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INFLUENCE OF NON-PLANAR BLADE TIPS ON ROTOR PERFORMANCE

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Abstract

At the Department of Aerospace Engineering of the RWTH Aachen, University of Technology, a research programme concerning structural loads and noise emission of helicopter rotors has been conducted. One of its main goals is the reduction of the intensity of Blade-Vortex-Interactions (BVI), the major source of impulsive noise, by using special non-planar blade tips, so-called winglets.

To investigate the influence of such winglets on rotor performance, measurements of rotor force and power are presented in this paper. A fully articulated helicopter rotor model was studied in low-speed wind tunnel tests. Two-bladed and four-bladed rotors have been investigated at different values of forward velocity and rotor speed while blade loading has been varied from non-lifting to stalled conditions.

The results show that winglets can reduce induced drag significantly. The best results have been found for twisted winglets. Compared to a reference configuration, a reduction of the required power up to more than 10% was obtained for a highly loaded hovering rotor. The improvement results mainly from the non-planarity, as the comparison with a planar blade of the same planform shows. Forward flight tests indicate that the winglets of the current shape are favourable up to medium forward flight speeds (advance ratio of 0.2), while disadvantages are to be expected at faster forward flight. Moreover, winglets were found to be more effective at four-bladed than at two-bladed rotors.

Nomenclature

A	rotor disc area	r_C	vortex core radius
BVI	blade-vortex interaction	T	rotor thrust
c_P	rotor power coefficient	U_∞	wind tunnel velocity
c_Q	rotor torque coefficient	z	axial position
c_T	rotor thrust coefficient	$z_{1,2}$	blade vortex miss distance
FM	Figure of Merit	β	angle of tip path plane (tilt angle)
HHC	higher harmonic control	Γ	vorticity
n	rotor rotational speed	μ	advance ratio
P	rotor power	ρ	air densitiy
Q	torque moment	σ	rotor solidity
R	rotor radius	ψ	azimuth
r	radial position	ω	rotor frequency

1. Introduction

The acceptance of future helicopters will considerably depend on their noise emission. Therefore helicopter noise had been recognized as a problem many years ago [1]. Blade-Vortex-Interactions (BVI) are known as a major source of impulsive noise (Fig.1). Because BVI-noise occurs near ground under approach and landing flight conditions, its reduction is of special interest.

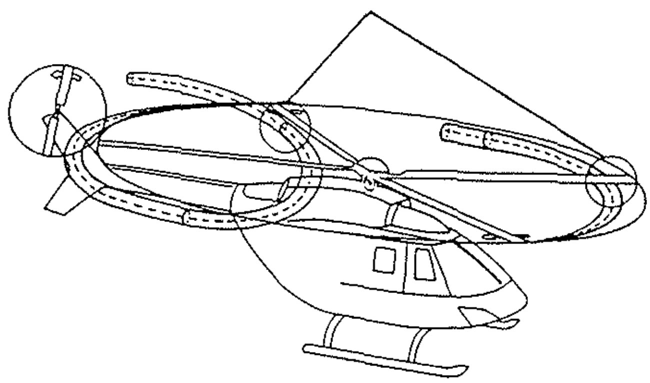

Fig.1 Blade-vortex-interactions

As BVI-noise is governed by the induced velocities of tip vortices, it depends on blade-vortex miss distance, vortex strength and vortex structure. A reduction of noise levels requires a decrease in velocities induced on the rotor. Possible approaches are to reduce the vortex strength, to modify the vortex structure (e.g. by increasing the vortex core size) or to enlarge the blade-vortex miss distance.

For a given number of blades it is difficult to reduce the vortex strength without performance penalties, since the vortex strength is directly related to the blade lift. Higher harmonic control (HHC) of blade pitch may be used to reduce just the strength of interactive vortex segments, but recent investigations [2] show that noise reduction by HHC is combined with increasing vibration levels. Several attempts were directed to an increase of the core size by varying the blade tip geometry (e.g. the Ogee tip). A study of Widnall and Wolf [3] has shown a significant influence of vortex structure on BVI-noise in the case of close interactions.

The increase of blade-vortex miss distance was found to be the most efficient approach to reduce BVI-noise [4]. A way to increase the miss distance is the use of non-planar blade tips. Different shapes of non-planar blades have been developed since the early eighties in France [5] and Germany [6]. In Aachen the influence of blade tips pointing downward (Fig.2) has been investigated in detail.

The non-planar blade tips were mainly designed to reduce noise emission; a decrease of the sound power level in the range of 6 dB has been realized. However, it is also of interest to know their influence on the required power. In this paper, the effects of different blade tips on rotor performance were analysed in wind tunnel tests under hover and forward flight conditions.

2. Experimental set up

2.1 Blade geometries

Fig.2 presents the blade tips tested in the research programme. Blade No.1, the reference configuration, has a planar rectangular planform using an untwisted NACA 0015 airfoil. Blade No.2 is the basic winglet. It is untwisted and has a swept-back tip for better high speed characteristics. The nose is extended in forward direction to improve lift at the retreating side and to avoid additional pitching moments caused by the sweep. The non-planarity, defined as the distance between the blade tip and the rotor plane, has a value of about 0.65 chord lengths. Blade No.3 is a modified winglet having a twisted tip region. Twisting starts at a radius of 91% and reaches 7° at the tip. This gives extra bound vorticity at the tip region and pushes the vortex further downward. To investigate just the influence of non-planarity, a planar blade with the same planform was built as blade No.4. For comparison purposes, non-planar blade shapes designed at ONERA [5], having an 'anhedral' tip shape, were also included in the test programme as blade No.5. This blade has a non-planarity of 0.18 chord lengths and a significant sweep.

