

Weight Optimization of a Landing Gear Steering Collar using Tosca in Abaqus

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Abstract: The adoption of topology optimization as a tool in the design cycle of a landing gear was tested using Tosca in Abaqus. The optimization process was carried out in collaboration with one of the leading landing gear manufacturers. The manufacturer is already a user of CATIA and Abaqus and was interested to see the capabilities of Tosca. To test Tosca's capabilities, a landing gear steering collar which was already in production and had previously gone through several phases of design iterations was used as the sample component. The steering collar weighed 35.155 lb before the optimization and there was little room for further material reduction largely due to multiple contact regions and multiple loading conditions. The manufacturer had chosen the steering collar as a test to see the strengths of Tosca as far as contact nonlinearities and multistep analysis are concerned. The analysis included multiple loading conditions such as oversteer, maximum spin up, and fatigue. Various manufacturing and geometrical conditions were also taken into consideration. Using a combination of CATIA, Abaqus, and Tosca, an optimized steering collar design was achieved with an approximately 19% reduction in mass when compared to the original design of the steer collar. The final mass of the redesigned steer collar was 28.521 lb. The results were well appreciated by the design team of the landing gear and the team is now under consultation with senior management over the adoption of Tosca as a necessary tool in their design cycle.

Keywords: Abaqus Topology Optimization Module, Aircraft, CAE, Design Optimization, Landing Gear, Minimum-Weight Structures, Nonlinear Optimization, Steer Collar, Topology Optimization

1. Introduction

In recent years, there has been a tremendous shift throughout all industries towards building more lean and efficient products. This is especially true for the aerospace sector, where efficiency plays a major role in design and performance. This shift towards efficiency is due to a combination of economic and environmental concerns. While most industries are subject to stringent environmental regulations, the aviation industry has not had much restrictions on pollutant emissions. A study by the European Commission, showed that the aviation emissions in Europe had more than doubled since the 1990s while the total emissions have slightly declined (Runge-Metzger, 2011). As a result, most efforts to build efficient and light aircraft have been dictated by economic and engineering needs. Profit margins of airlines have been declining over the years and studies suggest that the decline may be in part due to the fluctuation of fuel prices in the market. By building lighter aircraft, fuel costs for airlines can be reduced. The use of FEA-based

optimization techniques allow aircraft manufacturers to innovate and look at more efficient ways to create aircraft components which are both reliable and light.

Many aircraft manufacturers today are already focused in creating lighter and more reliable aircraft components. The use of composites in aircraft manufacturing has helped bring down the total weight of the aircraft and thus improve its fuel efficiency. In 2014, fuel costs accounted for over 31% of the operating costs of airlines (International Air Transport Association, 2015). Each kilogram of weight saved on an aircraft can result in a cost savings of \$750 - \$1500 over the life of an aircraft (Lee, 1992). The use of composite materials in the landing gear however is restricted, due to the loading and manufacturing restrictions of landing gear components. In order to reduce the weights of landing gear components, the parts have to be redesigned so that they have the most optimal shapes. Optimal shapes of components may be created by building on lessons learned from existing components in service and from lab testing. However, such optimization processes can be costly and time-consuming. Furthermore, some optimal solutions may not be easily apparent in physical testing of components. Finite element software like Abaqus do provide the platform for carrying out virtual testing, however it may be impractical to explore all possible design options even in a finite element analysis (FEA). FEA-based optimization techniques can help in the determination of the most optimal load paths based on different loading, geometry, and manufacturing conditions. Low weight aircraft components can also help pave the way for cleaner engines and alternate sources of propulsion for aircraft.

In the study presented in this paper, the Tosca module available within Abaqus/CAE was used to optimize a landing gear steering collar, so that the benefits of topology optimization in aerospace can be evaluated. The steering collar was a good candidate for this study as it posed challenges from an analysis point of view, including multiple contact regions, manufacturing restrictions, and geometric restrictions. The optimization techniques presented in this paper can be used to optimize other more simple components of the aircraft.

1.1 Steering Collar

The steering collar is a critical component of the nose landing gear of an aircraft. Its purpose is to provide on-ground steering of the aircraft. Steering is transmitted to the collar through the use of two hydraulic actuators. When not engaged the steering system also provides automatic shimmy damping.

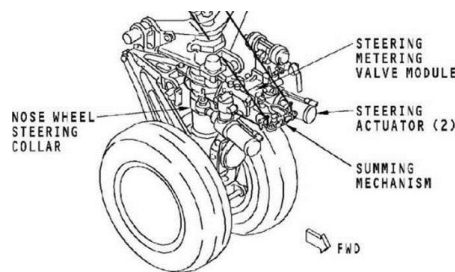


Figure 1. Boeing 737NG nose wheel steering system (The Boeing Company, 1997).

