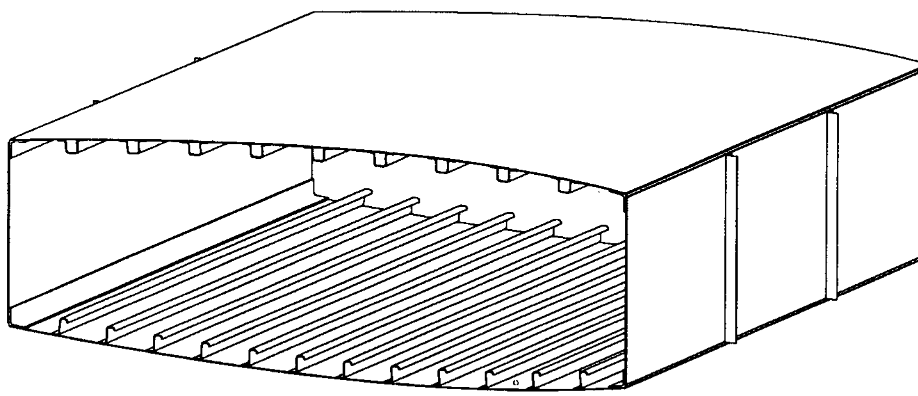
Report LR-627

WingDesign: Program for the Structural Design of a Wing Cross-section

April 1990

R.P.G. Zoontjes/A. Rothwell



TU Delft
Delft University of Technology

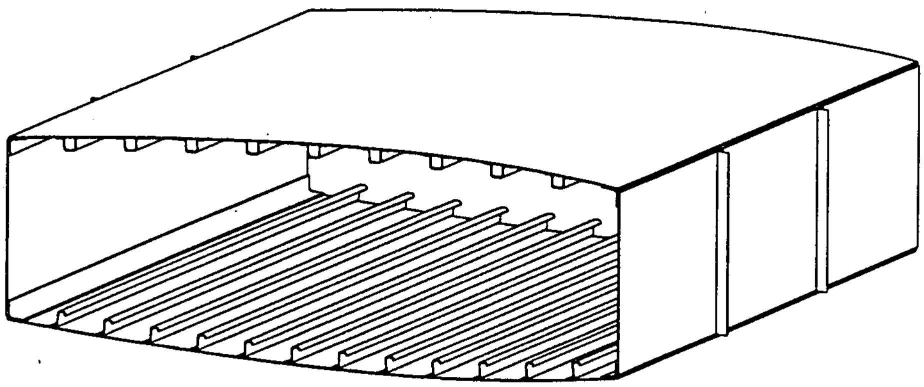
Faculty of Aerospace Engineering

Report LR-627

WingDesign: Program for the Structural Design of a Wing Cross-section

April 1990

R.P.G. Zoontjes and A. Rothwell



TU Delft
Faculty of Aerospace Engineering

SUMMARY

A computer program for the structural design of a wing cross-section is described. The program is typically intended for use at the preliminary design stage. The wing is assumed to be of conventional metal stressed-skin construction, with two spar webs. The analysis of a proposed design may be followed by optimization for minimum weight. Easy modification of the design, and the facility to 'fix' any of its dimensions at any stage, allows the user to remain in control of the progress of the design. The program is suitable for use on a personal computer.

CONTENTS

1. INTRODUCTION

The design of an aircraft structure involves much repeated analysis and design while it gradually takes its final form. In the early stages the weight of the structure can only be estimated - one of the reasons that the loading on it cannot yet be precisely determined. Many of the details of the structure are unknown, and only its principal features are of interest. The program for a wing cross-section described in this report is a convenient design tool at the preliminary design stage. It can be used to assess the effect of different parameters involved in the design, and to make a more accurate estimate of the weight of the structure. The analysis of a wing cross-section can be performed rapidly, with easy user interaction to modify the design and to change material properties and other parameters. The optimization option in the program is a powerful means of achieving a weight saving in the structure.

