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DESIGN OF A CONNECTING ROD FOR INTERNAL COMBUSTION ENGINE BY APPLYING TOPOLOGY OPTIMIZATION

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Abstract. *This work presents the design of a connecting rod (conrod) for a lightweight spark-ignition four-stroke internal combustion engine by applying topology optimization. Topology optimization methodology combines FE analysis with a powerful optimization algorithm to find the optimum mass distribution inside the defined design volume concerning the loads and boundary conditions and considering a specified optimization objective function (e.g., minimum compliance, minimum mass, maximum first mode frequency) and constraints. This approach innovates the design process in the mechanical industry while changes the project information and decision flow, because the design is defined by the CAE engineer (supported by an optimization algorithm) and no longer by the CAD designer. The project includes the simulation of the combustion to predict the static load (gas pressure) that is applied to the conrod. With this it is possible to determine the loads that are applied to the conrod. The performed optimization process consists in four phases: 1- finite element mesh generation and modeling using Altair Hypermesh®; 2 - topology optimization routine using the software Altair OptiStruct® as the optimization solver; 3 - CAD documentation of the final result; 4 - finite element analysis validation of the designed conrod. Two optimization problems are formulated, the first is to minimize the compliance for a defined maximum mass and the second is to minimize the mass for a defined maximum stress. Manufacturing constraints are applied to assure the feasibility of the conrod design in the end of the optimization routine*

Keywords*: topology optimization, finite element analysis, connecting rod, conrod, manufacturing constraints, engine design, internal combustion engine*

1. INTRODUCTION

The automotive industry and society demands more efficient vehicles and internal combustion engines. Fuel economy and emissions are the most important drivers of the industry in the last ten years and will continue to be in the next decade. The global warming problem, air pollution in large cities and the price of fuels are issues that make the development of efficient engines so necessary and important. Reducing the mass of the moving parts of internal combustion engines associated to the engine down-sizing (more power in smaller engines) is necessary to achieve the industry objectives. By doing this, the engine needs less fuel (energy) to run and that means that the engine is more efficient and less polluter.

This work presents the design of a connecting rod (conrod) for an ethanol converted lightweight spark-ignition four-stroke internal combustion engine by applying topology optimization (Bendsøe and Sigmund, 2003), aiming for mass reduction of the component. Topology optimization combines FE analysis with a powerful optimization algorithm to find the optimum mass distribution inside the defined design volume concerning the loads and boundary conditions and considering a specified optimization objective function (e.g., minimum compliance, maximum first mode frequency) and constraints. This approach innovates the design process in the mechanical industry while changes the project information and decision flow, because the design is defined by the CAE engineer (supported by an optimization algorithm) and no longer by the CAD designer.

Conrod development focused, mainly, on two drivers: cost reduction and pin holes improvement. Optimization for cost reduction is performed by Shenoy and Fatemi (2005) considering the material selection and shape optimization for fatigue requirements. Optimization considering contact to improve pin holes design is performed by Meske, Mulfinger and Warmuth (2002). Therefore, in this work contact of the pins are neglected because it is focused on the connecting rod web development.

To design the connecting rod, a one dimensional flow and thermodynamic modeling is performed by using Ricardo WAVE®, a CAE engine simulator, to determine the length of connecting rod by the engine compression rate analysis. With the results of combustion pressure and engine speed, the loads on the connecting rod are determined.

Topology optimization method is becoming increasingly common in the automotive industry and it has been a challenge for engineers. That is because the project methodology is not disseminated and still not well defined. The objective of this work is to define a design methodology that assures that the mechanical and manufacturing requirements are achieved when applying topology optimization method to reduce the connecting rod mass, with Altair

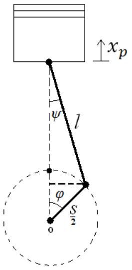
OptiStruct® solver. Defining the best approach is to define the right objective function and constraints of the optimization problem.

