DESIGN OF A BASELINE WING FOR A TILTROTOR CONFIGURATION

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Abstract

Objective of this paper is to describe the preliminary design of a composite wing for a tiltrotor configuration. After a brief introduction of the tiltrotor aircraft concept, wing design tasks and aeroelastic problems are discussed. Main emphasis is on the combined application of a wing structure analysis program with a dynamic rotor coupling program. Both codes and the newly created linking program are briefly described. A baseline wing is set up, checked for structural integrity in one selected static load case, and some parameter studies are conducted for dynamic stability with respect to ply thicknesses of the different layers of composites. It is shown, that more realistic results as compared to a simple beam-box model are achieved. Opportunities to adapt the ply thickness distributions to critical load distributions are demonstrated while still assuring dynamic stability of the rotor-wing combination. Results are given in root locus plots of the eigenvalues with speed as an additional parameter. A very high sensitivity of critical speed as a function of nacelle C.G. has been detected. The program chain with the established baseline wing is ready to be implemented in a larger multidisciplinary design optimization framework for systematic optimization of wing and rotor tailoring.

Introduction

Tiltrotor (TR) aircraft combine the unique performance features of a helicopter with the outstanding cruise qualities of a turboprop aircraft. They are one possible realization of the vertical take-off and landing (VTOL) concept, which can meet the increasing demands by the military, air carriers, passengers, and air traffic control.

With its rotors horizontally, i.e. in helicopter mode, the TR is able to take off and land vertically as well as hover. Thus its required on-ground infrastructure is but a vertiport. VTOL capabilities largely reduce the noise footprint so that acoustical pollution restrictions in inner-city areas, such as space-limited roof tops, can usually be matched. As air speed increases, the rotors are tilted forward. In the aircraft mode, the rotors function as proprotors. Lift is generated by the wing alone, leaving all engine power to overcome aerodynamic drag in high speed cruise.

Productivity and cost effectiveness of an aircraft can be expressed by the productivity index (PI) [1]:

$$PI = \frac{\text{Payload } W_P \times \text{Blockspeed } V_{Bl}}{\text{Empty Weight } W_{oe} \times \text{Fuel Weight } W_f} \quad (1)$$

A high cruise speed resulting in a high block speed drastically increases the PI. The proprotor drives with fuel efficient turboshaft engines are also favorable to the PI, since they minimize the required fuel weight. However, along with those advantages comes a set of major drawbacks. As the constructional efforts to realize the TR aircraft configuration arise, so do manufacturing cost and empty weight surplus with respect to a conventional helicopter. There is a significant maintenance cost surplus compared to a turboshaft aircraft due to the sophisticated wing-tip mounted engines, their conversion actuators, the interconnecting shaft units (to enable emergency maneuvers during one engine off) and others. The main difficulty however is to derive an aeroelastically stable wing, which meets all design tasks.

All these effects either impede the PI or deteriorate direct operational cost (DOC) as well as they dramatically increase research and development efforts to optimize TR aircraft configurations.

The XV-15 demonstrator aircraft as well as the larger and more advanced V-22 have proven to be very successful in extensive flight testing. European helicopter manufacturers in a joint venture are currently in the preliminary design phase of the EUROFAR [2] (EUROpean Future Advanced Rotorcraft) as shown in Figure 1. This data shall serve as reference case in the present study.

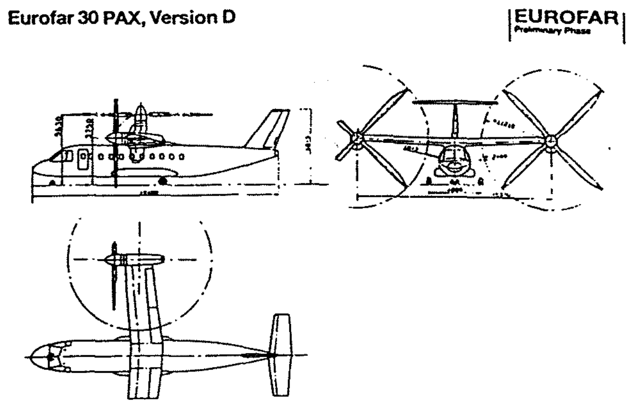

Figure 1: EUROFAR configuration 30 PAX

One of the fields of research at Georgia Tech and TU Braunschweig aims at TR wing aeroservoelastic optimization on a multidisciplinary approach. One of the first steps was to establish a feasible baseline wing analyzing wing structural integrity and coupled rotor-wing dynamics. To accomplish this task, two existing codes had to be linked for modeling a cantilevered wing-proprotor configuration and wing internal parameters had to be found which ensure aeroelastic stability especially concerning whirl flutter.

