Boss-Quattro and MSC/PATRAN: A New Generation of Open-architecture Multidisciplinary Optimization Software

Patrick Morelle*, John Klintworth**

* SAMTECH s.a.
** MSC Ltd.

ABSTRACT

Today's design in industry is in fact a combination of techniques whose primary goal is to understand the model's behavior. The next step is then to analyze the performance of the model using numerical simulation. Various sequences of trade-off, parametric analysis, sensitivity analysis, are then performed in order to formulate the final optimization problem properly. A basic feature of many design problems is their multi-disciplinary nature. As a result, more and more physical phenomena are being modeled and taken into account in the design problem formulation. This has required the use of more disparate and heterogeneous analysis and simulation software.

For those reasons, Samtech s.a. has developed an open design and optimization architecture: BOSS-QUATTRO. This new software has been applied with success in multi-disciplinary (e.g. fluid/structure) analysis and optimization as well as in parametric studies and Monte Carlo analysis. In particular, a very powerful system has been build by linking the BOSS-QUATTRO system to the MSC/PATRAN environment, providing new capabilities for multi-disciplinary optimization by taking advantage of MSC/PATRAN's existing links to multiple analysis codes.

The BOSS-QUATTRO environment is designed as an application manager: it includes existing analysis chains in arbitrary loops and sequences, and provides new capabilities like parametric studies, Monte-Carlo simulation, sensitivity analysis or optimisation. BOSS-QUATTRO is linked to application programs in a standard way through drivers. This open architecture means that the system is able to exchange information with present and future commercial products as well as with in-house codes. For example, drivers exist for popular commercial software MSC/PATRAN, MSC/NASTRAN, SAMCEF, PRO-ENGINEER and CATIA. In addition, any application using a text file for input and output can be linked through a flexible "neutral" driver.

Within the present paper, two applications developed in the context of a BRITE/EURAM project (MODSYSS, CT94-0590) are presented. The first takes advantage of links between MSC/PATRAN and several analysis codes to perform multidisciplinary analyses on a component. The second links a parametric CAD system to an analysis code to allow full three-dimensional shape optimization. These examples demonstrate the ability to link together disparate commercial software systems to perform effective design optimization.

---

* Scientific Manager
** Product Development Manager

INTRODUCTION

Today's Computer Aided Design in industry is in fact a combination of techniques whose first goal is clearly to understand the model's behavior as a function of some design options. The next step is then to analyze the performances, trying to determine which objective is already satisfied and which is not, if some constraints are violated, if some are conflicting or if it exist at least a feasible design, that means some design satisfying the whole set of constraints. Various sequences of trade-off, parametric analysis, sensitivity analysis, are performed in order to formulate the final optimization problem comprehensively. Furthermore, more and more constraints are taken into account even in the early design phases so that multi-disciplinarity is another basic feature of today's design problems. An increasing number of physical phenomena are modeled and taken into account in the design problem formulation. This has the effect to involve more and more disparate and heterogeneous analysis and simulation software as well as CAD tools, analytical models, etc. The response to this need is an open architecture and this paper describes the BOSS QUATTRO system, which has been developed in order to satisfy those requirements.

THE BOSS-QUATTRO OPEN ARCHITECTURE

The BOSS-QUATTRO system is designed as an application manager: that means that its first capability is to launch external tasks as batch processes on UNIX networks. Those tasks are normally external CAD and CAE modelling software, each of them being considered as a black box reading parameters and providing some responses. Using the BOSS architecture, it becomes possible to include them inside loops and sequences of tasks and provides new capabilities (like parametric studies, Monte-Carlo simulation, sensitivity analysis or optimisation) to simple parametric software chains.

The architecture is summarised on Figure 1 where it is clearly illustrated that, in addition to the task management itself, BOSS-QUATTRO has the capability to exchange several categories of information with those external tasks. In particular, this data includes:

- Parameters (coming from CAD tools or parametric pre-processors)
- Responses or "functions" (generally extracted from a result file produced by an analysis or simulation system)
- Sensitivities (they are used as input by the internal optimisation algorithms).

