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A Shape Optimisation Tool for Multi-Disciplinary Industrial Design

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Abstract. The final objective of the OPTIM project was the development of inverse approach in design problems, which must aim at increasing the quality of designed products while decreasing design time and cost. The practical goal within the project was the development of tools which allow such an approach, for a range of applications as wide as possible, and for multi-disciplinary problems. This necessitates a software architecture able to handle optimisation for a number of models and some optimisation methods adapted to a wide range of problems. Another goal was the application of these techniques to two fluid mechanics related fields : aeronautics and hydrodynamics.

1 INTRODUCTION

As analysis numerical tools become more and more present and efficient in the design process of a wide range of products, it appears interesting to use them in the best way to improve as far as possible the final product, while decreasing the design time and cost. This can be performed through the use of software tools which help the designer to carry out parametric studies, and automatic optimisation of the designed systems.

The present project aimed at developing such optimisation tools, with some requirements on their applicability to a range of disciplines and applications as wide as possible. The second objective was the application of the developed tools to two fluid mechanics related fields : aeronautics and hydrodynamics.

The first work consisted in the design and development of a general architecture able to match the above requirements. This architecture had to be independant from shape modelling tools, from analysis tools, and also up to a point from optimisation methods, and its main role is the tasks and data management. The goal is to be able to add one geometric or analysis model by plugging it to this architecture with little effort. This aims at allowing a wide range of applications, and multidisciplinary optimisation.

Another task consisted in studying and developing a set of optimisation algorithms which are able to solve a wide range of optimisation problems. Two kinds of methods were studied : local approximation methods and global or mid-range approximation methods.

The problem of shape processing within the optimisation procedure was also addressed. In particular, the ways to use CAD software packages and to generate perturbed meshes for sensitivities computation were studied.

In the aeronautic application, the aerofoil aerodynamic and structural performances problems were concerned, as well as manufacturing and operational constraints, and a validation work was performed on relevant cases, including simultaneous fluid-structures interactions.

In the hydrodynamic domain, the studied problems concerned ship forward resistance and seakeeping of floating bodies. A validation work, including coupled hydrodynamic/structural problems and experimental tests, has been performed.

2 TECHNICAL DESCRIPTION

2.1 General architecture

One main goal of the architecture was to allow the users to assemble their application with help of a unique tool which should be able to deal with parametered systems in order to perform several optimisation loops automatically. It was thus necessary to build an open architecture that could :

- accept easily any new user analysis tool,
- make the use of the optimisation algorithms independent of the programmation,
- make the user independent of any internal database manipulation.

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This is achieved by adopting the SAMTECH's BOSS architecture (Figure 1). Through this architecture, each task (CAD, analysis codes,...) is managed by a script, and all the data required for optimisation (variables, functions, bounds,...) are transmitted between tasks (analysis, optimiser,...) and BOSS by using a unique protocol (a requests/answers system), through a set of programs (called drivers). The internal communication within the optimisation package is ensured by a database system (SAMCEF database).

This architecture is implemented into an interactive environment, BOSS/Quattro :

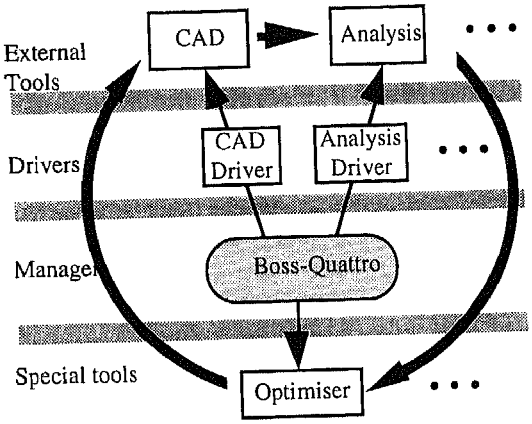

Figure 1. General Architecture

2.2 Shape processing

One of the project objectives was to perform shape optimisation on 2.5D geometry (shell problems). This means that it is necessary to compute the sensitivities of the system responses (structural, aerodynamic or hydrodynamic responses) with respect to parameters related to CAD geometry. The developed method assumes that the analysis modules use one of the following approaches : finite elements, boundary elements or finite differences. The common point is that those methods use a grid or a mesh as the basis of the computations.