This paper is organized as follows: in Section 2, the engine performance simulation and the load modeling are briefly presented. In Section 3, topology optimization methodology is defined, concerning to the objective functions and constraints. In Section 4, results for the topology optimization design are presented, for several optimization problems. In Section 5, some conclusions remarks are given.

2. LOAD MODELING

2.1. Load Modeling Equations

Connecting rod load modeling considers the static force applied by the piston which results from the combustion pressure, and the dynamic load due to the linear oscillation of the piston mass. Oscillating inertial force of the conrod is neglected in this first approximation (Basshuysen and Schäfer, 2004). Figure 1 describes the cranktrain geometry.



Definitions:
x_p - piston position
s – piston displacement
l – conrod length
φ – crankshaft angle
ψ – conrod angle

Figure 1. Cranktrain geometry.

The load equations are:

$$F_{comp} = p_{max} A_p \tag{1}$$

$$F_{trac} = m_p \ddot{x}_{p_{max}} \ ; \qquad \ddot{x}_{p_{max}} = \frac{s}{2}\omega_{\max}{}^2\left(\cos\varphi + \frac{r}{l}cos2\varphi\right) \tag{2}$$

Where F_{comp} is the compressive force aligned to conrod axis, F_{trac} is the tensile force aligned to conrod axis, F_{bend} is the bending force perpendicular to conrod axis, m_{piston} is the piston mass, p is the combustion pressure, A_P is the piston head area and ω is the engine rotational speed.

Figure 2 illustrates both load cases considered in the optimization problem.

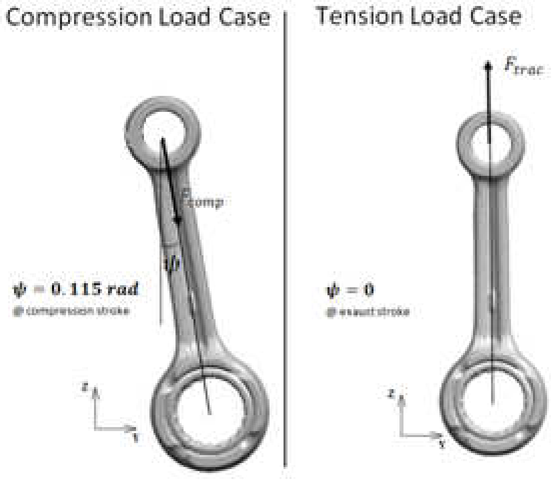


Figure 2. Load case diagram for compression and tension. Baseline original conrod design.

2.2. Combustion pressure

The engine is modeled using the software Ricardo WAVE®, an engine performance simulator. The inputs are the geometry of the engine (cranktrain, intake and exhaust system, valves, etc), the fuel properties and combustion model. The baseline of this work is an ethanol converted lightweight four-stroke spark-ignition internal combustion engine. The combustion gases pressure curve of the engine at the maximum torque shaft rotational speed is shown in Fig 3. The maximum pressure is 3.5 MPa at the conrod angle ψ equal to 0.115 rad (see Fig. 2).

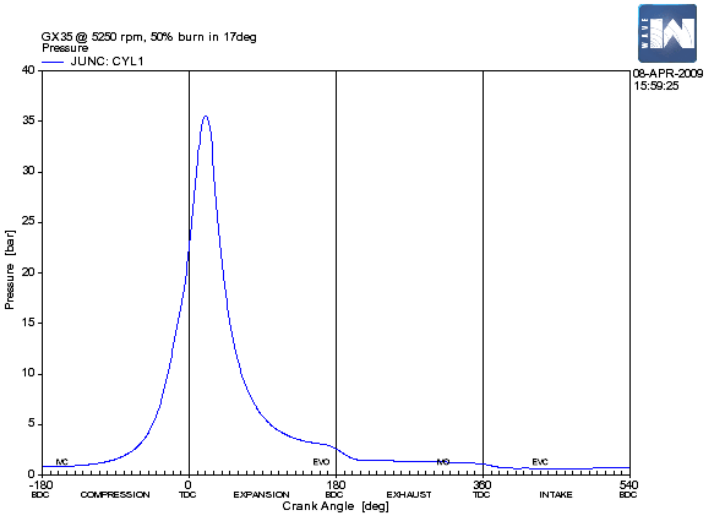


Figure 3. Combustion gases pressure *vs.* crank angle for ethanol fueling.

