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A CAD based framework for optimizing performance while ensuring assembly fit

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Abstract. The optimization of an individual component usually happens in isolation of the components it will interface with or be surrounded by in an assembly. This means that when the optimized components are assembled together fit issues can occur. This paper presents a CAD-based optimization framework, which uses constraints imposed by the adjacent or surrounding components in the CAD model product assembly, to define the limits of the packaging space for the component being optimized. This is important in industrial workflows, where unwanted interference is costly to resolve. The gradient-based optimization framework presented uses the parameters defining the features in a feature-based CAD model as design variables. The two main benefits of this framework are: (1) the optimized geometry is available as a CAD model and can be easily used in the manufacturing stages, and (2) the resulting manufactured should be able to be assembled with other components during the assembly process. The framework is demonstrated for the optimization of 2D and 3D parametric models created in CATIA V5.

Keywords: Optimization, Industrial Product Design, CAD systems.

1 Introduction

With advances in the field of computers and their progressive use within the industrial design process, the need for costly physical design prototypes has been extensively reduced and replaced with that for digital models which are constructed and analyzed using computers. Nowadays product design typically starts with the construction of a computer-aided design (CAD) geometry of an initial concept, and the goal is to deliver an optimized and validated geometry as a CAD model. If this is achieved the optimized model can then be directly used for downstream applications including manufacturing and process planning.

In recent years, optimization has become an essential part of an industrial design process. However, optimization is usually performed on a component by component basis. Modern CAD systems like CATIA V5, SIEMENS NX, Solidworks etc. uses feature-based modelling strategies to create a parametric CAD model. Also, feature based

CAD systems use many parameters when defining the shape. Even simple models can have tens or hundreds of parameters, while complex models can have thousands. Therefore, in many processes, the shape of the component is extracted from the CAD systems to be optimized.

However, CAD systems provide significant advantages to companies in the way they capture and unify design information. One good example is how they enable designers to create relationships between parts or assemblies to enforce their design intent on how the products fits together, or in how they can be used to feed manufacturing simulation processes. This means that if the model has been extracted from the CAD system for optimization, it is necessary to bring it back into the CAD system to realise these bigger advantages. This process can be complex for some optimisation processes (e.g. mesh based approaches [1]), and to reassociate an externally optimized geometry with a set of CAD features and parameters is virtually impossible, and if required has to be created from scratch.

In general, mechanical design processes are not only driven by performance but are also subjected to constraints. Often constraints are performance based, e.g. Walther and Siva [2] presented an adjoint-based shape optimization for a multistage turbine design, with the objective to maximize the efficiency while constraining the mass flow rate and the total pressure ratio. Kontoleon et al. [3] presented a constrained topology optimization approach for ducts with multiple outlets, where the flow constraints are in-forced at each outlet defining the volume flow rates, flow direction and/or mean temperature of the outgoing flow. Sometimes constraints can be geometric, for example Shenren et al. [4] presented an approach employing a set of test points to impose the thickness and trailing edge radius constraint for the optimization of a nozzle guide vane. However, one important constraint from a manufacturing perspective is fit within the packaging space defined by the adjacent or surrounding components in an assembly.

Since different components are designed and optimized by different engineers, simultaneously to and in isolation from the components adjacent to them in an assembly, when the components are assembled together, issues such as fit often occur. The consequence is the need for engineering changes late in the product development cycle [5], or rework of the manufactured parts. Either is undesirable, therefore it is important for designers and manufacturers to devise methods to ascertain that the designed component can be assembled within the space available, before the actual component is released for manufacture. Current approaches to achieve this are to specify bounds on parameter ranges acceptable for individual parameters [6], but these bounds can become outdated quickly as all of the components in the assembly are refined.