The development of the program is described in detail in Ref. 1. The wing is modelled as a conventional metal stressed-skin structure, with two stiffened spar webs. Only the torsion box, between the two spar webs, is taken into account. A choice of stringer type is available in the program. If required these can be chosen from a list of 'standard' sections, during optimization the program itself making the appropriate selection. Design criteria include various buckling modes, maximum stress limitations and a minimum torsional stiffness. Up to four loading cases are allowed but these, as well as the design criteria, can be expanded during the further development of the program.

The philosophy behind the program is that the user must remain in control of the progress of the design - not that the program itself obliges the user to accept a given design! Nevertheless it is realized that the user has less than full knowledge of the limitations of his design at the beginning of the design process. For example, it may not be apparent at the start that the stringer pitch in some designs will become unacceptably small during the subsequent optimization process if no restriction is placed on it. At the same time the user is not always able to specify a minimum stringer pitch until he has chosen a type of stringer and has more information about its dimensions, the skin thickness, and so on. Similarly the rib pitch is a parameter chosen by the user. However, with some exploration of the influence of rib pitch on the weight of the structure (and of course due consideration of all the other aspects affecting rib pitch) a change in rib pitch might well be decided upon.

To implement this philosophy it is anticipated that the program will be used repeatedly, the primary goal being to minimize the weight taking into account all the necessary design criteria. This is achieved by manipulating the design, or by optimization with the facility of fixing any of the dimensions or leaving them free to vary. After each change, the stresses, torsional stiffness and weight of the structure are automatically updated by a structural analysis. In this way the status of the design - results of the analysis and all dimensions - is continuously available to the user. The program is written in standard FORTRAN 77, which implies that the input and output must be in purely numerical form. Although a relatively easy user interaction is provided, sometimes the user has to pass through several menus before he can perform the actual task. This might distract him from his principal task of steering the design process. This aspect has led to the development of a graphics-based user interface. Ref. 2 is the user manual for this interface, use of which is optional. However, unlike the FORTRAN 77 program, it is machine dependent and runs only on Sun workstations. The advantage of a graphics-based user interface is that all relevant information about the status of the design is directly displayed on the screen, changes to it being very simply made by editing the display.

The present program is a prototype version, suitable for use on a personal computer, and one of a set of special-purpose programs under development. It is intended that this program for a wing-section will be used later in a multi-level optimization procedure for a complete wing structure. Interactions between adjacent cross-sections are then taken into account by appropriate sensitivity data at the level of the complete structure. This multi-level approach is described further in Ref. 3.

2. GEOMETRY AND MATERIAL DATA

The wing profile in a cross-section perpendicular to the flexural axis is defined by up to nine coordinate points for the upper surface and up to nine for the lower surface. The coordinate system is defined in Fig. 1 (i.e. origin on the front spar web, x-axis positive in the direction of the rear spar web and perpendicular to both webs, y-axis positive upwards). A polynomial interpolation is used between these points. The skins and spar webs are of uniform thickness; all four may of course be different. Stringers are at uniform pitch on the upper skin and on the lower skin. On the front and rear spar webs the stiffeners are also at uniform pitch. All stringers on the same skin panel, and all stiffeners on the same spar web, are of the same type and dimensions.

