EXTREME OPTIMIZATION

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ABSTRACT

A method is presented which optimizes solid FE meshes, using MSC.Nastran, linked to a genetic modification algorithm. This technique can work with stress, strain, stiffness or fatigue life modification as the design goal. The algorithm improves designs for many generations to ensure that all design and manufacturing constraints are satisfied. An interesting development has been a facility to optimize the structure with fatigue life as a goal. When this feature is selected, theoretical constant failure over the entire external surface of a component is possible.

Examples are presented demonstrating this radical but effective mass reduction technique, applied to existing designs which were previously considered optimal. Typical mass reductions of 10-25% are not uncommon using the technique with an improvement of the component stress, stiffness or fatigue damage is also introduced.

Keywords : Automotive, Aerospace, Optimization, Fatigue, MSC.Nastran

INTRODUCTION

There are two fundamental variables that influence a successful design :

1. material specification
2. component geometry

At first glance, producing an optimum design should be an easy process to follow, since only two parameters are involved and one of these (material specification), is usually selected early on in the design cycle and is not a variable.

Computer Aided Optimization (CAO) has evolved over many years into mainstream products and is used regularly in the design cycle. These products tend to be biased to the conceptual / definition aspects of the design and do not fully address the significant structural inefficiencies, which can be targeted towards the end of the design cycle. Indeed it can be a refreshing point to perform an optimization, since manufacturing limitations are well understood, load cases are now well defined, and historic boundary conditions removed from the final assessment.

Description of Current Methods

Many different strategies to perform a successful optimization are required. Volumetric methods using element erosion to identify dominant load paths within the structure, followed by parametric dimensioning of solid models to find optimum designs, is an emerging science and has been used successfully for many years [1].

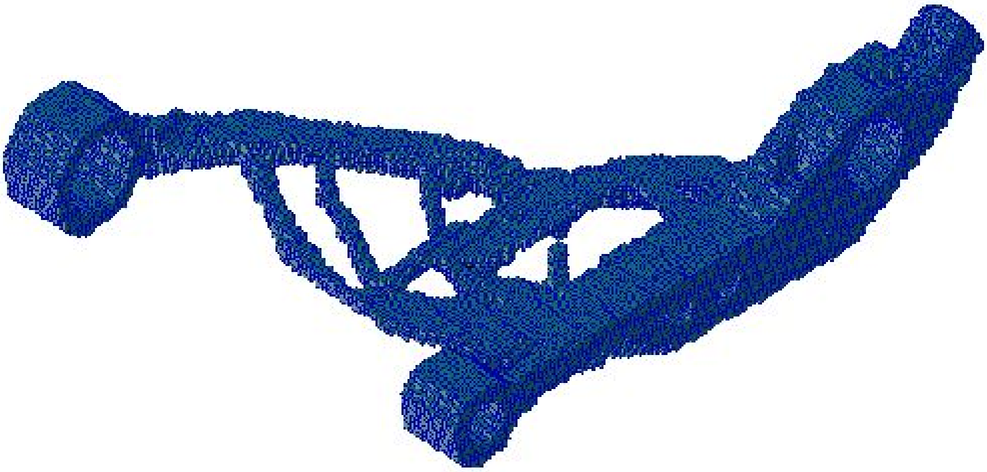


Figure 1 : Example of load path definition at beginning of product definition stage

Structures suggested by these techniques are not directly useful, but require converting back into CAD (Computer Aided Design) solid models considering manufacturing limitations in their construction. A typical project will cycle between the CAD and CAE (Computer Aided Engineering) departments exchanging models and FE (Finite Element) reports. Analysts will attempt to describe areas of the structure in need of improvement or identify potential mass reduction areas. Not all of the suggestions will be embodied in the latest design maintained by the CAD department, since the CAE departments tend to be slow in their deliberations of stating structural acceptability.

An Alternative Approach

It is apparent that the CAD / CAE report driven loop is inefficient. Competent designers with a good understanding of analysis will know how to interpret the FE report and make appropriate adjustments. A culture to 'just add material' to the design to improve performance still exists, with many designers reluctant to remove any identified material. Therefore, a method of supplying the designer with optimum geometry is at the core of the development of an algorithm to improve FE models towards the end of the design cycle.

A code called X-OPT has been written that controls the shape optimization process, it has taken about 10 years of development to get to its current form. It has been used on various structures and has always shown a structural efficiency improvement, without exception.

