_I \end{bmatrix}$$

The generalized eigenvalue problem is

$$\left[K - \Omega_n^2 M\right]\phi_n = 0$$

Transform the physical coordinate x as

$$\overline{X} = \begin{bmatrix} X_N \\ X_I \end{bmatrix} = \begin{bmatrix} \phi_{NN} & \phi_{CN} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} q_N \\ X_1 \end{bmatrix}$$

The eigenvectors are mass normalized. Thus,

$$\tilde{M}_{NN} = \phi_{NN}^T M_{NN} \phi_{NN} = I$$

$$\phi_{NN}^T K_{NN} \phi_{NN} = \Omega_n^2$$

where Ω_n^2 is the eigenvalue matrix for the fixed interface modal analysis.

4 Dynamic Analysis of Engine Block

Aircraft engines are subject to multiple types of dynamic loads from rotor harmonic vibrations, pressure fluctuations from turbulence, unbalance loads and frequency shock due to landing and payload handling. Many of the loads are periodic and occur at harmonics of the rotor system. Other loads are random in nature and still others are truly frequency or shock pulses. Often these loads occur simultaneously and thus analyze the need to evaluate their combined effect. This complex interaction of different dynamic loads is well supported by the Altair OptiStruct FEA response simulation capabilities which were used for all forced response analysis and function processing. Unit varying load is applied about 20 N at a particular node number 47817; at this node location, forced vibration is acting when engine gets started. Frequency response analysis is carried to solve the dynamic behavior of engine block.

4.1 Analysis Results for Engine Block Made of Stainless Steel Material

Stainless steel material is also applied for the same engine block and calculated the results for comparing the stress and displacement. Using Radioss software, gravity analysis is carried out for stainless steel engine block. Acceleration results are shown below in all directions. Aluminum 2024 alloy generally has better corrosion resistance than steel and weighs roughly 1/3 of stainless steel. The two different analyses of the engine block are displayed. Based on the results, the shape optimized stainless steel engine block is having less percentage variation compared to aluminum alloy 2024, but stainless steel engine block is little better in displacement comparison.

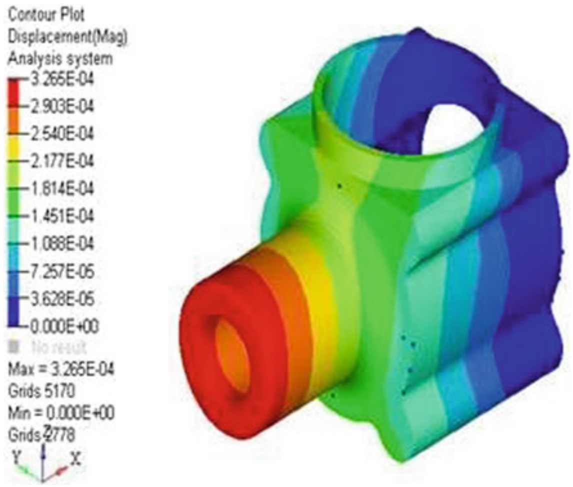
4.2 Optimization Results and Redesign

The modified shape of engine block is given by shape optimization. The same model should be redesigned and should rerun the analysis of optimization and check the comparison of new shape of engine block and previous shape of engine block (Figs. 3, 4, 5 and 6).

For two materials, the same shape of engine block is given by Altair OptiStruct software. Create a load collector in which card image should be GRAV. In that mention the gravity value 1 along which axis the rotation is required. In all three directions are the requirement, so separately created for x-direction, y-direction and z-direction. This is shown below how to apply in hypermesh. Results for engine block after shape optimization displacement and stresses are shown below for new design model of aluminum alloy 2024 material (Figs. 7 and 8) (Table 2).

Displacement and stresses that are compared for stainless steel engine block and aluminum 2024 engine block are shown in results. The shape optimized model of the engine block will have more strength in running condition, because when compared, the displacement and stresses results of second (shape optimized) model with the old or reference model of the engine block give stiffer outcome. With the engine block shape optimized results, there is no requirement of doing any kinematic simulation. When compared to stainless steel shape optimized model, the stress and displacement variation is little, whereas in aluminum alloy 2024 shape optimized model, variation