As can be seen in Figure 1, the steering collar has multiple contact regions, which must be accounted for in any finite element analysis and optimization study. The steering system (excluding the steering collar) was simplified for the purposes of this study. The FEA results of the simplified assembly were first validated with test results to ensure that the simplifications were within reasonable bounds. These simplifications were made due to time constraints. An analysis on a fully detailed assembly of the landing gear would have been too time consuming. The steering collar used in the study is already in production and being used on one of the latest long-range passenger jets. The model of the steering collar used in the study accurately represented the one currently in production.

Table 1. Material and mass information for the production steering collar.

Material Information	Original Mass
Name: Ti-6Al-4V Young's Modulus: 16542 ksi Poisson's Ratio: 0.31	35.155 lb

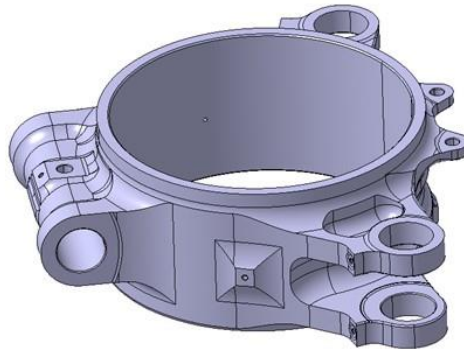


Figure 2. The CAD model of the production steering collar is shown above.

1.1.1 Loading Considerations

The landing gear has to be tested for multiple loading conditions, involving both static and dynamic events. However, topology optimization software currently only support static analyses.

Thus the loadings taken into consideration included static loads experienced during landing, turning, and braking. Four different scenarios were considered.

1. Maximum spin-up (critical case)
 - a. A push force (aft direction) of 37.191 kip was applied to the right hydraulic actuator
 - b. A pull force (nose direction) of 37.191 kip was applied to the left hydraulic actuator
 - c. A lateral force (left) of 5.579 kip was applied to each hydraulic actuator
2. Oversteer (abuse case)
 - a. A pull force of 41.634 kip and a lateral force (left) of 86.946 kip was applied to the right hydraulic actuator
3. Regular operational load 1
 - a. A pull force of 4.847 kip and a lateral force (right) of 4.471 kip was applied to the left hydraulic actuator
4. Regular operational load 2
 - a. A push force of 8.025 kip and a lateral force (right) of 15.224 kip was applied to the right hydraulic actuator

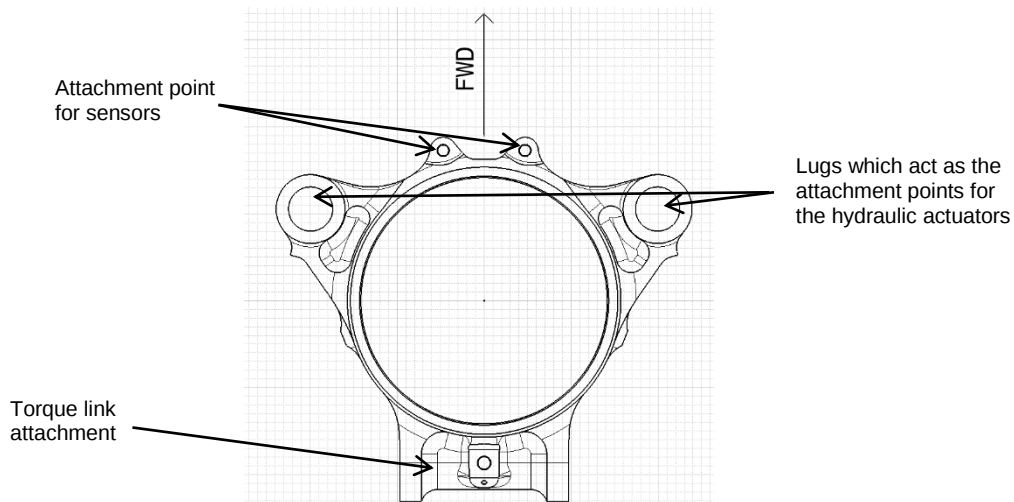


Figure 3. The FWD represents the direction towards the nose of the aircraft. The circular features located on the extreme left and right of the collar are the attachment points of the hydraulic actuators. The aft most feature represents the attachment point for the upper torque link.

1.1.2 Manufacturing and Geometry Considerations

The steering collar is machined from a forged part. To keep costs low, similar radii should be used for rounded features of the collar so that tool changes can be minimized. Furthermore, transitions between radii must be kept to a minimum. The Federal Aviation Administration (FAA) requires all FEA results to be backed by analytical methods or physical tests (Federal Aviation Administration, 2016). In order to perform classical analysis, the section cuts of the steering collar must represent fairly simple geometrical sections.

