DEVELOPMENT OF A CONCEPTUAL DESIGN METHOD FOR ROTARY-WING AIRCRAFT USING DIGITAL COMPUTERS[1]

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Abstract

Presented in this paper is the development of a conceptual design method for rotary-wing aircraft. This method allows to perform conceptual design studies for a helicopter or tiltrotor based on a given mission and with the help of Carpet-Plots. The corresponding computer program, which has a modular structure, contains a number of subroutines, where the most important ones are those to simulate the engine behaviour including fuel consumption, to calculate the weight break-down and to compute aerodynamic forces, performance and trim. The variation of some geometric parameters is presented for a light helicopter and a tiltrotor. The comparisons of the optimized data for the light helicopter and the tiltrotor show good agreement with those for some designed aircraft.

Notation

n_{LOAD}	maneuver load factor
H	altitude
IGE	in ground effect
OGE	out of ground effect
P_i	induced power
P_O	profile power
P_P	parasite power
P_{TR}	Total power of the tail rotor
P_T	Total power of the helicopter
TOGW	Take-off gross weight

Introduction

The definition of design parameters of a new rotary-wing aircraft able to satisfy the mission requirements and to produce the most efficient flight vehicle, usually requires an iterative process to strike a balance among contrasting requirements. In addition, several constraints have to be observed. The design process requires the knowledge, experience and ideas of many engineers. Instead of attempting to provide an automated selection of the best configuration out of all possible candidates, it is more realistic to use design methods to identify the best candidate for

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each possible configuration provided by the engineers. The computer can only be a useful tool to make this process more effective.

In contrast to the fixed-wing aircraft, there are not many available design methods for rotary-wing aircraft, because each helicopter manufacturer has his own aircraft design programs. Miura (Ref. 1) presents a survey of the design optimization methods till 1984. The most important ones were the mathematical programming methods of Szumanski (Ref. 2), the program HELISOTON of Ramos and Taylor (Ref. 3) and the design method for transport helicopters of Stepniewski and Sloan (Ref. 4). Knapp describes in his paper (Ref. 5) the design of the main-rotor parameters, such as the disc loading, tip speed, number of blades etc. A constrained optimization was conducted to find the best design of four different configurations.

The first comprehensive computer program for the helicopter design was HESCOMP (Ref. 6). This program integrates all the aspects of the conceptual design such as aircraft configuration sizing, performance aerodynamics and weights into a multidisciplinary rotary-wing design tool. Two other similar but simpler programs were developed at the Naval Postgraduate School in Monterey (Ref. 7) and in Munich under the name LEIREV (Ref. 8).

During the past 15 years much progress has been made in the development of rotary-wing aircraft with advanced technology. The reason has been the need for a rotorcraft that hovers like a helicopter and cruises at high subsonic speeds. The goal is to integrate efficient low-speed capability and high speed cruise in a single rotorcraft concept. A summary of all new concepts and a more detailed conceptual definition of the five most attractive of them is given by Schneider in Ref. 9. One of the first trade-off studies of tiltrotor versus helicopter was conducted in the Naval Postgraduate School of Monterey (Ref. 10) using the computer programs VASCOMP II and HESCOMP. Paisley (Ref. 11) investigated the variation of rotor geometry from the baseline design, which optimizes cruise performance without reducing hover performance. Other detailed investigations were carried out by Frandenburgh (Ref. 12) and Farell (Ref. 13).

The developed program, presented in this paper, allows the study of the influences on performance, when the geometric parameters, e.g. aspect ratio, taper ratio, blade twist, sweep of the blade tips, wing aspect ratio or wing area etc. have been changed. These parameters are varied to study their influences on performance and on a target parameter, e.g. weight, direct operating costs, life cycle costs. The target parameter can be optimized, and the important parameters that influence this target parameter can be identified. A chart method is provided that shows directly the relationships among these parameters and the various design requirements. This program integrates all the aspects of the conceptual design and can be used for three weight classes, i.e. light, medium and heavy helicopters.

Conceptual Design Process

At the beginning of the conceptual design process (Fig. 1) is the prescribing of the mission requirements and the payload. After that the user has to estimate the take-off gross weight and the major geometric parameters, e.g. overall length, height, disc loading, aspect ratio, wing loading and etc. These parameters can be taken from helicopters or tiltrotors that have already been designed. With the help of an engine simulation and a performance program the required fuel weight $(W_F)_{REQ}$ will be determined, while at the same time the weight program estimates the empty weight of the rotary-wing aircraft. The estimated available fuel weight $(W_F)_{AVA}$ and the required fuel weight are then compared during an iterative process. The computation is stopped, when convergence is achieved. The result of this iteration is shown in Fig. 2. The intersection point between the curves of the required $(W_F)_{REQ}/W_{TOG}$ and the