This exchange of information is realised by using some specialised *drivers* and a communication protocol. This mechanism links the system with present and future commercial products in an efficient manner. In addition, in-house codes can be linked to the architecture by using the so-called "neutral driver" based on text files.
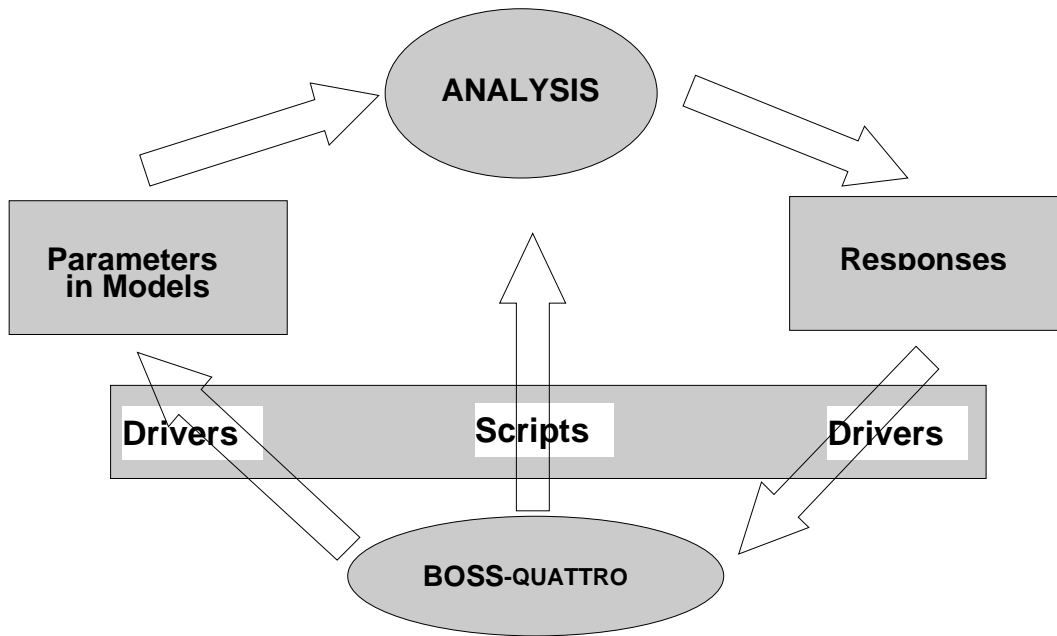
Figure 1: BOSS-QUATTRO Architecture

BOSS-QUATTRO: COUPLING WITH MSC/PATRAN

As an application of the BOSS open architecture, a dedicated driver has been developed for MSC/PATRAN within the MODSYSS project. In this way, users can automatically use all analysis codes supported by MSC/PATRAN preferences, including MSC/NASTRAN, SAMCEF, ABAQUS and ANSYS. In addition, the user can also take advantage of MSC/PATRAN's extensive links with popular CAD systems to include geometry creation in an automated optimisation loop. This is illustrated in Figure 2.

The MSC/PATRAN driver has been implemented in a general way using variables, which can be referenced, by spatial fields. The fields can then be used to define element properties and loads/boundary conditions on the analysis model. This immediately opens up the possibility of multi-physics optimization where the response of one analysis can provide input for a subsequent analysis.
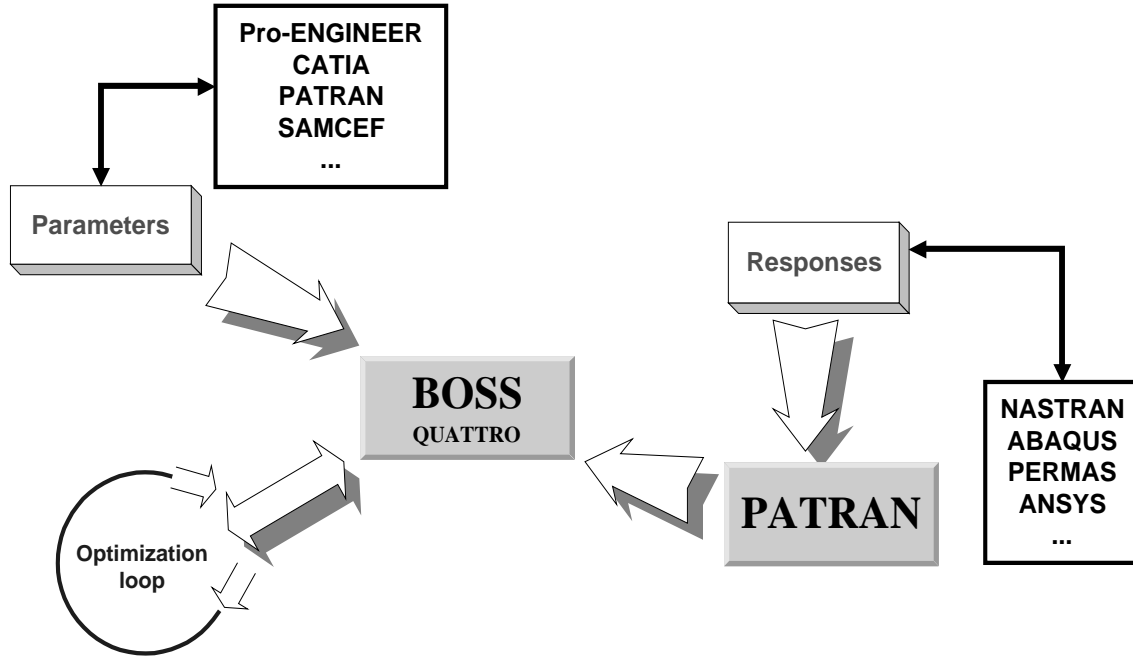
Figure 2 : BOSS - MSC/PATRAN Coupling

THE GENERAL OPTIMISATION LOOP

The general structural optimisation problem can be formulated as follows:

$$\begin{cases} \min_{p} f(p) \\ \underline{c_j} \le c_j \le \overline{c_j} & j = 1, m \\ \underline{p_i} \le p_i \le \overline{p_i} & i = 1, n \end{cases} \tag{1}$$

where p_i are the design variables, f is the objective function and c_i are the constraints. In the present context:

$\Rightarrow p_i$ can be geometrical variables from an external CAD model or some physical properties defined in a *MSC/PATRAN* model

$\Rightarrow f$ and c_i are normally related to structural behaviour and are obtained from one or several Finite Element models accessed through MSC/PATRAN.