2. Baseline Finite Element Model and Results

Before the optimization study, a finite element model (FEM) of the production steering collar was created and analyzed. This was done to examine the stress distribution on the steering collar and to determine the validity of the model. The results were validated with those observed in physical testing.

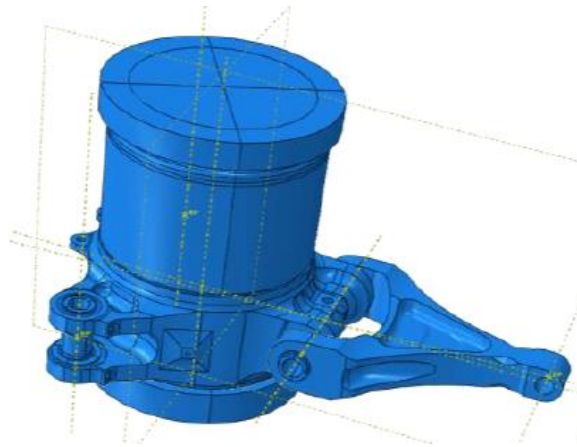


Figure 4. The steering collar is shown with the simplified landing gear assembly.

The steering collar was represented using a fine mesh of linear tetrahedron (C3D4) elements in Abaqus/CAE. Linear tetrahedron elements were chosen to reduce computational time. For the purposes of topology optimization, load paths are important rather than the magnitudes. Fairly coarse meshes were used for other components of the landing gear assembly to reduce computational time. Tangential and normal frictional behaviors were defined for the contact regions in the model. For tangential frictional behavior, the penalty formulation available in Abaqus 6.14 was used, while the hard contact pressure-overclosure relationship was used for modeling normal contact. Contact stabilization was used in areas where convergence issues were expected. Oversteer case described previously was used as the loading scenario. The results for the baseline model corresponded well with the observed results.

3. Optimization Process

Two types of optimization techniques currently exist in the industry, namely, parametric and non-parametric optimization. Parametric optimization techniques generally employ the use of statistical methods to obtain a solution. SIMULIA's Isight is an example of a parametric optimization software. Non-parametric optimizations when applied to FEA, use finite element results to drive the optimization process. The Tosca interface available within Abaqus 6.14 allows topology, shape, and sizing optimizations. For the results presented in this paper, the topology optimization module was used inside Abaqus/CAE.

In the design of a component, topology optimization should be done in the preliminary stage of the design cycle. Once the loads, boundary conditions, material, and design envelope of the part have been determined, optimization can be performed. Early optimization of parts helps reduce the chances of changes later in the design cycle. The intent of the topology optimization is to obtain an optimal shape of the part. This shape can then be refined to design and build a production part.



Figure 5. Suggested design flow with topology optimization.

3.1 Topology Optimization in Abaqus

The topology optimization module in Abaqus 6.14 allows the determination of optimal load paths in a structure using FEA results. Given an initial volume of material subject to various loading conditions, Tosca in Abaqus will produce a new volume by scaling the relative material densities of elements in the original design domain. Elements with low relative material densities are treated as voids while elements with high relative material densities are treated as filled. The final configuration can then be used to drive the design of the optimized shape.

Two types of algorithms can be used for topology optimization in Abaqus, namely, condition-based and sensitivity-based. The sensitivity algorithm is more generic and has the capability of considering a large number of constraints and objective functions. For the optimization study on the steering collar however, condition-based algorithm was used. The condition-based algorithm is efficient and was sufficient for the purposes of this study.

With the condition-based algorithm, the only objective function available is compliance. By minimizing the compliance, the maximum possible stiffness can be achieved (Dassault Systèmes, 2014). The final desired volume of the material acts as a constraint and it may be defined as a fraction of the original material volume. Furthermore, loading, manufacturing, and geometrical constraints can be added to the definition of the optimization task.

The topology optimization module within Abaqus/CAE uses Abaqus as the FEA solver and Tosca for topology optimization. In each optimization iteration, an Abaqus solve is first performed, followed by an optimization run. The optimization process then repeats this Abaqus-Tosca process until the desired volume constraint is reached. Once the objective is achieved, the results can be extracted and the new topology can be created. Topology optimization results are generally very coarse and require reconstruction of the part in a CAD software such as CATIA V5.

