TILTROTOR PERFORMANCE SENSITIVITIES FOR MULTIDISCIPLINARY WING OPTIMIZATION

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ABSTRACT

An automated procedure for tiltrotor performance sensitivity calculation based on a V/STOL aircraft performance and sizing code, VASCOMP, is presented. The technique utilizes internal UNIX utilities and shell scripts, and will provide the option of changing the analysis code. Hence, VASCOMP is a testbed for future application of this approach on different analysis codes in an aeroservoelastic wing optimization process. Sensitivities are analyzed for different configurations deviating in single design variables from a EUROFAR-type baseline. A speed parameter and wing thickness to chord ratio are identified as major design drivers. It is concluded that, if only VASCOMP was to be used for optimization of the productivity index, PI, the resulting configuration would be prone to aeroelastic instability. Thus, inclusion of wing static load and aeroelastic stability constraints using more sophisticated tools is strongly recommended.

NOMENCLATURE

ACP	analysis module: coupling of aircraft, wing, rotor, and unsteady aerodynamics
AEROS	analysis module: unsteady wing and control surface aerodynamics
AR	wing aspect ratio
CA	contributing analysis
CSD	analysis module: control system design
ELAPS	analysis module: equivalent plate model of the wing structure
GSE	global sensitivity equation
K	vector of constants
M	Mach number
PADE	analysis module: Padé-approximation of unsteady aerodynamics
PI	productivity index
TR	tiltrotor aircraft
S	wing area
t/c	wing thickness to chord ratio
v_{bl}	block speed
v_c	cruise speed
v_D	dive speed
VASCOMP	analysis module: mission analysis, calculation of fuel weight required
W_f	fuel weight
W_e	empty weight
W_p	payload weight
W_w	wing weight
X	vector of design variables
Y	vector of behavior variables

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INTRODUCTION

Tiltrotor aircraft (TR) feature vertical take off/landing (VTOL) and hover performance similar to that of a helicopter, and long range, high speed cruise performance comparable to that of turboprop aircraft. Thus, they open unique mission opportunities for civil and military applications. In the civilian market, the tiltrotor's capacity to take off and land vertically with virtually no runway requirements promise improvement from the current tendency towards increasing time delays due to airport congestion. Reduced taxi times, combined with cruise speeds of 300+kts will result in reduction of block times on medium range missions. The tiltrotor generally generates low noise levels in cruise configuration. High rate of climb and descent capabilities make very steep climb/approach procedures possible. Thus, the tiltrotor is also very attractive with respect to public acceptance. In fact, service to vertiports on rooftops or spanning urban interstate highways is feasible so that the passenger will be able to reach inner cities without having to change the means of transportation - and without impacting residential areas with airport noise. The tiltrotor, on the other hand, combines not only the helicopter's and fixed wing aircraft's performance virtues, but also their problems. In particular, rotor and elastic aircraft aeroelastic modes couple to form an instability peculiar to the tiltrotor: proprotor whirl flutter, a major driver for both rotor and wing design.

Obviously, an attempt to optimize a tiltrotor configuration for a certain mission must therefore include performance, structural and aeroelastic considerations. A flutter suppression controller should also be considered for structural weight reduction and stability enhancement. Current research by Chattopadhyay and Narayan[1] and Nixon[2] aims predominantly at optimization of the rotor. A different approach to this multidisciplinary task was presented during the 4th AIAA / USAF / NASA / OAI Symposium on

CA	Input X	Y	K	Output Y	Constraint Output
VASCOMP	**wing planform; cruise speed v_c; (rotor hover/cruise diameter)**	**wing wt. W_W**	**mission profile; a.c. configuration**	**PI** **dive speed v_D**	**Fuel weight difference: $(RF_R - RF_A)/RF_A$**
ELAPS	wing planform; wing int. layout	-	wing material density and elastic properties; nacelle inertial properties	wing eigenvalues, eigenvectors, gen. masses (lowest), wing wt. W_W	structural margin of safety, static load cases
AERO	wing planform	wing eigenvalues, eigenvectors, gen. masses; dive speed v_D	air density	modal aerodynamic influence coefficient matrices (AIC) at wing natural frequencies	-
PADE	-	modal AIC matrices;	-	Padé approx. AIC matrices	-
ACP	-	wing eigenvalues, eigenvectors, gen. masses (lowest); Padé approx. AIC matrices	rotor configuration sensor location	state-space system dynamics, output, and control matrix	(smallest damping ratio of system if no CSD is provided)
CSD	-	state-space system dynamics, output, and control matrix	-	-	rms gust response, states and controls

Table 1: CA Data Input and Output

Configuration	Design Variable wing sweep 1	*speed* 2	taper ratio 3	aspect ratio 4	(t/c) root 5	(t/c) tip 6	wing loading 7
(Baseline) 1	- 5 degr	300 kts	1.0	6.11	0.23	0.23	79.44 lb/sqft
2	**-30 degr**	300 kts	1.0	6.11	0.23	0.23	79.44 lb/sqft
3	- 5 degr	**350 kts**	1.0	6.11	0.23	0.23	79.44 lb/sqft
4	- 5 degr	300 kts	**0.8**	6.11	0.23	0.23	79.44 lb/sqft
5	- 5 degr	300 kts	1.0	**8.0**	0.23	0.23	79.44 lb/sqft
6	- 5 degr	300 kts	1.0	6.11	**0.184**	0.23	79.44 lb/sqft
7	- 5 degr	300 kts	1.0	6.11	0.23	**0.184**	79.44 lb/sqft
8	- 5 degr	300 kts	1.0	6.11	0.23	0.23	**95.3 lb/sqft**