Even in the context of a linear elastic problem, the f and c_i functions are non-linear, perhaps non-convex functions of the design variables. However, their most serious difficulty is that they are also *non-explicit*.

Moreover, because we are addressing here shape optimisation problems, it is clear that the geometry will change during the optimisation loop. That means that the mesh, which has been generated based on the initial geometry, will probably have to evolve and to be adapted to those modifications of geometry.

The general methodology to solve this problem has been established in the 70s [1] and known as the Convex Linearization Method: is to use the functions and sensitivities to build an explicit approximation of problem equation (1) where the non explicit functions are replaced by their convex linearization:

$$f(p_i) \cong f(p_i^0) + \sum_{>0} \frac{df}{dp_i^0} (p_i - p_i^0) + \sum_{<0} \frac{df}{dp_i^0} (p_i^0)^2 (\frac{1}{p_i^0} - \frac{1}{p_i}) \quad (2)$$

The new explicit but approximated problem has a unique solution because of its convexity. Solving this problem leads to a first approximation of the true optimum. A loop over this process has proved to be a very efficient methodology in the linear elastic domain. Generally less than 10 iterations are needed to reach the optimum.

However, in a more general and non-linear context, strong variations of curvature may lead to oscillations and problems of convergence of the classical method. In BOSS, the following new algorithms have been implemented:

- GMMA : Generalised Method of Moving Asymptotes [2]
- MDQA: Method of Diagonal Quadratic Approximation [3].

Using those methods, the information coming from the previous iteration is used to generate a better second-order approximation of the non-explicit functions. The consequence is that, using BOSS-QUATTRO, it is possible for the user to define constraints or objective functions using responses of non-linear or transient models.

To apply these optimization solutions to real industrial problems, it is necessary to transfer design variables, responses and sensitivities between the analysis codes and the optimizer, and to manage this process in a coherent way. We are now going to examine each implication of the architecture on the problem formulation and discuss the advantages or disadvantages of using an open architecture as compared to integrated systems

Design variables

a) *Shape Design Variables*

In today's situation, nearly all the CAD systems are parametric. What does it mean exactly? That means that it is now possible to designate some geometric dimensions as parameters and to rebuild automatically the geometry when their value is modified because of the user's wishes. But the hidden question here is also the possibility to impose geometrical constraints and to clearly distinguish between dependent and independent parameters. In this regard, CAD companies presently take two approaches: Variational Geometry and Feature Based methodologies

Variational Geometry techniques allow the assignation of dimensions and geometrical constraints to a given geometry [6], [7]. As a result, the CAD model contains not only geometrical information, but also conceptual design features. The shape is no longer changed by redefining geometric data but by giving numerical values to "dimensions" (for example, an angle between lines, radius of a circle, etc.).

Associativity and *feature* concepts are based on establishing relations between basic design entities that are automatically handled in order to construct the final model. The most common approach consists in relating basic solid entities to two-dimensional variational profiles [8]. The basic solids can be identified with design features such as holes or ribs and have a dimension associated to a 3-D sweeping operation. The final model is made up of a series of *features* and when a dimension either of a profile or of a swept operation is changed, the effect can be automatically reflected within the model.

Today's systems like *PRO-ENGINEER and CATIA* integrate more and more of those powerful capabilities, but in the present situation, it is clearly recognised that that solution remains completely specific to each system. There is absolutely no standardisation about parametric models. As a result, while it is just possible to transfer shape between systems, most of the parameterisation (the constraints which have been defined when creating the model) is lost during the exchange. So, this demonstrates clearly the very first weakness of using an integrated approach where the model has to be translated into a proprietary format: the geometrical constraints will generally have to be re-created and sometimes adapted to the new environment as some of the graphic tool have no equivalent in the competitor's system!

In contrast, using an open architecture, the user always uses the CAD system utilised for the initial model creation so that parameterisation remains in its native format. The disadvantage is the obligation to launch the CAD system as soon as model updating is required with a limited but real impact on the system efficiency.

b) Sizing Design Variables

Since its initial release, MSC/PATRAN has supported the concept of a data field, which can be referenced by Materials, Element Properties and Loads/Boundary Conditions. The field can be quite sophisticated, accommodating spatial or temporal dependencies, vectors as well as scalars and even general mathematical expressions defined using PCL (PARTAN Command Language). The fields are evaluated immediately before an analysis deck is produced, so users have always been able to conduct parametric studies manually by modifying the fields.

Recently, variables have been added to MSC/PATRAN (7.5) to support MSC/NASTRAN optimization and provide a basis for interfacing with parametric CAD systems. Fields can also reference these variables by including their name in a PCL expression. Then, when the field is evaluated the parameters will be replaced by the current value.