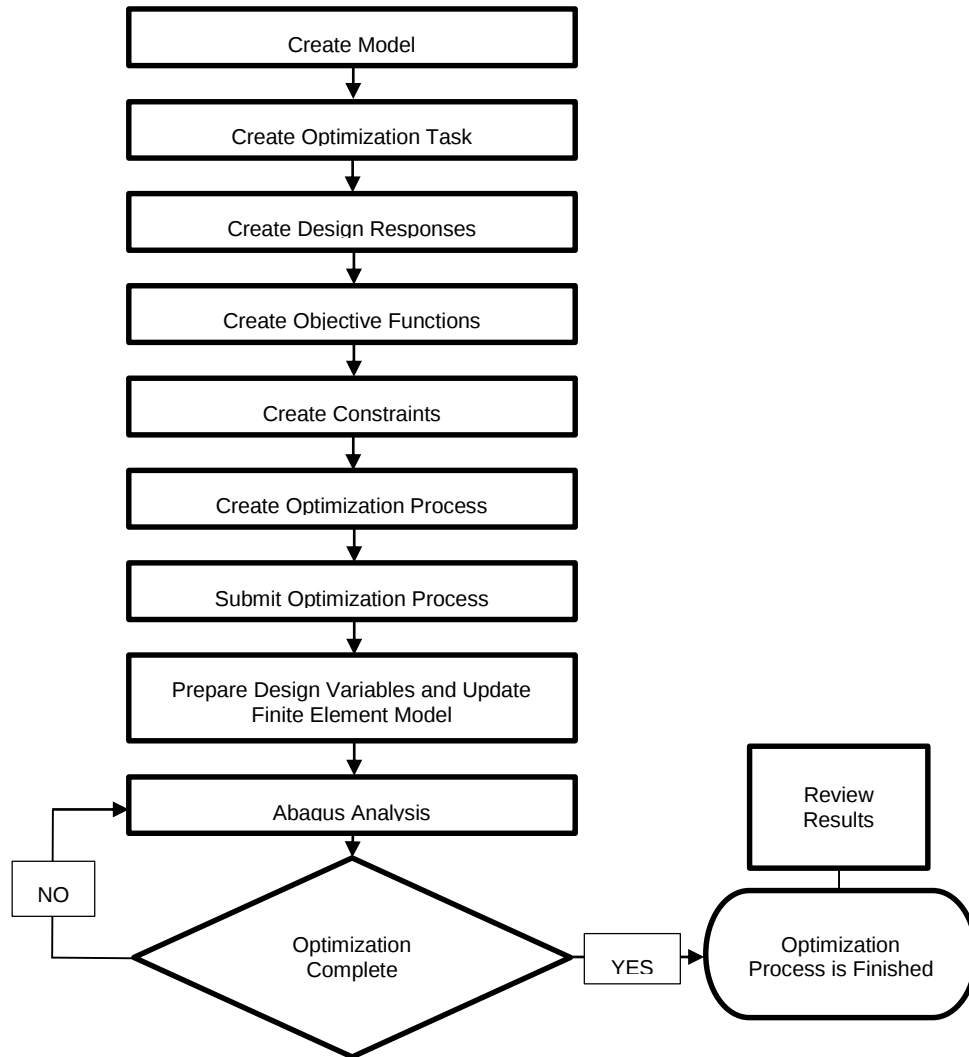


Figure 6. Optimization workflow for Tosca topology optimization in Abaqus (Dassault Systèmes, 2014).

4. Optimization Methodology for the Steering Collar

The optimization study was divided into two parts. In the first part, the existing steering collar design was used for optimization. This part of the study was done to determine whether there is room on the existing design for weight reduction. Oversteer loading condition was used in this section of the study. CAD reconstruction was not done for this part of the study.

The design flow described earlier in Figure 5, suggests that optimization should be performed in the beginning stages of the design cycle. Thus, in the second part of the study, a design envelope for the steering collar was used (Figure 7). This design envelope had the same interfaces as the production steering collar. However, the volume space where material could theoretically be present, was retained. The four different loading conditions described earlier were used in the optimization study. Optimization runs were first performed for each of these loading conditions independently. Finally, the four loading conditions were considered simultaneously. The results of the final optimization task involving the four loading conditions considered simultaneously were then exported to CATIA V5 through Tosca GUI. A CAD model was then reconstructed taking into account the manufacturing and geometric limitations. The resulting CAD model was then imported into Abaqus/CAE and a validation run was conducted to ensure the validity of the results. The results of independent optimizations were also compared with the result of simultaneously considered loading conditions. This was done to determine which loading case was dominant in the optimization process.

