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EFFICIENT PROCEDURES FOR THE OPTIMIZATION OF AIRCRAFT STRUCTURES WITH A LARGE NUMBER OF DESIGN VARIABLES

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Abstract

Variable reduction in an optimization process is a necessary task to match acceptable computation times and costs in the predesign phase. A method is presented which reduces the number of design parameters in the optimization process with large structures, without cutting the variational degrees of freedom, such as the variable-slaving method will do. Both, the optimizor and the finite-element analysis program are separated and the parameter set is determined out of an interpolating routine which is controlled by the optimizor itself. The advantage of this procedure is to reduce the computation time rapidly due to the small parameter-set in the optimizor. Variations with the onedimensional and twodimensional interpolating functions, such as polynomials and splines are carried out with aircraft structures in comparison to 'full-variable-size' optimizations and those with the classic 'variable slaving' method. This contribution is completed by a view on how to implement this method in CAD environments and on future extensions with it.

Introduction

The design process for aircrafts is a complex task which is intensified by the ever growing demands on the performance and profitable aircraft yield. Nowadays it is absolutely necessary to use powerful computer systems and software products to match these demands in the aircraft design process. In structures FE methods are carrying out the stress analysis and are used for determination of dynamic processes, in aerodynamics CFD methods such as Euler codes and Navier-Stokes computations are able to calculate the aircrafts aerodynamic behavior. Those processes are coupled indirectly in CAE systems [1] and the variational tasks are partly controlled by numerical optimization routines, especially in the field of structures [2,3].

Acting together of those topics will become much more important in the future to realize the additional potentials by common variation in between the design process.

But although the computer performance increases heavily, it is nearly impossible to handle larger optimization problems which are important for the predesign phase in aeronautics, because of the tremendous computation times, needed for them. Two main tasks for it may point out the evidence of implementing efficient routines to the optimization process, to make those tasks practicable today:

- The 'overall' design process
- The interactive design process

Figure 1 describes the disciplines of the computer aided predesign phase within an 'overall' design process. Numerical analysis methods are coupled by optimization routines. Parameters of this task is the surface geometry or to relate to the analysis methods, the node point locations of the FE and the CFD grids, nearby the dimensions (sizes) of the elements and their mechanical behaviour for structures in special. A node point variation itself results in a form-optimization process in general and a shape variation process for structures, such as the tapering of stringers and the shaping of a hole. A variation of the thickness- or the stiffness-distributions results in a sizing process in general.

The size of the analyzing models are different. A finite-element model will have a total number of DOF of about several 10.000 with a detail analysis for a complete aircraft model [4]. Main parameters of it are the element thicknesses as described above, nearby node point locations for shape variation. The number of parameters with this model reaches more than 1000. And the parameter sets for the computational fluid dynamics model with typically more than 100.000 grid points for analysis [5], reaches the number of 1000, too.

Nearby those topics other analyzing models have to be considered in the 'overall' design process, such as the flight-mechanics model, a aero-thermodynamic model where necessary, systems-technology and flight-management models nearby engine analyzation. With those models and their parameter sets, the total number of free design variables increases up to several thousands.

This task is dependent mainly on the computer performance and on efficient optimization routines in conjunction with excellent FE and CFD analysis methods. The 'overall' design process is difficult to be

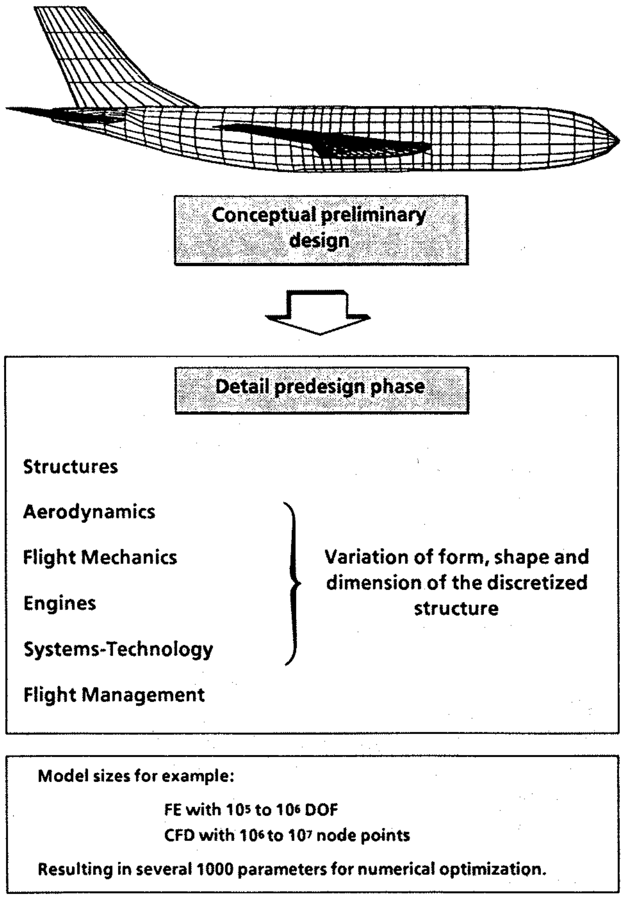


Fig. 1: The 'overall' design process in the detail predesign phase

carried out in the near future because of the extreme number of DOF and number of parameters which will result in days and weeks of pure CPU time even with the fastest machines. So a variable reduction without cutting the variational degrees of freedom will make this process practicable today.

But not only this design process is based on efficient procedures, but also the interactive design process with structural optimization or fluid dynamic computations is essential and should be highlighted.

This 'desktop' design process, which is carried out by the designer interactively, consists of the following steps for structures:

- Make up the initial geometrical model for your aircraft or spaceplane
- Attach the preprocessor to generate the node point and element set
- Choose the optimizor and attach the parameter model to it
- Start interactive optimization and receive a data set after each iteration from the mainframe. This data set is presented graphically on the workstation. Decide wether the process works well and stop it on convergence.