Table 2: Configuration Input/Design Variables

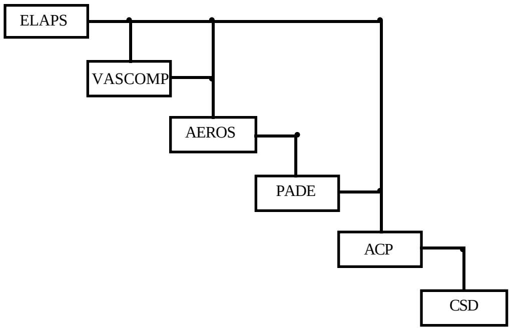

Fig. 1: Nsquare Diagram

Multidisciplinary Analysis and Optimization[3]. Fig. 1 shows an updated block diagram of the contributing analyses (CA's) involved and their interconnection; Table 1 lists the data transferred between the CA's. It was decided to choose an objective function which would provide a simple means for measuring how attractive an aircraft is for an operator. This productivity index, PI, is defined as

$$PI = \frac{\text{Payload } W_p \times \text{Block Speed } v_{bl}}{\text{Empty Weight } W_e + \text{Fuel Weight } W_f}$$

As a rule of thumb, acquisition cost is proportional to the aircraft empty weight, and fuel weight is a major factor in determining operating cost; thus, the denominator of PI can be interpreted as an indicator for the sum of acquisition and operating cost. Thus, PI relates the aircraft productivity to total cost.

The overall task can be summarized as follows:

"Vary a set of design variables describing the structure of a composite tiltrotor wing such that for a specified mission the productivity index PI is maximized. Design a flutter suppression controller using rotor controls, flaperon and elevator deflection to keep the aircraft free from proprotor whirl and fixed-wing flutter cases, and to minimize rms gust response. Ensure that the configuration is feasible with respect to constraints imposed by the mission to be flown (fuel weight avalibale = fuel weight required), structural integrity in limiting static load cases, and control system activity / actuator saturation. Investigate the impact of replacing a baseline proprotor by a variable diameter design (VDTR). Perform this task with as little computational effort as possible."

Concerning the structure of the optimization, a final decision was made in favor of strictly non-hierarchic decomposition in order to allow greatest flexibility. In other words, the (global) sensitivities of the CA outputs, Y, (behavior variables) with respect to the design variables, X, will be calculated by solving the Global Sensitivity Equation (of type GSE2 according to Sobieszczanski-

$$[S]\left(\frac{dY}{dX_k}\right) = \left(\frac{\partial Y}{\partial X_k}\right)$$

$$[S] = \begin{bmatrix} I & 0 & 0 & 0 & 0 & 0 \\ -\frac{\partial Y_{VASCOMP}}{\partial Y_{ELAPS}} & I & 0 & 0 & 0 & 0 \\ -\frac{\partial Y_{AEROS}}{\partial Y_{ELAPS}} & -\frac{\partial Y_{AEROS}}{\partial Y_{VASCOMP}} & I & 0 & 0 & 0 \\ 0 & 0 & -\frac{\partial Y_{PADE}}{\partial Y_{AEROS}} & I & 0 & 0 \\ -\frac{\partial Y_{ACP}}{\partial Y_{ELAPS}} & 0 & 0 & -\frac{\partial Y_{ACP}}{\partial Y_{PADE}} & I & 0 \\ 0 & 0 & 0 & 0 & -\frac{\partial Y_{CSD}}{\partial Y_{ACP}} & I \end{bmatrix};$$

$$\left\{\frac{dY}{dX_k}\right\} = \begin{pmatrix} \frac{dY_{ELAPS}}{dX_k} \\ \frac{dY_{VASCOMP}}{dX_k} \\ \frac{dY_{AEROS}}{dX_k} \\ \frac{dY_{PADE}}{dX_k} \\ \frac{dY_{ACP}}{dX_k} \\ \frac{dY_{CSD}}{dX_k} \end{pmatrix}; \quad \left\{\frac{\partial Y}{\partial X_k}\right\} = \begin{pmatrix} \frac{\partial Y_{ELAPS}}{\partial X_k} \\ \frac{\partial Y_{VASCOMP}}{\partial X_k} \\ \frac{\partial Y_{AEROS}}{\partial X_k} \\ \frac{\partial Y_{PADE}}{\partial X_k} \\ \frac{\partial Y_{ACP}}{\partial X_k} \\ \frac{\partial Y_{CSD}}{\partial X_k} \end{pmatrix}$$

Fig. 2: Global Sensitivity Equation GSE2

Sobiesky[4], Fig. 2) with the matrix of local sensitivities [S], the unknown vector of global sensitivities of behavior variables with respect to a certain design variable X_k. on the left hand side, and the known vector of local sensitivities on the right hand side.

In preparation for the complete analysis, previous research focused on sensitivity studies around wing aeroelastic stability only[5,6], i.e. concerned vector and matrix partitions in the first and fifth row of the equation (since the aircraft plant model ACP is wrapped around the Proprotor Aeroelastic Stability Analysis PASTA[7]). In this paper, terms in the second line are being investigated. Furthermore, an automated finite differencing procedure for an existing analysis program is presented. Application of internal UNIX utilities for input file manipulation and data extraction from CA output files allow the CA to remain untouched; process control in a UNIX shell script automates the procedure and adds further flexibility.