3. TOPOLOGY OPTIMIZATION METHODOLOGY

3.1. Finite element modeling

The extended design space is defined based on the conrod length and pin holes diameters. Figure 4 shows the discretization performed in finite elements with Altair Hypermesh® Software by generating a mesh of 120,000 eight node solid elements. Two different design regions are defined, a design domain (blue) and a non-design domain (yellow) to assure the existence of the pin holes by the end of the optimization. The conrod material is SAE 4340 steel alloy which properties are specified in Tab. 1.

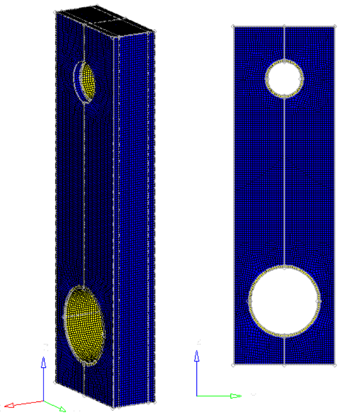


Figure 4. Finite element design domain of the conrod.

Table 1. Steel alloy SAE4340 mechanical properties.

Poisson´s Ratio	ν	0.3
Young´s modulus	E	210 GPa
Yield Strength	σ_y	473 MPa

Two load cases are defined, the first is the compressive force and the bending force associated to the combustion gases pressure at the angle of maximum gas pressure ψ (see Fig. 2) and the second is the tensile force associated to the maximum acceleration of the piston mass at the engine top rotational speed ω equal to 14 rad/s. The forces are applied to the small pin hole (piston pin) considering a uniformly distributed load along 120º region of the pin hole (Webster, Coffell and Alfaro, 1983). For each load case a displacement restraint is applied to the big pin hole (crank pin) to the nodes along 120º region. For compression the forces are applied to the lower part of the small pin hole and restraints to the upper part of the big pin hole. For tension the opposite is done. Figure 5 shows the boundary conditions applied to the design space.

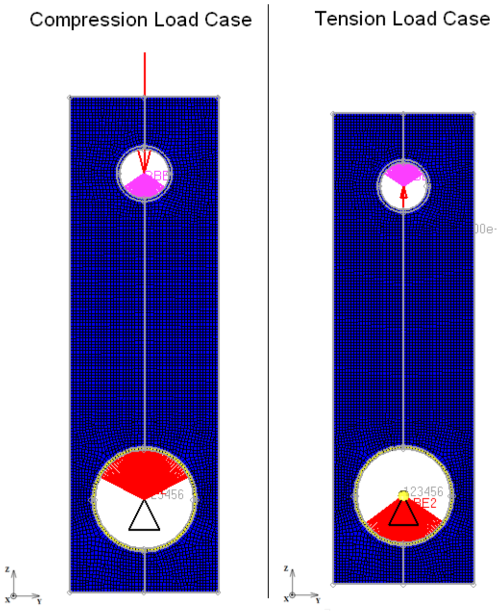


Figure 5. Optimization load cases.

3.2. Objective function and constraints

To define the topology optimization methodology it is necessary an analysis of the mechanical and manufacturing requirements. First, the von Mises stress should not exceed the yield strength, considering a safety factor (*SF*) of 1.6 (Sonsino and Esper, 1994). Second, the deflection between the conrod pin holes must be small to assure the engine operation, that means that a larger stiffness is better for the conrod. Finally, the design must have a split mold draw direction (aligned to the pin hole axle, x direction in figure 5), a constraint for forging, casting and sintering manufacturing. Those three processes are the most important in the industry (Basshuysen and Schäfer, 2004). A one plane symmetry, defined by the pin holes center lines (xz plane in figure 5) is also defined to assure conrod balance.