The user interface for variables facilitates creation, assignment to model variables (e.g. element properties), modification, verification and deletion. In particular, it is possible to import a fixed model and parameterise it on the basis of particular features like element property set.

Left Panel

Action: Create

Object: Variable

Method: Property

Existing Variables

LM_Layup_1_Plate_Offset

Variable Name

LM_Layup_2_Plate_Offset

Description

Created from set
<LM_Layup_2> and word
<Plate Offset>

Value

0.2

Dimension: 2D

Type: Shell

Select Property Set

LM_Layup_1
LM_Layup_2
LM_Layup_3

◇ Select All

Select Property Name

Nonstructural Mass
Plate Offset

Apply   Close

Right Panel

Action: Create

Object: Spatial

Method: PCL Function

Existing Fields

LM_Layup_1_Plate_Offset

Field Name

new

Field Type

◆ Scalar   ◇ Vector

Coordinate System Type

◆ Real   ◇ Parametric

Coordinate System

Coord 0

Scalar Function

'X+LM_Layup_1_Plate_Offset

Independent Variables

'X
'Y
'Z
LM_Layup_1_Plate_Offset

Create Variable

−Apply−

Figure 3: MSC/PATRAN parameters

7

It is possible to handle parameters both from within a *MSC/PATRAN* session (see Figure 3) and by direct database access. The latter allows external packages, such as BOSS, to interrogate the database and set new values for parameters directly. This means that an external task manager can control all the parametric features of MSC/PATRAN. This, in turn, opens the way for flexible multidisciplinary optimization.

Constraints and objective functions

The problem in shape optimisation is that the shape and so the mesh is going to evolve during the optimisation loop. In order to deal with this specification, most of the systems today can **use CAD entities in the analysis and optimisation problems formulations,** boundary conditions, material data, constraints, etc. [9], [10].

The important fact here is to be able to formulate the whole problem, not based on node and element numbers, but on the geometry, that means in a way independent of the mesh. Otherwise, the user will have to redefine the problem completely after each iteration.

The problem for BOSS-QUATTRO is that not every finite element code exhibits this capability: the solution is to use groups or sets of elements. This is then the user's responsibility to define those sets based on geometry (to define for example: "the set of elements belonging to the surface number *x*") in order to keep the formulation mesh-independent.

The same problem arises (with different consequences) when dealing with transient analyses: the use of time reference is very dangerous because usually the time value refers in fact to a given event. The instant this event arises will clearly change from one iteration to the next, which makes it impossible to use an absolute time reference. In that case, BOSS allows the user to use "*dynamic references*" corresponding to the satisfaction of a pre-defined condition (for example, the contact between two lines).

A last problem may arise when using automatic time step computation techniques: an absolute time reference may be meaningful … but not be present in the result table! In that case, BOSS will perform automatically an interpolation between the two neighbouring time steps.

The MSC/PATRAN response driver can take advantage of MSC/PATRAN's capabilities of identifying elements associated with geometrical features, as well as results manipulation and display.

Sensitivity Analysis

The sensitivities are basically the derivatives of the functions f and c_i with respect to the design variables. There are basically three methods for computing sensitivities:

a) Analytical method can be used when the explicit dependency of functions f with respect to c_i is known. It is obviously the cheapest one … but it requires full knowledge of function dependency!

b) For problems with large number of variables involving an explicit equation, the sensitivities can be computed by the semi-analytical method, which consist in differentiating the equilibrium equation and using a finite difference scheme to compute derivatives of elementary matrices. This is the most common approach for linear problems. In that case, the relation is :

$$\frac{dq}{dp} = K^{-1}(\frac{dg}{dp} - \frac{dK}{dp}q) \tag{3}$$

c) Finally, when no other method is available, the sensitivities can be computed by pure finite differences. This is the most expensive but most flexible method! This is the one used by BOSS as the standard methodology when the sensitivities are not available from outside: parameters are perturbed and the computation re-run in a transparent way (those computations are managed by the BOSS application manager)

Inside the shape optimisation loop, sensitivity analysis is not independent of the meshing technique in such a way that, a perturbation of the boundary involves a perturbation of internal points and so of the mesh. This question arises when computing the stiffness matrix derivatives in formula (3), as perturbed positions of nodes are required to compute the perturbed stiffness matrix. Recently, some methods have been developed so as to use free mesh generators in the sensitivity analysis of the mesh. A first method [5] [11] [12] is based on a perturbation technique of the boundary by CAD techniques, and on smoothing methods (Laplacian or others) to propagate the perturbation inside the structure and thus on internal nodes of the finite element mesh. The problem arises when different systems are used from heterogeneous software packages. Basically, this has been the main result of the MODSYYS project [13] to provide the BOSS-QUATTRO architecture allowing users to compute such a velocity field with mesh produced in one package and CAD parameters defined in another one.

Let us note that a very easy way to overcome this difficulty is to use topologically constant techniques like transfinite mesh generators because in that case, an *explicit* relation between the boundary surface and any internal point exists. However, when dealing with three-dimensional problems, this solution is not at all satisfactory for the industrial end user!