AUTOMATED SENSITIVITY CALCULATION

Data handling tools in optimization are usually tailored to the specific input/output formats of the analysis programs used. Traditionally, the analysis modules are even hardwired in one executable code. If a module is to be replaced, adaptation of the data transfer structure can be a very cumbersome task. In order to allow the future user of the analysis introduced in Reference 3 to run different analysis and optimization tasks, or to replace particular analysis programs chosen for one of the CA's to enhance accuracy, the overall data handling approach will be similar to that employed in the PATHFINDER system for the HSCT[8].

A set of UNIX shell tools for file manipulation and program flow control is in preparation. These utilities are programmed such that it is possible - with a limited number of standard shell tools - to "wrap" a data handling and sensitivity calculation "shell" around a certain analysis code which accepts standardized input and produces output of only analysis-relevant data in the same standardized format. Thus, the analysis block becomes a "black box" as seen from the optimization or user. Replacing an analysis program is simplified, since only the file manipulation tool input information needs to be updated. Changes in the analysis or optimization task can be handled by merely programming a shell script using the prepared CA "black boxes".

VASCOMP PERFORMANCE SENSITIVITIES

The mission analysis with the VTOL performance and sizing code, VASCOMP[9], as its centerpiece was chosen as a testbed for the first set of utilities. Only three tools are necessary for performing several different tasks:

(1) `unv` updates variables in a FORTRAN namelist input file; the variable names and new values are supplied in a separate file, the name of which - as well as the name of the old and the updated namelist - is specified in the tool call;

(2) `pnv` is similar to `unv`, but it perturbs values in a namelist by a factor that can be specified in the tool call;

(3) `sens` is a shell script using `pnv` to automatically calculate CA output values and output sensitivities for a certain design point. To date, VASCOMP is directly called from within `sens`; eventually, the name of the actual analysis program (executable file) will be specified in the tool call.

A fourth shell script was used in this particular case for calculating VASCOMP output sensitivities for a set of different design points. `unv` is used to change one wing design variable at a time; then, `sens` is called to provide sensitivity information at this particular design point. The VASCOMP task is to size a 30 PAX civil tiltrotor aircraft for a EUROFAR-type configuration using baseline data provided e.g. by Caramaschi[10]. Fig. 3 shows the mission to be flown, similar to that identified by von Reth et al.[11]. Table 2 lists the design variables, which correspond to thosein the "input" column of Table 1, and provides an overview of the different configurations analyzed.

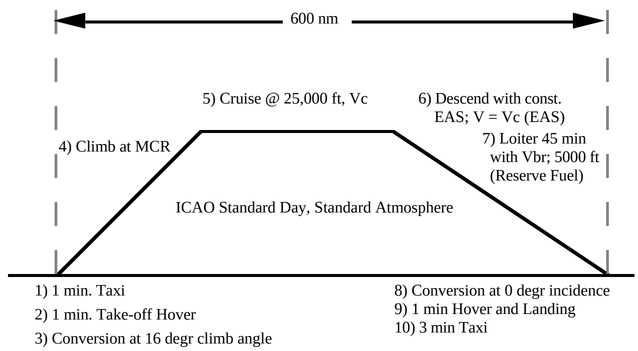

Fig. 3: Design Mission

Variable 2 "*speed*" is printed in italics throughout this text since it does not correspond to one value only, but to a set of velocity inputs into VASCOMP. These include the actual cruise speed, equivalent air speed for descent (which is chosen to be the value of the cruise speed converted into equivalent air speed), engine design speed for cruise condition (335 kts at 5000 ft for the baseline) as well as wing design cruise and dive speed (350 kts and 450 kts, respectively). In the sensitivity analyses, these values are perturbed simultaneously. If a numerical value is mentioned in this paper with reference to the variable "*speed*", then it should be understood as the mission cruise speed value. The productivity index, PI, is not an output of the original program, but is calculated in the shell script using VASCOMP output data.

The application of VASCOMP and its output in this test case is different from that to be used in the multidisciplinary framework. Here, the program is used for actually sizing the aircraft (i.e. fuel weight required RF_R = fuel weight available RF_A automatically; compare with Table 1) and the internal wing weight estimation option is used. Eventually, VASCOMP will calculate fuel weight required for a given empty weight basing on a fixed fuselage weight plus the actual wing weight from the Equivalent Laminated Plate Solution ELAPS[12], which is also used for structural integrity checks and wing modal analysis. The normalized difference of fuel weight required and fuel weight available will then be output as a constraint.