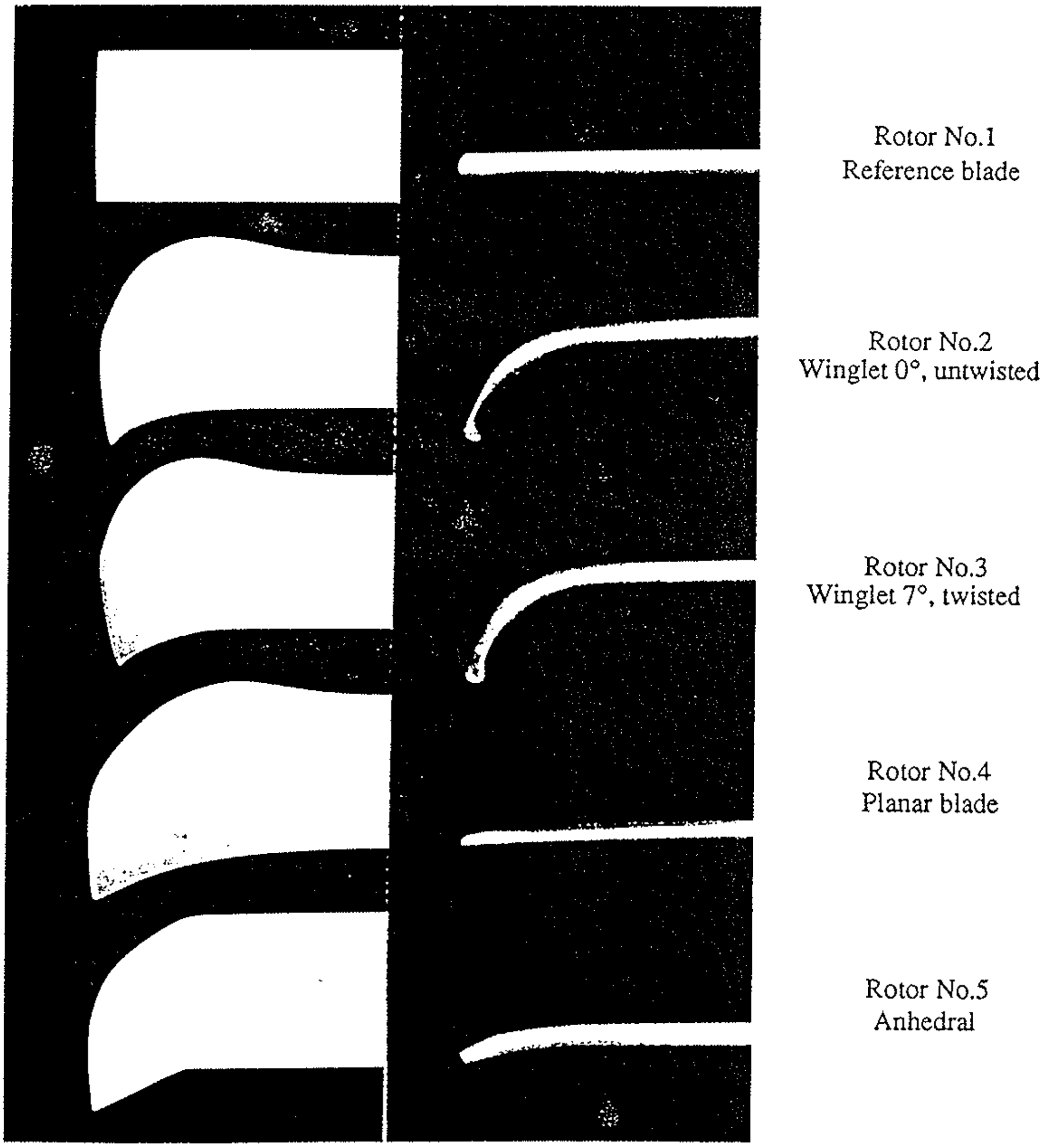

Fig.2 Blade tip shapes

All blades are made in glass-fibre-composites and have NACA 0015 airfoil sections of 0.054 meters main chord length which gives the four-bladed rotor a solidity of about 0.105. To be comparable, also for the 'anhedral' tip a NACA 0015 profile has been used.

The effects of the chosen winglet configurations on BVI intensity are illustrated in Fig. 3. It shows that the tip vortex of a winglet blade is generated significantly underneath the rotor plane. Using the winglets 7° an increase in miss distance of about one blade chord is obtained as measurements show (Fig. 4). The vortex positions were achieved by digital processing of flow images [7]. Fig.4 indicates that a direct vortex encounter can be avoided in most cases by the use of winglets.