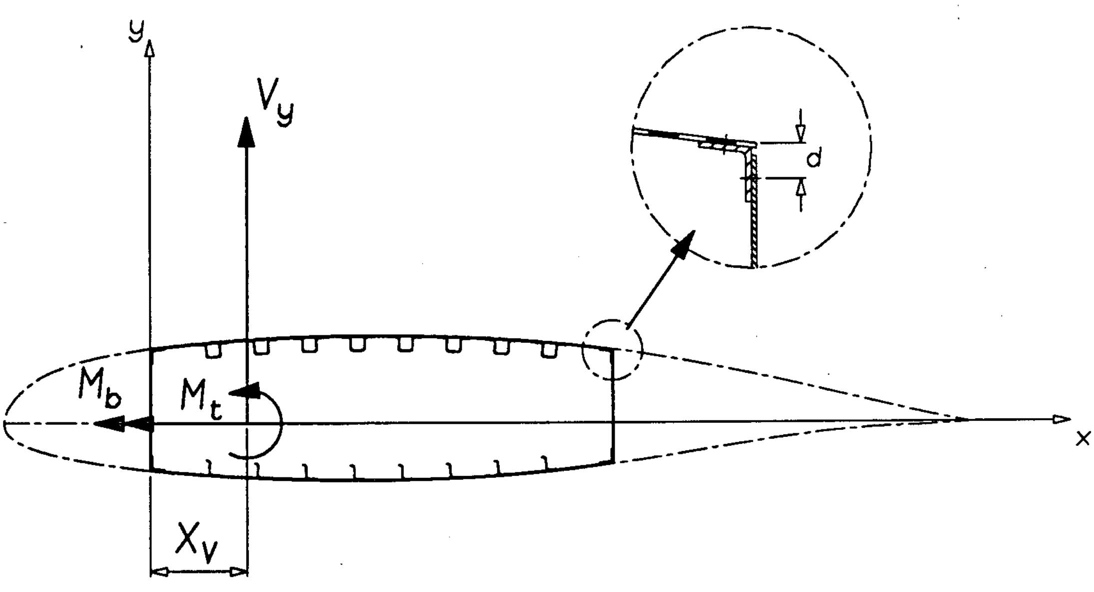


Figure 1: Cross-section of the wing and applied loading. (Inset: dimension 'd' defining distance between skin and web rivets.)

The spar webs have simple angle-stiffeners (type 1) on one side of the web ('single') or on both sides ('double'). The skin panels may have plain Z-section stringers (type 2), lipped Z-section (type 3) or hat-section (type 4). All four types may be confined to a series of 'standard' sections, or alternatively may be unrestricted. These standard sections are the same as those available in Ref. 4, relevant data for the sections already being contained within the program. When the stringers or the stiffeners are not chosen from the standard sections their dimensions must be supplied by the user. Fig. 2 shows the various stringer and stiffener shapes, and the dimensions that must be specified. The dimension '*d*' in Fig. 1 (inset) is the 'distance between skin and web rivets', implying the row of rivets furthest from the skin if there is more than one row. (This dimension is required to determine an effective simply-supported height of the spar webs for buckling, and may need a different interpretation when the detail of the attachment of the spar webs to the skins is known.) The rib pitch must be specified by the user, but the design of the ribs does not enter into the program in any other way. All dimensions should be entered in units of mm.

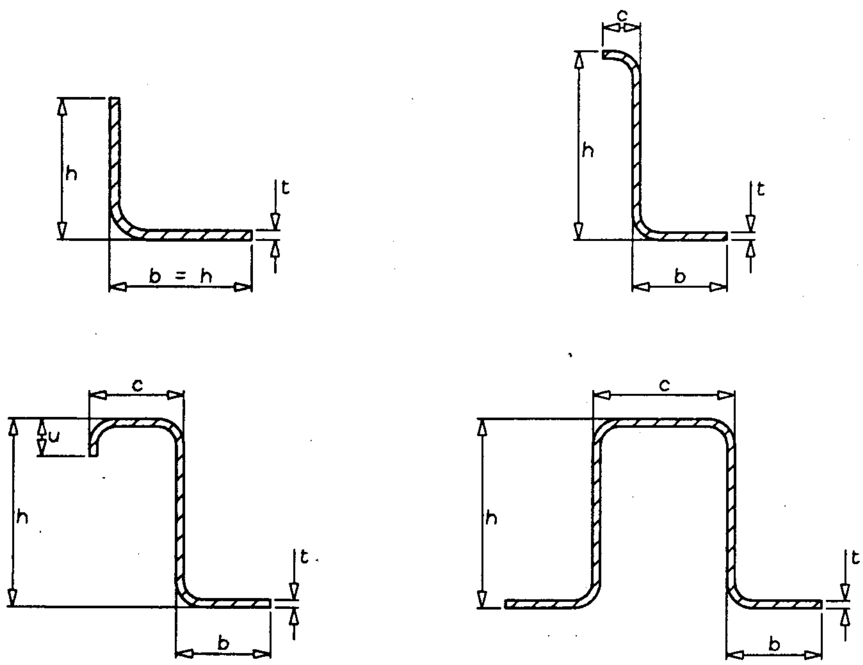


Figure 2: Available sections for web stiffeners (type 1) and stringers (types 2, 3 and 4). All sections are of uniform thickness.