Basically, the tool has to transform a modification of a CAD parameter into its equivalent on the resultant mesh, keeping the mesh topology constant. Then the goal is to compute the deformations of a mesh triggered by some perturbations in the values of the parameters used in the geometric definition of a structure. In this project, only the surfacic mesh (shell meshes) deformations has been implemented.

Two basic CAD software packages were considered : the parametric pre-processor of the SAMCEF finite elements software (SAMCEF/Bacon), which was used for structural applications, and can be extended to others, and the parametric general purpose PRO/Engineer package. This last tool was used for hydrodynamic applications and adapted for specific needs (structured mesh generation, shape perturbations,...).

2.3 Optimisation algorithms

Two kinds of optimisation algorithms were studied within the project : local approximation, and global or mid-range approximation algorithms.

With local methods, due to the implicit relationship between design functions (objective function and constraints) and design variables, the efficient solution strategy is to handle a sequence of explicit subproblems which are generated by means of local approximation methods.

Convex approximation methods were widely and successfully used in optimisation of large-scale mechanical systems. Basically, they can be classified as monotonic and non-monotonic approximations. The first type, such as CONLIN (CONvex LINearization) and MMA (Method of Moving Asymptotes) methods, means that related approximations have unchanged signs of first order partial derivatives for any values of variables in the allowed design space. This is the case in most structural sizing problems. The second one means that the first order partial derivatives of approximations can change their signs in terms of variables. This is often the case in hydrodynamic and aerodynamic design optimisation.

The main advantage of using convex approximations consists in that each nonlinear constrained-subproblem defined in the primal design space can be equivalently transformed into a simplified, easily solved quasi-unconstrained problem in the dual space . For this reason, this approach is adopted in the current multi-disciplinary industrial design project.

Because involved functions may be quite different in nature (structural, aerodynamic, hydrodynamic, or manufacturing...) and in form (linear, nonlinear, reciprocal...), appropriate approximation schemes have to be selected to ensure the efficiency of the design procedure, the convergence of iterations as well as the feasibility of the obtained solution.

Two optimisation algorithms (optimisers) were developed. The first one called GMMA (Generalized Method of Moving Asymptotes) is based on the monotonic convex approximation. The second one, MDQA (Method of Diagonal Quadratic Approximation), is based on the non-monotonic quadratic approximation. Both methods are established to deal with non-linear problems including equality constraints.

For some optimum design applications, it is profitable to build global or mid-range approximation models of objective function and constraints that create an explicitly known approximate optimisation problem in the complete design space or a part of it.

Response surface modelling is a powerful tool to build global approximate models. These strategies were originally developed for the model fitting of physical experiments [1]. As shown by [2], response surface techniques can be successfully applied in structural optimisation. Construction of response surfaces is an iterative process. One starts with postulating the approximate model functions (usually polynomials) and selects the design points in the design space where to carry out the analyses. Next, the model functions are fitted to the results in a least-squares sense and are used as problem functions in the optimisation process. Changes to the model functions or additional analyses may be necessary to improve the accuracy of the function models. Global approximations can give the designer a better idea of the influence of some important design variables on the response, and may lead to promising starting points of a local sequential approximate optimisation process. Global approximation concepts are not only valuable for the preliminary design investigation. After an optimum has been found, global approximation models built around the optimum can be used to investigate changes in the optimisation problem specifications like changes in design variables or constraint bounds without the need to run the analysis code again. Another important feature is that noise and other irregularities can be averaged out, avoiding multiple local minima and preventing premature convergence of the optimisation algorithm.