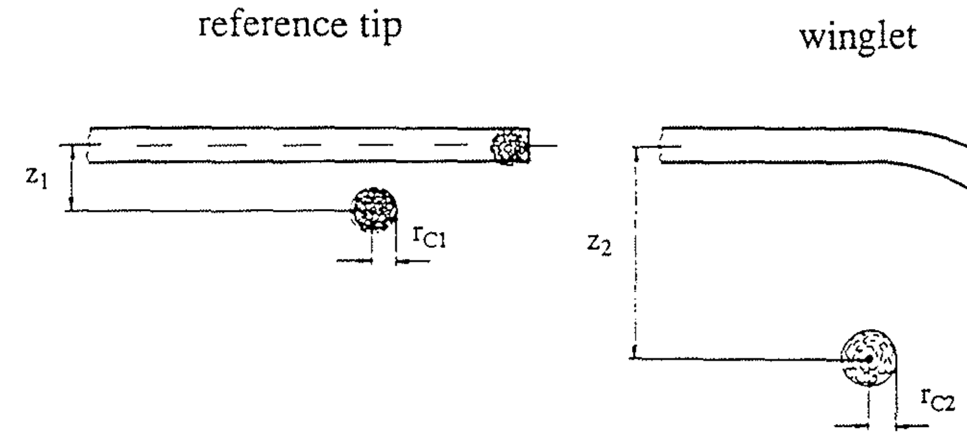

Fig.3 Mechanisms of BVI-intensity reductions

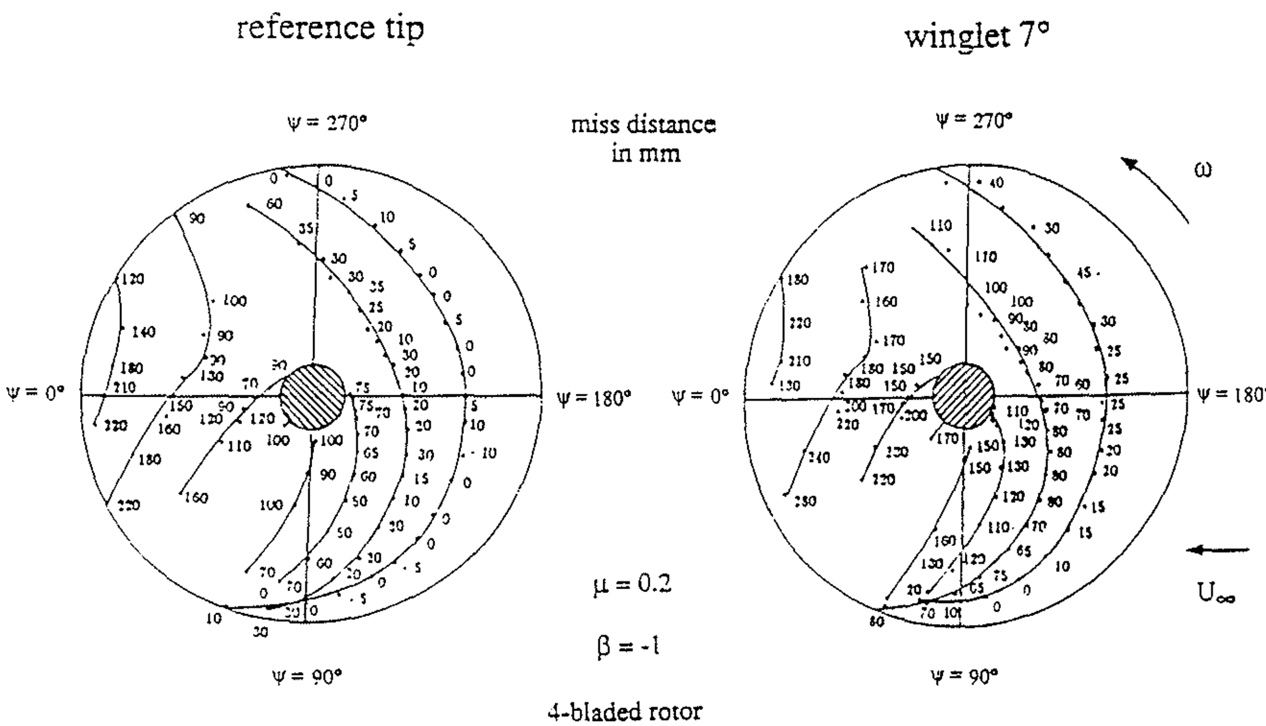

Fig.4 BVI-miss distance measurements

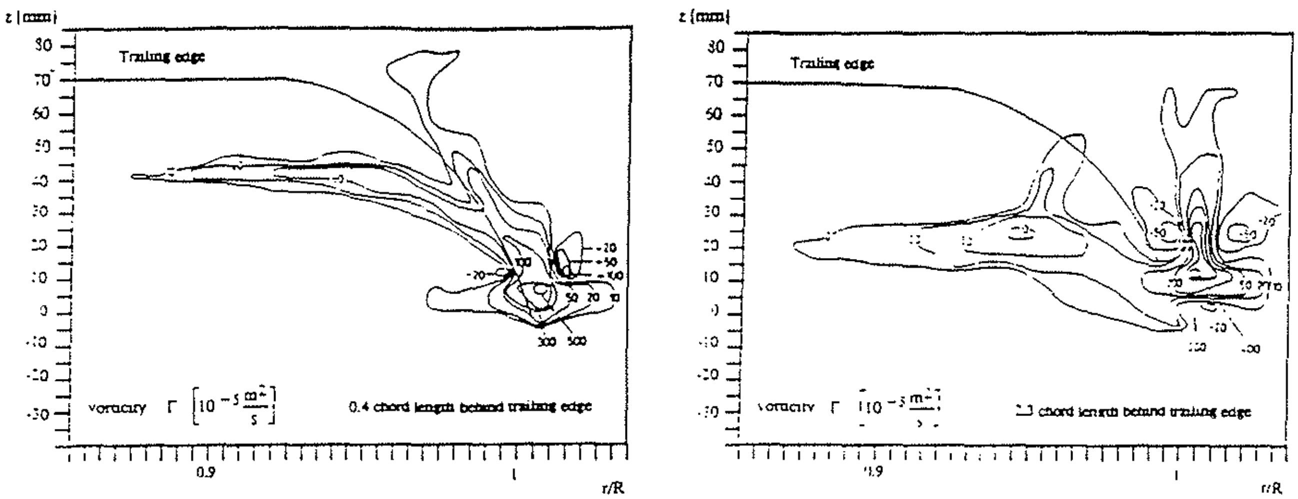

Fig.5 Winglet tip vortex structure

Moreover, downward pointing winglets have a different roll-up mechanism which leads to a modified vortex structure. Since the core radius is increased, the modified vortex structure induces weaker interactions for the same vortex strength. As Müller [8] found by LDV experiments in a water tunnel, a double vortex (Fig.5) is generated at a downward pointing winglet which merges to a large vortex further downstream leading to smaller induced velocities of those vortices.

In this way, winglets use the two most efficient mechanisms - increase of miss distance and increase of vortex core - to reduce BVI intensity significantly. This results in a lower vibration level, less dynamic blade loads and a reduction of rotor noise levels up to 6 dBA under landing flight conditions.

2.2 Test facility