When using free mesh generators, several solutions have been proposed (including the "zero velocity" field where only the boundary is supposed to move) in order to compute this new position of nodes when boundary geometry is perturbed. The formulation used in BOSS is a Laplacian smoothing based on a built fictitious K matrix [5]. The consequence is that the dimension of this matrix is no longer the number of degrees of freedom but the number of nodes. This is especially cost effective for 3 dimensional problems. We use a relation:

$$\begin{bmatrix} K_{ii} & K_{ib} \\ K_{bi} & K_{bb} \end{bmatrix} \begin{bmatrix} dv_i \\ dv_b \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{4}$$

where i refers to the internal nodes (unknown displacement) and b to the one on the boundary (imposed displacement = the modified geometry). We have from (4):

$$dv_i = -K_{ii}^{-1}K_{ib}\overline{dv_b} \tag{5}$$

Which is the explicit expression of the velocity field. Figure 4 illustrate this "reposition method" (with an amplified boundary motion) on a three dimensional geometry.
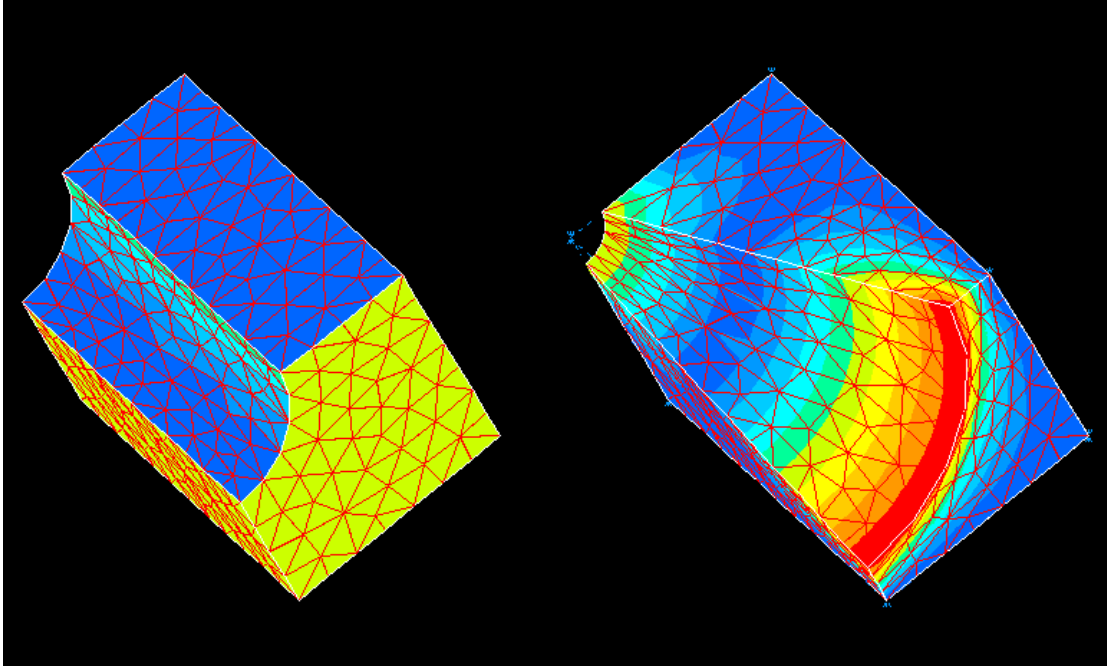
Figure 4: Three-dimensional Velocity Field

Managing the loop

In BOSS, the loop is specified by the user who defines:

- which models have to be computed and in which sequence,
- what are the dependencies between the models and if some of them have to be re-computed first before the depending one can be evaluated

The *Task Manager* "knows" automatically that a perturbation loop has to be managed when there is no other way to compute sensitivities. This has not to be included in the task sequence. But an important problem lies in the Finite Element method itself and from the fact that the geometry is going to change: this is the question of adaptive meshing and of the control of the finite element approximation.

Error control is an important feature in the optimisation loop in order to keep constant precision from one iteration to the other and also to avoid that uncontrolled error increase will give impression that the constraints are satisfied when they are far to be! There are currently no industrial package exhibiting these capabilities when dealing with h-refinement methods. Some research work has been performed but not really translated in industrial codes. A shape optimisation code based on p-refinement method exists [14] but exhibits some limitations.