In modern CAD systems it is possible do the assembly of components, creating a digital mock-up (DMU). Interference checking can be carried out on the DMU within the CAD environment. Some of the early works in the field of interference detection between two solids were found in [7]. Recent developments in this field included the works in [8], which enable interference detection directly using CAD models. Zubairi et al. [9] developed a sensitivity approach to eliminate any interference in a 3D CAD assembly, by identifying which parameters defining the CAD features need to be modified, and by how much, to eliminate interference. The approach is effective in this role

(eliminating interferences), but the effect of the resulting shape change on the performance of the individual components was not considered, meaning that the process of eliminating interference could also reduce the performance of a products, or even make it unsuitable for its role.

In this paper, a framework is described which will optimize a component in terms of its performance, but will consider the constraints on packaging space imposed on the system due to adjacent or surrounding components in a CAD system. The developed approach is demonstrated on 2D and 3D parametric CAD models built in CATIA V5 and assembled with other components in CATIA V5 assembly workbench. ABAQUS CAE is used for solving structural mechanics problems, Helyx solver provided by ENGYS [10] is used for flow simulations, and Python 3.5 is used as the programming interface.

2 Background

2.1 Adjoint methods

The key issue with optimizing models with many parameters is the high computational cost, however this can be mitigated with the use of gradient based optimization. The focus of this work is optimization using adjoint methods, enabling the computation of gradients at a cost which is essentially independent of the number of design parameters. The underlying theory and implementation of adjoint methods is well documented in literature [11, 12]. In Fig. 1 the contours shown are surface sensitivity, ϕ , which represents the change in overall performance which would be caused by a small localized movement of the boundary. For the model in Fig. 1, pulling the model boundary outward in red regions or inward in the blue regions will improve performance. The reverse movements will reduce performance.

Fig. 1. Adjoint sensitivities map: to minimize the objective function the surface should be pulled out at positive values and pushed in at negative values

Typically, the adjoint is computed as a separate load case after the primal solution, and many adjoint solvers provide ϕ as an output. Once the adjoint sensitivity information is available, the change in performance dJ due to changes in the values of the CAD parameters $d\mathbf{P}$, can be predicted as

$$dJ = \phi \frac{d\mathbf{X}_s}{d\mathbf{P}}. \quad (1)$$

$d\mathbf{X}_s$ is the change in the position of the mesh nodes caused by a change in the parameter values $d\mathbf{P}$.

2.2 Design velocity

Design velocity, V_n , is the normal component of the movement of the boundary of a model caused by a parametric perturbation. In this work design velocity is computed for the CAD model, and interpolation used to compute the change in position of the surface nodes sitting on the boundary. Therefore

$$V_n = \frac{d\mathbf{X}_s}{d\mathbf{P}} \cdot \hat{n}, \quad (2)$$

where $\hat{n}$ is the outward unit normal of a point on the surface of the model.

Fig. 2. Parametric CAD model, (b) vector representation of design velocity

Fig. 2(a) shows CAD model of a cylinder in solid yellow, where the location of the bottom of the defining sketch is defined to be at the origin. The transparent shape superimposed is the model after the radius defining the cylinder is changed from 25mm to 26mm. In Fig. 2(b), the arrows represent the design velocities as the boundary changes from the original to the perturbed model. The convention adopted throughout this work is that a positive design velocity represents an outward movement of the boundary, and negative is inward. The approach used in this work for calculating design velocity is developed by [13], and is applicable to any feature-based CAD modelling package.

2.3 Gradient Computation

For the optimizer to establish a new search direction it is necessary for the gradient to be evaluated with respect to each design variable. In this case, it means evaluating the change in objective function, dJ , and the constraints due to a perturbation of a CAD parameter, $d\mathbf{P}$. This means that for each parameter, i , a sensitivity value S can be computed as

$$S_i = \frac{dJ}{dP_i} = \int \phi V_{n_i} dA. \quad (3)$$

where A is the surface area of the model.

3 Interference detection

Interference occurs when components in an assembly violate each other by attempting to occupy the same physical space. Most CAD systems have interference detection tools, although the name of the function, and the information returned differs from system to system. The interference detection tool in CATIA V5 provides capabilities to obtain the penetration depth between the interfering components, which is described as the minimum distance required to translate a product to avoid interference whereas Solidworks returns the interference volume. In addition, the clearance distance between two components can also be obtained.