In this paper, measurements of rotor forces and rotor power are presented and discussed. These tests were performed in the open test section of a low-speed wind tunnel (Fig.6). A fully articulated helicopter rotor model - without a tail rotor - was mounted on a 6-component-balance to measure lift, drag, sideforce, pitching moment, rolling moment and torque. The yawing moment is assumed to be negligible in non-slip conditions. Rotor power was determined by measuring rotor torque and rotor speed:

$$P = Q * \omega$$

Since the results were found to be very sensitive to exact trim in forward flight, sensors were implemented in the helicopter to measure cyclic and collective pitch.

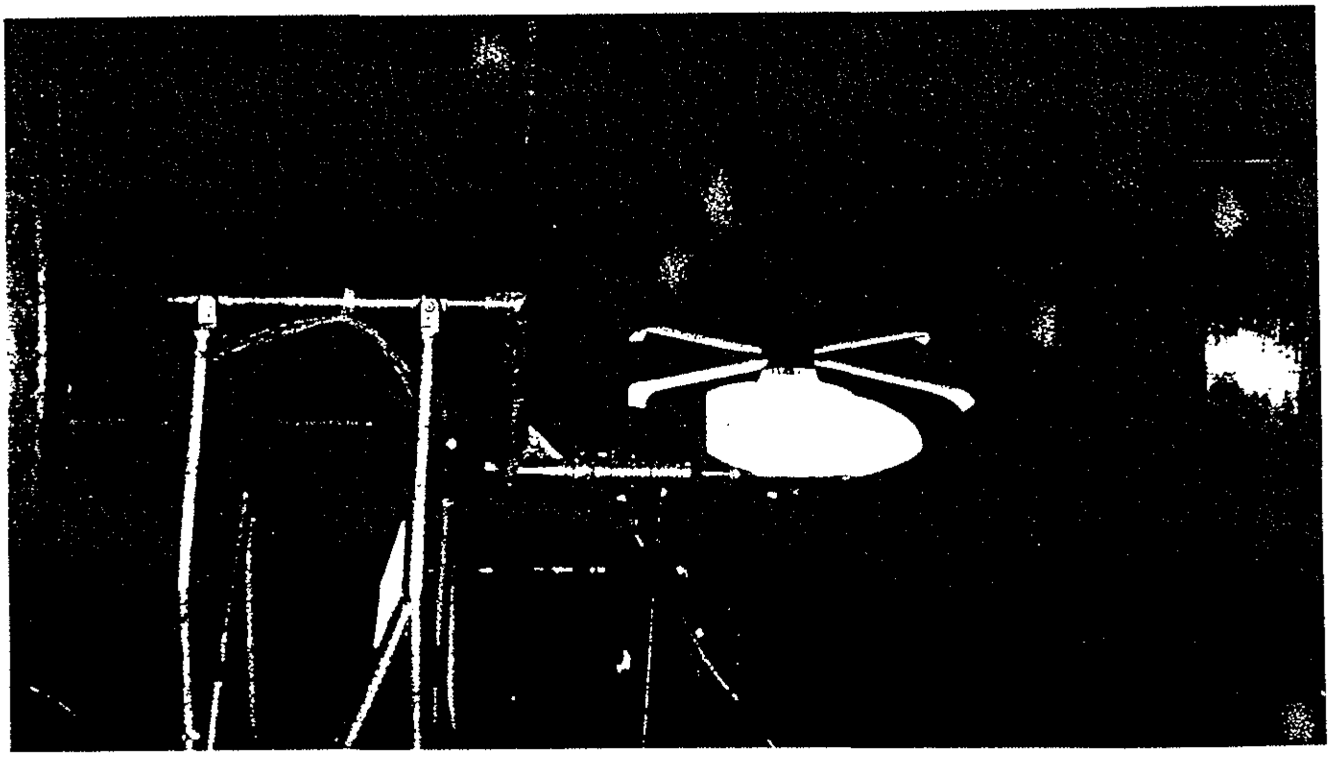

Fig.6 Helicopter model in wind tunnel

Two-bladed and four-bladed rotors of 0.5 meters radius have been tested in hover and forward flight conditions. The advance ratio has been varied from 0.1 to 0.3, rotor speed from 600 to 1500 min^{-1} and blade loading from non-lifting to stalled conditions. As soon as rotor speed was higher than 800 min^{-1}, only a very slight performance improvement was observed with increase of rotor speed. So most tests were run with a constant rotor speed of 1200 min^{-1}.