Since all following sensitivity information is presented in normalized form, Fig. 4 provides a reference for the actual output values for block speed (Vb), fuel weight (Wf), empty weight (We), wing weight (Ww), gross weight (Wg), power per engine (HP/Engine), total initial investment cost for 300 aircraft (IC/300 AC; as calculated by VASCOMP basing on 1992 data) and productivity index (PI) for these configurations (the values in parentheses listed in the legend represent the values for the baseline, configuration 1). In order to show the differences between the configurations more clearly, the change in output variables with respect to

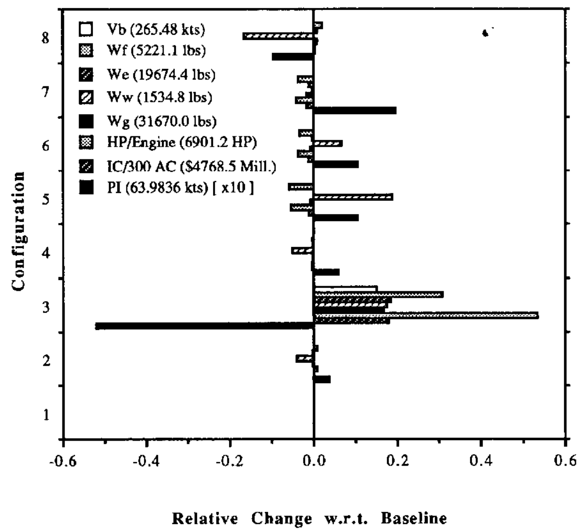

Fig. 4: Configuration Output Comparison

configuration 1 (baseline), divided by the baseline value is shown. The change in productivity index PI is furthermore enhanced by a factor of 10 for clarity.It should be noted that a similar study[13] on tiltrotor performance sensitivity has been performed previously. However, the focus in this paper is on demonstrating the use of shell tools for automated sensitivity analysis with respect to wing-related parameters, whereas Reference 13 presents trend studies for variations in rotor variables and only a few wing parameters.

A sensitivity analysis for one design point (configuration) took about six minutes (system time, not CPU time) on Georgia Tech's Sequent 581. Results are shown in Fig. 5 to 12. Plotted are normalized sensitivities of the output variables with respect to the seven design variables. "Normalized" means in this context that the values shown represent percent change in output divided by percent change in design variable (in this particular case 5%). The sensitivities are therefore the result of simple forward finite differencing.

Sensitivities w.r.t. wing sweep (design variable 1)

The influence of wing sweep on all output variables is very small, and only detectable for configuration 2. Noting that the aircraft cruises at about Mach number M = 0.5 (M = 0.58 for configuration 3), it is not surprising that the sweep influence on aerodynamics is negligible. However, an increase of wing weight with the absolute value of sweep was expected. Fig. 6 shows though that wing weight actually decreases, while fuel and power required rise. A possible explanation for this effect could be found in the structure of the wing weight estimation in VASCOMP: It contains all design variables but wing sweep. It appears that if all other design variables are held constant, a reduction in wing area and span is feasible, so that wing and empty weight decrease. However, the configuration seems to become less optimal in cruise, since cruise power required increased from 13802 HP for the baseline (configuration 1) to about 13906 HP for configuration 2, whereas conversion and take-off power required hardly changed at all. This seems to indicate that the increase in fuel required can be contributed to a decrease in the internally computed Oswald efficiency factor (a reduction of wing area and thus increase of wing loading improves cruise performance; see Tables 3 and 4). The effect is not yet understood and requires further investigation. An explanation could be found in the fact that VASCOMP resizes the aircraft for each design variable perturbation.

Sensitivities w.r.t. *speed* (design variable 2)

The sensitivity of block speed is slightly less than unity for all configurations since cruise and descent speed determine flight velocities for the largest part of the mission. Most obvious result is the positive sensitivity of power required, with a numerical values of about 2.25. One exception from this value can be detected for configuration 8 with increased wing loading (refer to Fig. 12), where the sensitivity is reduced. This result is easily explained through the well known observation that the speed of maximum L/D increases with wing loading. For configuration 8, this speed is thus closer to the cruise speed of 300 kts than for the other configurations. Since the power curve is "flatter" in this region, the sensitivity of power with respect to speed changes is reduced. The equivalent explanation holds for the second exception - configuration 3, with increased *speed* - where the sensitivities of fuel weight and power required are much larger. It is interesting to note that, with regard to PI, for all configurations except number 3 (which appears to be far off the original design point) the weight increase is overcompensated through the increase in block speed, so that the PI sensitivity is also positive. The positive sign of the investment cost sensitivity reveals that although the aircraft seems to cruise PI-suboptimal (since *speed* increases still yield improvement), it is superoptimal with respect to investment cost - definitely a result of the presence of block speed in the numerator of PI.

Sensitivities w.r.t. wing taper ratio (design variable 3)

For fixed wing area and root thickness to chord ratio, an increase in taper ratio is equivalent to a decrease in absolute root thickness, hence to a decrease in root stiffness, unless material is added. Therefore, the wing weight sensitivities of all configurations are positive, resulting in a small negative value for PI. The latter effect is slightly larger for configuration 6 (with reduced root t/c). Aerodynamic effects appear to be negligible.

Sensitivities w.r.t. wing aspect ratio (design variable 4)

The general increase in wing weight with aspect ratio is as familiar as the associated reduction in induced drag and thus power required. A change in gross weight is not observed; it seems that increased structural weight and

Configuration	1	1 (modified)
Power Required [HP]:		
Take Off	10722	10667
Conversion	12219	12496
Cruise	13802	13764
Mission Fuel per Segment [lbs]:		
Taxi, TO, Hover	92.1	91.7
Conversion	45.8	47.6
Climb	313.4	316.5
Cruise	3269.9	3268.8

Table 3: Effect of Wing Loading on Power Required and Mission Fuel (Configuration 1)

Configuration	8	8 (modified)
Power Required [HP]:		
Take Off	10621	10641
Conversion	13374	13743
Cruise	13835	13927
Mission Fuel per Segment [lbs]:		
Taxi, TO, Hover	91.7	92.1
Conversion	52.8	55.1
Climb	318.5	334.5
Cruise	3306.2	3334.9

Table 4: Effect of Wing Loading on Power Required and Mission Fuel (Configuration 8)

decreased fuel weight compensate each other. The sensitivity of PI is positive, but relatively small. Notice also the opposite signs of investment cost and PI, meaning that increasing the aspect ratio has a positive effect on both acquisition cost and PI (in contrast to the influence of *speed*).