Fig. 3 Displacement magnitude



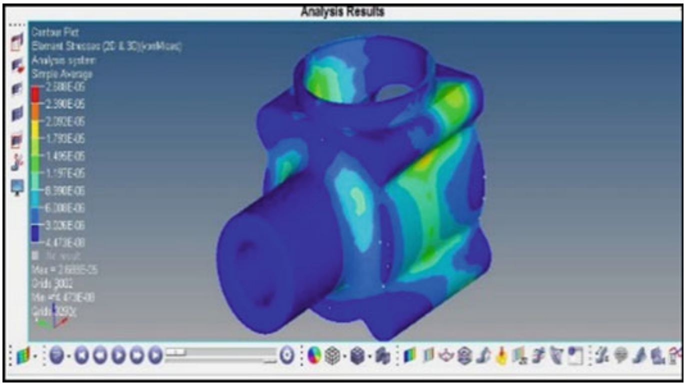


Fig. 4 Stress contour plot of engine block made of aluminum alloy 2024 material

Fig. 5 Modified shape of engine block in Altair HyperView

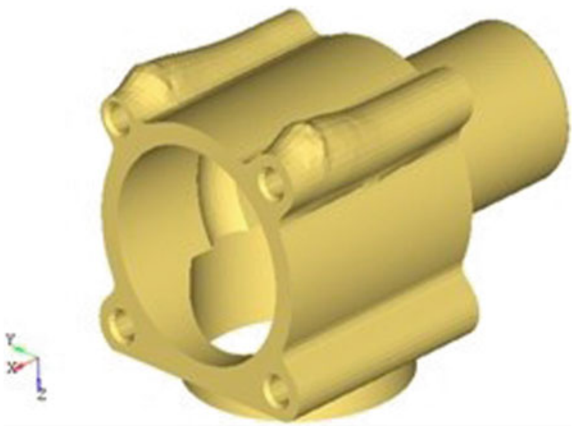
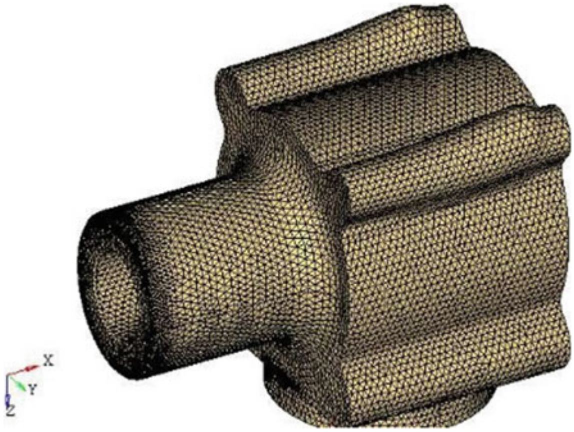


Fig. 6 Engine block is meshed using tetra mesh with 30 mm element size



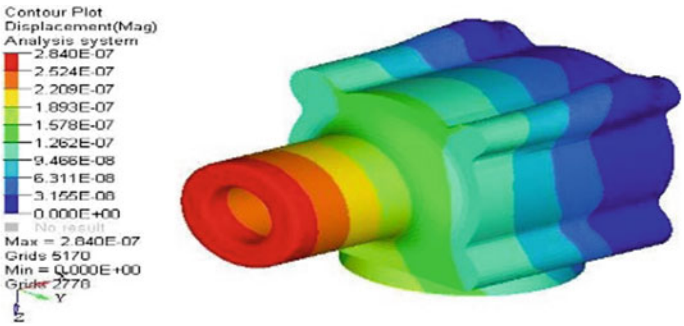


Fig. 7 Displacement of new design in magnitude

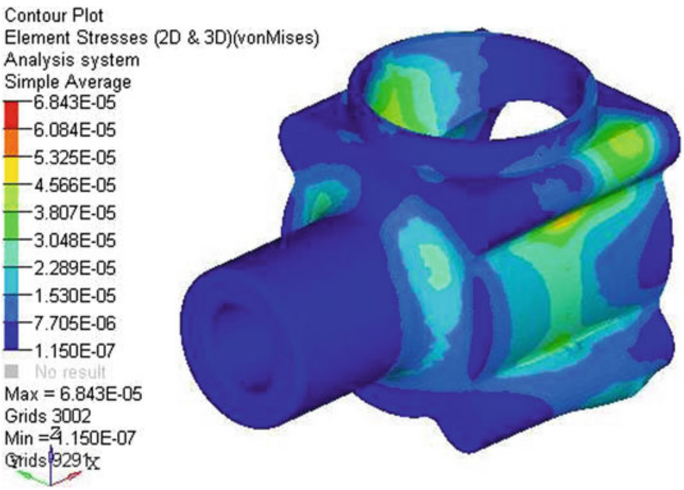


Fig. 8 Engine blocks new shape optimized analysis results SS

Table 2 Comparison of displacement and stress for stainless steel and aluminum alloy 2024

	Displacement		Stress	
	Minimum	Maximum	Minimum	Maximum
Stainless steel	0	2.924	1.1.36	7.11
Aluminum alloy 2024	0	3.265	4.473	2.688

in stress and displacement is somewhat countable that may help in providing stiffer engine block model.