3. Results

Most results shown in this paper are given in 'thrust versus power' diagrams for different blade tips. The results are presented as dimensionless coefficients:

$$c_P = \frac{Q\ \omega}{\rho\ A\ (\omega\ R)^3} = \frac{Q}{\rho\ A\ (\omega\ R)^2\ R} = c_Q$$

$$c_T = \frac{T}{\rho\ A\ (\omega\ R)^2}$$

The power coefficient is equal to the torque coefficient since $P = Q * \omega$.

3.1 Hover

The results of all five blade types (s. Fig.2) are plotted in Fig.7 for the hovering case. All curves rise from zero thrust condition, where the profil drag predominates, to nearly stalled condition.In case of zero thrust, the winglets have a somewhat higher profile drag which is simply explained by the larger blade surface. This explaines the higher zero thrust power. The reference-, planar- and anhedral blades do not vary too much in blade surface and have about the same profile power.

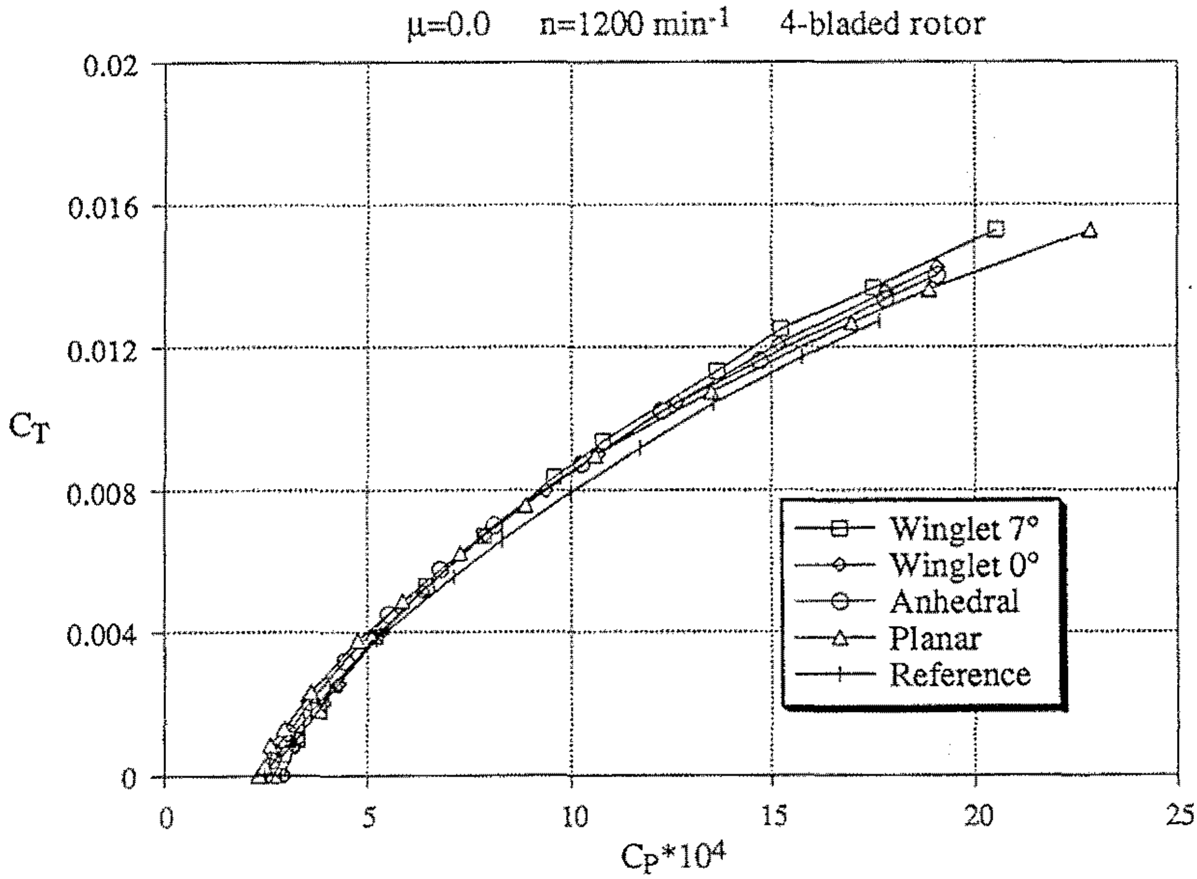

Fig.7 Hover performance measurement

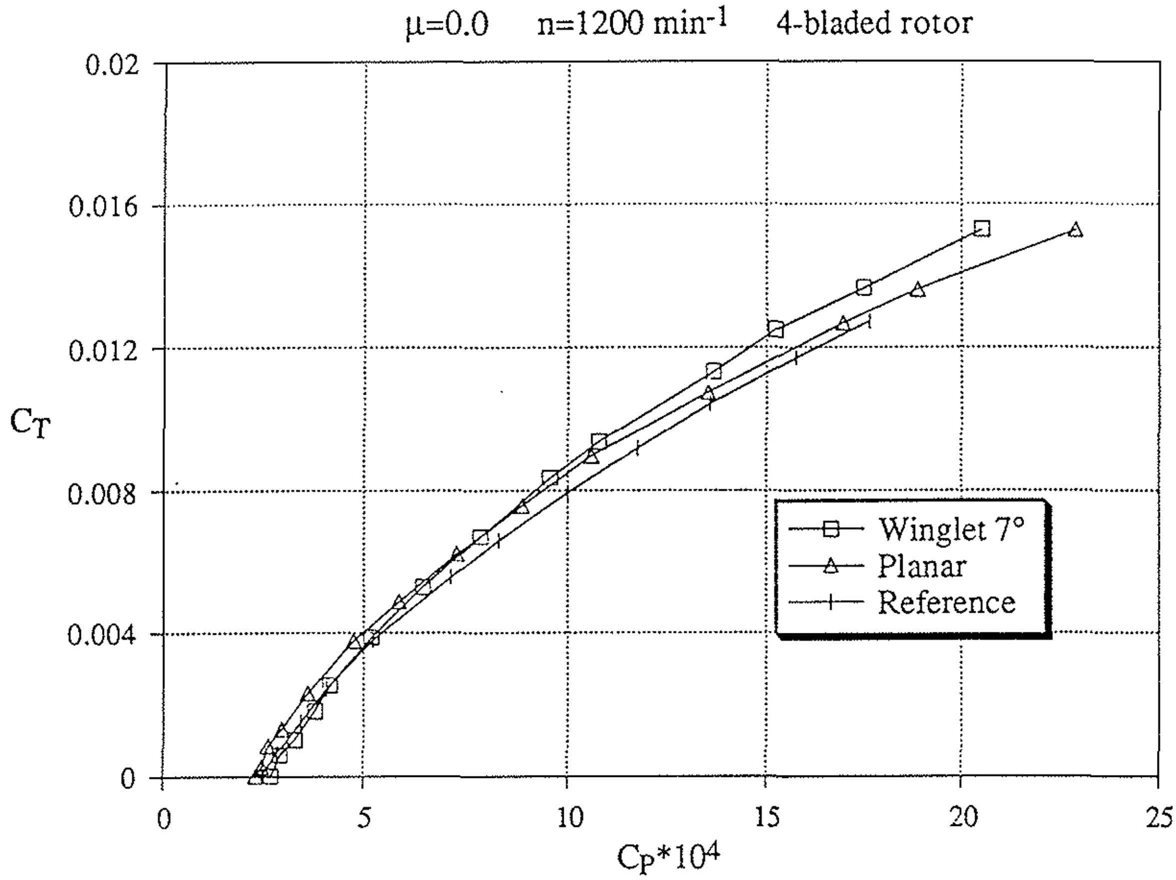

Fig.8 Hover performance measurement (selected blades)

Fig.8 selects just three blades; reference blade (No.1), planar blade (No.4) and the twisted winglet (No. 3). With increasing thrust, the power penalty of the winglet configuration shrink and above $c_T \approx 0.007$ the twisted winglet is found to be the best configuration. This behaviour can be explained by a significantly lower induced drag, which also was measured in fixed wing tests with winglets. Due to the concentration of the circulation at the blade tips, winglets are much more efficient at rotors than at fixed wings.

Best results were found at high blade loads. At the same thrust, the winglet No.3 needs up to 11.9% less power than the reference blade. As Fig.8 shows in addition, the advantage of winglets are to be explained both, by non-planarity and by advanced planform. The influence of planform variation (e.g. sweep) is uncovered by comparison of planar- and the reference blade. A maximum reduction of required power of 7% occurs at medium blade loading ($c_T \approx 0.009$), while these improvements decrease to about 4% with higher loads. Since improvements with winglets increase with increases of thrust all the time, the advantage of non-planarity predominates for a highly loaded rotor while shaping the tip is more important at lower loads.

The Figure of Merit compares the rotor performance of an ideal rotor with an actual one and is often used as a measure of rotor hovering efficiency [9]. The Figure of Merit is given by:

$$FM = \frac{c_T^{3/2}/\sqrt{2}}{c_Q}$$

Fig.9 compares the Figure of Merit for the different blades. All 'advanced' blades improve the rotor efficiency, while the twisted winglet provides the best Figure of Merit, 12.9% higher than the value of the reference blade. It is followed by the untwisted winglet (8.4%), the anhedral (6.1%) and the planar blade (3.6%).