Wing Design Tasks and Aeroelastic Problems

Wing Design Tasks

Wing design in TR design requires a different approach than in the case of a conventional aircraft since there is no (nearly) elliptical lift distribution in helicopter mode but a discrete force at the end of both wings each carrying half the weight. Examples for the design goals are: minimization of drag in cruise mode and of wing weight, wing structure has to comply with maneuvers and crash load factors, wing has to meet stiffness and damping requirements to guarantee aeroelastic stability in all flight modes, and the wing planform has to provide for means (e.g. large trailing edge flaperons) to reduce the wing area exposed to rotor downwash in helicopter mode. In the present work, the design criteria weight, structural integrity, planform and aeroelastic stability are considered.

Aeroelastic Problems

As the TR aircraft covers the entire flight regime of a helicopter and that of a turboprop aircraft, so does it encounter aeroelastic problems of both as well as purely TR aircraft specific phenomena (Figure 2).

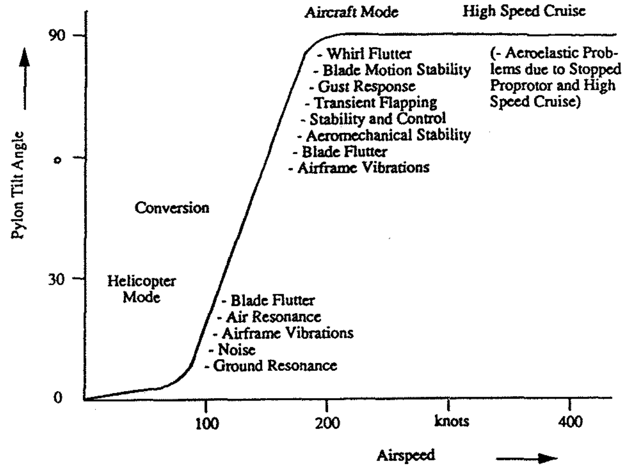

Figure 2: Aeroelastic and stability problems

Aeroelastic and flight dynamic stability problems in the helicopter mode can be investigated independently from the aircraft mode considerations and are not subject of this paper. So are gust responses and transient effects, since they require special type approaches.

Elastic Modes. The TR aircraft can experience several different body modes [3] such as wing beam, chord, and torsion; engine pitch and yaw; pylon yaw; and others. They are classified into symmetric and asymmetric modes as exemplarily shown in Figure 3 from [3]:

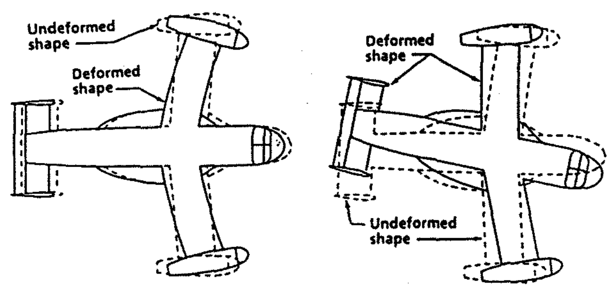

Figure 3: Wing chord mode shapes

Whirl Flutter. Whirl flutter is an instability which can occur on flexibly mounted propeller-nacelle installations. It involves a self-sustained or divergent whirling precessional motion of the propeller hub about its undeflected position.