Figure 2 presents this task and its necessary computer equipment.

The interactive design process such as described above depends mainly on short turnaround times for the interactive tasks and for the information flow during the optimization cycle. To keep this period short, the size of the analyzing model should be moderate and the parameter number for the optimization process has to be cut down. A very effective method for this task is decribed later on.

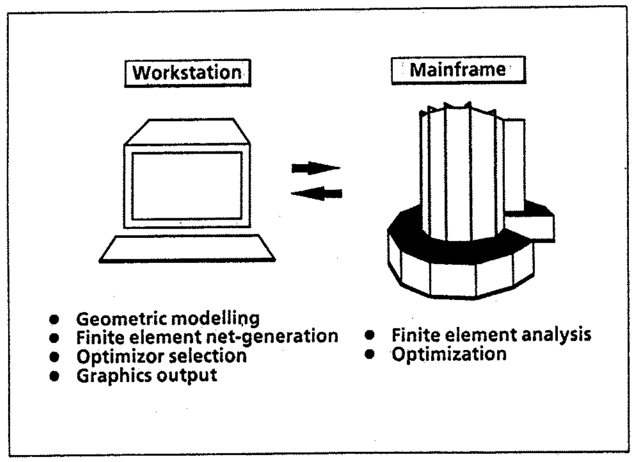


Fig. 2: The 'interactive' design process and its computer equipment

Tasks in structural optimization in special

In structural design the finite-element analyzer is controlled by an optimizing routine and pre- as well as postprocessors as interfaces. These modules are capable in handling the dimension variation process and also the shape optimization process with arbitrary structures, load conditions and arbitrary initial parameter vectors. Each finite element and its thickness information nearby the node-point locations of separated structural parts are parameters in this automatic design process. This leads to huge variable sets due to the large number of finite elements in structural analysis (typical up to several thousands). In practice the large variable set especially for thickness optimization has to be reduced.

To demonstrate the increase in computation time with an increase in variable number, figure 3 presents a time log with a calculation of a wing structure for example. The weight optimization (sizing of the thicknesses of the elements) with a moderate Finite-Element set with 430 elements results in a total optimization time of 1.8 hours. For comparison a computation time of 24 hours results for a refined model with 4300 elements and a reduced gradient computation with only 1/10th of the gradients are analyzed.

Additionally figure 3 presents a computational task with the same structure but a reduced parameter set. Here the rough model as well as the refined model is controlled by 57 parameters. Supposed that the reduced parameter model gives the full variational freedom, the resulting structure and the weight will be nearly identical compared with the 'all-free' optimization process. For the smaller model the resulting computation time is 26 minutes, compared with the 1.8 hours of the free set (factor of 4.2). For the refined model a total time of 3.3 hours results with it (factor of 7.4). Optimization with this reduced set gives an advantage in computation time. That means a cost reduction and a possibility for larger structural optimizations, such as the 'overall' design process or the interactive design task.

	430 elements 430 parameters	4300 elements 4300 parameters
Total optimization time	6630 sec ~1.8 h	88400 sec ~24 h
	430 elements 57 parameters	4300 elements 57 parameters
Total optimization time	1595 sec ~26 min	12025 sec ~3.3 h

10 iteration steps to convergence on CDC 180-860 mainframe

Fig. 3: Comparison of time-logs with the weight optimization of a twinjet wing-box

Reduction of the parameter number seems to be self-evident in structural optimization. Several methods are useful for this process and they are listed in Figure 4.

Let us begin with the 'all-free' model, it means the parameter set is identical to the variable set of the analyzing routine. The variational potential with this method is large and is limited only by the degree of refinement of the FE model and its resulting degrees of freedom.

Reduction of this large parameter number comes with an interpolating functional set. It may give the 'all-free' potential if the functions are implemented correctly, so that their behaviour describes the optimal thickness contours. This method gives acceptable results with a continuous behaviour of the dimensions or the shape. For example it may be excellent with the nearly square thickness distribution in spanwise direction of a two-spar wing box.

In most practical calculations the variable slaving method is used. This method is acceptable with manufacturing constraints, such as the constant thickness distribution of a fuselage shell-structure or the skins of a sandwich flap-construction. But

Variable treatment	Variational potential
- Full variable size	Full potential with the variational freedom of the analyzing model
- Interpolating functions	In most cases full potential with correctly adapted interpolating functions
- Variable slaving	Reduced variational potential, useful in conjunction with manufacturing constraints
- Variable neglection	Extremely reduced variational potential

Fig. 4: Methods for parameter reduction in structural optimization

reaching the weight optimum with this method is not possible in general because of the reduction of variational degrees of freedom. And the quality of the weight optimum decreases mainly with the intensity of variable coupling.

Variable neglection is a further possibility to reduce the parameter number. It is useful were parameters may not or must not be variated in the design process. It needs no discussion, the optimum is extremely cutted off from the design-space and it should not be the first choose for parameter reduction.

An efficient method for variable reduction

Normally the numerical optimization process consists of the analyzer and the optimizor coupled by pre- and postprocessors. This way of module interfacing isn't very effective from various points of view:

- There is still the full variable size to handle within the optimizor
- Weak variances between elements and their gradient information are not used to reduce the variable number

Various investigations have been carried out by the authors and one method comes out to be very effective with structural optimization. Figure 5 presents this special way to interface the program-modules of the optimization process. The finite-element analyzer and its pre- and postprocessors are handling the full variable set of the refined model. In contrast to it the optimizor variates only a reduced parameter set to control the interpolating functions and it receives the full constraint set from the postprocessor. From this reduced parameter set an interpolating function computes the variables for the preprocessor and the analyzer.