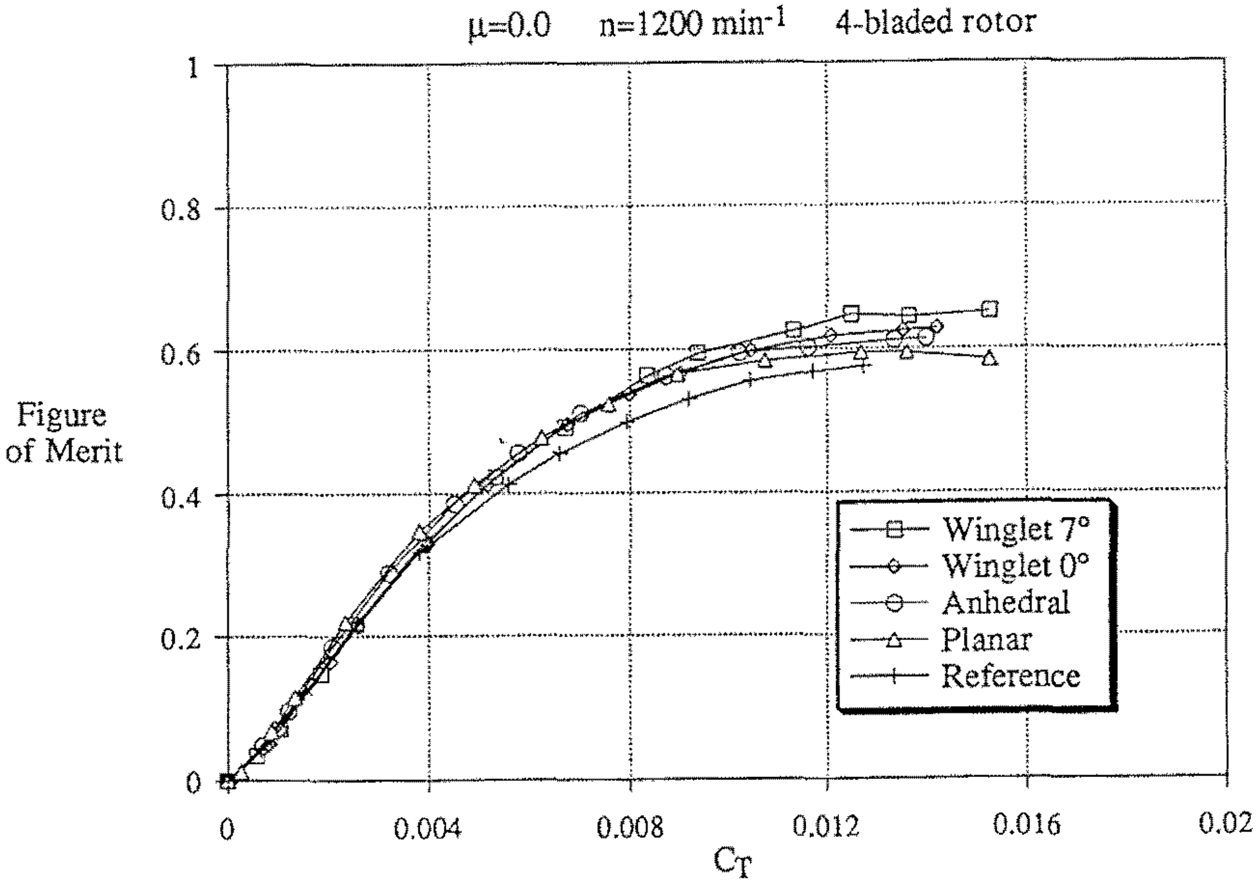

Fig.9 Figures of Merit

3.2 Forward flight

The measurements were performed under conditions where the parasite drag was balanced by the forward component of thrust. In this way, c_T-values were coupled to tilt angles, so that different c_T were obtained by varying the tilt angle between -12° and almost 0°.

A transfer of the results to another size of helicopter would not keep the absolut power values, but it is to be expected that the results would be correct regarding the basic influence of the various tip shapes.

Low speed (μ=0.1)

For a low speed flight advance ratio of μ=0.1 the corresponding results are seen in Fig.10. Again the twisted winglet requires less power than the reference blade, especially at higher loads. With a power reduction of up to 9.5% the amount of improvement is slightly lower than in hover. The decrease of advantages seen at highest loads may be explained by the beginning stall.

Medium speed (μ=0.2)

An advance ratio of μ=0.2 was choosen as a medium speed case. Its results are combined in Fig.11 for all blades tested. The advantage of the modified tips shrink almost to zero, while the twisted winglet requires significantly more power than all other blades. The anhedrals show a slightly better efficiency than the untwisted winglets.