Fig. 3. Interference between two boxes in CATIA (a) Interference, (b) Contact, and (c) Clearance

Fig. 3 displays the part-to-part interference detection interface in CATIA V5 which shows if the selected parts are interfering or are in contact or have a clearance between them. In this work a negative value of interference represents the clearance between components. For this work the main requirements is to automatically compute the amount of interference between the CAD model being optimized and other components in the CAD model assembly. This is obtained using the CAD system API, which is configured to compute the interferences between the component being optimized and the other components in the assembly.

At each optimization step, the developed CAD system API records the interference values which are used as constraints on the optimization. The other requirement is the computation of gradients of each interference value with respect to the parameters used to define the CAD model. So, to compute the gradients of constraints, each parameter of the CAD model is perturbed by a small amount, and the interference tool is used to obtain the interference values between the component being optimized and the other components. The respective gradients of the constraints are then obtained using a finite difference method.

4 Optimization framework

In this work a gradient based optimization framework has been developed with the CAD system at its center. The adjoint based optimization process is used to guide the design towards a local optimum over multiple optimization steps.

Fig. 4. CAD-based optimization using constraints from assembly components

A general optimization can be defined as:

$$\begin{aligned}
 &\text{Minimize:} && \text{objective function,} \\
 &\text{Subject to:} && \text{interference} < 0 \\
 &\text{Design variables:} && \text{vector of CAD parameters}
 \end{aligned}$$

In this work, the CAD models are created in CATIA V5 and optimized using Sequential Least Square Programming (SLSQP) method implemented in Scipy. The optimization process (Fig. 4) is implemented using Python 3.5.

5 Results

In this work, the use of assembly constraints during optimization is demonstrated for two test cases. One is for a simple cantilever beam, while the other is for the optimization of an automotive ventilation duct.

5.1 Cantilever Beam optimization

The first test case is a cantilever beam loaded at one end. The optimization is a compliance minimization problem, therefore the objective function for this test case is to minimize the strain energy. This type of problem is self-adjoint, meaning that a special adjoint solver is not required to compute the surface sensitivities. Here the contours of strain energy density on the surface of the model indicate the change in strain energy in the component that can be achieved by moving the boundary.

The beam's geometrical configuration, the loading applied, and boundary conditions are shown in Fig. 5(a). The top edge of the beam is defined by a Bézier curve with four control points, while the bottom, left and right edges are defined using straight lines. The beam is modelled in CATIA V5. In the initial geometrical configuration, the strain energy density (adjoint sensitivity) is higher at the left-hand corners of the beam as shown in Fig. 5(b). This means that when minimizing strain energy, the geometry is

expected to move outward in that region. A constant volume constraint was also imposed for the test case to ensure the model did not grow indefinitely (as an objective of minimizing compliance would encourage).

Fig. 5. (a) Cantilever beam with boundary conditions, (b) strain energy density plot

The optimization of this component was carried out twice. For the first optimization there was no constraint imposed on the packaging space for the component. For the second optimization a rectangular box was added representing an adjacent component, restricting the amount of outward movement possible by the top edge, Fig. 5(a).

Fig. 6. Optimized cantilever beam with (a) constant volume constraint, (b) assembly constraints

Fig. 7. Optimization history for cantilever beam

The optimization results are shown in Fig. 6 and Fig. 7. The optimization without the constraint on packaging space Fig. 6(a) has resulted in the expected thickening of the left-hand side of the beam, and a subsequent narrowing of the right-hand side to maintain the overall volume of the model. It is obvious that this has caused the boundary to

move outwards in the regions of highest strain energy density (remembering that the bottom edge is constrained to be a straight line). In the other optimization, Fig. 6(b), it is apparent that the outward movement of the model is restricted due to the presence of the block component. As a result, the optimizer finds a different solution and as shown in Fig. 7, this results in comparatively lower reduction in the strain energy of the beam. It should be noted that the optimized model in Fig. 6(a) would have interfered with the block component by approximately 8mm.