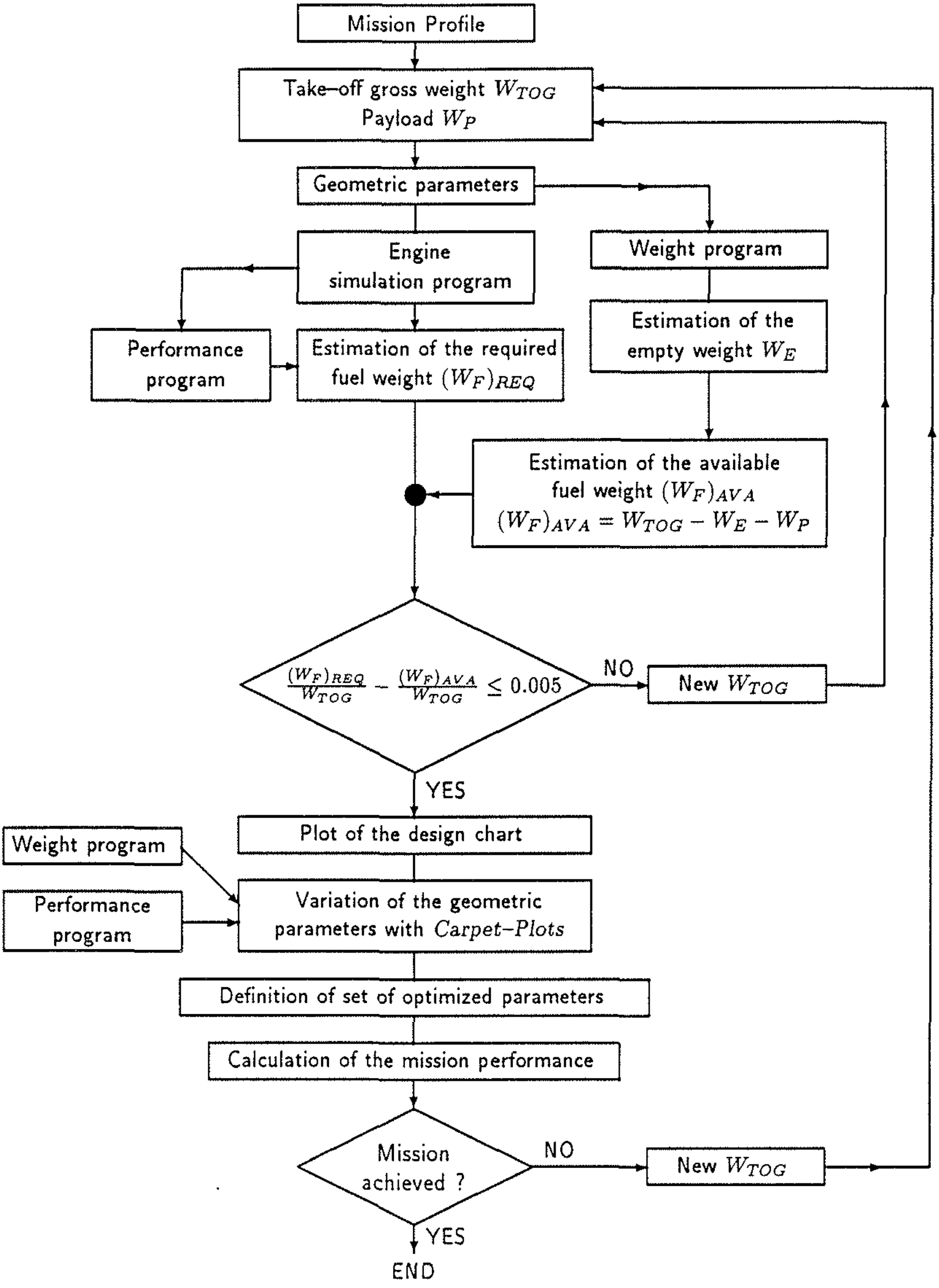


Fig. 1: Flow chart of the conceptual design process

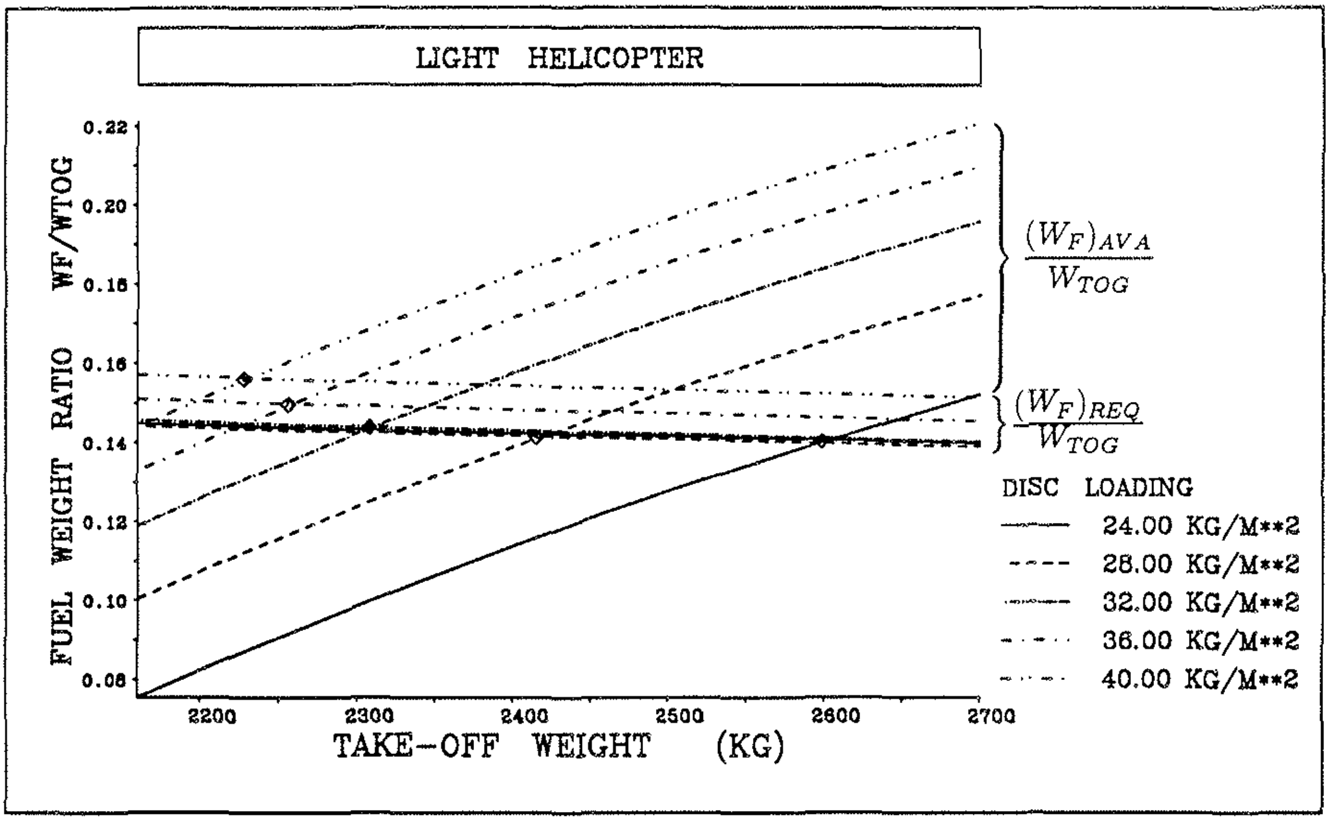


Fig. 2: Variation of the fuel weight ratios vs. take–off weight

available fuel weight ratio $(W_F)_{AVA}/W_{TOG}$ supplies the resultant gross–take off weight for a definite disc loading.

The conceptual design process continues with the so–called design chart, where the power–to–weight ratio is plotted versus disc loading, blade loading or wing loading using curves to demonstrate several point performances of the helicopter. The variation of the geometric parameters with Carpet–Plots will lead to the definition of set of optimized parameters. After that the user has to calculate the mission performance. It frequently happens that the mission requirements are so severe that no compromise can be found to design a helicopter or tiltrotor of acceptable size or costs. The search for a suitable compromise that contains different mission requirements and results in an acceptable design then starts again. The user will choose an other take–off weight and the design process begins again.