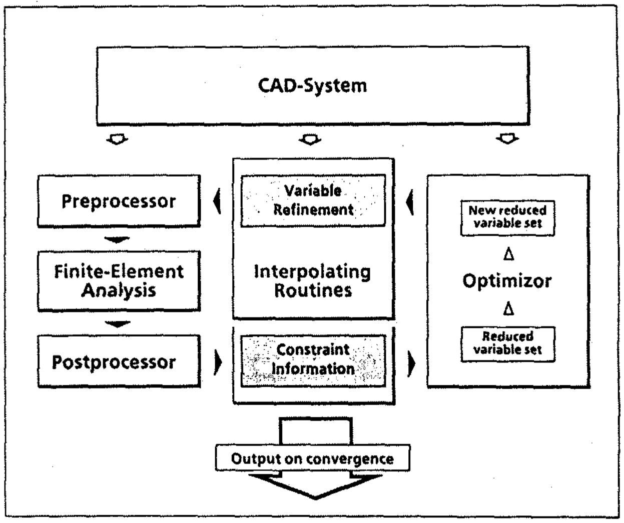


Fig. 5: Interaction of numerical routines for structural optimization in a CAD environment

But it should be mentioned here that this process is not quite so new. Interpolating functions are used with the shape variation for a long time (6,7) and there have been investigations with airfoil optimization and interpolating functions too (8). So the idea was to bring in this exellent variable reduction routine to the thickness- or in general, the dimension-variation (sizing) process.

Let us have a view on how to implement interpolating functions for variable reduction to the optimization process in general. Normally an objective function is to be minimized, subject to constraints and a variable set:

$$\min F(\mathbf{x})$$
$$g(\mathbf{x}) \leqq 0$$
$$h(\mathbf{x}) = 0$$
$$\mathbf{x} = [x_1, \ldots, x_{nv}]$$

In structural optimization with a finite-element analyzer and a discrete element set, the weight of the structure has to be minimized subject to limit stress constraints:

$$\min W(\mathbf{x})$$
$$(\sigma(\mathbf{x})_i/\sigma(\mathbf{x})_{lim} - 1) \leqq 0 \qquad 1 \leqq i \leqq n_{el}$$

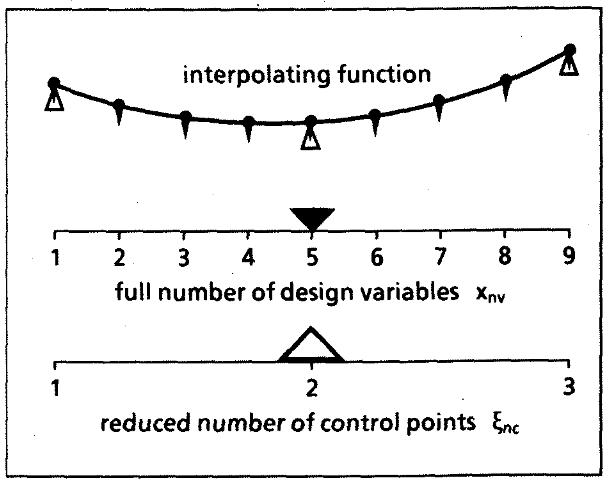
The vector of variables **x** consists of the thicknesses of the finite-elements if we are changing the dimensions, or it consists of the node point or surface geometry if a form or shape variation has to be carried out:

dimension $\mathbf{x} = [t_1, \ldots, t_{nv}]^T$

shape $\mathbf{x} = [x_1, y_1, z_1, \ldots, x_{nv}, y_{nv}, z_{nv}]^T$

As described before, this variable set may be identical to the parameter set in the optimization process, but it is very uneffective to walk this way.

If we are using interpolating functions for variable reduction the objective function as well as the constraint set remains the same. But the variable set itself is influenced by a reduced number of control points, so that the timeconsuming optimization process and its gradient computation comes out to be more effective.



With this the variable vector decreases to the control point set of the interpolating function itself:

interpolated variable set $\mathbf{x} = [\xi_1, \ldots, \xi_{nc}]^T$

No discussion that the variational freedom with such a function is reduced to the freedom of the function itself. So it will be impossible to have an accurate variable set with a square function if the optimum values are distributed in a cubic manner. And in addition to it, unsteady distributions in the optimum are filtered so that the unsteady value lies in between the interpolated region of the function. If those points are fundamental for the optimum itself, they should be treated separately or the function should be piecewise steady.

An additional advantage with this method, which should be pointed out is a more stable convergence rate to the optimum because of the steady variation capability of the variable set.

Interpolating functions

In design of aircraft structures the handling with almost continuous dimension distributions for large structural parts, such as for the panels for example, could be stated. The problem of variable reduction, a cut of variational freedom can be reduced if a type of interpolating function is used which matches the behaviour of the free model in the optimum. Care has to be taken into account in areas were single forces are to be adapted or the structure changes its geometric behaviour (e.g. a kink), as mentioned before.

In practice two types of functions are used which fit the above mentioned demands very well:

- Polynomial functions in one- and twodimensional projections
- Spline functions in one and two dimensions

Figure 6 presents typical parameter models with the related functional types. In general spline functions are stiffer in their behaviour and they are almost implemented in CAD Systems, which is an advantage to use those subroutines from this program package. This point should be highlighted later on again.

It is worthwile to have a look onto the possibilities with such a parameter model. Assumed we are using a cubic/square twodimensional polynomial function, this model will fit the requested variational freedom to control the thickness distribution of a wing panel. Figure 7 describes the parametric freedom which can be obtained with this model.

Only 12 parameters are necessary to fit the thickness distribution of the upper panel for the all free variation. With this set it is possible to control a finite-element net with 25 panels for the predesign task. And it will be possible to control this model with a onedimensional polynomial function, too. The next step to a more accurate analysis is a refinement with 125 panels for the upper-plate structure. And in a further refinement phase it is also possible to extend the number of Finite Elements up to an arbitrary value. In the figure a refinement with 500 elements for high accuracy analysis is presented for this design task.