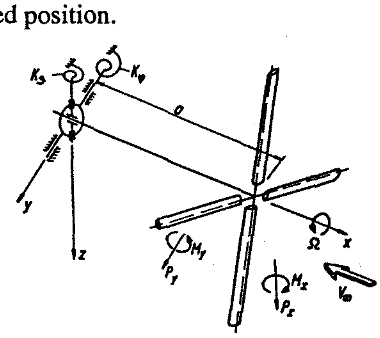

Figure 4: Simplified propeller-nacelle system

Looking at the simplified propeller-nacelle system [4] in Figure 4, one can easily derive the following equations from the LAGRANGEAN equation:

$$\left.\begin{aligned} I_y\ddot{\varphi}+C_\varphi\dot{\varphi}+K_\varphi\varphi+I_x\Omega\dot{\vartheta}&=aP_z-M_y \\ I_z\ddot{\vartheta}+C_\vartheta\dot{\vartheta}+K_\vartheta\vartheta-I_x\Omega\varphi&=aP_y+M_z \end{aligned}\right\} \quad (2)$$

With $\Omega \neq 0$ both equations are coupled gyroscopically causing a 'whirly' motion of the hub on a generally elliptical path. This again results in a cyclic change of blade pitch. Additional aerodynamic forces can exceed the elastic restoring forces leading to instability and finally failure of the drive shaft or installations. This critical condition can either be reached by increasing airspeed or angular velocity Ω. If in addition the proprotor blades are connected to the hub through hinges or flexbeam assemblies, flapping and lead-lag degrees of freedom (DOF) have natural frequencies close to the rotor frequency. Pertubation forces due to pitch of a free-to-flap proprotor can cause proprotor whirl flutter. Therefore, this DOF has to be included in all dynamic analysis of TR aircraft.

Applied Computer Programs

Program Flow

In order to easily implement the wing structure analysis and the dynamic coupling routines into a larger multidisciplinary design optimization program, a consecutive order of program execution is required. Figure 5 illustrates this approach.

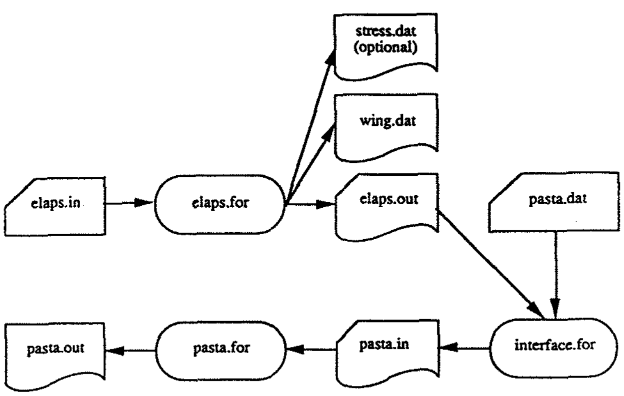

Figure 5: Program flow chart

Geometric and other wing parameters as well as the load cases are stored in the input file elaps.in. Elaps.for performs static and dynamic analysis of the wing, optionally provides a stress and strain check, and creates the output file elaps.out including wing dynamic properties. Interface.for as linking program transforms these data into PASTA notation and writes them together with parameters from pasta.dat into the pasta.in file. Finally, pasta.for performs the dynamic coupling of wing and rotor and stores its output in pasta.out.

ELAPS

An Equivalent LAminated Plate Solution (ELAPS) was introduced by GILES [5] in 1986. It is an equivalent plate analysis of aircraft wing box structures with general planform geometry. On of its major advantages over finite element analysis is the up to 60 times shorter computation time encountered in calibration runs [5]. Hence, ELAPS provides capabilities desirable for combination with rigorous optimization procedures.

The RITZ method is used to obtain a stationary solution to the variational condition on the total energy E of the wing box structure.

$$E = V + Q - T \quad (3)$$

The energy terms in (3) for potential energy in bending V, potential energy of lateral non-conservative loads Q, and for kinetic energy T associated with masses can all be expressed in terms of deflection W [5]. W is assumed to be the sum of contribution C_i from a set of specified displacement functions W_i.

$$W = \sum_{i=1}^{n} C_i W_i \quad (4)$$

E is stationary with respect to C_i, if the partial derivatives disappear, leading to a system of n simultaneous equations, which can be expressed in matrix form as:

$$[K]\{C_i\} - \omega^2 [M]\{C_i\} - \{P_i\} = 0 \quad (5)$$

This system can be solved to obtain natural frequencies using standard mathematics library routines.

The original source code has been slightly modified to meet the input requirements of PASTA. Therefore the mass matrix in (3) is transformed into generalized form using the modal matrix.