Computer Program

The developed computer program contains a number of subroutines, where the most important ones are the performance and trim program, the weight program and the engine simulation program.

The performance and trim program consists of two levels. The first level uses simple performance equations (Ref. 14) that offer sufficient accuracy to simulate major trends, but are not too time–consuming and still allow the many parameter variations that are neccesary in the conceptual design process. In addition, these equations do not require too much detailed information about the geometry of the aircraft since this information is often not available at the beginning of the design process. This level determines a lot of peak performances of the rotary–wing aircraft, such as the hovering ceiling (IGE and OGE), the service ceiling, the max.

		$V_F = 0.0$ m/s			$V_F = 65.0$ m/s		
		1. Level	2. Level	BO–105	1. Level	2. Level	BO–105
P_i	(KW)	297.0	297.0	252.5	52.0	59.0	50.0
P_O	(KW)	95.0	90.0	120.0	167.0	216.0	170.0
P_P	(KW)	0.0	0.0	0.0	187.0	190.0	225.0
P_{TR}	(KW)	35.0	34.0	37.0	16.0	10.0	17.0
P_T	(KW)	422.0	421.0	420.0	422.0	475.0	462.5

Tab. 1: Comparison of the computed results with the test data of the BO–105

rate of climb, the max. cruising speed etc.

The second level of the performance program is more accurate than the first one. It computes the aerodynamic forces for each rotor blade section and uses more complicated performance equations, that are based on the blade element method. However, it also requires more information about the input data, e.g. a more accurate description of the geometry, the airfoils etc. On the other hand, it also allows a more accurate study of the influences on perfomance, when the geometric parameters in the Carpet–Plots have been changed. Both levels use a trim program that finds the simultaneous equilibrium of all six components of force and moment on the helicopter. In addition it calculates the collective and cyclic pitch angles, the tailrotor pitch angle, the fuselage angle and the lateral tilt angle. Tab. 1 shows the comparison of the results of the performance program with the test data of the BO–105, obtained from Ref. 15. Both levels show a good agreement in the hover flight, whereas in the fast forward flight only the results from the more accurate second level are similar to the test data.

The weight program calculates the components weights for 17 different components of the helicopter. These components weights are calculated using detailed statistical weight equations developed by Beltramo (Ref. 16). There are such relationships for each weight class, i.e. light, medium and heavy helicopters. These equations require as input data, the estimated gross take–off weight, the fuel weight, the main rotor planform area and the tail and body surface area. The calculated components weights are then added to determine the empty weight of the helicopter. The weight program for the tiltrotor estimates the group weights for the structure group, the propulsion group and the fixed equipment group. All these groups consist of many components and their sum equals the empty weight. The calculation of this weight is based on the statistical weight equations developed by Torenbeek and Nicolai as presented in Ref. 17.

The engine program simulates the behaviour of the helicopter and tiltrotor engines. This program is only valid for twin shaft turboprop engines, a type that is often used in rotary–wing aircraft. However, a program extension for other engine types is also possible. This program requires some input data and the compressor and turbine characteristics. It calculates for a given altitude the available engine performance, the specific fuel consumption and the shaft torque.

Results

One of the most common graphs in the design process is the design chart. It demonstrates the relationship between the disc loading or the blade loading and the power–to–weight ratio of a helicopter for different performance requirements. These requirements are also point performances of a given mision, and each of them defines a design limit, that shows the allowable design area. All these limits form the boundary of an area, within which the design point (DP) can be defined. The following missions are put together to compute the first results (Tab. 2).

	LIGHT HELICOPTER
1.	Vertical Climb Flight (V_C = 3.0 m/s, H = 20 m)
2.	Forward Climb Flight (V_F = 50 m/s, V_V = 4.5 m/s, H = 1000 m)
3.	Forward Flight (V_F = 40 m/s, H = 1000 m)
4.	Forward Flight (V_F = 64 m/s, H = 1000 m)
5.	Hover Flight (H = 1000 m)
6.	Maneuver Flight (V_F = 50 m/s, n_{LOAD} = 2.1, H = 1000 m)
7.	Forward Descent Flight (V_F = 40 m/s, V_V = 6.0 m/s, H = 30 m)

	TILTROTOR
1.	Vertical Climb Flight (V_C = 4.5 m/s, H = 30 m)
2.	Forward Climb Flight (V_F = 60 m/s, V_V = 6.0 m/s, H = 1000 m)
3.	Forward Flight (V_F = 90 m/s, H = 1000 m)
4.	Forward Flight (V_F = 125 m/s, H = 1000 m)
5.	Hover Flight (H = 1000 m)
6.	Maneuver Flight (V_F = 70 m/s, n_{LOAD} = 1.8, H = 1000 m)
7.	Forward Descent Flight (V_F = 70 m/s, V_V = 8.0 m/s, H = 0 m)

Tab. 2: Mision profile for the light helicopter and the tiltrotor

Fig. 3 shows which of these requirements has the largest influence on the choice of the design point (DP). The slow forward flight, the forward climb flight and the descent flight have a low power–to–weight ratio and are not so significant for the helicopter design. The behaviour of the other requirements is quite different. The hover flight, the vertical climb flight, the forward flight and the maneuver flight show the highest power–to–weight ratio and are more important for the choice of the disc loading and the blade loading. A low value of the disc loading results in a high radius and therefore to low power required to hover and lower autorotative rate of descent. On the other hand, a high disc loading results in a compact size and a low empty weight. The choice of the blade loading C_T/σ is made with the aim to strike a balance between the maneuver and hover performance. By choosing a low value for level flight, such as 0.04, the designer can provide a rotor that develops high maneuvering load factors before stalling. However, he would be reducing the hover performance, because for most rotors the figure of merit is maximum at a blade loading coefficient value of about 0.10, and that it may be less than half its maximum at a value of 0.04. For this reason the most present–day helicopters are designed to operate at an initial C_T/σ of about 0.07 at the design gross weight at sea level.