Different material data can be specified for the upper skin panel, lower skin panel, front spar web and rear spar web. The required material data is the maximum tensile stress, 0.2% proof stress in compression, maximum shear stress, Young's modulus, Poisson's ratio, the Ramberg-Osgood parameter, and the density. Typical material data to be input is displayed in the material properties table (Fig. 3). Alternatively one of the standard materials in the program can be chosen. The Ramberg-Osgood parameter in Fig. 3 is the index *m* in the formula for the strain:

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_2}\right)^m$$

where σ is the stress, σ_2 is the 0.2% proof stress and E is Young's modulus. Material data should be entered in units of N/mm^2 (MPa), and the density of the material in kg/mm^3.

MATERIAL PROPERTIES	UPPER SKIN	LOWER SKIN	FRONT SPAR	REAR SPAR
Material :	AL7075-T6	AL2024-T3	AL2024-T3	AL2024-T3
Maximum tensile stress [MPa]:	540.00	440.00	440.00	440.00
0.2% proof stress [MPa]:	480.00	260.00	260.00	260.00
Maximum shear stress [MPa]:	310.00	250.00	250.00	250.00
Young's modulus [MPa]:	71000.00	72000.00	72000.00	72000.00
Poisson's ratio :	.3000E+00	.3000E+00	.3000E+00	.3000E+00
Ramberg-Osgood parameter :	25.60	16.40	16.40	16.40
Density [kg/mm^3]:	.2700E-05	.2700E-05	.2700E-05	.2700E-05

Figure 3: Table of material properties (user may also define his own material).

3. DESIGN REQUIREMENTS

Up to four loading cases can be specified, with different combinations of bending moment, shear force and twisting moment on the wing cross-section. It is assumed that these are all ultimate (factored) loads. The sign convention for the loading is given in Fig. 1. Typical loading data to be input is displayed in the loading cases table (Fig. 4). The bending moment and twisting moment are defined perpendicular and parallel to the flexural axis of the wing. The shear force is assumed to act parallel to the spar webs. The distance (mm) from the front spar web of the point through which it acts (positive in the direction of the rear spar) must be specified by the user. All forces and moments should be entered in units of N and Nmm.

DESIGN REQUIREMENTS		CASE 1	CASE 2	CASE 3	CASE 4
Bending moment	[Nmm]:	.8000E+09	-.3200E+09		
Hor coord shear force	[mm]:	375.00	375.00		
Shear force	[N]:	.2000E+06	-.8000E+05		
Twisting moment	[Nmm]:	.4000E+08	-.1600E+08		
Minimum torsional stiffness	[Nmm/(rad/mm)]:	.17500E+14			

Figure 4: Table of loading cases (user may define up to four loading cases).

For each loading case the program calculates the maximum tensile or compressive stress in the upper and lower skin panels, and the maximum shear stress in the front and rear spar webs. Stresses are calculated according to engineer's bending theory. These are the stresses which appear in the results table (Fig. 5) for comparison with stresses derived from the various design requirements, as follows:

- permissible tensile stress in upper and lower skin panels
- flexural and local buckling of upper and lower skin panels
- permissible shear stress in front and rear spar webs
- shear buckling of front and rear spar webs
- minimum torsional stiffness of the section.

RESULTS OF ANALYSIS		AXIAL STRESS		SHEAR STRESS	
		UPPER SKIN	LOWER SKIN	FRONT SPAR	REAR SPAR
Loading case #1	[MPa]:	-342.10	404.39	-122.89	97.36
Loading case #2	[MPa]:	136.84	-161.76	49.16	-38.95
Maximum tensile stress	[MPa]:	540.00	440.00	-	-
Local buckl. strength	[MPa]:	-402.95	-181.57	-	-
Euler buckl. strength	[MPa]:	-317.72	-211.27	-	-
Maximum shear stress	[MPa]:	-	-	250.00	250.00
Shear buckl. strength	[MPa]:	-	-	152.46	170.10
Actual torsional stiffness	[Nmm/(rad/mm)]:	.23055E+14			
Minimum torsional stiffness	[Nmm/(rad/mm)]:	.17500E+14			
Mass per unit length	[kg/mm]:	.03845485			

Figure 5: Table displaying result of structural analysis.