<u>Sensitivities w.r.t. root t/c (design variable 5)</u>

Here, the negative effect of increased profile drag (resulting in increased power and fuel required) dominates the positive structural effects of increasing the thickness to chord ratio at the wing root, i.e. better material utilization. As a result of increased power plant size and weight, empty weight and investment cost increase, leading to a negative sensitivity of PI with respect to root t/c.

<u>Sensitivities w.r.t. tip t/c (design variable 6)</u>

Similar tendencies can be detected for this variable. The significant difference is found in the fact that increasing t/c near the tip does not result in better material utilization like at the root, since the bending moments are much smaller. Hence, wing weight is not increases (with the exception of configuration 7, where the tip structure is already weakened, and number 8, where the overall stress level in the structure is higher). Since aerodynamic effects prevail, the absolute values of sensitivities of output other than wing weight are in general larger than for root t/c.

<u>Sensitivities w.r.t. wing loading (design variable 7)</u>

Noting that, if all other wing parameters are constant, an increase in wing loading is equivalent to reduction of the wing size, the negative sensitivity of wing weight with respect to wing loading is almost intuitive. Explaining opposite signs of fuel weight and power required sensitivity requires a more detailed investigation of the VASCOMP output file, summarized in Tables 3 and 4 (the values in the right column were calculated using the input deck for configuration 1 and 8, respectively, with wing loading increased by 5%):

Increasing wing loading results in a slightly more efficient cruise configuration, as indicated by reduced fuel required in this mission segment, and a slightly downsized engine. Due to the smaller wing, hover download is also reduced, as reflected in the decreased value for power required in this condition. However, the downsized wing produces more induced drag at lower speeds such as in the conversion and climb segments, and fuel consumption is increased. The optimum value for wing loading was exceeded in configuration 8 though (Table 4). These results confirm the tendencies reported in Reference 13.

<u>Influence of Design Point on PI Sensitivities</u>

In view of the future application of the sensitivity analysis presented within a multidisciplinary optimization framework, it is interesting to know how much the PI sensitivities are effected by changing the design point, or, in other words, how nonlinear PI is as a function of a particular design variable. The answer to this question is critical in terms of accuracy of the finite differencing scheme.

In Fig. 13, PI sensitivities are plotted vs. the design variables for all eight configurations investigated. As discussed earlier, the influence of wing <u>sweep</u> appears to be negligible. Discarding this design variable could be conceived; however, previous studies show a significant effect on aeroelastic stability[2, 6].

PI is very sensitive to changes in <u>*speed*</u>; the actual values also depend very much on the design point. An optimum value should be found between that for configuration 2 and the others, as indicated by the changing

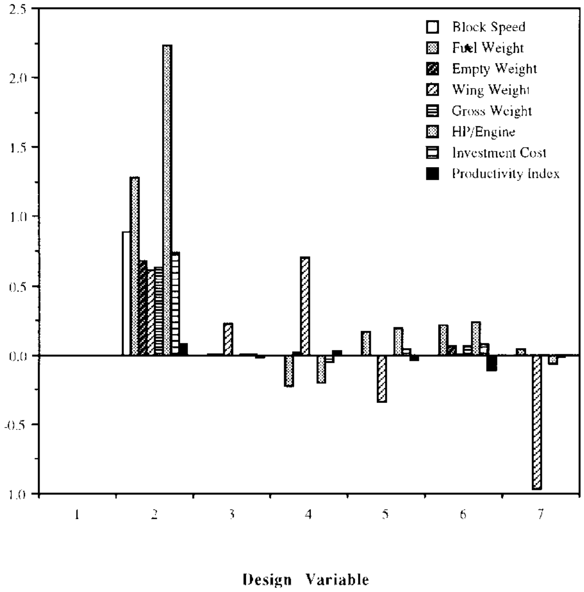

Fig. 5: Normalized Output Sensitivities, Configuration 1 (baseline aircraft)

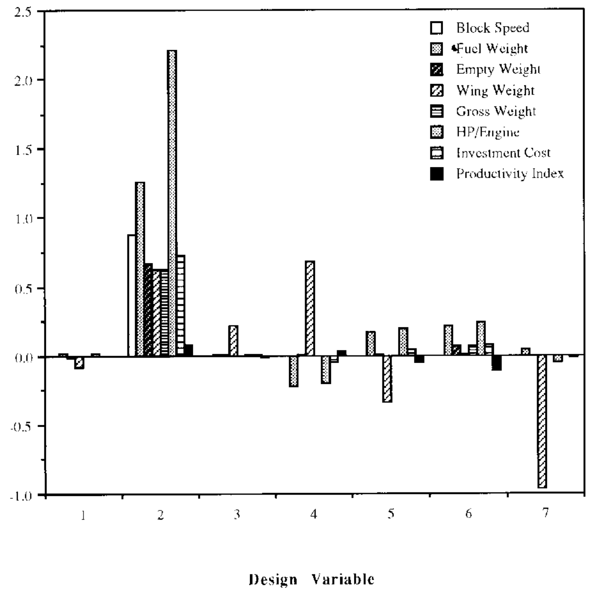

Fig. 6: Normalized Output Sensitivities, Configuration 2 (wing sweep + 500%)