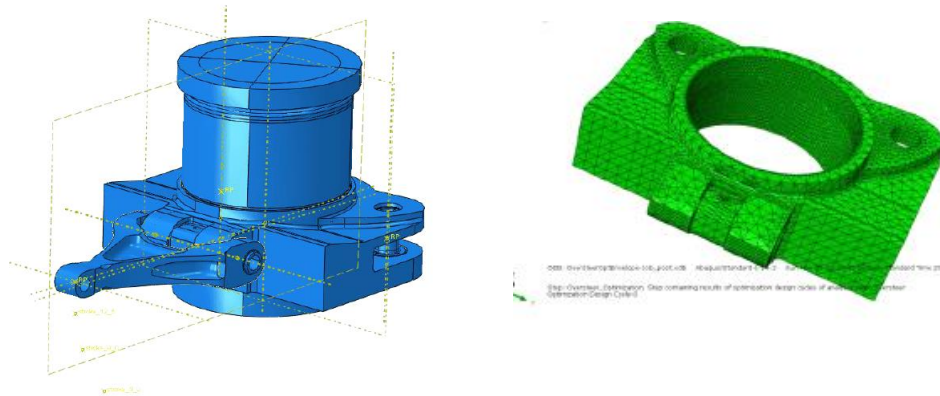


Figure 7. The figure shows the steering collar design envelope configuration.

With condition-based optimization, approximately 15 iterations are recommended to achieve convergence (Dassault Systèmes, 2014). However, in order to reduce computation time a maximum of 10 iterations were allowed per optimization task.

Table 2. Topology optimization parameters.

Objective function	Minimize strain energy / compliance (maximize stiffness)
Volume constraint	60% of original production volume (for first study) 19% of original envelope volume (for second study)
Geometrical constraint	Symmetry about longitudinal axis of the aircraft. All loaded areas, regions with boundary conditions applied, and contact regions were defined as frozen regions. Furthermore, the lubrication holes were also frozen as their locations are carefully determined based on maintenance studies. Frozen areas are excluded from the optimization process such that the elements included in the frozen areas cannot be eroded or represented as void. However, these elements still contribute to the analysis by carrying and transmitting loads.
Manufacturing constraint	Forging constraint was applied to ensure no undercuts were present in the optimized solution.
Maximum iterations allowed	10 iterations were chosen for computational reasons. Each iteration took approximately 75 minutes to complete on 8 cores.

5. Optimization Results on Production Steering Collar

The optimization task successfully completed in 10 iterations. Validation runs showed that the optimized part did not exceed the maximum allowable stress for the oversteer case (120 ksi). Attempts to run the optimization task again with less than 60% of the original volume failed.

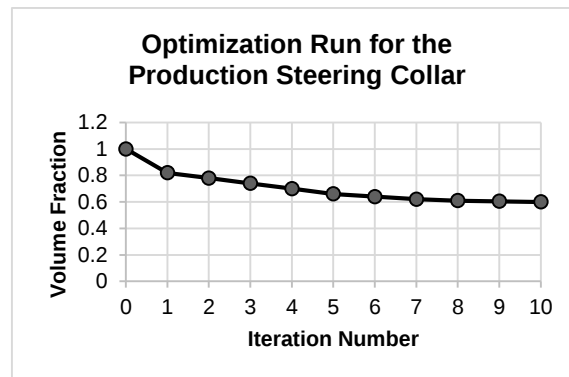


Figure 8. The progress of the optimization task for the production steering collar.

The results showed that the thickness of the steering collar around the main cylinder of the landing gear had excess material. This suggested that the thickness of the steering collar walls could be reduced considerably. Further, it showed that the lugs which act as attachment points for the actuators, could be made thinner. The lug attachments were also significantly optimized and had excessive material removal. In comparison with the non-optimized collar, instead of having a fillet for reducing material on the lug attachments, there was a cavity. It must also be noted that although the optimized shape showed significant reduction in mass, it was not practical. Two sensor attachment points located near the front of the steering collar were shown as detached from the main part Figure 9. This is because no loads were applied to the attachment points and thus the sensor attachments were excluded from any load path. Furthermore, the variable sections on the lugs and main cylinder would not be feasible from a manufacturing point of view. The torque link attachment area (aft section of steering collar) showed cavities, which from a manufacturing point of view would be unfeasible currently. Thus considering the material that would have to be added back to make the optimized result feasible to manufacture and certify, it was determined that the solution obtained for the production steering collar would not be of much difference from a weight point of view to the production steering collar.

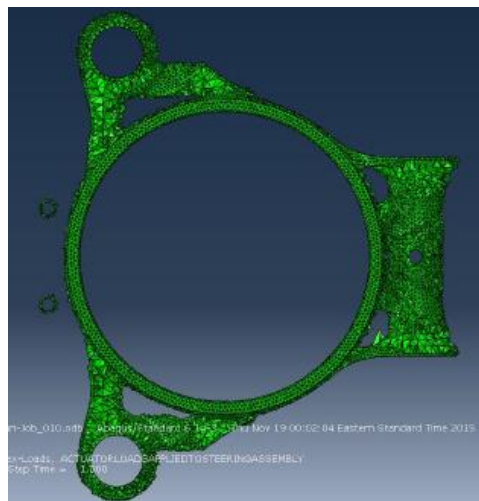


Figure 9. The optimized shape for the steering collar is shown. The two circular frozen regions in the left of the image above are attachment points for sensors.