To achieve those requirements, three different approaches are proposed for multi-load case (compression and tension) optimization. One is to minimize the mass considering a stress constraint (case A). Second, is to minimize the compliance (weighted compliance for multi-load case optimization) for a desired volume (case B). "Case B" is performed for two different volume fraction constraints. "Case B1" volume fraction is defined by the baseline original conrod volume (see figure 2 in section 2.1) that is the typical approach when there is a project history of the part. "Case B2" volume fraction is defined by the "case A" OptiStruct log file result for a comparison of the conrod performance (stress and displacement) of both approaches.

Case A: Objective: minimize mass
Constraints: von Mises stress $< \frac{\sigma_y}{SF}$, draw direction (x axle), 1 plane symmetry (xz plane)
Design variable: design element densities (can assume values from 0 to 1)

Cases B1, B2: Objective: minimize weighted compliance (maximize stiffness)
Constraints: maximum volume fraction, draw direction, 1 plane symmetry
Design variable: design element densities (can assume values from 0 to 1)

The weighted compliance is defined by the scalar sum of each load case.

4. NUMERICAL RESULTS

As described in section 3, four different optimization problems are defined in Altair OptiStruct® software considering the load cases described in section 2.

“Case A” objective is to minimize the mass considering maximum Von Mises stress of 330 MPa (SAE 4340 steel and safety factor of 1.6) and manufacturing constraints of split mold draw direction and symmetry (section 3). Figure 6 illustrates the optimized design of the conrod for “case A”.

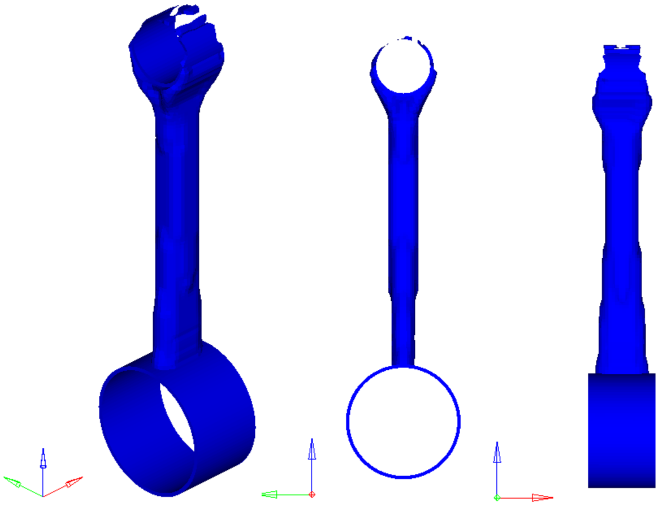


Figure 6. Topology optimization result for “case A”.

“Case B1” objective is to minimize the weighted compliance considering maximum volume fraction relative to the initial design domain volume of 15% and the same manufacturing constraints of “case A”. Figure 7 illustrates the optimized design of the conrod for “case B1”.

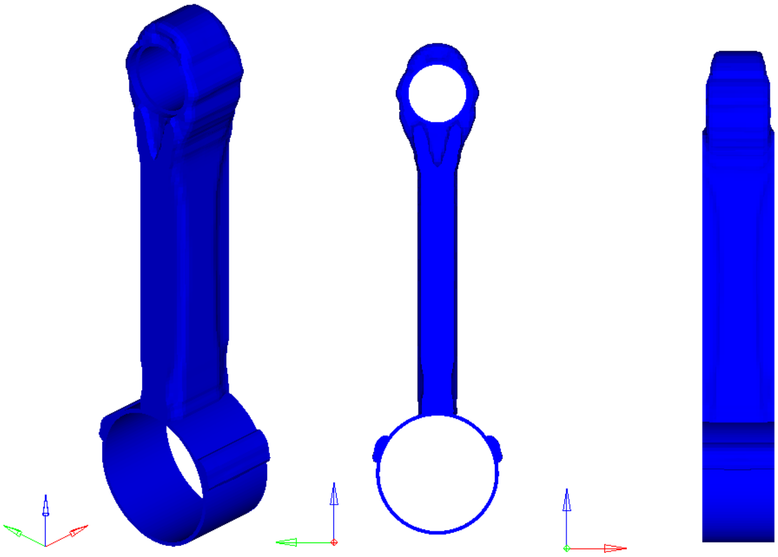


Figure 7. Topology optimization result for case B1.