4.3 Cost Analysis

The results conclude that the weight of stainless steel engine block is more (1,285,000 g), when compared to aluminum alloy 2024 engine block that weighs very less (498,400 g) which may result in weight and cost reduction at the same time. The purpose of the project is partially achieved here with a good percentage of saving on material cost and efficiency of the engine due to the less weight. The cost of aluminum alloy 2024 in market is about Rs. 113/-, whereas the stainless steel costs about Rs. 200/-. The weight of the aluminum alloy 2024 engine block is 498.400 Kgs, and the stainless steel engine block weighs 1285Kgs. The engine block material cost for aluminum alloy 2024 498.400 $\times$ 113 = Rs. 56,319/- and stainless steel is 1285 $\times$ 200 = Rs. 257,000/-, thus the saving is about 257,000−56,319 = Rs. 200,681. The result outcome is a net savings of Rs. 200,681/-.

5 Results and Discussion

5.1 Comparison of Results of Old and New Designs of Engine Block

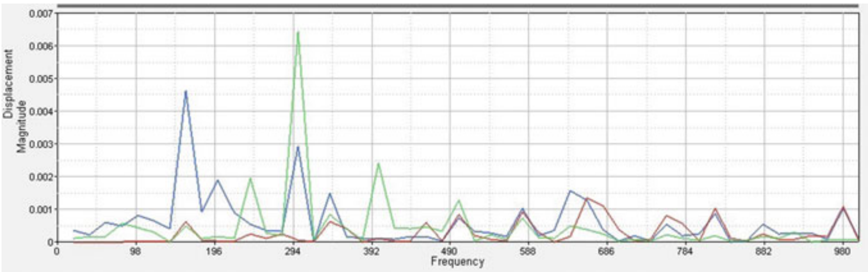
The results obtained from the comparison of displacement and stresses of the reference engine block and the new shape engine block are displayed.

5.1.1 Dynamic Analysis Results Are Shown Below

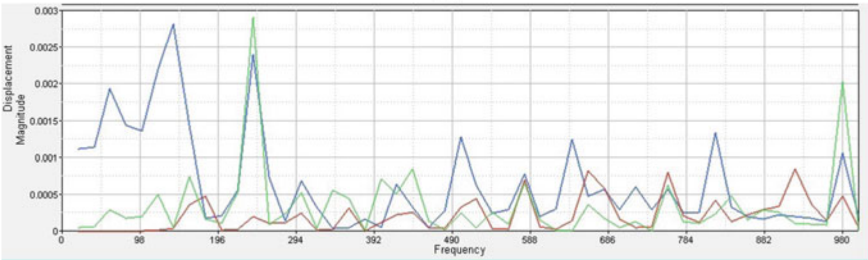
Displacement curve for both the designs are shown in above graph, which represents that red curve is for aluminum 2024 optimized design, blue color indicates base design, and green indicates stainless steel material. Stainless steel material curve if we observe in above graph is having large displacement at 190 to 300 Hz range. Green curve is failing at 20–110 Hz range. Blue curve is for aluminum base design which is having frequency about 80–118 Hz. Red curve indicates optimized aluminum model graph. If we observe the curve above, it is not having any vibration from 0 to 118 Hz. Remaining two cases are failed at the vibration level itself (Graph 1).

Finally, by seeing the graph, we can conclude that optimized model is perfect which suits the engine in running condition. Stainless steel weight is 1285000 g, and aluminum 2024 engine block weight is 498400. By observing the weight of optimized engine block design of two materials that is stainless steel and aluminum 2024, aluminum material is perfect suitable for engine block.