BOSS-QUATTRO OPEN ARCHITECTURE: ENABLING MULTIDISCIPLINARY OPTIMISATION PROBLEMS

The open architecture is especially well designed to cover multi-disciplinary optimisation problems. For this class of problem, the most important requirements are:

10

- The possibility to mix parameters coming from as many models as required and of different natures (geometrical, physical, …)
- The possibility to treat as many models of any type (explicit formula, CAD model, FE model, any other software considered as a black box) and any discipline.
- The possibility to formulate the optimisation problem using any response coming from any model as constraint/objective function.
- Automatic management of the optimisation loop and transparent automatic management of the perturbation loops for automatic finite difference sensitivity computations
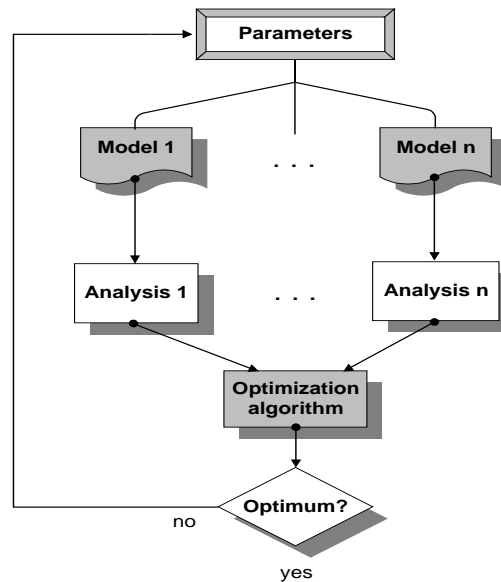
Figure 5: Multi-model Optimisation

MULTIDISCIPLINARY OPTIMIZATION: SHEET METAL COMPONENT

Many components in the transport sector are manufactured by sheet metal forming and then subjected to loading conditions which are affected by the manufacturing process. For example, most automotive wheels are pressed from steel, and are cyclically loaded under their normal operating conditions. This means that the dominating factor affecting their design is fatigue life.

In order to quantify this, it is first necessary to simulate the forming process itself as this has a significant effect on the final thickness distribution through the component. This initial analysis will also quantify the expected springback and the residual stresses in the component. Then, structural analysis has to be performed to calculate the cyclic stresses due to pressure and contact loading to generate the varying stresses. By combining residual and varying stresses, it is then possible to predict the fatigue life. The analysis steps are shown in Figure 6.
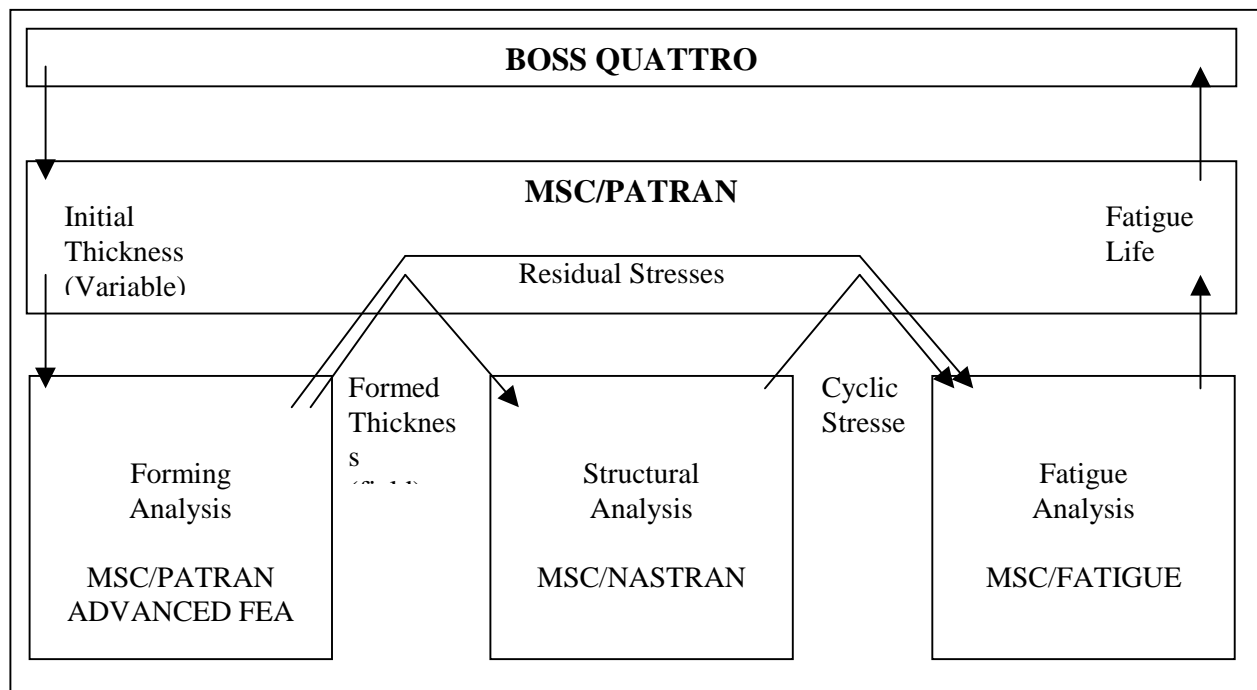
BOSS QUATTRO

MSC/PATRAN

Initial Thickness (Variable)

Fatigue Life

Residual Stresses

Formed Thickness

Cyclic Stresse

Forming Analysis

MSC/PATRAN ADVANCED FEA

Structural Analysis

MSC/NASTRAN

Fatigue Analysis

MSC/FATIGUE

Figure 6: Analysis Steps for a Sheet Metal Component

It is clear that even if only a single parameter were examined, such as initial thickness, the effort for repeated manual calculation would be prohibitive. However, the task management capability of BOSS QUATTRO reduces this to a straightforward problem of definition. The other difficulty of linking the disparate analysis codes is reduced to a trivial problem by using MSC/PATRAN's ability to define continuous FEM fields to map the results of the forming analysis onto the input of the structural analysis.