When searching for the highest levels of structural efficiency an alternate strategy can sometimes be performed. This tool is aimed at improving the design in the latter stages of product design, when manufacturing methods and part topology is almost complete. It is preferable for load paths not to change substantially as a consequence of the optimization at this point in the component design. Extreme optimization has been coined as a general expression of a desire to remove material and improve product performance at any opportunity in the design process. X-OPT is considered to be a FE mesh polishing tool which will seek to improve any FE mesh. X-OPT supports all MSC.Nastran elements and is aimed at primarily solid type structures.

The process can be likened to an organic approach where designs are evolved for many generations with successful designs retained. Refinement is limited to changing the outside shape with respect to the local goal [2]. From a finite element perspective, only very small variations of the external mesh can be produced, before the elements are too distorted to give acceptable results. Techniques of mesh relaxation for the core and surface elements are regularly employed with automatic volumetric re-meshing conducted to preserve a good quality mesh. Surface refinement algorithms can be used to preserve edge features if required. Material is added or removed from the model at each generation. The amount of material added or removed in a generation is a function of the local variable (stress, element strain energy - ESE, fatigue life etc) calculated from the previous generation results. This iteration strategy is progressed until all the desired constraints are met if possible. Non monotonic change to surface variables are conducted as a guide to when surface or core smoothing is required for the next iteration.

Used on simple structures such as cantilever beams, the algorithm yields a predictable response. If we start with a cuboid design volume and set a goal of constant stress for the component, within a few iterations fully variable I beam sections start to evolve. The web will vary in thickness to carry the constant vertical shear (since the web depth is varying), and the areas of the flange will be adjusted to carry the linearly increasing bending moment.

Other optimization tools may use parametrically driven solid models to create meshable models by analysts, necessitating good links between the designer and analyst, to keep this iterative loop active. X-OPT takes as input existing FE models and optimizes them, keeping the process firmly within the domain of the analyst. Once the optimized designs are evolved, VRML or IGES 3d models are transferred back to the designer at the end of the process to re-master back into solid models. Due to the sophistication of the optimized models (variable elliptical fillets, fully variable lofts etc) a significant amount of re-mastering time should be allowed to gain the full benefits of the process. To date most companies that have elected to use the process have grossly underestimated the time taken to re-master parts to gain the full advantage of the process. Indeed if the re-mastering is not conducted rigorously by well seasoned CAD engineers, some performance penalty may be introduced in the structure, forcing another round of re-analysis.

Constraints

The algorithm can deal with four classes of geometry constraint that may need to be defined for the structure :

1. Hard constraints – areas of structure that are fixed and cannot be modified, such as bearing bores, existing fixing point locations, or 'A' surface or styling surfaces on

components

2. Soft constraints - areas of structure that can move in a free form direction or can be guided in a specific direction, to maintain manufacturability or apply symmetrical / asymmetrical boundary conditions. This is the default constraint assumption.
3. Packaging constraints – areas of structure defined so that the model can grow until the packaging structure is met but penetration is prevented. The model can grow around the object if desired. Surface to surface intersection calculations determine the limit of part growth towards the packaging constraints.
4. Manufacturing constraints – defined wall sections that may be adjusted within certain limits (e.g. webs on the component must lie between 3-6mm thick). Similarly walls with a predefined draft can be specified.

The latter two areas of constraint are current development areas that need further research to identify robust methods.

Goals

Typically within optimization cycles it is desirable to have some goals to meet or exceed. The current code can accept goals such as stress, strain, element strain energy (ese) or stiffness. Additionally, structural natural frequencies or eigenvalues from linear buckling modes can be accepted and optimized on a mode by mode basis. Indeed any nodal surface result that MSC.Nastran can calculate could be used to guide the surface modification.

However, the relationship has to either vary proportionally or inverse proportionally to the local problem. Therefore the algorithm relies on a local problem / local solution strategy. So CFD studies for example would not fit in this class of problem. Surprisingly, a broad class of common structural problems can effectively be solved using this technique.

Once an optimization cycle is underway, seamless links to a robust, fast solver are required. Links to Output2 on MSC.Nastran are used to provide the computational engine at the core of the optimization. MSC.Nastran provides all the variables such as stress, strain, displacement, element strain energy and linear buckling eigenvalue solutions of structural natural frequencies. When fatigue life optimization is desired, links with fatigue software [3,4] or the integral simplistic stress / strain life model can supply the surface damage parameters to guide the next optimization iteration. When this option is selected optimizations based on a fatigue life goal are available, giving an opportunity to design a structure with theoretically constant fatigue life over the entire external surface. From a practical perspective one crack growth may exceed another's, or may stunt alternative crack growth incubation periods. So the reproducibility of this feature is still governed by statistical processes.