In an additional subroutine the material exploitation expressed by maximum stress and strain criteria is implemented.

$$\text{max. stress criterium} = \frac{\sigma_{\text{actual}}}{\sigma_{\text{maximum}}} \quad (6)$$

Furthermore, the HOFFMAN failure index FI, a slight modification of the TSAI-WU theory [6], is calculated.

$$\left(\frac{1}{x_t}-\frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t}-\frac{1}{y_c}\right)\sigma_2 + \frac{\sigma_1^2}{x_t x_c} + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{s^2} = FI$$

(If FI < 1, the lamina is assumed to be 'safe') (7)

Interface

PASTA requires modal displacements and rotations at the position of the rotor hub for each desired mode. ELAPS however only provides translational wing displacements on a discrete grid. The interface code therefore interpolates the displacements at the nacelle attachment point, calculates the missing rotational deflections, and applies those to the hub offset vector. Additionally this linking program rearranges the other output parameters of ELAPS, adds some data from pasta.dat, and writes the pasta.in file. Therefore the input format of PASTA could remain unchanged.

PASTA

The analysis described so far is equivalent to that of a pure fixed wing aircraft. Special feature of the TR aircraft is the aeroelastic coupling of the complex dynamic system of the proprotors and the wing. KVATERNIK [6] introduces the Proprotor Aeroelastic STability Analysis PASTA. It uses the LAGRANGEAN equation to describe the coupled system. For quasi-steady rotor blade aerodynamics the resultant equations of motion can be written in the general matrix form as:

$$\overline{\mathbf{M}}\ddot{x} + \Gamma\dot{x} + \overline{\mathbf{C}}\dot{x} + \overline{\mathbf{K}}x = \mathbf{Aero_1}(q)\dot{x} + \mathbf{Aero_2}(q)x \quad (8)$$

The matrix Γ is included to account for the presence of gyroscopic coupling forces. Both aerodynamic matrices Aero_1 and Aero_2 are not only dependent on system parameters but also on dynamic pressure. They can be moved to the left-hand side leading again to a standard form of a dynamic system of second order. PASTA solves the eigenvalue problem and provides these along with the corresponding eigenvectors.

Wing Design

A wing planform resembling the EUROFAR [2] configuration has been implemented in the program. Its dimensions are given in Figure 6.

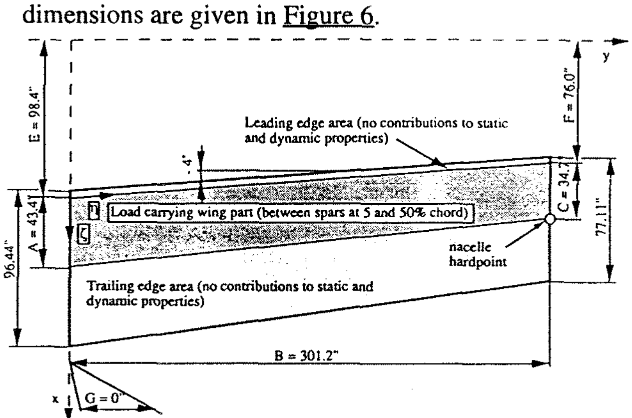

Figure 6: Wing planform

Since no airfoil data for this wing has been available, the airfoil geometry of the V-22 [8] has been used. The generated plate grid of the load carrying wing section (between 5 and 50% chord) is depicted in Figure 7.

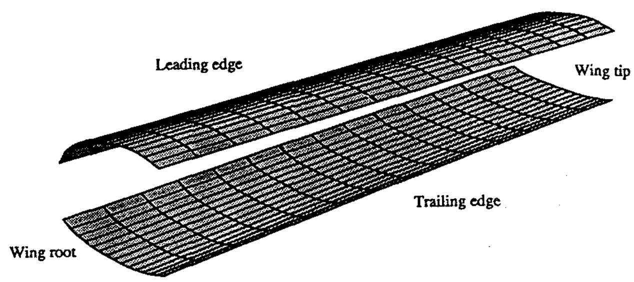

Figure 7: 3D view of load carrying wing section

The wing has been modeled with three layers of graphite-epoxy material. Fiber directions are 0° and ± 45°. Front and end spars at 5 and 50% chord [2] are considered.