6. Optimization Results on Steering Collar Envelope

The optimization tasks (four independent) and one coupled all completed successfully. Further optimization attempts below a volume fraction of 0.19 were unsuccessful. It must be noted that the sensor attachments described previously, were not frozen for this part of the study. However, they were added later on during the CAD reconstruction of the steering collar. Results for oversteer and

the two regular operational load cases were similar to the one obtained in the optimization study conducted on the production steering collar. However, more material was observed near the aft of the steering collar (close to the torque link).

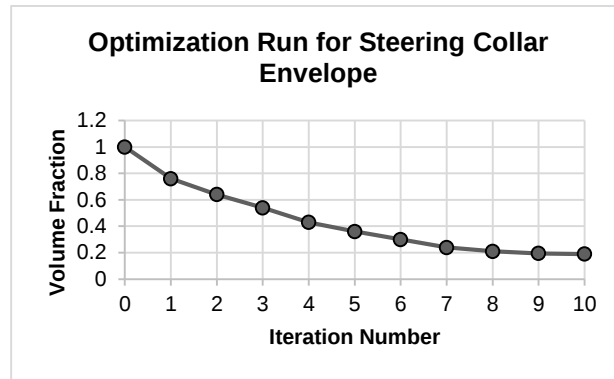


Figure 10. The progress of the optimization task for the steering collar envelope.

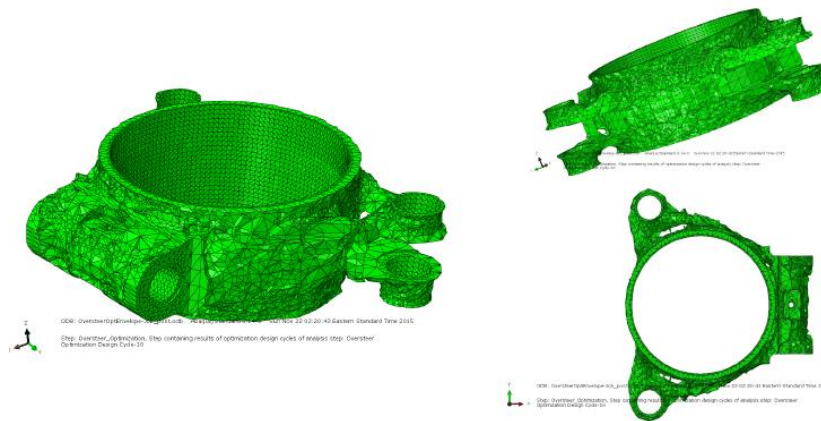


Figure 11. Optimization results from oversteer and regular operational load cases on the envelope.

The maximum spin-up case showed a significantly different solution than the production collar. The lug attachments were found to be reduced by nearly half. Furthermore, the lug attachments pointed solely towards aft of the aircraft. By comparison, the results for oversteer and regular load optimization cases showed that lug attachments were built up more towards the front of the collar (towards the nose of the aircraft). Similar to oversteer and regular operational load cases, more material was found towards the aft of the steering collar, near the torque link attachment.

Validation runs on all optimized shaped showed that the stresses were within the maximum allowable values.

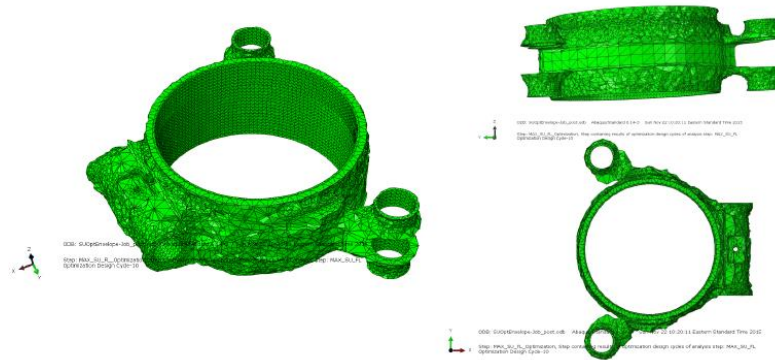
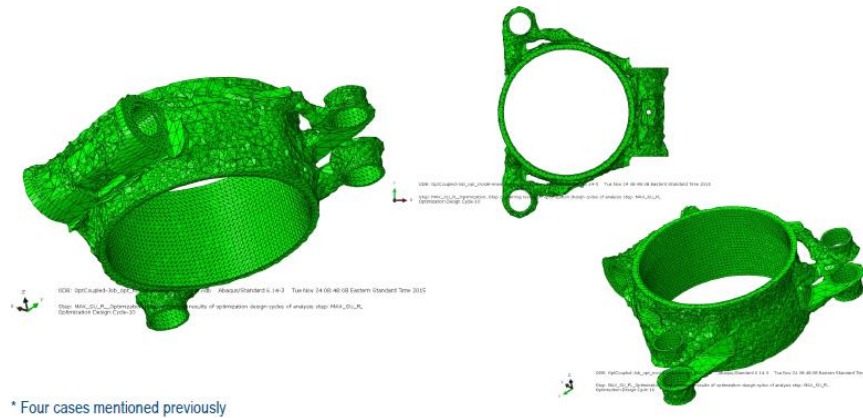