SHAPE OPTIMIZATION: SNECMA TURBINE BLADE [13]

Here, the part to be optimised is an aircraft turbo-engine blade fixed on the disk. The numerical 3D volumic model is built with specific boundary conditions in order to take into account the cyclic symmetry of the whole disk. The part is submitted to centrifugal forces.
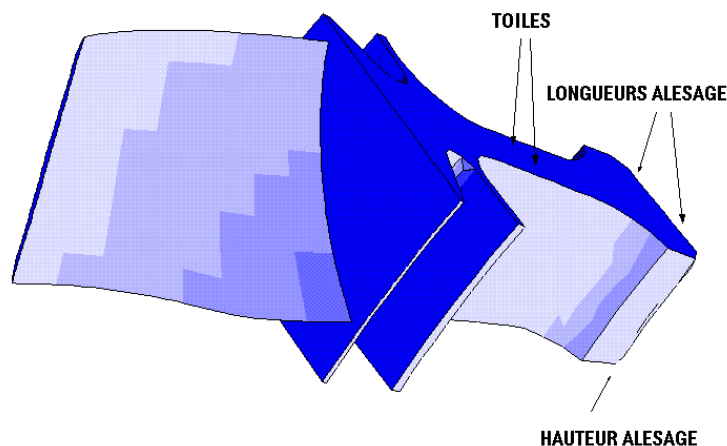

Figure 7: Design variables

12

The optimisation problem is the following:

"***Minimise the total mass, with Von Mises equivalent stresses lower than 210 MPa***"

The (shape) design variables (illustrated on Figure 7) are some characteristic dimensions of the disk geometry. Note that the shape of the blade will not change.

TOILE_DROITE	= 5.9 mm variation interval	[3., 10.]
TOILE_GAUCHE	= 5.5 mm	[3., 10.]
L_ALES_DROITE	= 14.7 mm	[10., 25.]
L_ALES_GAUCHE	= 14.7 mm	[10., 25.]
HAUTEUR_ALESAGE	= 8.9 mm	[5., 15.]

In order to illustrate the previous concepts, the velocity field related to the "TOILE_GAUCHE" CAD parameter is illustrated on Figure 8.
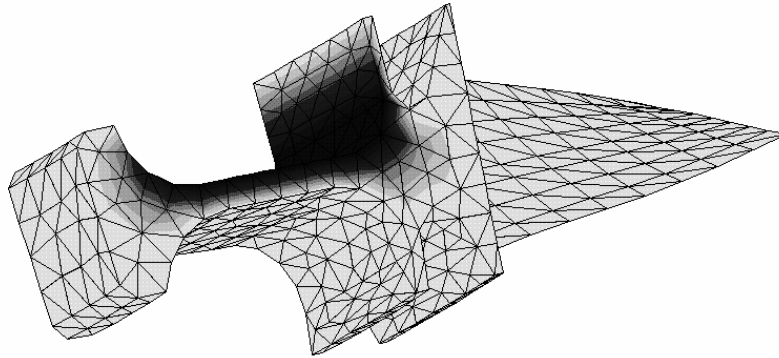