In the design chart for the tiltrotor (Fig. 4) the power–to–weight ratio is plotted versus disc loading for the helicopter mode performances and versus wing loading for the airplane mode performances. The most stringest performances define also here the design point (DP). But the design chart has always a great disadvantage. Changing one of the design parameters, e.g. take–off weight, geometric parameters or mission requirements, will lead to different design points and therefore to new design charts. A helpful instrument to simultaneously demonstrate the influences of more than two of these parameters is the Carpet–Plot. A typical Carpet–Plot is shown in Fig. 5. The blade chord and the radius are being varied and plotted versus the

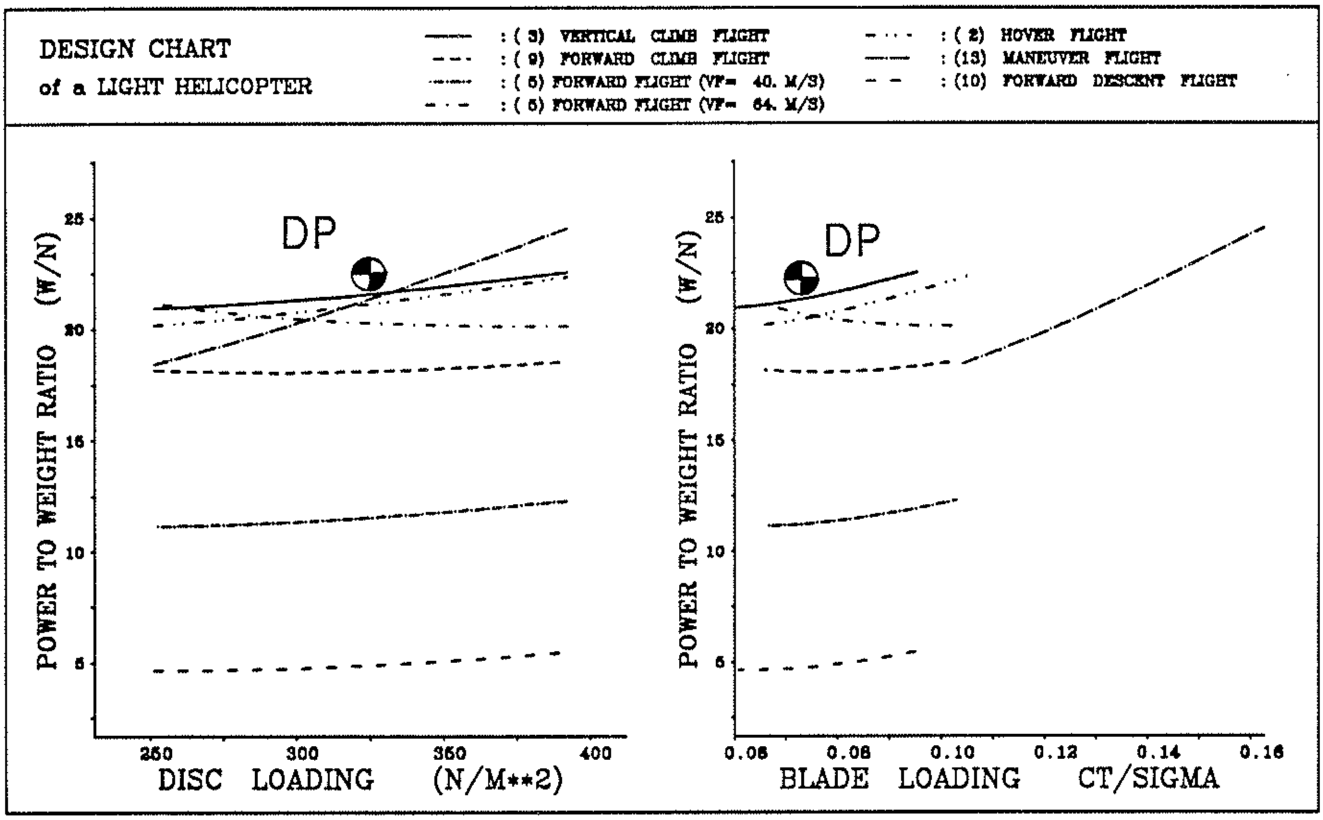


Fig. 3: Design chart for a light helicopter

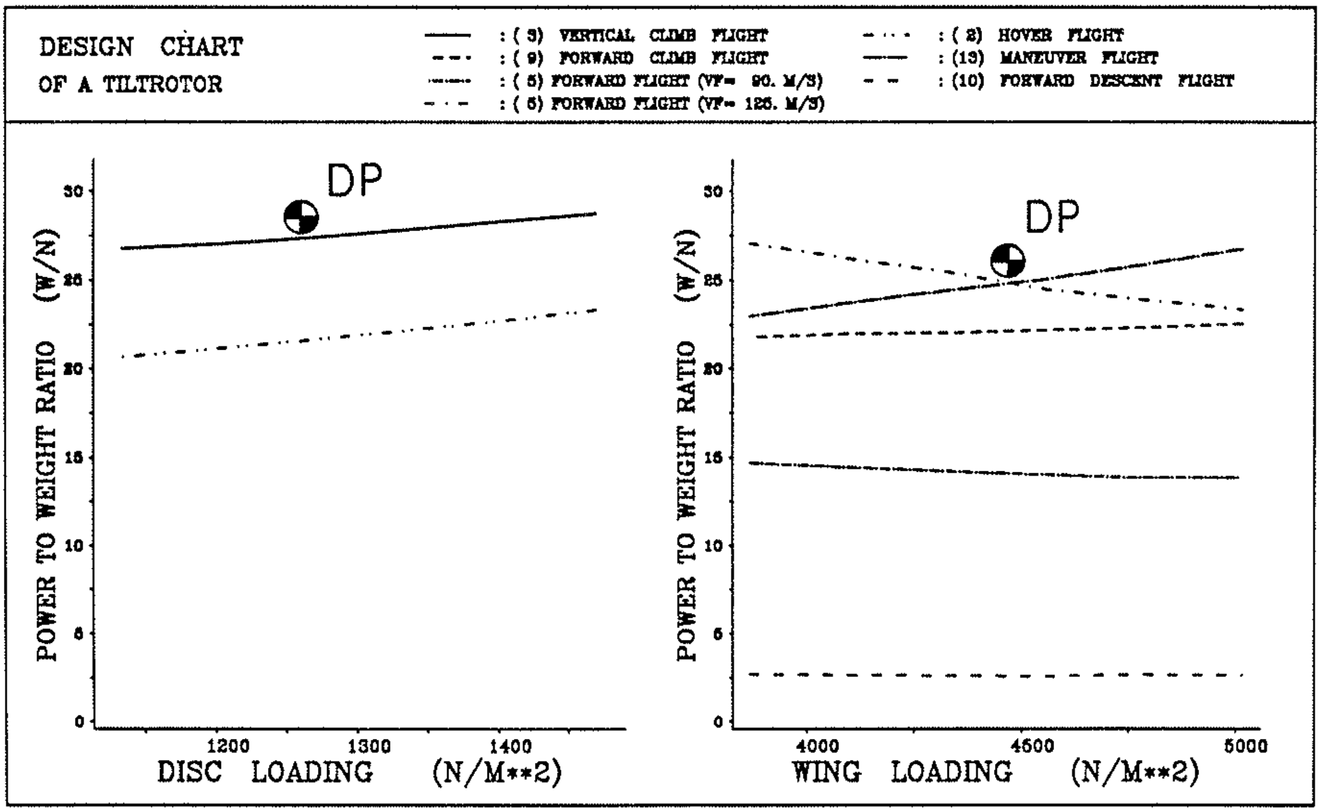


Fig. 4: Design chart for a tiltrotor