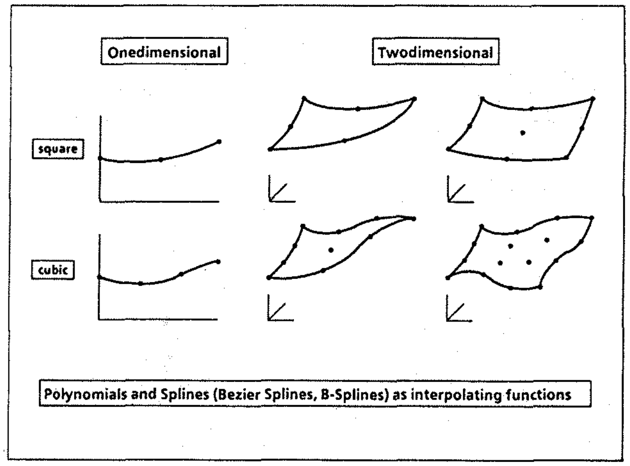


Fig. 6: Interpolating functions in one- and two-dimensions

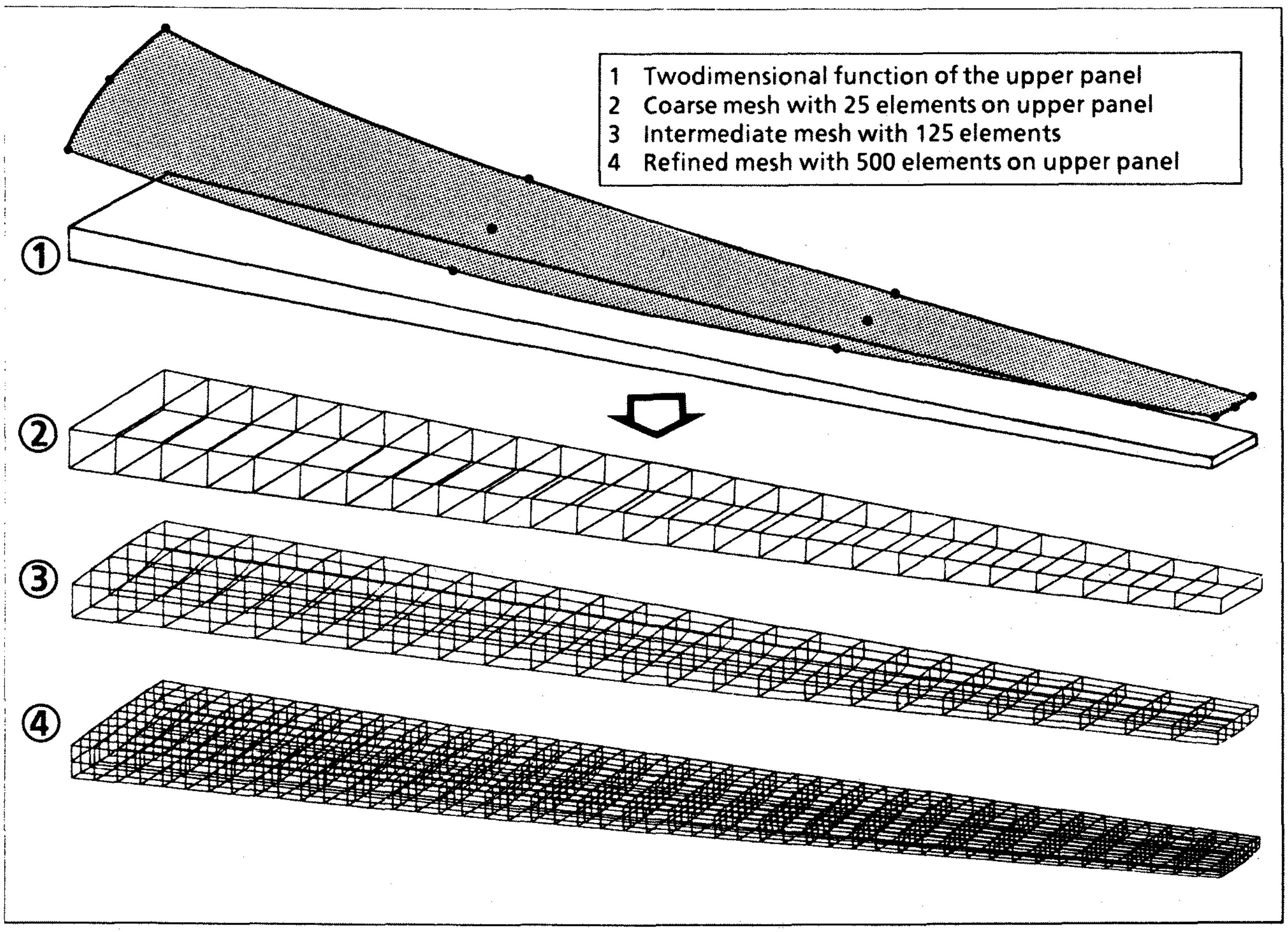


Fig. 7: Different degrees of refinement with a wing-box structure, controlled by an interpolating function. Number of elements and function for the upper-panel

It should be mentioned here, that each element brings in its own stress constraint into the optimization process, so that the variation process itself is not limited because of a reduction in accuracy for the stress analysis. The major effort is the reduction of the computation time due to the variable cut down, as it will be presented later on.

Aircraft structures with this method

It has been described that this method of variable reduction will give almost the full variational freedom if it is implemented correctly and if there are no discontinuities in the force distribution nor the geometry of the structure itself. Some aircraft structures should be presented and their according interpolating functional sets.