Mid-range approximations [3] are designed to be valid in a smaller region than the region for global approximations. Such a region is usually bounded by movelimits. As a consequence, simpler model functions and less design points can be used. Two strategies can be distinguished for the choice of the design points the models are fitted to. The first strategy uses data from single points along the iteration path in the design space, so called single-point-path methods. The design points are the solutions of the sequential optimisation subproblem. All points within the movelimits are used to build the approximation. As the optimisation progresses, more design points become available to fit the models to, and hence improving the approximation. Approximations derived from data computed in clusters of design points along the optimisation path are called multi-point-path methods. Around each solution of the optimisation subproblem one or more extra points are generated. This method is valuable if no sensitivity data can be used, for instance if problem functions have a noisy character, or if efficiently computed sensitivity data is not available. In the latter case, the mid-range method is preferable to using local approximations based on finite differences sensitivities.

2.4 Aeronautic application

The design space of interest to aeronautical application is that associated with transonic aerofoils. In the OPTIM programme the computational tools developed at British Aerospace's Sowerby Research Centre have been tested on two dimensional aerofoils in inviscid flows. The aerofoil configuration is defined by a set of rational B-spline curves from which the resulting vertices of the defining polygonal net are identified as the set of shape variables. Typically around 23, 8th order B-spline vertices are used. During aerodynamic shape optimisation these B-spline vertices are moved to improve the shape aerodynamics.

Within the wing design environment the engineer requires a good approximation for the flow field variables and the aerodynamic sensitivities. Instead of using a CFD code at each required design point, a new methodology has been devised, implemented and demonstrated. The method, termed Projected Implicit Reconstruction, produces good approximations to the flow field at each design point at a much reduced cost primarily due to using only one steady state flow field from a CFD code as initial input data. The PIR method is based on the "quasi-analytic" approach, widely cited in the literature. An Euler Approximate Riemann solver code was written to provide the initial CFD solution for the PIR code and also to provide results against which results from the PIR method and a function approximation algorithm could be validated. It is estimated that for a typical testcase the PIR method can construct the design space within 5% of the time taken by direct methods.

The PIR method was extended to provide a Design Space Approximation Technique. This produces a mathematical description of the design space in terms of polynomials where the function is constructed using a small number of values from PIR iterations. This approach enables the function to be found quickly and without compromising the accuracy. In the testcases considered the analytic function can be an aerodynamic coefficient, the aerofoil area or a cost function. The advantage of the DSAT method is the typical saving of 95% of the time taken to acquire the required data base compared with when the straight PIR approach is adopted [4].

An optimisation study which aimed at evaluating the suitability to aerodynamic optimisation was also undertaken. This considered both stochastic and gradient based methods [5].

A formulation for the cost function and constraint definition for shape optimisation by sensitivity analysis of a transport aircraft has also been developed. A process is defined in which direct operating costs are minimised, based on a trade-off between aerodynamics, manufacturing tolerances and operational requirements.

2.5 Hydrodynamic application

Two kinds of hydrodynamic problems were considered. The first one is the forward resistance of ships moving at a constant forward speed in calm water. To solve this problem, an existing boundary element method is used through the computer code REVA [6]. This code needs as input the meshed immersed geometry of the ship, and provides a number of outputs which can be taken as optimisation criteria :

- the forces applied to the body, in particular its wave resistance,
- the wave heights around the ship,
- the pressures on the ship or in the fluid,
- the velocities on the ship or in the fluid.

Some work has been performed to decrease the sensitivities computing time, mainly by making use of the perturbation smallness to replace the inversion of perturbated linear systems by matrices products, and to set up a filter for the computation of only sufficiently perturbated influence coefficients.

The problem of static and dynamic equilibrium related with the shape evolutions and with the flow induced displacements was also studied.