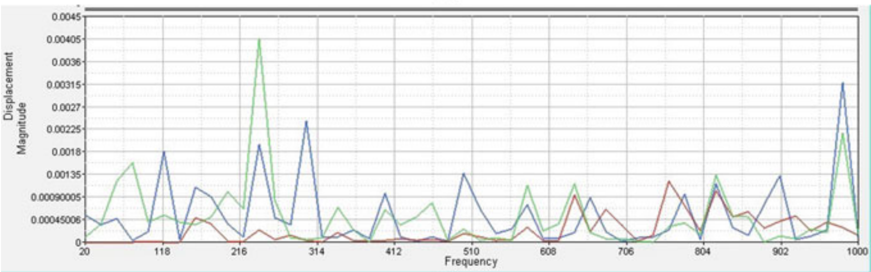
(a) Aluminum alloy 2024 engine block weight = 498400 g
(b) Stainless steel engine block weight = 1285000 g



(a)



(b)



(c)

Graph 1 Displacement curve between magnitude and frequency

Engine block weight is more if stainless steel is considered, whereas weight of aluminum alloy 2024 is very less compared to stainless steel material. For stress and displacement graphs for new shape optimized models, the 2D plot is matching which indicates that same graph is replaced for two materials: stainless steel and aluminum alloy 2024. There is no huge change in results of optimized models. Complete analysis is done for base design of engine block using two different materials like stainless steel and aluminum alloy 2024 which are regularly used in aircraft engines.

6 Conclusions

Gravity analysis has been done by using CMS technique. The experimental data provided by the engine manufacturer was compared with the computed results. The results quite match with reference to model virtual analysis. To give better design for engine manufacturer, the shape optimization is used and solved using Altair OptiStruct. The frequency response analysis for the engine block using CMS technique has drawn the displacement difference between the materials used in the analysis when running at different frequencies. The aluminum alloy 2024 has shown 11.24% more deformation when compared with stainless steel material. From the cost analysis due to the weight of materials, by using aluminum alloy 2024, the cost decreased by 78.08%. Vibrations were not observed until 118 Hz for the optimized engine block. The optimized model with aluminum alloy 2024 which was 61.21% lesser weight has shown better performance when compared to the stainless steel material. Finally concluding that second shape optimized aluminum alloy 2024 engine block design can be suggested to original equipment manufacturer for the latest design of the engine block for the market of model aircraft.

References

1. Henderson, R.P., Martins, J.R.R.A., Perez, R.E.: Aircraft conceptual design for optimal environmental performance. Aeronaut. J. **116**(1175), 1–22 (2012)
2. Chai, S., Crisafulli, P., Mason, W.: Aircraft center of gravity estimation in conceptual/preliminary design. In: Aircraft Engineering, Technology, and Operations Congress (1995)
3. Böhnke, D., Nagel, B., Gollnick, V.: An approach to multi-fidelity in conceptual aircraft design in distributed design environments. In: 2011 Aerospace Conference. IEEE (2011)
4. Tao, J.S., Liu, G.R., Lam, K.Y.: Design optimization of marine engine-mount system. J. Sound Vib. **235**(3), 477–494 (2000)
5. Camicia, G., Timelli, G.: Grain refinement of gravity die cast secondary AlSi7Cu3Mg alloys for automotive cylinder heads. Trans. Nonferrous Met. Soc. China **26**(5), 1211–1221 (2016)
6. Filippone, A.: Theroretical framework for the simulation of transport aircraft flight. J. Aircr. **47**(5), 1679–1696 (2010)
7. Jakobsson, H., Larson, M.G.: A posteriori error analysis of component mode synthesis for the elliptic eigenvalue problem. Comput. Meth. Appl. Mech. Eng. **200**, 2840–2847 (2011)

8. Zingoni, A.: Symmetry recognition in group-theoretic computational schemes for complex structural systems. Comput. Struct. **94–95**, 34–44 (2012)
9. Bathe, K.J.: The subspace iteration method—revisited. Comput. Struct. **126**, 177–183 (2013)
10. Yin, J., Voss, H., Chen, P.: Improving eigenpairs of automated multilevel sub structuring with subspace iterations. Comput. Struct. **119**, 115–124 (2013)
11. Jenkinson, L., Simkin, P., Rhodes, D.: Civil jet aircraft design. Butterworth Heinemann (1999)
12. Koch, A., Nagel, B., Gollnick, V., Dahlmann, K., Grewe, V., Karcher, B., Schumann, U.: Integrated analysis and design environment for a climate compatible air transport system. AIM Aviation Technology, Integration and Operations Conference (2009)
13. Kroo, I., Takai, M.: A Quasi-procedural, knowledge-based system for aircraft design. AIM 6502 (1988)