STETTNER indicates in [1] that the jump take off is one of the most severe static load cases. The wing structural integrity is checked against the forces during a 2.0g jump. This static load case has been applied to a wing beam box with constant thickness distributions. The results are presented in Figure 8. Highest stress criteria occur close to the wing root. Material utilization steadily decreases towards the wing tips due to smaller bending moments.

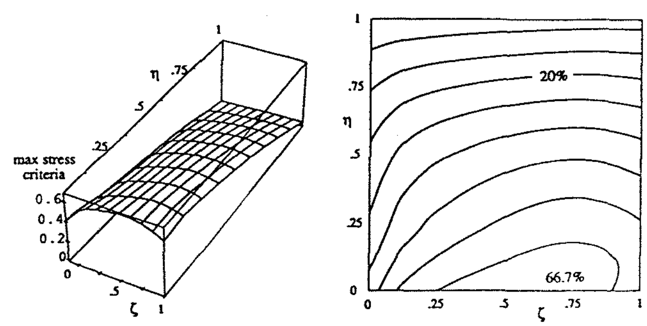

Figure 8: Material utilization of lower 0° layer

The impact of the leading and trailing edge spars can clearly been seen. The stress criteria decrease at the leading and trailing edges causing local bending of the contour lines in Figure 8.

Low stress values in the outboard regions of the wing justify linear thickness distributions. Efficient material utilization can result in a large reduction of wing weight. Same stress levels can be reached by increasing the 0° layer thickness and decreasing the ± 45° layer thickness or vice versa. However, the second case is much more favorable for weight reduction as depicted in Figure 9.

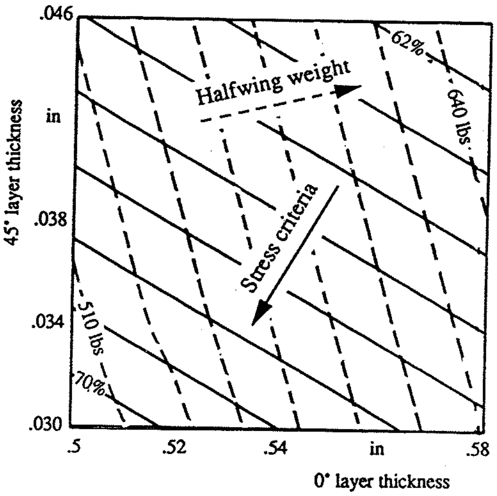

Figure 9: Weight and stress criteria with respect to layer thickness

Table 1 shows the wing data for the two compared cases of constant and linear thickness distribution.

thickness distribution	constant	linear
layer thickness	.48/	.5-.4η/
(0°/45°/-45°)	.042/.018 in	.042/.018 in
max. stress criteria	66.77%	65.79%
half wing weight	761 lbs	534 lbs

Table 1: Wing properties

Tremendous weight reductions can be achieved by tailoring the layer thickness distribution to the 2.0 g jump take off load case. With the linear variation of layer thickness, a much larger portion of the wing is carrying a high but still tolerable stress level. The material utilization is much more efficient than in the previous case as visualized by Figure 10. The sharp drop in stress occurs much further towards the tip indicating less wasted material.

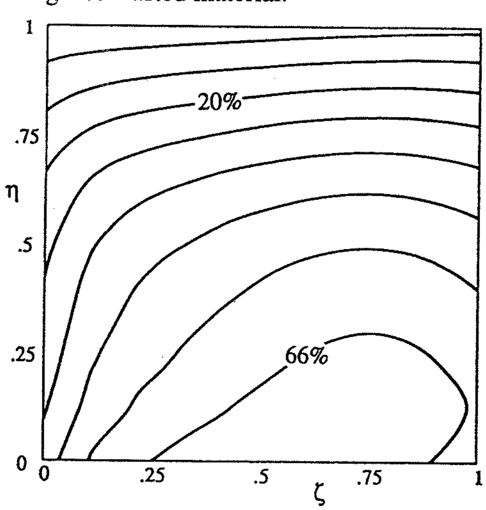

Figure 10: Stress criteria (linear 0° layer)

Linear and maybe even higher order distributions in spanwise direction seem promising for future systematic optimization.