Figure 8: Velocity Field for Variable TOILE_GAUCHE

The results of the optimisation are given on Figure 9 and 10. One notes that the initial design of the part was not admissible (vM stress = 233 MPa). The optimiser finds first an admissible design, then performs the optimisation itself. The stress threshold at 210 MPa is satisfied and the mass decreases of 11%
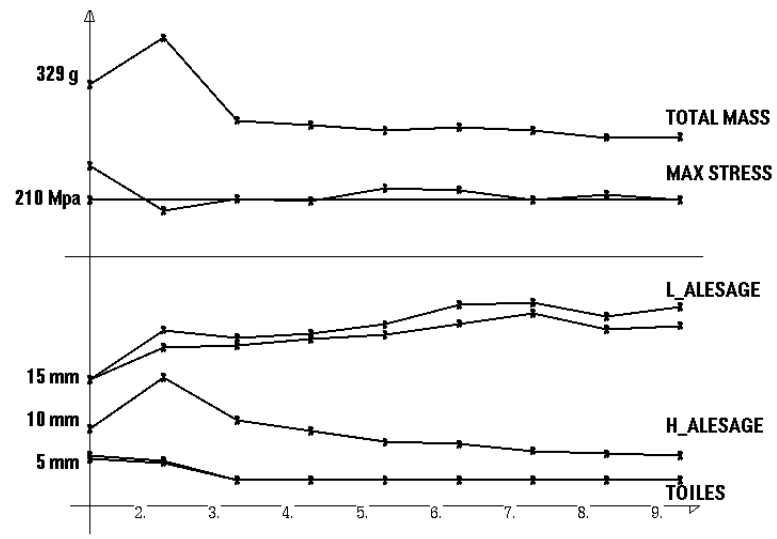
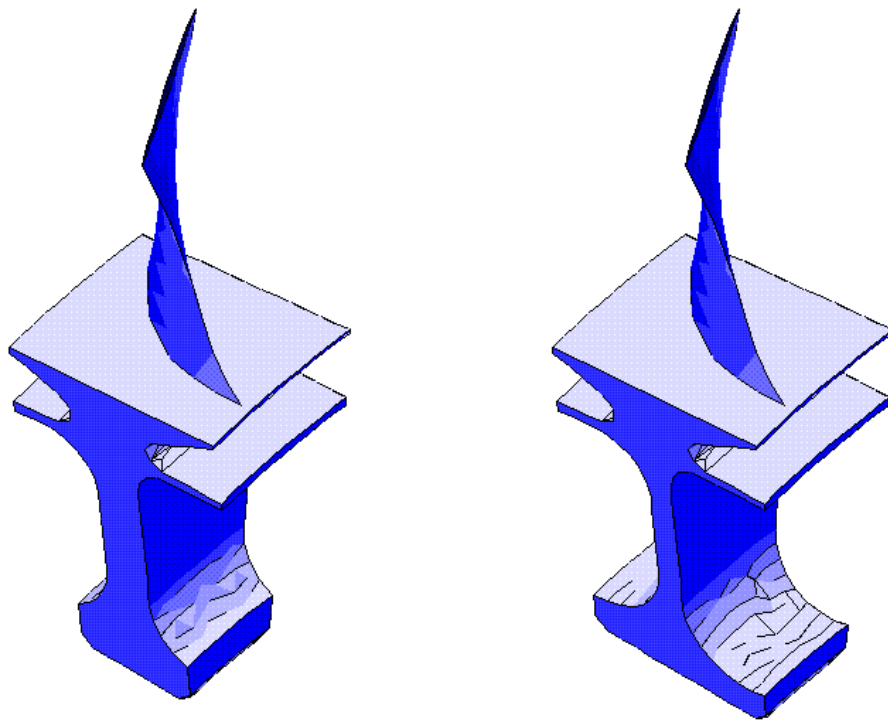*Figure 9: Convergence Curve for Design Variables, Objective Function & Constraints*

Figure 10: Comparison of Initial and Final Geometry

14

ACKNOWLEDGEMENTS

REFERENCES

[1] FLEURY C., Le dimensionnement automatique des structures élastiques, PhD Thesis, L.T.A.S. University of LIEGE, 1978.

[2] FLEURY C., W.H. ZHANG - Selection of appropriate approximation schemes in multi-disciplinary engineering optimization, OPTI 95 Conference, Miami, September 95. Published in Computer Aided Optimum Design of Structures IV, Structural Optimization, pp 11-18, Editors Hernandez, El-Sayed and Brebbia, Computational Mechanics Publications

[3] ZHANG, W.H. and FLEURY C. et al., A generalized method of moving asymptotes (GMMA) including equality constraints, WCSMO-1, Goslar, Germany, 1995.

[4] BRAIBANT V., optimisation de forme des structures en vue de la conception assistée par ordinateur, PhD Thesis, L.T.A.S. University of LIEGE, 1978.

[5] MORELLE, P., BRAIBANT V, Shape optimal Design and free mesh generation, Structural Optimisation, II, pp 223-231, 1990.

[6] LIGHT R. A., GOSSARD D. C. 1983. Variational Geometry : A New Method for Modifying Part Geometry for Finite Element Analysis. *Computers and Structures*, Vol. 17, No. 5/6.

[7] TURNER J. U., WOZNY M. J., HOU D. D. 1987. Tolerance Analysis in a Solid Modeling Environment. *Proceedings of the 1987 ASME International Computers in Engineering*, Conference and Exhibition, August 9-13, New-York, 1987.

[8] I-Deas Solid Modeling User Manual, SDRC corporation. 2000 Eastman Drive, Mildford, Ohio 45150, USA, 1990.

[9] BRAIBANT V. and FLEURY Cl. 1986. Shape Optimal Design. *Computer Methods in Applied Mechanics and Engineering*, Vol. 1, 193-204.

[10] VENKAYYA V. B. 1978. Structural Optimization, A Review and Some recommendations. *International Journal for Numerical Methods in Engineering*, Vol. 13, pp. 203-208.

[11] DEMS K. and HAFTKA R. T. 1989. Two Approaches to Sensitivity Analysis for Shape Variation of Structures, *Mechanics of Structures and Machines*, 16 (4), 501-522.

[12] ZOLESIO J. P. 1981. *The Material Derivative (or Speed) Method for Shape Optimization. Optimization of Distributed Parameter Structures* (Eds. E. J. Haug, J. Cea), Sijthoff & Noordhoff, Alphen aan den Rijn, Netherlands, 1089-1153.

[13] MODSYSS, BRE2-CT94-0590 A multidiscipline Open Design System for Structural Synthesis

[14] RASNA. 1991. *Intergraph Corporation*, Huntsville, Alabam 35894-0001, USA.