The second kind of hydrodynamic problems is the seakeeping behaviour of floating bodies. The background code used is the AQUA+ boundary elements code which provides the following outputs as possible optimisation criteria [7] :

- the motions of the body in an harmonic swell,
- the pressures and forces on the body,
- the wave amplitude modification by the body.

The particular problem of the evolution of the inertia with the shape was also handled, mainly by using CAD capabilities to take into account these inertia.

3 RESULTS

3.1 Aeronautic results

In the PIR code, the design variables are the angle of attack, freestream Mach number, weight and the shape variables which parameterise the aerofoil. This code is used to describe the complete design space (of 23 shape variables, angle of attack and Mach number). Values of the aerodynamic coefficients are predicted by the PIR method to within a few percent of the corresponding CFD results for small perturbations in all design variables. The flowfields from the PIR run preserve the qualitative features of the flow and also quantitatively compare well with the corresponding flowfields produced by the Euler CFD code, even if shocks are smeared and some smoothness in the result is lost.

Typically a reduction in the drag coefficient of up to 25% was obtained when optimising a RAE2822 aerofoil. with constraints on the aerofoil area and pitching moment. Comparisons with results from the Broyden-Fletcher-Shanno algorithm [8] produced exactly the same optimised solutions.

Multi-point testcases have also been successfully investigated. These are useful experiments as they are the precursors to optimising over the complete flight path of a typical mission for an aeroplane.For example where the aeroplane travels for significant periods at two different Mach numbers, the objective function is taken as a linear combination of the objective functions from the two separate Mach number cases. The solution however is not a linear combination of the individual solutions due to the inherent nonlinearity of the physical problem.

To illustrate this case, a NACA0012 aerofoil base line was considered, at transonic speeds. The aim was to reduce the drag coefficient for a lift coefficient of 0.5 (typical for the aerofoil in cruise). The EPPLER, incompressible, viscous code was used to provide the aerodynamic coefficient data. The cross-sectional area of the aerofoil non-dimensionalised with respect to chord was required to be greater than 0.08. A limit was set on the overall shape of the aerofoil, such that the analysis method is able to provide the expected trend in the estimates of the drag, and the value of the zero lift pitching moment was restricted between -0.1 and 0.02

All but one vertex (taken as the reference vertex) were allowed to vary (i.e. 13 B-spline vertices). Constraints were set on the minimum size of the front and rear spar thicknesses and the minimum area of the aerofoil between the spars. An additional constraint was imposed on the variation in the curvature of the aerofoil to ensure smoothness and monotonicity on the upper and lower surfaces of the leading edge shape ahead of the front spar. Figure 2 shows the results of optimising a 23 pole B-spline for all but the leading edge pole. Here two objective functions were optimised: drag coefficient at a lift coefficient of 0.35 and drag coefficient at a lift coefficient of 0.2 plus drag coefficient at a lift coefficient of 0.6. Figure 3 shows the aerodynamic characteristics of the initial and resulting aerofoils, where the "buckets" indicate large tracts of laminar flow.

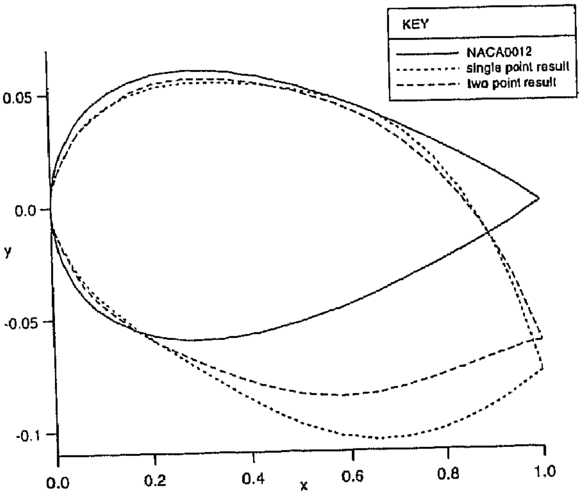

Figure 2. NACA0012 - Initial and final shapes

In a third case, aerodynamic drag in cruise was minimised subject to the structural constraint that the ultimate stress should not be exceeded in a 2,5g load case. This case is presented in figure6.