The permissible tensile stress defined in the material data can, if required, be chosen to make allowance for fatigue. Otherwise it is the normal material value. Flexural buckling is the conventional calculation based on Euler's formula, including a width of skin equal to the stringer pitch with each stringer. The effective simply-supported length is the rib pitch. For local buckling of the skin panels, interaction between the skin and stringers is taken into account by use of a local buckling formula

$$\sigma = KE\left(\frac{t}{b}\right)^2$$

where t is the skin thickness and b is the stringer pitch. A large number of values of the buckling coefficient K have been computed with the program in Ref. 5 for each of the three stringer types. The local buckling coefficient is obtained by interpolation between these values. For both flexural and local buckling, the approach of yielding is taken into account by use of the tangent modulus, derived from the Ramberg-Osgood formula. In general this will prevent the design from approaching too close to the proof stress of the material.

The shear stress in each spar web is limited by the permissible shear stress of the material. For buckling of the spar webs in shear, the graphical data of Ref. 6 is used. This data takes into account the restraint offered by the stiffeners against buckling of the web (the angle-section stiffeners are assumed to have no torsional stiffness, and the web is assumed to be simply-supported between the points defined by the dimension 'd' in Fig. 1). The graphical data of Ref. 6 has been converted into numerical form, the shear buckling coefficient being obtained by interpolation between these values. The torsional stiffness of the cross-section is defined as the twisting moment per unit rate of twist of the wing at the chosen section. It is calculated directly from the thicknesses of the various parts of the torsion box. The minimum required torsional stiffness must be specified by the user, in units of Nmm/(rad/mm).

3.1 Optimization

An option in the program enables optimization of the structure to be carried out at any stage. Object of the optimization is to minimize the weight of the structure (mass per unit spanwise length) subject to the design criteria in the previous section, also subject to maximum and minimum values of the design variables as specified by the user. Note that the weight of the structure does not include the weight of the ribs. With the geometrical restrictions discussed in section 2, the number of design variables for optimization of the cross-section can be reduced to 16, as follows:

- skin or web thickness
- stringer or stiffener thickness
- stringer or stiffener height
- stringer or stiffener pitch.

These four variables are repeated four times for each of the upper skin, lower skin, front spar web, rear spar web, thus 16 variables in total. Any of these may be 'fixed' by the user (at their current values) or may be left 'variable'. The 'stringer or stiffener height' above is dimension 'h' in Fig. 2. Apart from this dimension and the thickness, all other dimensions of the stringers are not treated as variables. Note, however, that the angle-section stiffeners on the webs are defined as 'equal-angles' implying that for these the width of the attached flange varies with the height of the stiffener. For a new design, initial values of all design variables must be supplied by the user. By choosing a particular stringer or stiffener from the list of 'standard' sections, its height and thickness are of course automatically specified. The rib pitch is treated as a parameter, i.e. it is not varied during optimization, also the type of stringer chosen is not affected.

Optimization is performed by the Fletcher-Reeves conjugate gradient method, which generates an appropriate sequence of search directions. Since this is an unconstrained optimization, the constraints (i.e. the design criteria of the previous section) are combined with the objective function (the mass of the structure) in an 'augmented Lagrangian' penalty function. This is essentially an exterior penalty function method, so that it is not necessary that the starting point of the optimization should be a feasible design, i.e. satisfy all the constraints. Therefore, as well as minimizing the weight of the structure, the optimization option can also be seen as a means of obtaining a design which satisfies all the design requirements when the current design does not in fact do so. All gradient evaluations required during optimization are made by finite difference, this taking little time because of the relatively simple formulation of the design requirements. The line search implicit in the Fletcher-Reeves method is by the 'golden section' method. No specific reference is given for the optimization methods referred to in this paragraph, since they can be found in any standard text on optimization theory.