Figure 8 describes a twinjet wing structure which has been presented before. Two cubic/quadratic patches are necessary to give the variational freedom for each plate structure. To match the discontinuities in the areas of engine and wheelbase attachment, each patch varies only in between these regions. If the wing structure isn't influenced by those attachment points, such as the structure of an executive jet for example, it may be useful to have only one cubic/quadratic patch, or, if a higher variational freedom is required, it may be necessary to use a bicubic function with only 16 parameters.

To control the spar- and rib-thickness distributions, several onedimensional functions are implemented. Square functions in between the related areas for the spars and an identical set for the ribs, if it is assumed for those ribs to have continuous thicknesses in chordwise direction.

With this model and its total parameter number of 57 it is possible to control a discretized structure with several thousand elements for analyis. In the figure the structural mesh consists of 430 elements and 900 degrees of freedom for preliminary design optimization.

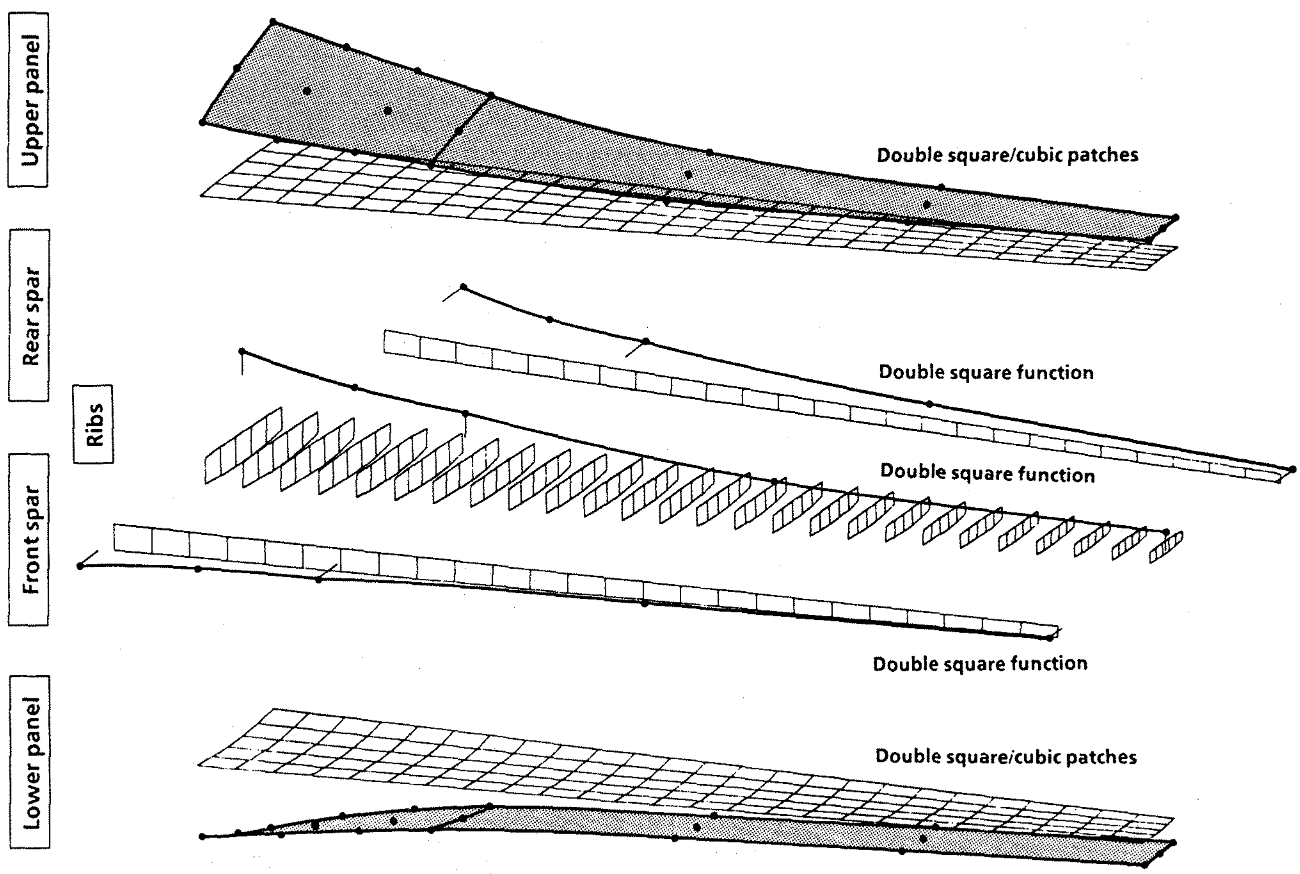


Fig. 8: Interpolating functions and control point set for the twinjet wing-box structure, consisting of 430 four-point continuous elements

Comparison of effectiveness and accuracy

Several optimizations have been carried out with the twinjet wing-box to discuss the effectiveness of this method and to compare the accuracy of reaching the weight optimum, given by the 'all-free' design with this Finite-Element model.

To reduce the graphics output and to have a better overview only the upper panel with its thickness and stress contours are presented for the final computation to convergence. But it should be mentioned that the complete wing-box has been taken into account for the calculations. Load case is 'flatten-out' in point 'd' of the velocity/load-factor curve.

The computations themselves have been carried out with a Penalty-Functions method for constraint reduction and a Conjugate-Gradient search algorithm (9,10). The finite-element model itself consists of continuous quadrilateral elements and the sensivity analysis itself is carried out internally by the FE analyzer.

Fig.9 presents the result of the 'all-free' design nearby the result with the interpolated model (Fig. 8).

Nearly the whole wing-panel is designed to the limit stress point. Only the wing-tip with its low thickness constraint does not reach this value. In spanwise direction the thickness distribution varies with a square to cubic behavior and has a weak discontinuity in the area where the engine and the kink is located. In chordwise direction a nearly square thickness behavior could be stated.