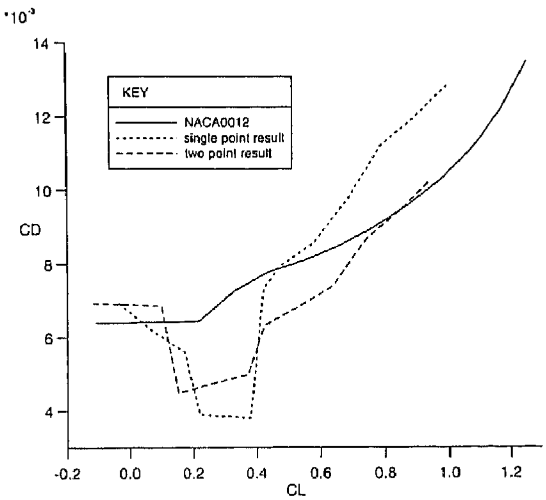

Figure 3. NACA0012, Aerodynamic characteristics

3.2 Hydrodynamic results

After the first validation tests which aimed at controling the hydrodynamic related developments and behaviour with respect to an optimisation procedure, two test cases, representative of what can be brought by the optimisation system were carried out.

Tuna boat - Ship resistance model

As an opportunity of working on an actual tuna boat which was currently studied by a French shipyard occured, this was chosen as a test case. One of the most critical problem was to fulfill contractual calm water speed requirement for a given installed power, so it was decided to mainly work on the forward resistance of the ship. As the main characteristics of the ship were already defined, the authorized geometric modifications were located at the bow, including a bow bulb. The geometry was retrieved from the shipyard CAD system (Catia), and a set of relevant shape parameters were defined in PRO/Engineer in order to authorize as large as possible acceptable deformations with as few as possible parameters.

The optimisation was performed in a number of cases with different objective functions and constraints. In particular, the computed ship resistance and the wave heights around the ship have been successively taken as objective functions with the same results, the constraint being a maximum value of the volumic displacement. The flow characteristics around the bow of the initial and final shapes are shown in figure 4 and explain why the resistance is decreased. The wave height is decreased, as well as the resistive pressure on the bow, behind the bulb.

In order to validate the results, experimental tests have been performed in towing tank, on the initial shape and on the final shape described above. The comparison of forward resistance is given in figure 5 and shows a good agreement. A gain of 10 % has been obtained on the resistance, which corresponds to a gain of 0.5 knots in the speed for a constant installed power.

Offshore platform - Seakeeping/structural models

The test case is a semi-submersible offshore platform for which seakeeping characteristics (heave motion at a given point) were optimised, with constraints on the structural characteristics. In this test case, both models interact with each other. The motions of the platform are computed using the AQUA+ software, and the constraints in the structure are computed by SAMCEF. The loads on the structure are due to its weight, hydrostatic pressure on the immersed part and dynamic pressure due to the swell and to the platform motions, computed by AQUA+.

So an entire procedure able to make the hydrodynamic model and the structure model communicate with each other was developed on the basis of the BOSS/Quattro philosophy. Three models were built :

- The **geometric model** is built with Pro/Engineer and is entirely parametered. The diameter and thickness of the bracing beams are also defined as variables (which have no hydrodynamic influence).
- The **hydrodynamic model** comprises a full set of data defining the hydrodynamic cases. The geometry itself is described by a mesh created by SAMCEF/Bacon.
- The **finite element structural model** is described by a mesh created by SAMCEF/Bacon. The hydrodynamic loads are computed by AQUA+ and converted into efforts on nodes of the SAMCEF mesh.

The purpose was to reduce the platform motions and to keep structural stresses below a given level for a given sea state. The objective function was the heave motion at one point of the platform. The constraints concerned the displacement of the platform and the maximum normal stresses in the bracing beams.