As already stated the stringers and stiffeners may be restricted to a set of 'standard' sections. If this is done, the optimization procedure is then as follows. The stringer (or stiffener) height and thickness are allowed to vary freely during a first optimization, in the same manner as for a stringer not restricted in this way. When the first optimization is complete, the nearest standard stringer is automatically selected on a 'least-squares' basis. (In spite of what was stated earlier, this step may necessitate a change in all the dimensions of the stringer.) The optimization is restarted with all stringers and stiffeners now 'fixed'. The result of this second optimization is the result displayed by the computer. At this stage it cannot, of course, be expected that the skin and the web thickness will correspond to any standard available material thickness. It is for the user to decide to re-optimize the structure with 'fixed' thicknesses chosen from the available range.

4. PROGRAM

The program WingDesign performs the design procedure described in this report. It is menu controlled, therefore no detailed explanation of the use of the program need be provided here. The program works in a similar way to, say, a word processor - it is possible to save a design to a file so that an old design can be re-used in a later design session. Under MS-DOS, WingDesign is started by typing:

WD *<Enter>*

First the user is asked to specify a name for a new job, or give the name of an old job that is to be edited. WingDesign automatically gives each file the extension '.WNG', unless another is explicitly specified. For a new job the user is asked to supply data on the wing profile, dimensions of the structure, material data and loading cases, as already described. All input data is in response to prompts which appear on the screen.

Once the data for the design has been input, the user can choose between the options offered by various menus displayed by the program. Fig. 6 shows the menu structure of the program. The 'Edit Menu' enables all parameters of the design and other data to be changed. In another menu there are options to optimize the structure, to 'fix' design variables and to set upper and lower bounds. With the option 'Show status of the design' the user can obtain all relevant information about the design at any stage in the design process. The option 'Print results' places this information in a file which can later be sent to a printer for a hard copy. The option 'Write LCIS-macro' causes a macro to be written which can later be called within the CAD program MEDUSA to create a drawing of the structure which has been designed. Further information about the use of this macro can be found in Ref. 2. This option is, of course, only of interest to users with access to MEDUSA.

```
Main Menu
  |-----> Edit Menu
  |         |-----> Return to Main Menu
  |         |-----> Edit geometry
  |         |-----> Edit dimensions
  |         |-----> Edit materials
  |         |-----> Edit design requirements
  |-----> Optimization Menu
  |         |-----> Return to Main Menu
  |         |-----> Select design variables and bounds
  |         |-----> Optimize
  |-----> Results and Save Menu
  |         |-----> Return to Main Menu
  |         |-----> Show status of the design
  |         |-----> Print results
  |         |-----> Write LCIS-macro
  |         |-----> Save to file
  |-----> New Job Menu
            |-----> Return to Main Menu
            |-----> Proceed with a new design session
```

Figure 6: Menu-tree used in the program.

4.1 Example

A suitable set of data is stored in file 'EXAMPLE.WNG'. It is recommended that a new user should use this file to become familiar with the program. The user can edit the data, proceed to an optimization, and so on as he wishes. Note that the data displayed in Figs. 3 and 4 relate to this example. Fig. 5 displays results of the analysis of the design defined by values of the design variables displayed in Fig. 7.

DIMENSIONS OF STRUCTURE		UPPER SKIN	LOWER SKIN	FRONT SPAR	REAR SPAR
Skin/web thickness	[mm]:	2.50	2.50	2.50	2.50
Stringer/stiffener type	:	Hat	Lipped Z	Single	Single
- size	:	0	0	19	19
- thickness	[mm]:	1.60	1.60	2.50	2.50
- height	[mm]:	30.00	30.00	25.00	25.00
- attached flange	[mm]:	20.00	20.00	25.00	25.00
- free flange / crown	[mm]:	30.00	20.00		
- lip	[mm]:		8.00		
- pitch	[mm]:	100.00	100.00	100.00	100.00
Rib pitch		[mm]:	500.00		
Distance between skin and web-rivets		[mm]:	20.00		

Figure 7: Table displaying dimensions of torsion box used in the example.