In relation to it the stress contour of the interpolated computation gives nearly the same results with a slight change in the fuselage-engine area, which comes from the differences of the thickness distribution, compared with the 'all-free' model. Here the thicknesses are slightly different in chordwise direction, because of the square degree of freedom in this direction, which causes some weak difficulties to match the distribution exactly. But to compare the stress values, these differences are smaller than 3% in relation to the limit stress-value, which means a difference of less than 5 N/mm^2 in practice. And the weight increase because of it is less than 1% for the upper-panel.

It could be stated here, that the chosen interpolating functions are matching a high accuracy 'all-free' design, but with only 57 parameters instead of 430. The saving in computation time and costs is about a factor of 4.2, Fig.10.

In comparison to it, a computation has been carried out with a constant thickness distribution in between the area of two ribs. The results of this computation are presented in Figure 11.

	Relative weight of complete wing-box	Maximum stress difference on upper panel	Number of parameters on upper panel	Relative total computation time
All free model	1.0	−1.5 %	125	1.0
All free interpolated	1.01	−3. %	21	.24
Chordwise constant model	1.11	−10. %	25	.37
Chordwise constant interpolated	1.11	−11. %	5	.17

Fig. 10: Comparative study with interpolating functions on a twinjet wing-box (upper-panel)

It needs no question the stress contour matches the design point only in a small area of the plate structure and the stresses themselves are varying much stronger. Here the maximum stress-difference for the upper wing-panel is nearly 10% of the limit-stress value, thats approximately 30 N/mm^2. And the contour realizes its maximum values in the rear spar area, nearby the fuselage, changing to the center of the panel in chordwise directions.

To interpolate this thickness contour a onedimensional double-square function is useful, such as for the spars and ribs. This reduces the number of parameters to 25 for the complete wing-box instead of 57. The resulting thickness distribution with it is nearly identical to that of the chordwise constant model. The worst difference does not exceed 1% of the reference values. This results in a nearly identical stress distribution and the same weight.

Accuracy and the computation times for this task are presented in Fig. 10, too. A time reduction of a factor of 2.2 could be stated without loosing the quality of the optimum for this computation.

General applications with interpolating functions

Previous examples with a twinjet wing-box and interpolating functions described the accuracy and the effectiveness with this method. But it should be possible to handle nearly every structure with it, if the dimension behavior, which is to be optimized, is smooth and is being discribed by polynomials or splines.

Figure 12 gives some more examples of aircraft structures and their interpolating functions for thickness variation of the upper panels, such as for the multicell wing-box and delta wing structure. The distribution for the first example is described by a bicubic patch and by an additional linear control

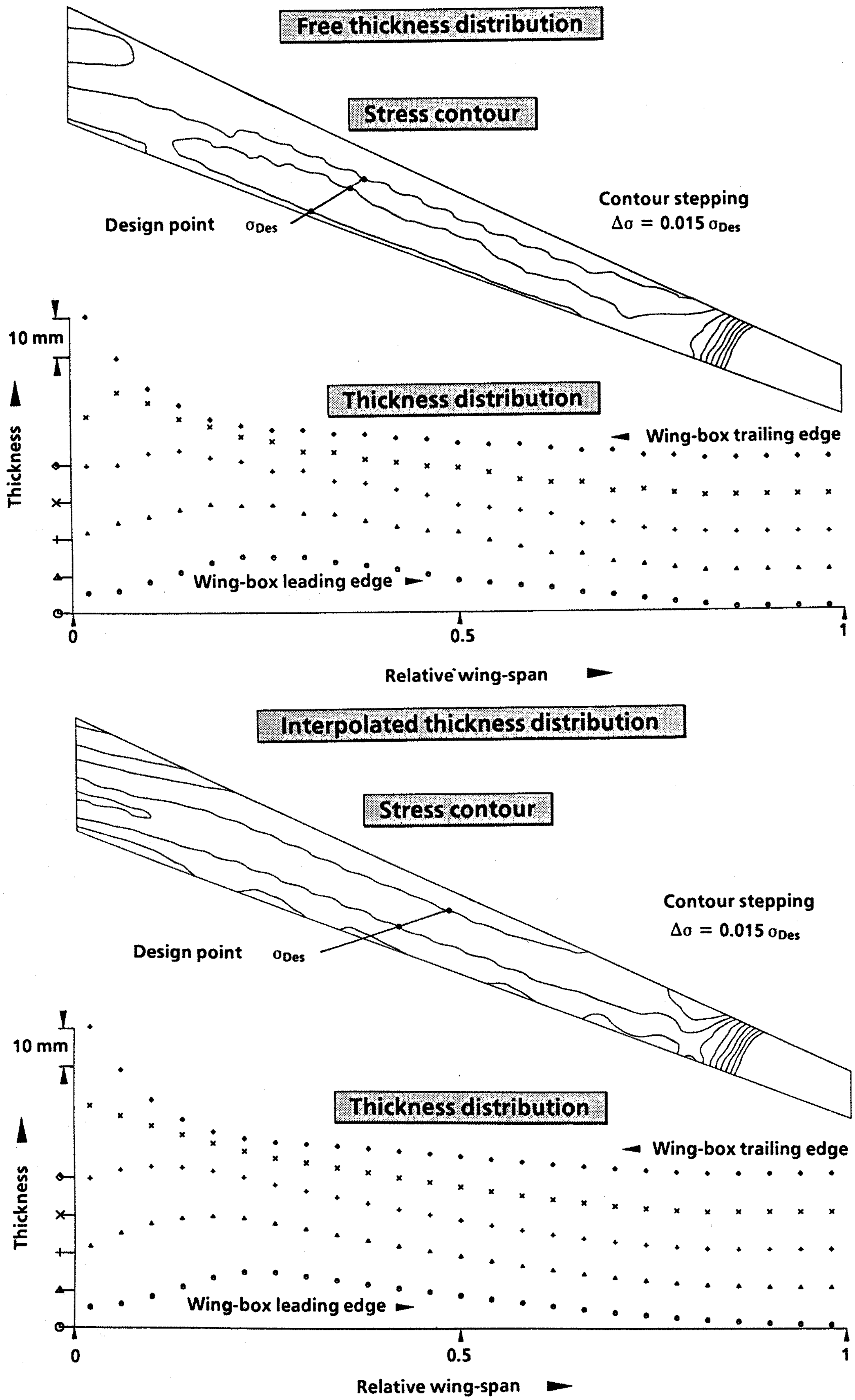


Fig. 9: Comparison of the 'all-free' and the interpolated weight optimum wing-box structures. Stress contours and thickness distributions for the upper-panel