Example 1 : Simply Supported Beam

As a test of the ultimate stability of the algorithm, a rectangular non-optimized section is selected, with a point load applied at the center. All external surfaces are free to move in any direction, apart from the fixing detail which are fixed. We anticipate a solution which would resemble an I-beam with variable thickness web and flanges to react the bending moment. Note that this test is strictly beyond the normal capability of the algorithm, since the original intention of the procedure was to act purely as a structural efficiency improver. However, it is valid to examine how it will react to extreme cases. We are particularly interested to ensure that the solution is reasonable and that convergence to the goal is stable and repeatable. Only a stress constraint is used in the model. The end connection detail is kept fixed to examine how the I-beam diffuses load into the rectangular boundary.

Figure 2a shows the results for the initial iteration and Figure 2b, iteration 14, just prior to a further surface smoothing cycle. The I-beam is optimized into a doubly parabolic tapered beam, with a parabolic thickness web. Stresses in the web and flange are starting to unify and the mass is reduced substantially. One paradox in the solution is the region of very low stress appearing in the center of the web, this is created by the algorithm making the web almost zero thickness, since the algorithm recognizes that the vertical shear can be carried by the remaining flange sections, with the shear bounding the anticipated hole.

Elliptical fillets are introduced at the end connection detail to minimize the stress concentration factor (SCF). Minimization of SCF's in structures are handled efficient in the algorithm and replicate similar features found in nature.

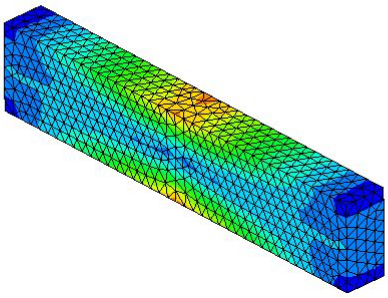


Figure 2a

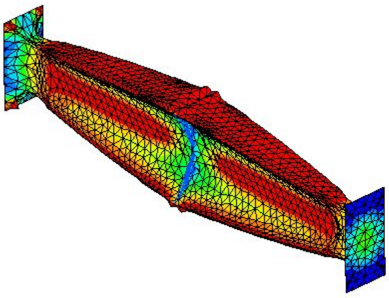


Figure 2b

An alternate optimized solution could have been posed if the extreme fiber elements were constrained, in this situation a rectangular beam with a variable thickness flange could have been generated.

Example 2 : Automotive Rear Axle Knuckle – Stress unification and stiffness enhancement

In this structure a total of 20 load cases are to be considered. This structure was previously optimized by conventional FE techniques, but loads have subsequently increased for a new application. The design brief is to reduce stress levels, increase component stiffness, adding the minimum amount of material. Component manufacturability should not change. The original geometry is shown in figures 3a and 4a, with the optimized geometry shown in figures 3b and 4b.