The same data will now be used to demonstrate how the program can be used to carry out parametric studies of a design. The wing-section in the example has a chord of 3000 mm and a thickness/chord ratio of 13%. The distance between the front and rear spar is one-half of the chord. Two loading cases are considered: positive (upward) bending moment 0.8×10^9 Nmm and shear force 0.2×10^6 N, and negative bending moment and shear force each 40% of the corresponding positive value. The wing has hat-section stringers on the upper skin, lipped Z-section stringers on the lower skin, and single-sided angle stiffeners on the spar webs. Standard sections are used only for the web stiffeners. The material is 7075-T6 aluminium alloy for the upper stringer-skin panel and 2024-T3 for all other parts. Other data can be read from the file 'EXAMPLE.WNG'. Apart from the size and pitch of the stiffeners on the spar webs, all design variables are chosen to be 'variable' (i.e. not 'fixed'). The minimum stringer pitch used in the calculations is discussed in the following two paragraphs. All other upper and lower bounds on the design variables are chosen so that they have no effect.

To illustrate first the effect of a minimum stringer pitch on the mass of the structure, a number of different lower bounds for the stringer pitch have been chosen (the same for the upper and lower skins). For these calculations the rib pitch is 500 mm. The mass of the structure per unit spanwise length (kg/mm) obtained by the program after optimization of the cross-section is plotted in Fig. 8. At the left hand end of this graph it is seen that the minimum stringer pitch has no effect, i.e. the optimum stringer pitch is slightly less than 80 mm. A significant increase in mass is found for larger values of the minimum stringer pitch. This sharply defined behaviour is a consequence of the torsional stiffness requirement.

Secondly, the effect of rib pitch on the mass of the structure is examined. In this case the stringer pitch is allowed to be variable (with a minimum of 60 mm). The mass after optimization is plotted in Fig. 9. The relative flatness of the curve is due to the high stress levels in this example - allowing the user considerable freedom in the choice of rib pitch. This graph does not, of course, include the mass of the ribs. To use Fig. 9 to investigate the variation of the total mass of the wing structure with rib pitch, an estimate of the necessary rib mass at each rib pitch must be made.

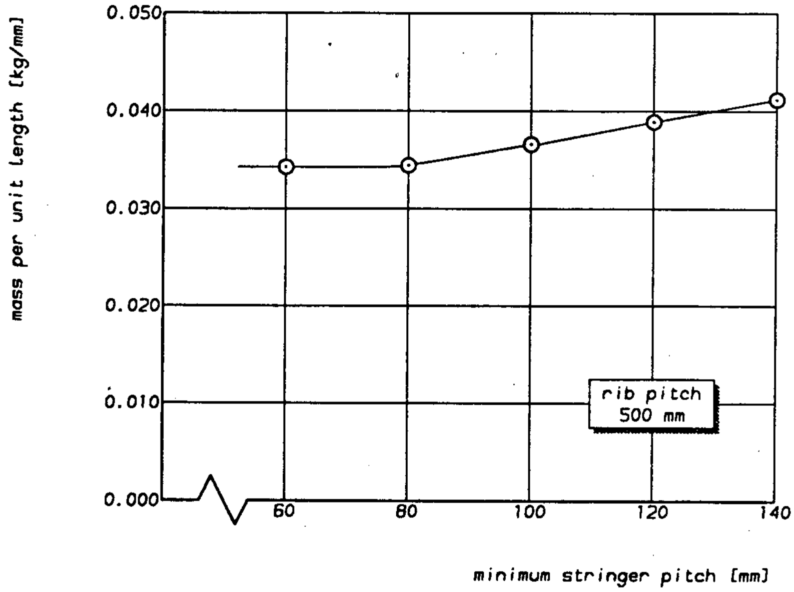


Figure 8: Effect of minimum stringer pitch on mass of wing structure.