Figure 12. Optimization results from the maximum spin-up case on the envelope.

The results for the optimization task which comprised of all four load cases showed an optimized solution which seemed to be driven primarily by the spin-up and oversteer loading scenarios. This was expected as both cases had significantly higher loading magnitudes than the regular operational loads. The result of this combined load case optimization was quite significant. The optimized solution showed different lug attachment shapes for the top and bottom sections. Furthermore, it was observed that for the optimization based on all scenarios, the material distribution was more uniform from aft to forward when compared to the individual loading cases.



* Four cases mentioned previously

Figure 13. The optimization result for four cases considered simultaneously.

The results were smoothened using Tosca.Smooth inside Tosca GUI. The smoothed results were then exported to CATIA V5 and reconstructed. Material was added in many areas to account for manufacturing challenges. Furthermore, simple and uniform geometrical sections were used so that the FAA requirement of using classical analysis for certification may be satisfied. The reconstructed geometry was then imported back into Abaqus/CAE and validated. The validation results confirmed that the new steering collar design did not exceed any of the stress allowable.

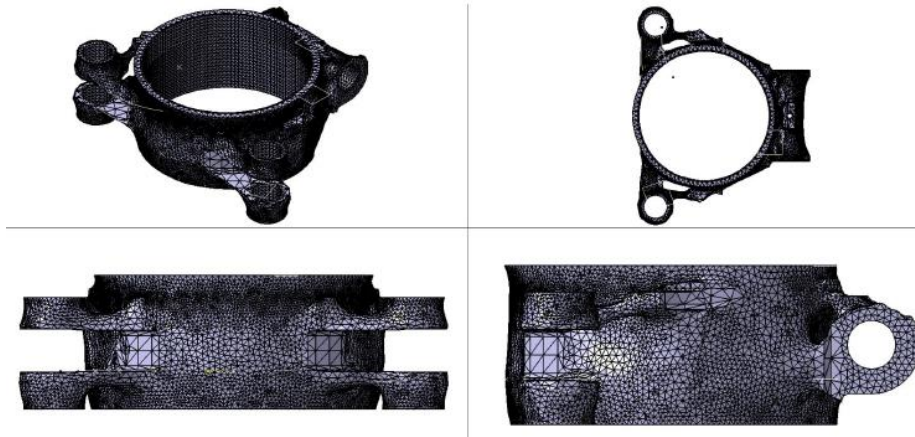


Figure 14. Smoothened results inside CATIA V5.

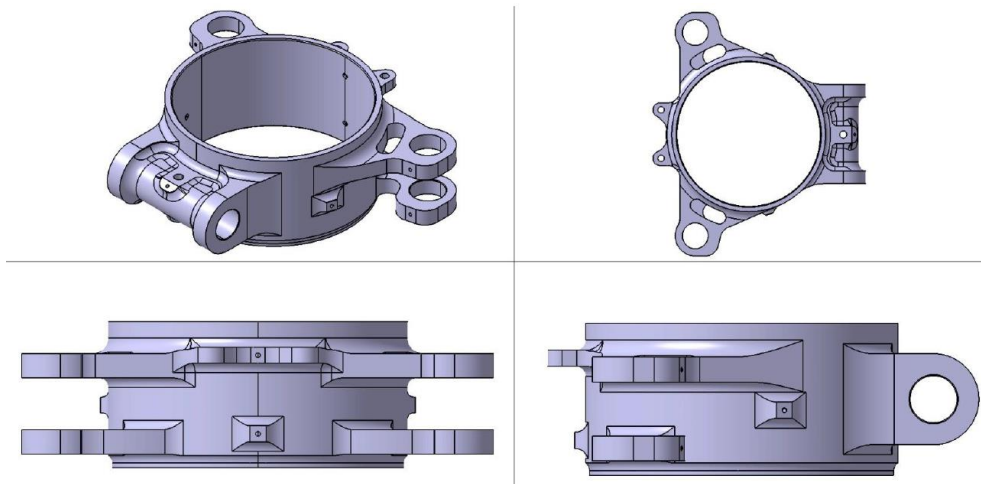


Figure 15. Reconstructed steering collar based on optimization results.