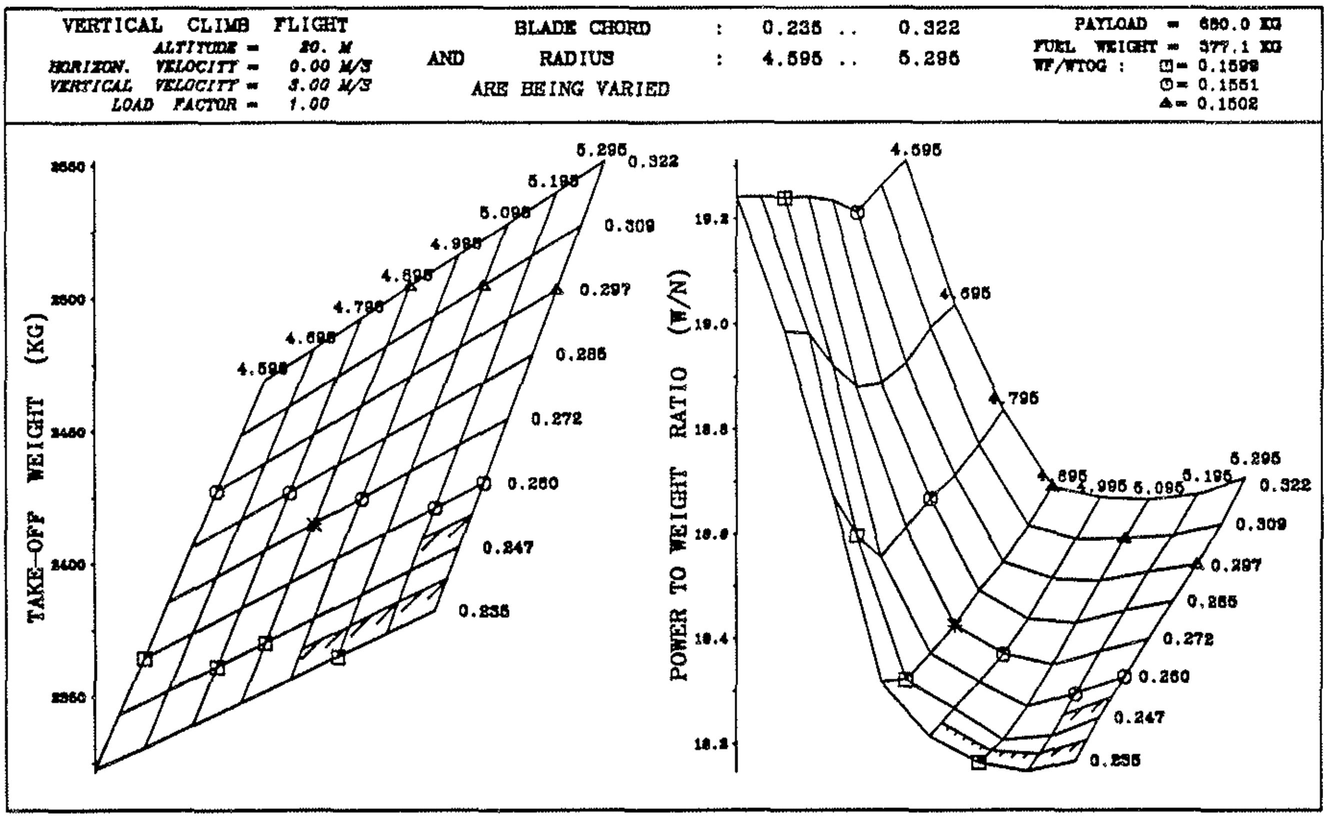


Fig. 5: Carpet–Plot for the light helicopter

take–off weight and the power–to–weight ratio for the vertical climb flight. Firstly the power–to–weight ratio falls while the radius increases, until a minimum is achieved, which depends on the value of the blade chord. After this the ratio goes up. The program also ensures that the aspect ratio, limited to 22, is not exceeded and plots the corresponding boundary on the Carpet–Plot if necessary.

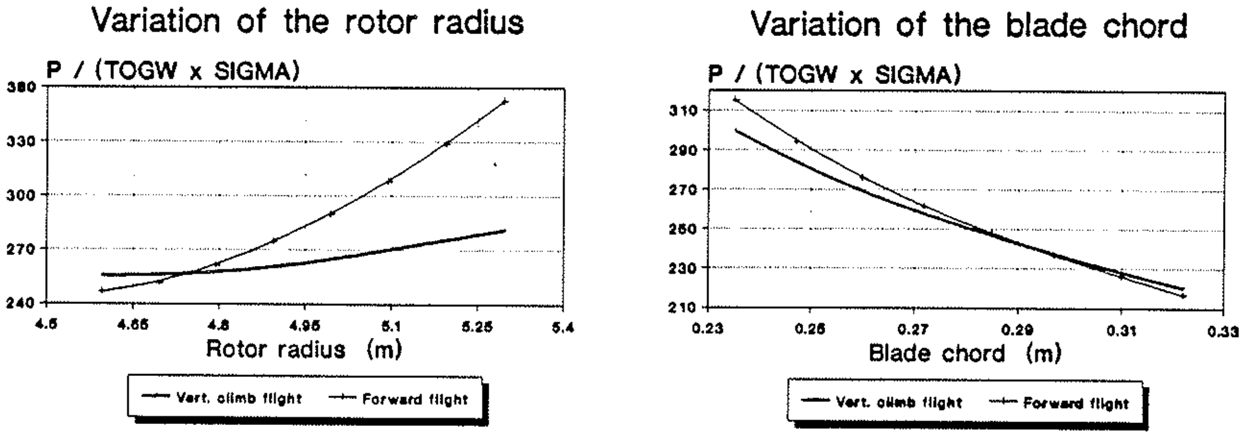
After the plot of the design chart, two baseline (BL) configurations for the light helicopter and the tiltrotor have been defined. Tab. 3 provides a summary of these configurations. The baseline configurations are described in some detail first, then with the help of the Carpet–Plots variations from the baseline configuration are used to illustrate the rotor parameter selection process.