The results of the optimisation loop are shown on figure 6 together with the initial and final shapes. The heave motion is actually reduced and the stresses that were initially well above the bound are below it for the final shape. This test case clearly shows the feasibility and the usefulness of multi-model optimisation.

4 CONCLUSIONS

A running prototype of an open software package is now available for managing optimisation processes including foreign software for shape parameterisation and analysis. This includes geometry processing tools (SAMCEF/

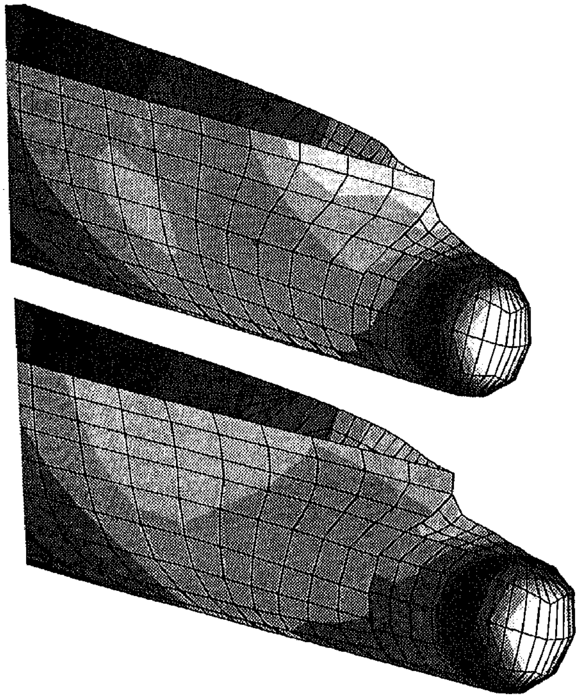

Figure 4. Flow around the ship bow (pressure) (white : overpressure, black: underpressure)

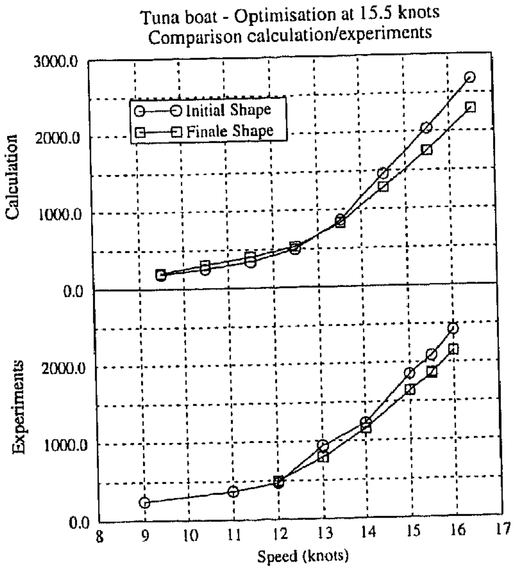

Figure 5. Calculated and experimental forward resistance

Bacon, PRO/Engineer) and mesh perturbator for SAMCEF/Bacon. An user interface for an easy exploitation of this optimisation package has been released (BOSS/Quattro). Several new optimisation algorithms have also been developed to match a number of users requests, and can be used within the optimisation procedure. This has been successfully applied to hydrodynamic analysis in two fields : ship wave resistance and floating bodies seakeeping, on the basis of existing CFD codes. In aeronautics, computational tools have been developed, aiming at a quick construction of a two-dimensional aerofoil performance results database, to be used in a global direct operating costs optimisation process. A validation task, including multi-model optimisation, was also performed.

Some additional work is now in progress to consolidate and enhance the capabilities of this tools : work on optimisation algorithms, on mesh perturbators, etc... However, a number of efficient pieces of software are already available for practical use (Boss/Quattro user interface, drivers...)