However, not only the static behaviour of the wing has to be considered. Aeroelastic problems as described before can pose a serious design constraint.

Dynamic Analysis

Aeroelastic stability has been verified for a maximum dive speed of 462 kts, derived from FAA requirements.

The implemented proprotor is a homokinetically gimballed rotor with a flexbeam assembly at the blade root. A complete table of rotor data as well as the different sources can be found in [9].

DOF

The first ten DOF have been taken into consideration. Extensive test runs were performed to identify the rotor and wing eigenmodes. They are given in Table 2.

DOF	Description	Abbreviation
1	Coning mode	a_0
2	Regressing whirl flutter	β^-
3	Progressing whirl flutter	$\beta+$
4	Backward precession (Blade inplane C.G. motion)	ζ^-
5	Forward procession (Blade inplane C.G. motion)	$\zeta+$
6	Rotor rotation	Θ_x
7	1st beamwise bending mode	1st beam
8	1st chordwise bending mode	1st chord
9	2nd chordwise bending mode	2nd chord
10	1st torsional mode	1st torsion

Table 2: Notations of DOF

Comparison of the isolated rotor DOF with those of the XV-15 [3] shows qualitative resemblance in all but the rotation eigenform and the backward precession. This may not surprise, since the rotor systems greatly differ in RPM (300 vs. 458), their rotor system (present case features flexbeam assembly), different airfoils and the lack of aerodynamics in the present case.

Results

Figure 11 shows the root locus plot for a rotor-wing system with a constant layer thickness distribution. Airspeed is varied from 150 KEAS up to the dive speed of 462 KEAS.

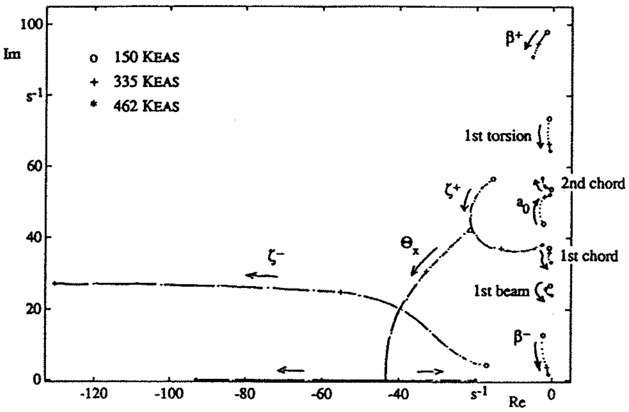

Figure 11: Root locus plot of coupled system with constant ply thickness

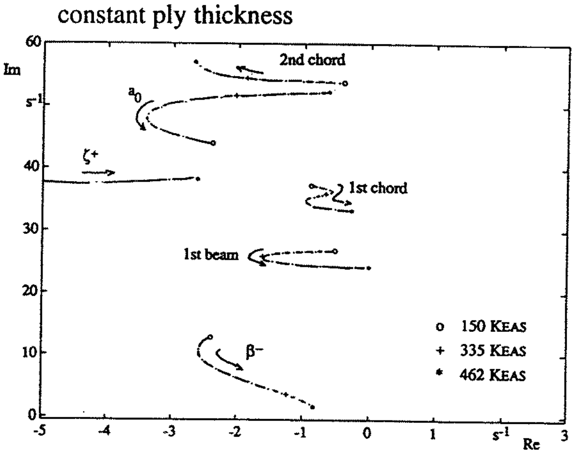

Figure 12: Close-up (constant thickness)

The close-up in Figure 12 visualizes that all eigenforms are still stable at dive speed, although 1st chordwise and beamwise bending modes have only minimal stability margins.

Parameter Variations

Again the effects of changing the linear thickness distribution has been investigated, however now in dynamic analysis. Variations of the 0° ply thickness as well of the ±45° layer results in Figure 13.