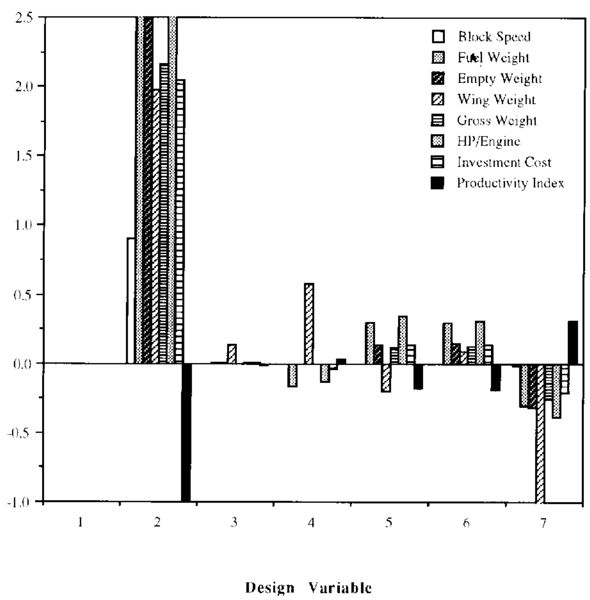

Fig. 7a: Normalized Output Sensitivities, Configuration 3 (*speed* + 16.7%)

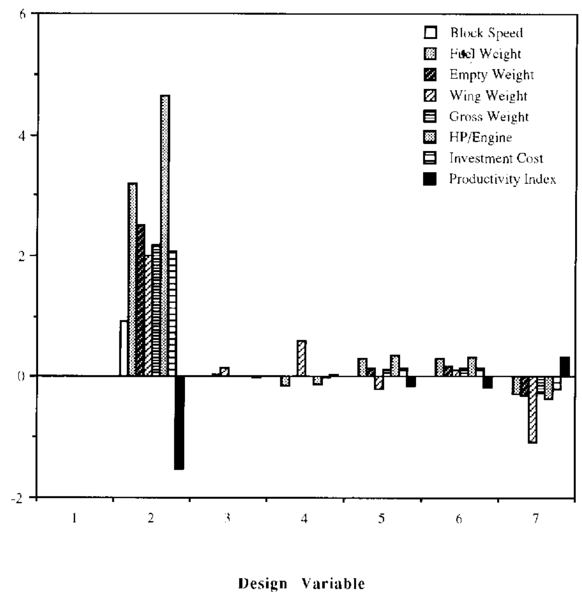

Fig. 7b: Normalized Output Sensitivities, Configuration 3 (extended scale)

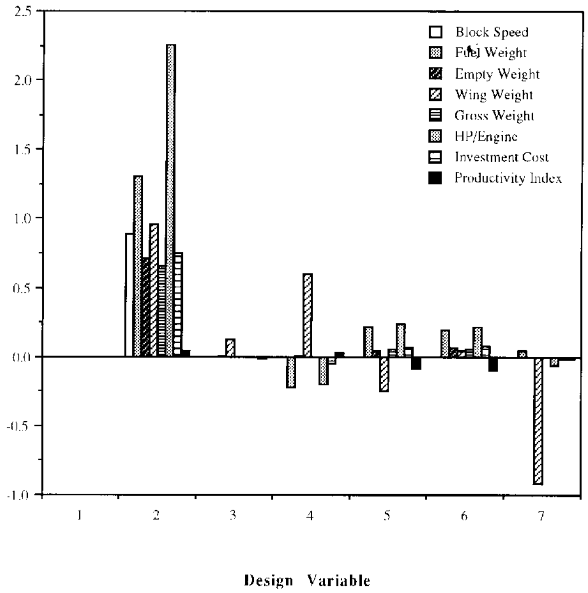

Fig. 8: Normalized Output Sensitivities, Configuration 4 (taper ratio - 20%)

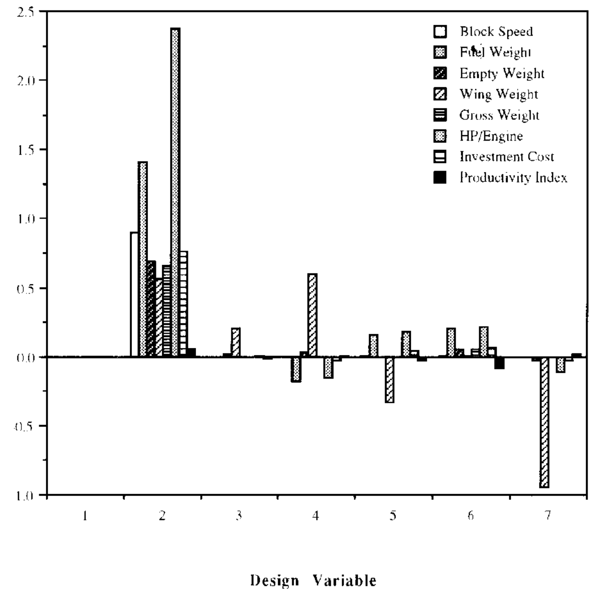

Fig. 9: Normalized Output Sensitivities, Configuration 5 (aspect ratio + 31%)