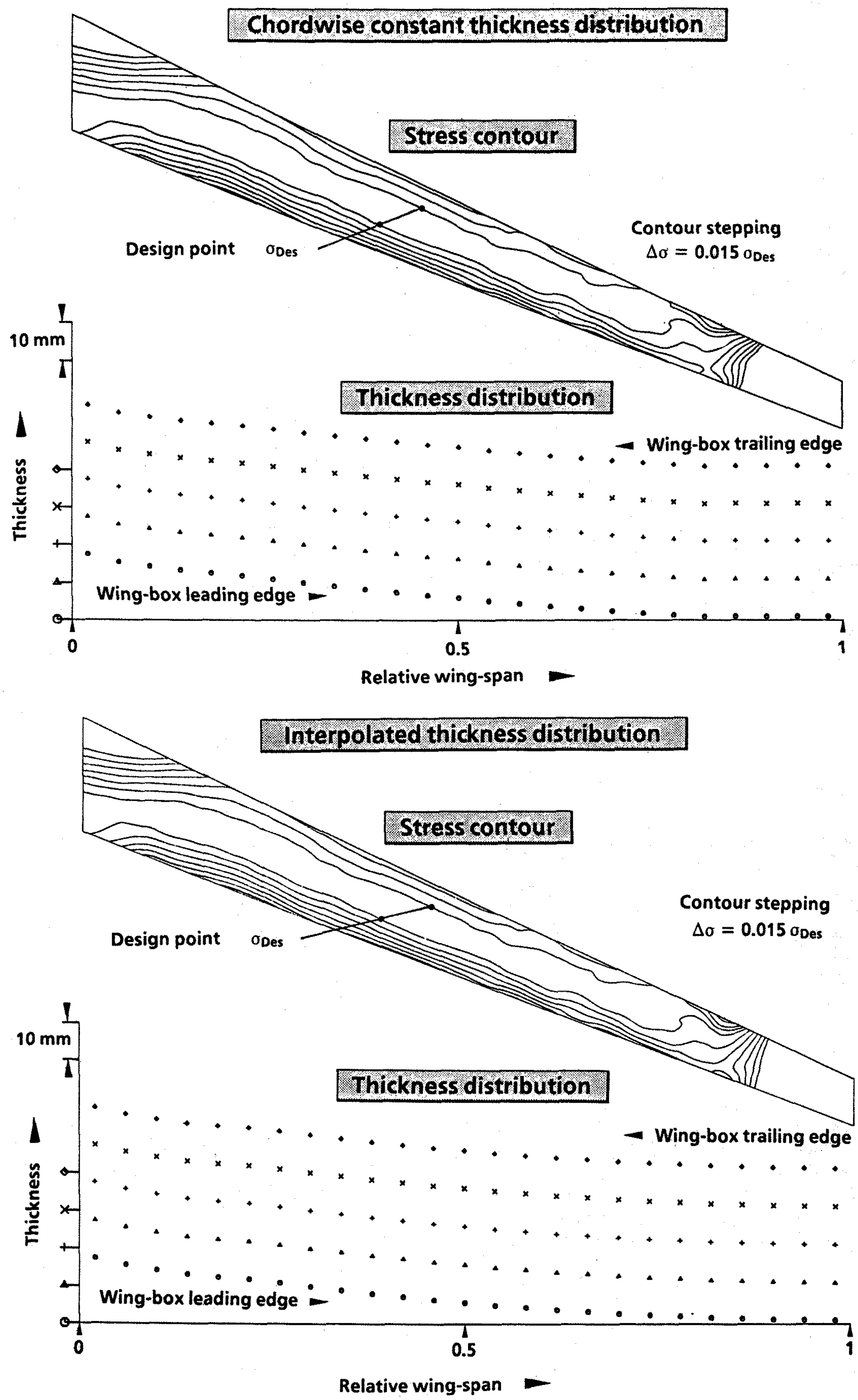


Fig. 11: Comparison of the 'chordwise constant' and the interpolated weight optimum wing-box structures. Stress contours and thickness distributions for the upper-panel

point set for the center wing-box. If this twodimensional function does not match the accuracy standard, maybe because of a more complex load condition, it should be no problem to extend the degree of freedom for it up to the desired value. For the delta wing upper panel an identical patch is used but with a higher degree of freedom in chordwise direction.

A further example is a fuselage shell structure which is a bit more difficult to handle it within the interpolating model because of the single force adaptions of the wing-fuselage intersection. For this type of structure the shell itself is not designed to be built with a strong varying thickness distribution. So a linear patch combination has been chosen to represent the thickness behaviour of it. Control points are related to the critical parts of the wing-fuselage intersection to match the desired accuracy.

But not only thickness or stiffness distributions of continuous structures are useful to be handled with this procedure. The figure presents a problem of shape optimization too. Here a small number of node points controls the shape of the hole. And because of the small number of parameters within this problem it may be possible to variate it simultanously within the optimization of the thicknesses of the wing-box structure. This will lead to an additional saving of computation time due to the reduction of multiple analysis models for shape optimization to be generated in detail analysis and variation.