"Case B2" objective is to minimize the weighted compliance considering maximum volume fraction relative to the volume of "case A" result of 6.2% and the same manufacturing constraints of "case A". Figure 8 illustrates the optimized design of the conrod for "case B2".

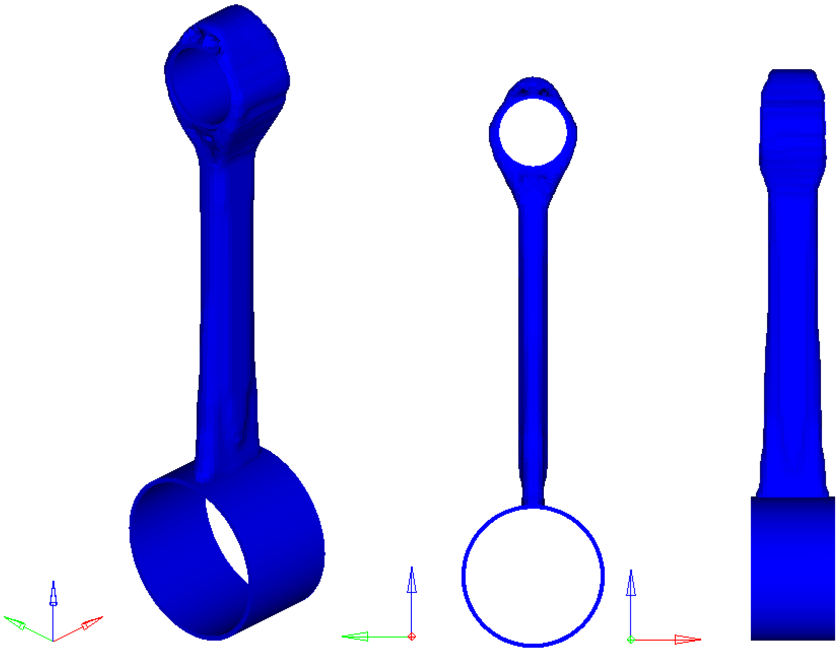


Figure 8. Topology optimization result for case B2.

To determine what is the best approach to the development of internal combustion engine conrod it is necessary to evaluate the performance parameters total mass, stress and displacement of each case. Table 2 presents the post processing results performed with Altair Hypermesh® software. A comparison of the results with the baseline connecting rod mass is also calculated.

Table 2. Performance parameters for each optimization case.

CASE	Objective	Constraint	Mass	Mass reduction (1)	Stress(2)	Displacement(3)
A	Min Mass	Stress(2) $\leq$ 330 MPa	6.6 g	72%	330 MPa	0.1 mm
B1	Min Compliance	Vol Frac $\leq$ 15%	15.8 g	33%	243 MPa	0.03mm
B2	Min Compliance	Vol Frac $\leq$ 6.2%	6.6 g	72 %	303 MPa	0.09 mm

(1): compared to the original connecting rod weight of *23.5g*
(2): von Mises stress
(3): maximum total displacement result of finite element analysis

5. CONCLUSIONS

The optimization problem defined as "case B2" lead to the best result. The mass reduction is 72%, the same of "case A". But, the von Mises stress is 9% lower and maximum total displacement is 10% lower. The comparison of the results of "case B1" and "case B2" shows how important is defining the right volume fraction constraint.

Defining the volume fraction for "case B2" by the solution of "case A" optimization problem leads to a better result of the conrod design. This approach needs more computing and time, because two optimizations problem need to be solved. In the other hand it assures that the volume fraction definition is well defined for the conrod optimization considering the load steps, material and manufacturing constraints. Indirectly this approach consider both mechanical requirements of the conrod, that are stress and stiffness.

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