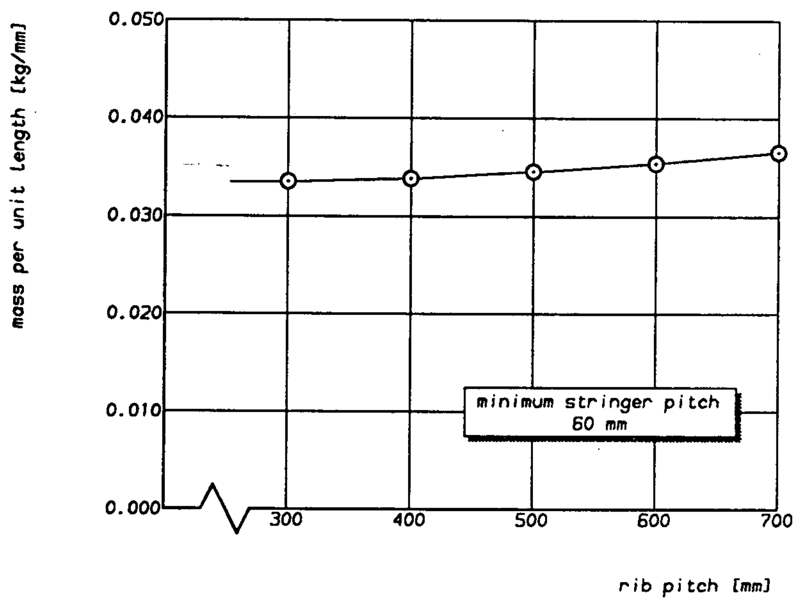


Figure 9: Effect of rib pitch on mass of wing structure (ribs not included).

The results in Figs. 8 and 9 must not be seen as generally applicable results for a wing structure, since they are entirely dependent on the loading on the wing and other data such as the minimum required torsional stiffness, stringer type, and so on. In fact it is one of the purposes of the program described here to enable the influence of the main parameters of the design on the mass of the structure to be explored.

5. CONCLUSION

The program demonstrates the usefulness of special-purpose, easy-to-use, interactive programs for structural design and optimization, especially at the preliminary design stage. A requirement is that the design problem can be reduced to one of 'standard' type, i.e. the form of construction is already defined and the geometry of the structure can be adequately defined with limited data. In the current version of the program this implies a two-spar wing with conventional stringer-skin panels and spar webs. It presents no particular difficulty to allow different stringer types within the program, and to limit these to a standard set of stringer-sections. The user retains full control over the progress of his design. Primarily this is achieved by the option of 'fixing' any of the design variables at values preferred by the user (e.g. for manufacture, or other practical reasons) at any stage in the design, also by enabling various materials, different rib pitches (and so on) to be chosen without difficulty. In this way a satisfactory - and hopefully efficient - design can be reached, ready for more detailed structural analysis to take into account features of the practical structure not available in the design program. The program is in regular use by students at Delft University of Technology in the course of their third year's design work.

REFERENCES

1. Zoontjes, R.P.G. WingDesign: a preliminary design program for a cross-section of a wing structure. Ir. thesis, Delft University of Technology, Faculty of Aerospace Engineering, August 1989.

2. Zoontjes, R.P.G. WingDesign: manual for the graphics-based user interface for use on Sun workstations. Memorandum M-632, Delft University of Technology, Faculty of Aerospace Engineering, April 1990.

3. Rothwell, A. Multi-level optimization of aircraft shell structures. Memorandum M-618, Delft University of Technology, Faculty of Aerospace Engineering, December 1989.

4. Van Bladel, P.G. Handleiding voor LR-hulpmiddelen in MEDUSA. Memorandum M-613, Delft University of Technology, Faculty of Aerospace Engineering, August 1989.

5. Notenboom, R.P. Finite strip elements in thin plate buckling analysis. Delft University of Technology, Faculty of Aerospace Engineering (to be published).

6. ESDU. Flat panels in shear. Buckling of long panels with transverse stiffeners. Engineering Sciences Data Item 02.03.02, Structures Sub-series, Vol. 10 (1983).