The optimization of the helicopter rotor geometric parameters was conducted for the most stringest performances, the vertical climb flight and the fast forward flight. Fig. 6 shows the variation of the rotor radius and the blade chord. Both variables are plotted versus the power to weight ratio divided by the solidity σ. The intersection points of the curves ($R = 4.795$, $c = 0.285$) provide the optimized design for these parameters. A higher value for the blade chord would reduce the forward flight performances, such as the service ceiling and the max. cruising speed. Fig. 7 shows the effect of variing the rotor blade twist and the rotor taper ratio. The increasing blade twist produces a lower power to weight ratio and actually for both mission performances. To make use of the increased hover performances and the better climb ability a value of $-$ 7.7 deg was selected. The intersection point for the taper ratio is at the value $\lambda = 0.85$. This brings a higher maneuver load factor, an increased service ceiling and an increased max. rate of climb.

A summary of the optimized parameters and the comparison with the data of the BO–105

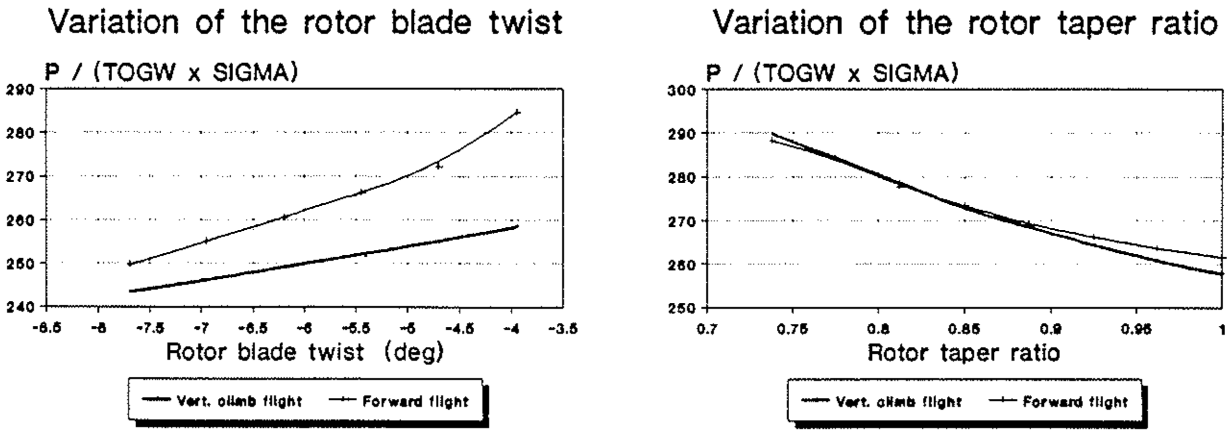
LIGHT HELICOPTER			TILTROTOR		
Main rotor radius	4.89	m	Radius	3.93	m
Number of blades	4	–	Number of blades	3	–
Aspect ratio	18.0	–	Aspect Ratio	10.7	–
Blade twist	– 6.2	deg	Blade Twist	36.12	deg
Taper ratio	1.0	–	Taper Ratio	1.0	–
Tip speed	220.0	m/s	Cruise tip speed	212.7	m/s
Tail rotor radius	0.95	m	Wing area	14.22	m^2
Tail rotor aspect ratio	5.27	–	Wing aspect ratio	6.12	–
Disc loading	32.05	kg/m^2	Wing loading	431.1	kg/m^2
Take–Off weight	2408	kg	Take–off weight	6130	kg
Empty weight	1351	kg	Empty weight	3935	kg
Fuel weight	377	kg	Fuel weight	620	kg
Payload	680	kg	Payload	1500	kg
Engines	2 x ALLISON 250–C20		Engines	2 x T700–GE	

Tab. 3: Baseline configurations for the light helicopter and the tiltrotor


Variation of the rotor radius

Variation of the blade chord

Fig. 6: Variation of the rotor radius and the blade chord for the light helicopter


Variation of the rotor blade twist

Variation of the rotor taper ratio

Fig. 7: Variation of the blade twist and the taper ratio for the light helicopter

is shown in Tab. 4. The greatest improvement was achieved in the forward flight performances by 9.1 % in the service ceiling, 13.6 % in the max. rate of climb and 3.1 % in the maneuver load factor. The reduced hover performances are due to the lower rotor radius and the higher blade chord. With this example is obvious, how difficult is to optimize simultaneously the contrasting requirements of the hover and the forward flight performances. The comparison with the BO–105 showed good agreement in the take–off weight and the empty weight. The differences in the peak performances were the result of the computation with the less accurate first level of the performance program.

		BASELINE	OPTIMIZED	BO–105
Radius	(m)	4.89	4.795	4.91
Blade chord	(m)	0.272	0.285	0.27
Blade twist	(deg)	– 6.2	– 7.7	– 8.0
Taper ratio	(-)	1.0	0.85	1.0
Blade tip speed	(m/s)	220.0	220.0	218.0
Tail rotor radius	(m)	0.89	0.89	0.95
Tail rotor blade chord	(m)	0.15	0.15	0.18
Take–Off weight	(kg)	2415	2396	2400
Empty weight	(kg)	1357	1340	1276
Hovering ceiling (IGE)	(m)	2342	2256	2560
Hovering ceiling (OGE)	(m)	1411	1342	1615
Max. vertical rate of climb	(m/s)	2.70	2.60	3.05
Max. cruising speed	(m/s)	72.0	73.0	67.3
Service ceiling	(m)	3912	4268	5180
Service ceiling, one engine out	(m)	464	624	890
Max. rate of climb	(m/s)	8.52	9.68	8.0
Max. maneuver load factor	(-)	1.27	1.31	–

Tab. 4: Comparison of the optimized light helicopter with the BO–105

The first parameter optimized for the tiltrotor was the radius of the proprotor. Fig. 8 shows the variation of the radius and its influence on the hover and airplane performance. As expected, the increasing radius produces an increase in hovering ceiling, while the service ceiling goes down. The best compromise between these contrasting behaviours was to select the same radius as in the baseline design with 3.93 m. After this the blade chord was varied. At a blade chord value of $c = 0.36$ m the service ceiling is maximum. On the other hand the hovering ceiling increases stadily. A good compromise is the intersection point between the two curves with the value of $c = 0.372$ m for good hover and airplane performances.