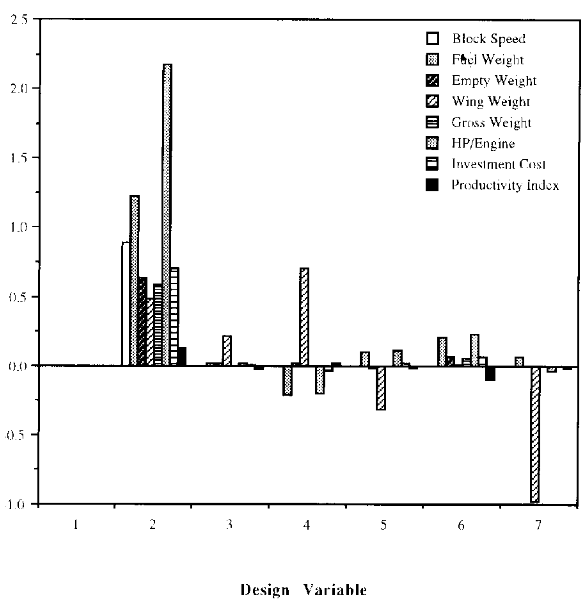

Fig. 10: Normalized Output Sensitivities, Configuration 6 (root t/c - 20%)

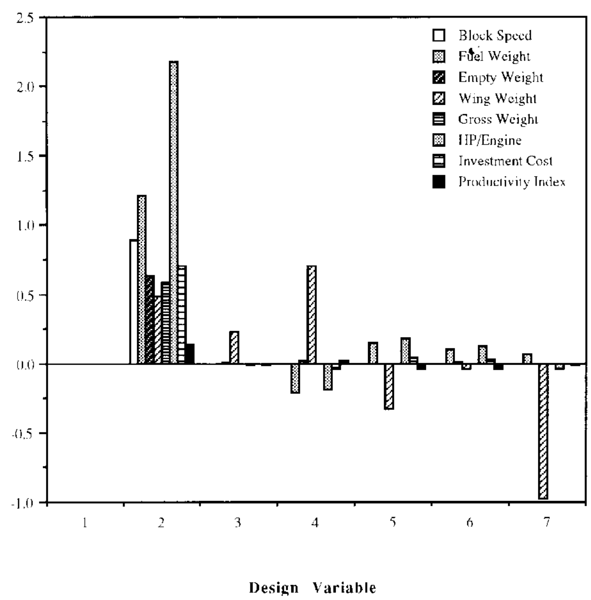

Fig. 11: Normalized Output Sensitivities, Configuration 7 (tip t/c - 20%)

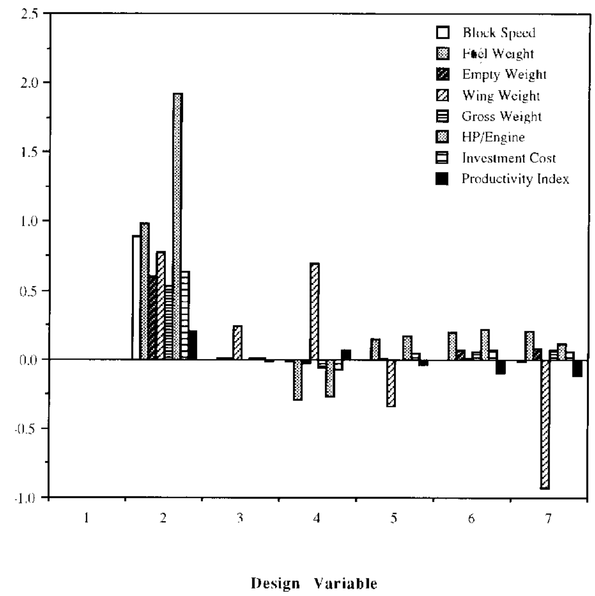

Fig. 12: Normalized Output Sensitivities, Configuration 8 (wing loading + 20%)

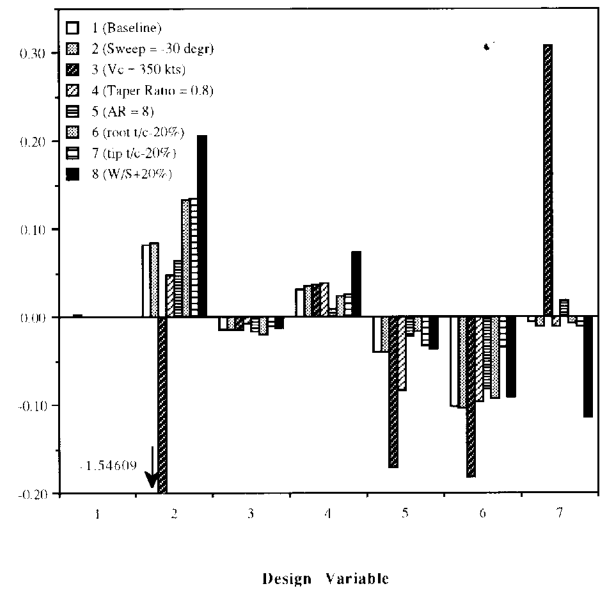

Fig. 13: Summary of PI Sensitivities

sign of the PI sensitivity. It appears that the aircraft cruise speed of 300 kts represents a PI-suboptimal value.