ACKNOWLEDGEMENTS

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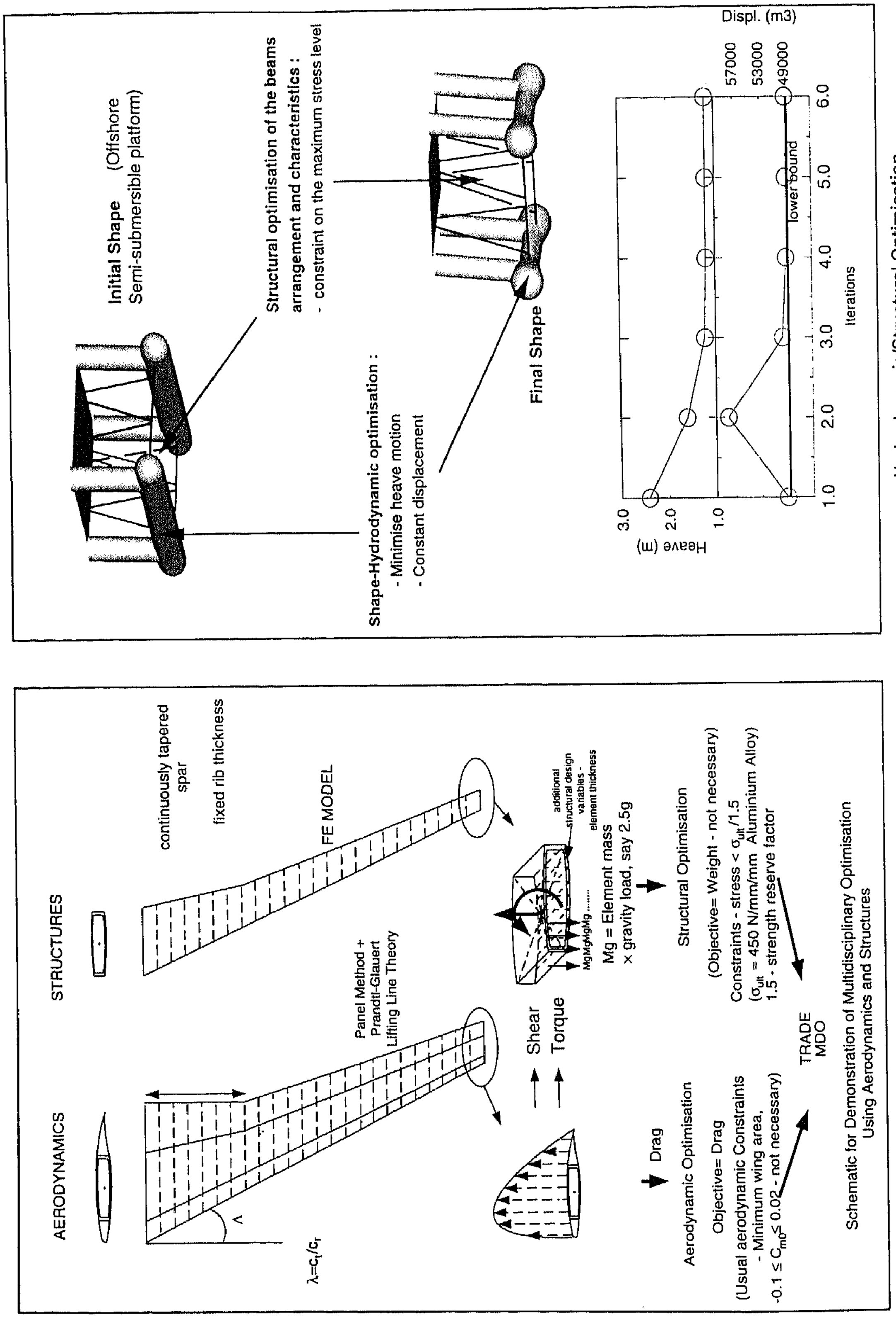

Figure 6. Multimodel optimization