The selection of the blade twist was based on a trade between Figure of Merit and propeller efficiency, as shown in Fig. 9. By increasing the blade twist the maximum Figure of Merit decreases, whereas the propeller efficiency shows the opposite behaviour. The blade twist selection will be also a compromise between hover and airplane modes. Based on this, a 38.78 deg twist was selected. Fig. 10 shows the variation of the taper ratio. For the higher taper ratio $\lambda = 0.83$ the max. Figure of Merit has almost the same value as the baseline design. But the propeller efficiency shows a small increasing. The make use of the higher service ceiling and the better climbing ability a taper ratio of $\lambda = 0.917$ was selected. The optimization of

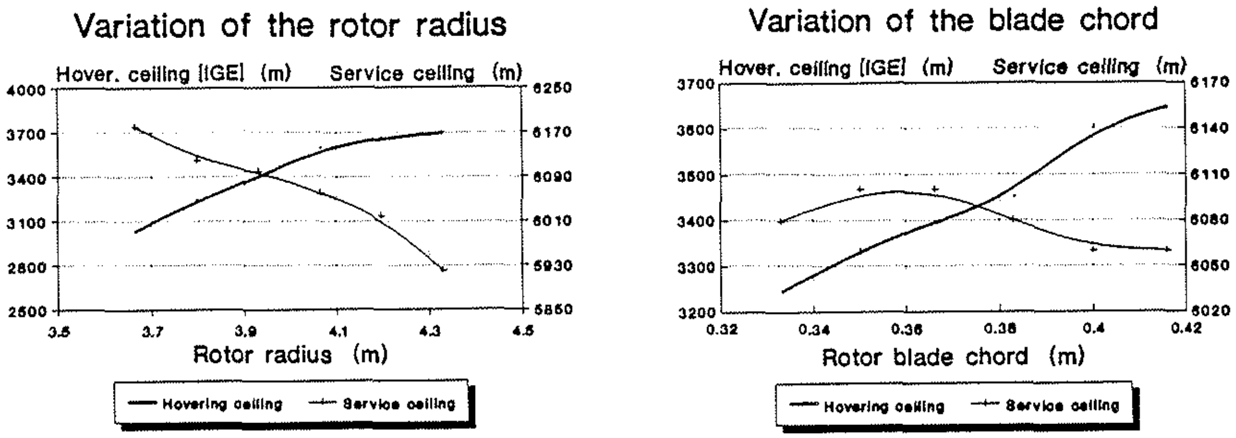


Fig. 8: Variation of the rotor radius and the blade chord for the tiltrotor

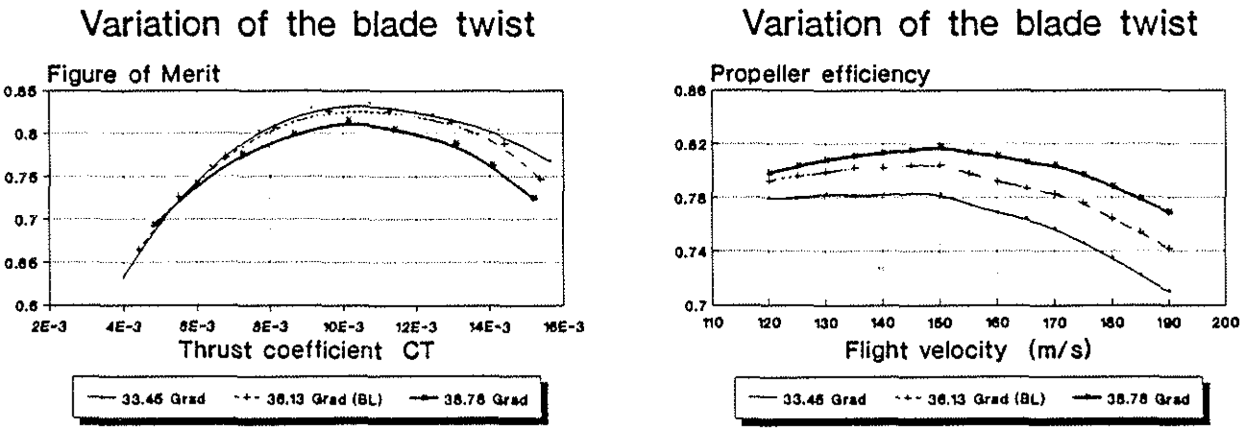


Fig. 9: Variation of the blade twist for the tiltrotor

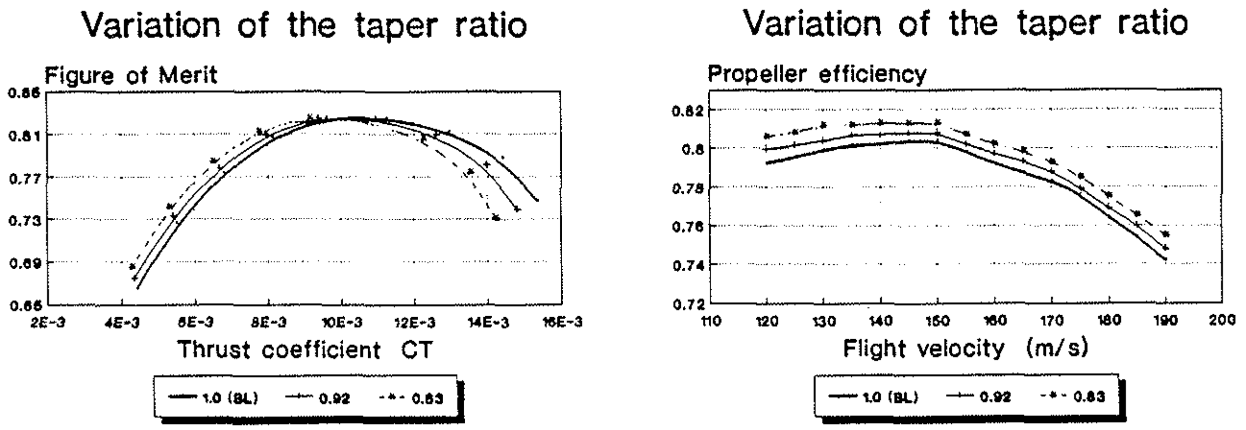


Fig. 10: Variation of the taper ratio for the tiltrotor

		BASELINE	OPTIMIZED	XV–15
Radius	(m)	3.93	3.93	3.81
Blade chord	(m)	0.366	0.372	0.27
Blade twist	(deg)	36.12	38.78	36.1
Taper ratio	(–)	1.0	0.917	1.0
Hover tip speed	(m/s)	232.5	232.5	225.4
Cruise tip spped	(m/s)	212.7	212.7	206.2
Wing area	(m^2)	14.22	14.58	14.2
Wing aspect ratio	(–)	6.12	6.287	6.12
Take–Off weight	(kg)	6130	6140	5897
Empty weight	(kg)	3935	3945	4341
Hovering ceiling (IGE)	(m)	3395	3440	3200
Hovering ceiling (OGE)	(m)	3125	3170	2635
Max. vertical rate of climb	(m/s)	10.66	10.8	–
Max. cruising speed	(m/s)	139.0	141.0	170.0
Service ceiling	(m)	6100	6140	8840
Service ceiling, one engine out	(m)	2840	2860	4570
Max. rate of climb	(m/s)	23.6	23.8	16.0
Max. maneuver load factor	(–)	2.13	2.15	–

Tab. 5: Comparison of the optimized tiltrotor with the XV–15

the other geometric parameters, such as the cruise tip speed, the wing aspect ratio, the wing chord etc. was carried out in the same way.

A comparison of the baseline data with the optimized results and the data of the XV–15 is shown in Tab. 5. The take–off weight and the empty weight didn't show any great changes at all. Slight improvements occur in all of the performance parameters. The hovering ceiling (IGE) is increased 1.3 %, the max. vertical rate of climb is increased 1.3 % and the optimized max. cruising speed is 1.4 % higher than the value in the baseline design. Compared with the data of the XV–15 the optimized design showed good agreement by the take–off weight and the empty weight. The increased hover performances were caused by the higher radius in the optimized design. In contrast to this the airplane mode performances showed greater differences. This difference varies between 21.4 % by the max. cruising speed and 60.9 % by the service ceiling. One reason is the higher take–off weight, radius and wing area that lead to a increased airplane drag and reduced airplane performances. But the more significant reason is the used drag and performance equations, which allow only a rough estimation of the airplane mode perfomances. More data about the rotor profile geometry would also be advantageous.

Conclusions