Figure 3a

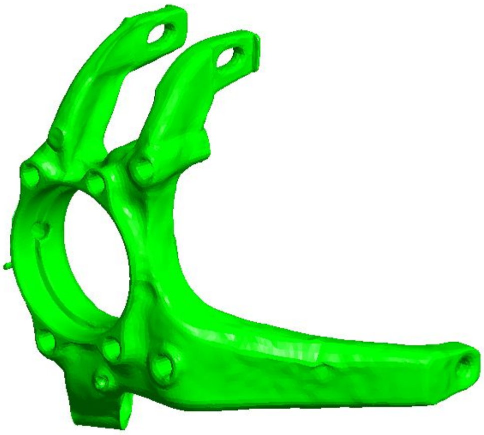


Figure 3b

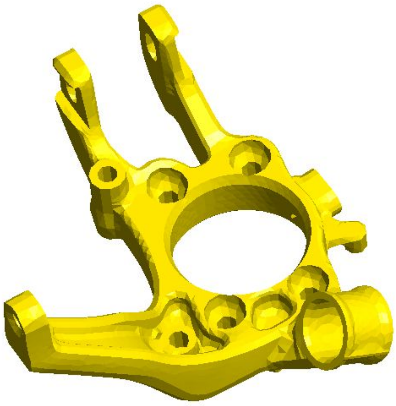


Figure 4a

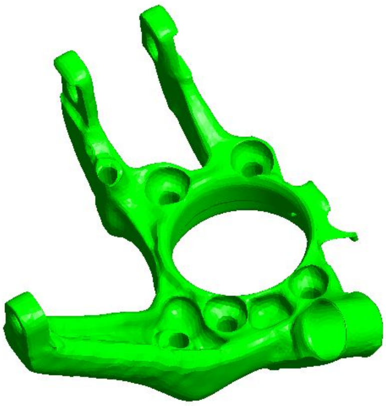
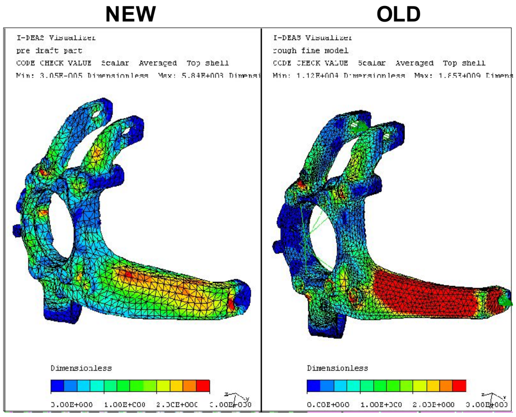


Figure 4b

Results for this optimization are impressive, although a mass of 100-150g was anticipated to be added to the 1700g component, the result of the study was a saving 170g compared to the original component. Stresses are significantly reduced and the part stiffness has been increased substantially for all load cases. Significant structure has been added to the horizontal arm, with the mass for this structure harvested from the remaining structure.



Load Case	NEW		OLD	
	Stress MPa	Peak Displacement	Stress MPa	Peak Displacement
1	421	0.074	507	0.175
2	352	0.990	583	2.560
3	583	2.560	1400	6.210
4	472	0.558	536	1.740
5	132	0.573	377	1.300
6	115	0.409	232	1.130
7	101	0.475	287	1.100
8	106	0.504	291	1.220
9	56	0.281	174	0.762

Figure 5 : Comparison of results between original part and the re-mastered design

Example 3 : Automotive Two Piece Wheel – Fatigue Analysis

An automotive wheel has been optimized for a cornering fatigue test. A requirement of the design is that the wheel must withstand a standard radial and lateral load fatigue test. Although the rim is not allowed to be modified due to manufacturing limitations (see figure 6a and 6b), some areas on the spokes are available for fatigue life reduction (optimizing area shown in magenta), since the current part passes the lateral fatigue test with a substantial margin. The design brief is to reduce the fatigue life, preserving the external styled surface, and reduce component mass.

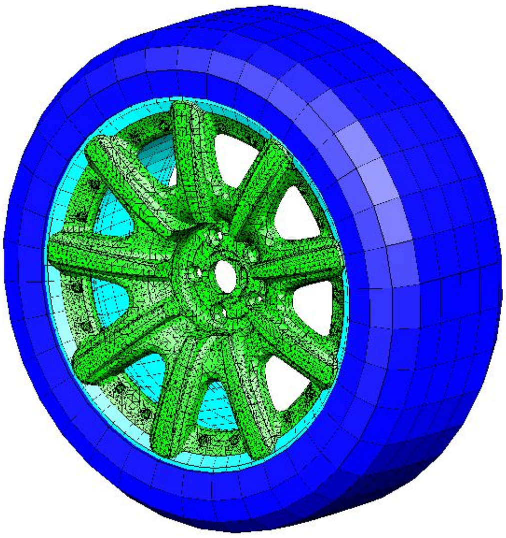


Figure 6a

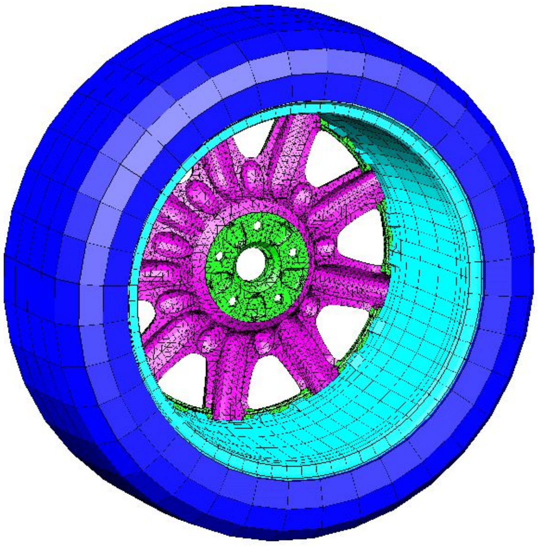


Figure 6b

The optimization was stopped when the fatigue life was reduced by a factor of 10, giving a mass reduction of 1200g per wheel compared to the original mass of 5400g. The size of critical area on the inside face of the spokes, which determines the component life, was increased in size. Figure 7a shows the fatigue life prediction of the original structure, with figure 7b the life after the optimization was terminated at 1200g reduction. Manufacturing constraints were included in this model to ensure that wall thickness minimum specifications were not violated during the optimization iterations.