Significant geometry modifications were performed on the optimized shape. In Figure 15 the lubrication holes can also be seen, raised a few units from the main structure (for accessibility reasons). Furthermore, the two sensor attachments in the forward area of the collar were added so that a fair comparison with the production steering collar may be made. The torque link attachment section was kept largely similar to the one on the production collar due to its already optimized shape. The reconstructed steering collar had a mass of 28.521 lb.

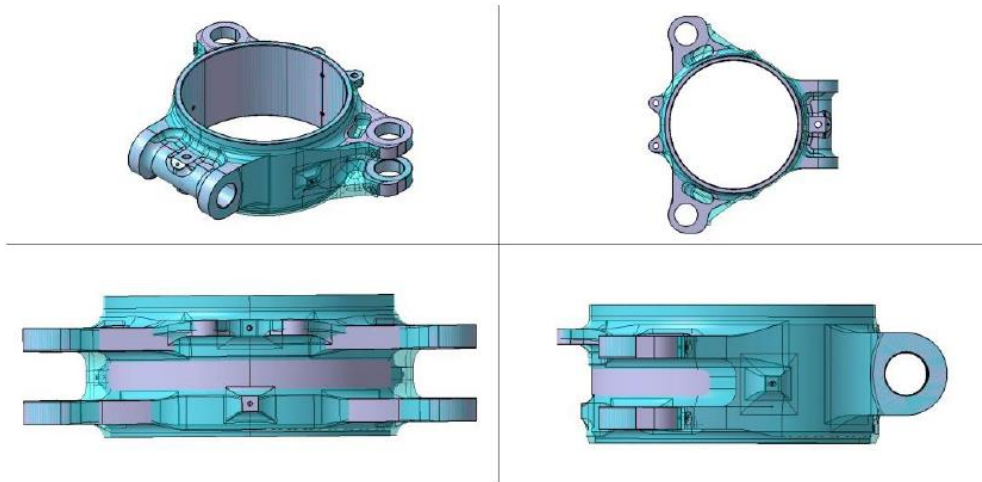


Figure 16. Overlay of production steering collar and optimized steering collar.

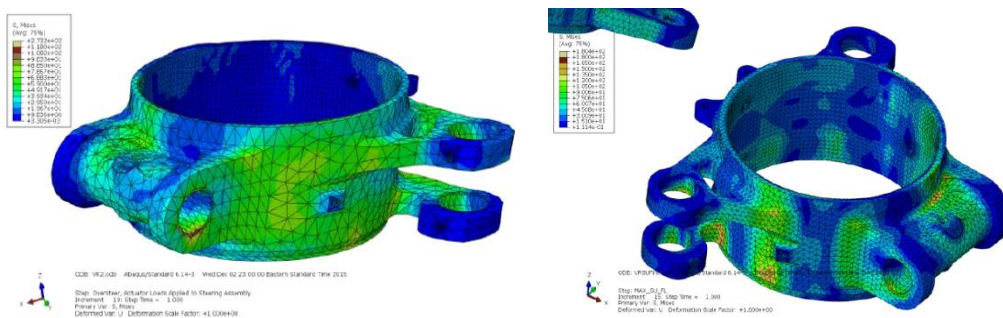


Figure 17. Two validation tests were done using oversteer (image on left) and the spin-up (image on right) loading conditions. The maximum allowable stress in each test was 120 ksi and 180 ksi, respectively. Both tests showed that the optimized part did not exceed the given limits.

7. Conclusions

A series of optimization workflows were outlined in this paper, with the goal of evaluating the impact of topology optimization applied to aerospace components. The optimization study results suggested that the best time to perform topology optimization is during the preliminary stages of the design cycle. It also showed that Tosca in Abaqus can handle several complex loading conditions simultaneously for the purposes of optimization. It was noted that optimization results can vary significantly based on the types of loads and boundary conditions being applied and thus it is suggested that multiple loading conditions must be applied simultaneously so that all load paths are considered in the optimization. The production steering collar studied in this paper weighed 35.155 lb, while the optimized, redesigned, and validated steering collar weighed 28.521 lb. Thus, a 19% reduction in mass was obtained. The study shows that topology optimization can be used successfully to design lighter, more efficient aircraft components. To further benefit from optimization, the optimization loop may be tied in with fatigue software, so that the part is also optimized for durability.

8. References

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