The development of a conceptual design method for rotary–wing aircraft was presented. This method allows the designer to find the optimized design point based on a given mission for a new helicopter or tiltrotor. The main problem in this early design stage is to simulate the performance behaviour of the aircraft with a sufficient accuracy, but without consuming a lot of computing time. For this reason the corresponding computer program consists also of two levels, that have different accuracy and require different computing time. The subroutines of the computer program integrate all the important aspects of the conceptual design and can be used for three weight classes, i.e. light, medium and heavy helicopters. This method allows the quickly determination of design trade-off relationsships between the various significant design parameters, such as the design graph and the Carpet-Plots. Comparisons of designs developed with the present computer code, with existing helicopters and tiltrotors showed for this early design stage good results so far. More investigations are planned to study the capabilities of the program and to validate it.

References

1. H. Miura, Applications of Numerical Optimizations Methods to Helicopter Design Problems - A Survey -, **10th European Rotorcraft Forum**, Den Haag, 1984, Paper No. 25
2. K. Szumanski, Optimization of the Rotor-Wing-System from Helicopter Performance Point of View, **10th Congress of the International Council of the Aeronautical Sciences**, Ottawa, Canada, Oct. 1976, Paper No. 76-37
3. O.R. Ramos and P. Taylor, Helicopter Design Synthesis, **7th European Rotorcraft Forum**, Garmisch-Partenkirchen, 1981, Paper No. 72
4. W.Z. Stepniewski and L.H. Sloan, Some Thoughts on Design Optimization of Transport Helicopters, **Vertica Vol. 6(1982)**, No. 1, pp. 1-17
5. L.G. Knapp, The Helicopter Preliminary Design Process, **AHS/HAI Commercial Users Design Conference**, Houston, Texas, Nov. 1982
6. H.J. Rosenstein and K.A. Stanzione, Computer Aided Helicopter Design, **37th Annual Forum of the American Helicopter Society**, New Orleans, Louisiana, May 1981, pp. 112-127
7. S.G. Kee, Helicopter Design Manual, Master's Thesis, **Naval Postgraduate School**, Monterey, CA, 1984
8. H.P. Schwartz, Integration des Hubschraubermassen - Synthese - Programms VAMPIR in das Hubschrauberleistungs- und Missionsprogramm TWLEIRES, Diplomarbeit Nr. 88/4, **Institut für Luftfahrttechnik und Leichtbau**, Universität der Bundeswehr München, 1988
9. J. Schneider and J. Wilkerson, Advanced Rotorcraft V/STOL - Rotary Wing with Airplane Qualities, **46th Annual Forum of the American Helicopter Society**, Washington, D.C., May 1990, pp. 535-547
10. T.P. Walsh, A Trade-off Study of Tilt Rotor Aircraft versus Helicopters using VASCOMP and HESCOMP, Master's Thesis, **Naval Postgraduate School**, Monterey, CA, Mar. 1986
11. D.J. Paisley, Rotor Aerodynamic Optimization for High Speed Tiltrotors, **43rd Annual Forum of the American Helicopter Society**, St. Louis, MO, May 1987, pp. 301-310

12. E.A. Fradenburgh, Improving Tilt Rotor Aircraft performance with variable - Diameter Rotors, **14th European Rotorcraft Forum**, Milano, 1988, Paper No. 30

13. M.K. Farrell, Aerodynamic Design of the V–22 Osprey Proprotor, **45th Annual Forum of the American Helicopter Society**, Boston, MA, May 1989, pp. 1–13

14. D. Palasis, Entwicklung eines Vorentwurfverfahrens für Hubschrauber mit einer Erweiterung für das Kipprotorflugzeug, Dissertation, **Universität der Bundeswehr München**, in preparation

15. M. Kloster, Hubschrauber Flugleistungen, **CCG–Kurs F2.03**, Carl–Granz–Gesselschaft e.V., *1986*

16. M.N. Beltramo and M.A. Morris, Parametric Study of Helicopter Aircraft Systems Costs and Weights, **NASA–CR–152315**, Jan. 1980

17. J. Roskam, Airplane Design, Part I: Preliminary Sizing of Airplanes, Part V: Component Weight Estimation, **Roskam Aviation and Engineering Corporation**, Ottawa, Kansas, 1985