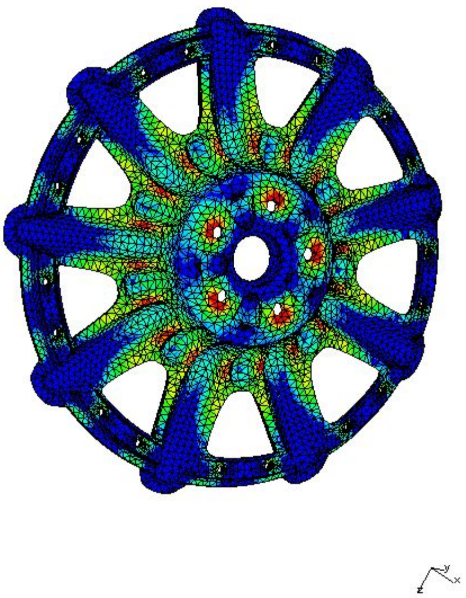


Figure 7a

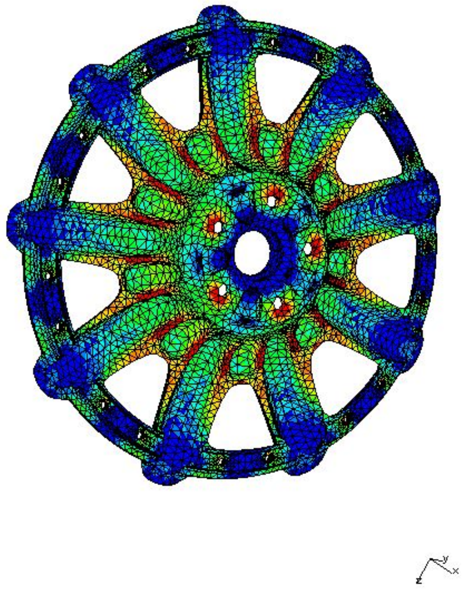


Figure 7b

DISCUSSION

Typically within the automotive industry mass reduction programs use $10000-$15000 per kilogram to identify the cost that the engineering department are prepared to spend to reduce mass. Higher figures will be used if the mass is 'unsprung' that is if it lies on the wheel / tire side of the primary dampers. Since this mass is difficult to control and significantly improves handling performance. On example 3 the mass reduction of 1.2kg per wheel results in an unsprung mass of 4.8kg on a vehicle. This provides the financial justification to embark on these refinement programs using external consultancy organizations.

Investment in a new generation of optimization software targeted towards the end of the design cycle will hopefully be developed commercially over the next few years.

CONCLUSIONS

1. Over recent years software tools focusing on producing a good optimized design have evolved. These tools have omitted to address the considerable benefits of conducting optimization throughout the design cycle. Shape optimization techniques are described, in this document, which enable optimization to be performed towards the end of the design cycle when the last few percent of performance increase would be desired.
2. The described tool is aimed primarily at analysts. It enables them to make design suggestions, in the form of 3d models to be relayed to the designers. Rather than supplying an FE report describing the response of the structure to various load cases, which are time consuming to produce, the deliverable from this process is a solid 3d model describing the optimum shape to fulfill the structural requirements. CAD departments are then free to use this solid model to re-master a new improved part. The analyst incorporates all the basic manufacturing requirements and package constraints, to ensure that the deliverable geometry will meet with the designer's requirements. This has the significant advantage of removing interpretation of a FE report by the designer and allows them to focus on re-mastering the part to improve its performance.
3. Shape optimization has shown itself to be useful in making very subtle changes, late on in the product development cycle, where the last 10% reduction in stress, improvement in fatigue life or increase in stiffness would be most appreciated to meet all the desired design targets. Add the incentive of also reducing mass at the same opportunity makes this an important tool in the analysts armory.
4. Dependant on the skill of the designer it is likely that another analysis by the CAE department may be required and appropriate time in the development program should be allowed to accomplish this task.
5. Mainstream FEA products such as MSC.Patran should investigate the opportunity to include this technology.
6. Access to X-OPT is available on a consultancy basis and Grey Space is examining the possibility of setting up a partnership agreement with MSC.Software Corporation, to further develop this technology.

ACKNOWLEGEMENTS

Example 2 and 3 given by kind permission of Bentley Motors Limited.

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