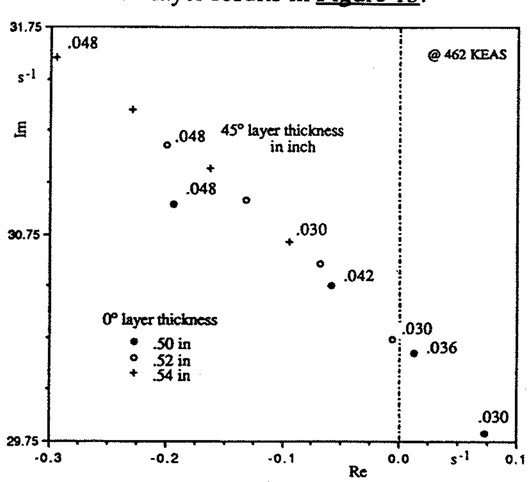

Figure 13: Eigenvalue of 1st chordwise bending mode

Both thickening the of 0° and ±45° layers pushes the eigenvalues into the stable half-plane. A 16% increase in the ±45° layers has about the same stabilizing effect as an 4% increase of the 0° ply. Strengthening the ±45° layers results however in a much smaller weight penalty as discussed before (11.4 lbs compared to 25.3 lbs).

Some thickness variations have adverse effects on the torsional eigenmode. Closer inspection of this phenomenon has revealed that airspeeds around 250 KEAS appear to be most critical. Systematic parameter variations in an automated optimization procedure must give further insight.

However, with the '.5-.4η; .040; .071 in' configuration a baseline wing, which is stable in all ten investigated eigenforms over the entire speed range of 150 to 462 KEAS has been found. It represents viable initial data for an optimization process.

Nacelle C.G. Variations

During variation of thickness parameters, a very high sensitivity regarding the C.G. position of the nacelle has been detected. The initial position is at the nacelle hardpoint, i.e. the moments from rotor system and drive system on the other end just cancel each other. As Figure 14 illustrates, already slight offsets of the conversion axis from the nacelle C.G. can result in much lower critical speeds, i.e. larger instabilities at dive speed.

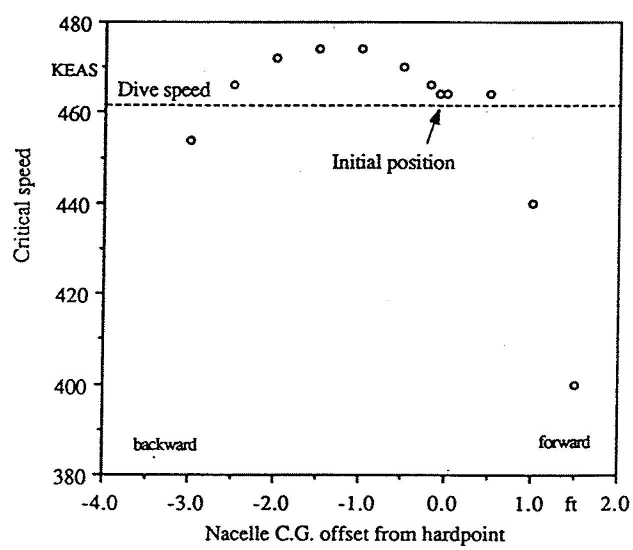

Figure 14: Critical speed with respect to nacelle C.G.

At the maximum critical speed the classical wing modes seem to be decoupled from the rotor system to a certain extend. Masses acting on the forward part of the wing promote classical wing flutter phenomena.

Conclusions

Several steps are necessary to establish a baseline wing for the specific demands of a TR aircraft configuration. In the iterative process of optimizing this wing, tailoring of the fiber layer thickness distributions for the most severe static load should be performed first. It has been shown that tremendous weight reductions can be achieved when providing a linear thickness distribution of the 0° layer in spanwise direction. Higher order functions, maybe even in chordwise direction, seem to be promising approaches for further systematic parameter variations.

A dynamic analysis of the coupled rotor-wing system has to assure dynamic stability in all eigenmodes at speeds up to the maximum dive speed. In the present study, coupling is clearly indicated in root locus plots. Whirl flutter eigenmodes have been identified. Again some initial parameter variations have been performed. Stability, especially of the very critical first beamwise and chordwise bending modes, can be increased by strengthening either the 0° or ±45° layers. However, the second is much more favorable in terms of weight increase.

The program chain of static plate element analysis program, interface module, and dynamic coupling code can easily be implemented in a larger multidisciplinary design optimization framework.

Improvements of the implemented rotor and wing models like consideration of aerodynamics is subject of ongoing research. First results have been presented by STETTNER et al [10].

Acknowledgements

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