The influence of taper ratio is much smaller, and PI seems to be nearly linear in this variable. Possibly retaining one value of the PI sensitivity is accurate enough for a early optimization cycles.

The sensitivity with respect to aspect ratio on the other hand differs significantly. Most obvious is a minimum value for increased aspect ratio (configuration 5) and the maximum value for increased wing loading (configuration 8). The first result hints at the possible existence of a PI-optimal aspect ratio above 8, the latter can be explained through induced drag effects (nonlinear in PI).

The most promising candidates for improvement of PI are the root and tip thickness to chord ratios. The actual absolute values are similar to those for *speed* , but they appear to be far less sensitive to the design point, so that inaccuracies in the sensitivity calculation might not result in suboptimality through errors in the initial determination of the search direction. Tip t/c reduction is about twice as effective for PI improvement as decreasing root t/c, which is well in agreement with material utilization considerations.

Wing parameters related predominantly to aerodynamics (*speed*, aspect ratio, wing loading) have a significant influence on the sensitivity of PI with respect to wing loading, whereas changing design variables of more structural character (sweep, taper, thickness to chord ratio) has little effect. The opposite signs for configurations 3 and 8 reflect the expected results for configurations cruising above and below their most efficient cruise speed, respectively. The baseline value for wing loading appears to be a little bit above an optimal value with respect PI.

CONCLUSIONS

The shell tools for data handling and program flow control proved to be efficient and flexible. The results of the productivity index, PI, sensitivity analysis indicate that wing thickness to chord ratio reduction could be a very effective way for increasing PI of the investigated baseline configuration. The PI-optimal value for aspect ratio is obviously located above 8, and the optimal cruise speed can be found between the current value of 300 kts and 350 kts.

The aircraft that would result from an optimization for PI, based on the current analysis, would therefore fly at higher speeds with a thinner, more slender wing - a tendency towards a presumably aeroelastically less stable condition. VASCOMP does not include a wing structural integrity check for static load conditions, and no aeroelastic stability constraint. Thus, inclusion of these elements is mandatory in future investigations.

ACKNOWLEDGMENTS

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REFERENCES

[1] Chattopdhyay, A., and Narayan, J. R.., "Optimum Design of High Speed Prop-Rotors Using a Multidisciplinary Approach," presented at the 48th Annual Forum of the American Helicopter Society, Washington, DC, June 3-5, 1992

[2] Nixon, M.W., "Parametric Studies for Tiltrotor Aeroelastic Stability in High-Speed Flight," AIAA/ASME/ ASCE/AHS/ASC 33rd Structures, Structural Dynamics, and Materials Conference, Dallas, Texas, April 13-15, 1992

[3] Stettner, M., and Schrage, D.P., "An Approach to Tiltrotor Wing Aeroservoelastic Optimization through increased Productivity," presented at the 4th AIAA/USAF/ NASA/OAI Symposium on Multidisciplinary Analysis and Optimization, Cleveland, Ohio, September 21 - 23, 1992

[4] Sobieszczanski-Sobieski, J., "Sensitivity of Complex, Internally Coupled Systems," *AIAA Journal*, Vol. 28, No. 1, January 1990, pp. 153-160

[5] Loewer, S., "Sensitivity of Tiltrotor High Speed Performance to Wing Structural Parameters," Diploma Thesis, Technische Universität Braunschweig/Georgia Institute of Technology, April 1992

[6] Friehmelt, H., "Design of a Tiltrotor Wing for a EUROFAR-type Configuration," Special Topic, Technische Universität Braunschweig/Georgia Institute of Technology, March 1993

[7] Kvaternik, R.G., "Studies in Tiltrotor VTOL Aircraft Aeroelasticity," PhD Dissertation, Department of Solid Mechanics, Structures, and Mechanical Design, Case Western Reserve, June 1973

[8] Dovi, A. R., Wrenn, G. A., Barthelemy, J.-F. M., Coen, P. G., and Hall, L. E., "Multidisciplinary Design Integration System for a Supersonic Transport Aircraft," presented at the 4th AIAA / USAF / NASA / OAI Symposium on Multidisciplinary Analysis and Optimization, Cleveland, OH, September 21-23, 1992

[9] Schoen, A.H., Rosenstein, H., Stanzione, K., and Wisniewski, J.S., "User's Manual for VASCOMP II, The V/STOL Aircraft Sizing and Performance Computer Program," Boeing Vertol Company Report D8-0375, Vol. VI, Third Revision, May 1980

[10] Caramaschi, V., " The EUROFAR Vehicle Overview," presented at the 47th Annual Forum of the American Helicopter Society, Phoenix, Arizona, May 6-8, 1991

[11] von Reth, R.D., Hagmann, U., and Huber, H., "EUROFAR - Projekt für ein senkrecht startendes Reiseflugzeug," Symposium 'Luftfahrt-Städtebau-Umwelt (II)', Aachen, Germany, January 17-18, 1989

[12] Giles, G.L., "Further Generalizations of an Equivalent Plate Analysis for Aircraft Structural Analysis," *Journal of the Aircraft*, Vol. 26, No. 1, January 1989

[13] Dunston, M. C., “A Study of the Effect of Design Parameter Variation on Predicted Tilt-Rotor Aircraft Performance”, Master’s Thesis, Naval Postgraduate School, Monterey, CA, December 1988