5.2 S-Bend optimization

An automotive ventilation duct is shown in Fig. 8(a). Components such as this are highly constrained in terms of the shape they can adopt due to the number of different vehicle sub-systems they are assembled adjacent to. In this test case a subsection of the duct is optimized. The parametric CAD model of the so-called S-Bend section is created in CATIA V5, with representative assembly components also created in the CATIA V5 assembly workbench as shown in Fig. 8(b). Here, the two cylindrical components are used to represent different components in the assembly that constrain shape optimization of the S-Bend boundary.

The S-Bend was modelled using eight 2D sketches at different positions and orientations along the length of the duct, with multi-section solid features passing through these sketch profiles. The duct is composed of three individual sections i.e. inlet, S-Bend and outlet as shown in Fig. 9(a). As the inlet and outlet ducts will join with other components their shape is fixed, so they are not considered for optimization. Here the optimization variables are the parameters defining the four sketches (shown in broken lines in Fig. 9) describing the interior profile of the S-Bend (48 parameters).

Fig. 8. (a) Automotive airduct [14], (b) S-Bend assembly with other components

As with the cantilever beam, this optimization was carried out with and without the constraints imposed by adjacent components. Where these constraints were considered, the location of assembly components (shown in Fig. 8(b)) were selected such that they would restrict the shape change in the regions suggested by adjoint sensitivity contours. They are created such that in its initial state the two cylinders are adjacent to the S-Bend with clearance distances of 1.03 mm and 0.53 mm. After optimization a reduction in power-loss of 8.35% was achieved for the S-Bend with the assembly constraints in place, compared to 10.14% achieved when optimized without any constraints imposed

by adjacent components. However, the unconstrained optimization result would have interfered with these components by 2.4mm and 0.38mm respectively, should assembly have been attempted.

The optimization history for minimizing the objective function is shown in Fig. 9(b). It should be noted that in the optimization subject to the assembly constraint, at iteration-7 of the optimization, the geometry is in interference with one of the parts in the product assembly. To remove the interference the optimizer moves the geometry such that an increase in objective function is observed.

Fig. 9. (a) CAD model of S-Bend duct, (b) Optimization for S-Bend with assembly constraint

6 Discussion

In this paper, an efficient approach to shape optimization with assembly constraints was demonstrated. It ensures fit between the optimized and adjacent components. The optimization framework was configured to exploit the capabilities of CAD DMU to incorporate assembly constraints imposed by other components in the assembly workbench. However, the framework can also be used for models created in other CAD systems to define these constraints.

The developed framework was first applied to the optimization of a simple beam model (analyzed in ABAQUS) constrained by a 2D block in the assembly. The objective function used was minimization of strain energy of the system which was a self-adjoint problem and thus required only one analysis to provide the surface sensitivities. It is interesting to note that for the unconstrained optimization results in Fig. 6(a), the strain energy density in the entire model is the same color. This indicates that for this model there is no further performance improvement possible (without removing the constraint of constant volume). The optimization process was completed in approximately 11 minutes.

The objective of the S-Bend duct optimization was to minimize the power-loss in the duct in the presence of two representative cylindrical components restricting the movement of the duct. These constraints are representative of the actual constraints imposed by the steering column and other mechanical equipment. The developed optimization framework successfully optimized the component without introducing interference during the optimization. The optimization process was completed in approximately 4.5 hrs. It was interesting to note that for both examples, optimizing the models

without considering adjacent components, resulted in optimized shapes which would have caused fit issues when assembly would have been attempted.

7 Conclusion

- An efficient shape optimization framework which includes interference information to ensure fit between the optimised components has been demonstrated.
- The constrained optimization employing the prior information from assembly components was successfully demonstrated for minimizing the objective function without violating the space available for storing other components in the assembly.

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