Conclusion

As presented before, interpolating functions have been used to reduce the variable number for the optimization process with structures. It was possible to cut down the computation times and costs for the optimization process rapidly without reducing the variational degrees of freedom for the task itself. With a moderate wing-structure consisting of 430 elements, the factor of time reduction was 4.2 compared with the 'full-variational' task and it increases with larger analysis models. Efficiency of this method could have been increased furthermore by combining it with the well known 'variable-slaving' procedure to match manufacturing constraints, such as constant thickness distributions in chordwise directions.

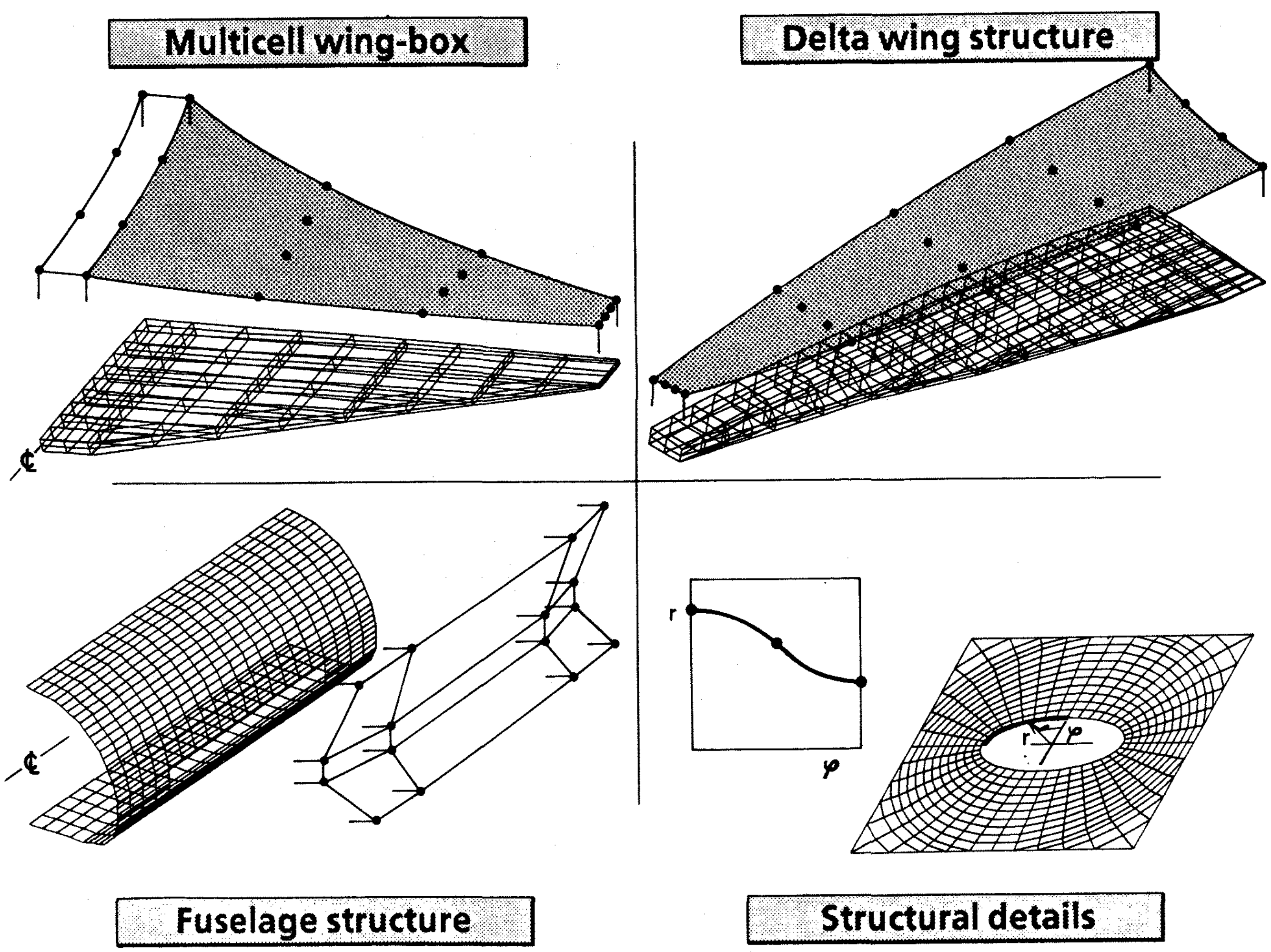


Fig. 12: Further Examples with interpolating functions on aircraft structures with the interpolating functional set and relating control points

Coming back to the two tasks which have been described at the beginning of this contribution, it should be possible to reduce the parameter number for the 'overall' design process to a value which will enable the designer to carry out this tasks with acceptable computation times on a large mainframe today. And it should be no problem to implement this method for variable reduction within the interactive design process. Relating to the twinjet wing box, a remaining turnaround time of approximately 2 to 3 minutes instead of 11 minutes will result with the presented models and interpolating functions. This should be acceptable for this task with graphic data output on the workstation.

Especially for the interactive design and optimization process, it is possible to bring in the interpolating functions from the CAD system directly. Geometric modelling of the structure deals with the generation of the structures contour which has to be refined and fitted by interpolating functions within this CAD system. Functions for it are almost splines, piecewise continuous and additionally implemented in patches. So a modern CAD system gives the structural designer the desired functions which may be implemented also in the variable reduction process.

It needs no discussion that this process depends mainly on the know-how of the designer to bring in the correct interpolating functions, patches and control points. Future systems will have the capability of 'knowledge based intelligence'. With this it might be possible to lead the user througout the design stages and help him to have a correct task with a hopefully excellent solution.

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