μ=0.1 n=1200 min-1 4-bladed rotor

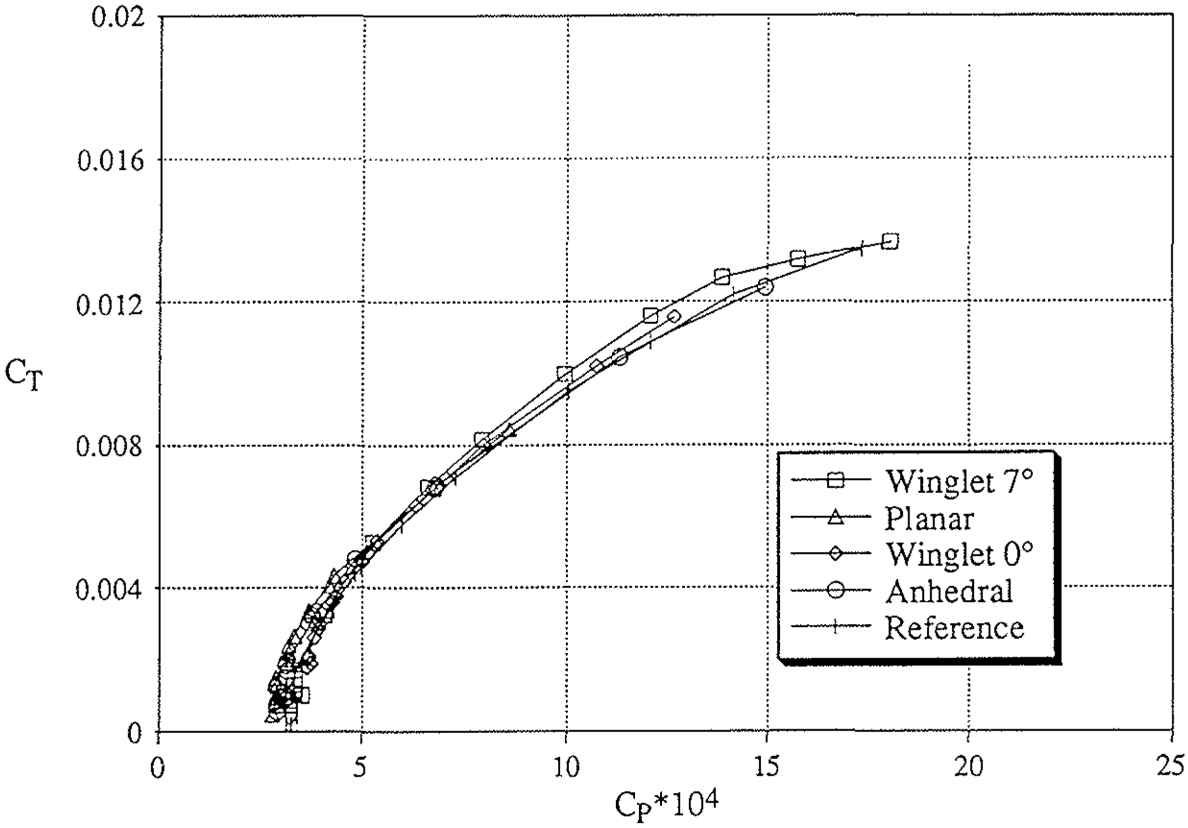

Fig.10 Low speed performance measurement

μ=0.2 n=1200 min-1 4-bladed rotor

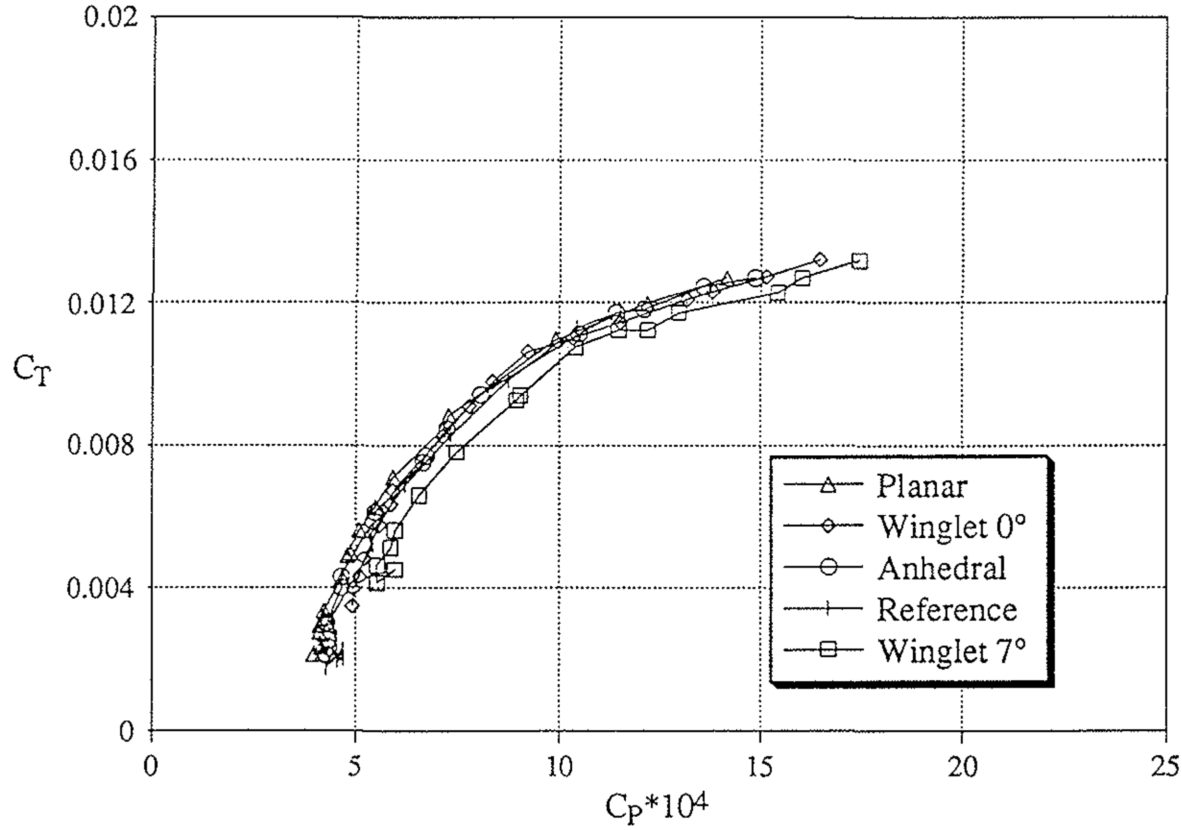

Fig.11 Medium speed performance measurement

High speed (μ=0.3)

The results were found to be very sensitive to correct trim, while exact trim became rather difficult with increasing flight speed. The importance of trim was reported by Desopper [10] as well. Thus, the reproducibility of the results given in Fig.12 is not too good in fast forward flight due to larger time-dependent fluctuation of moments.

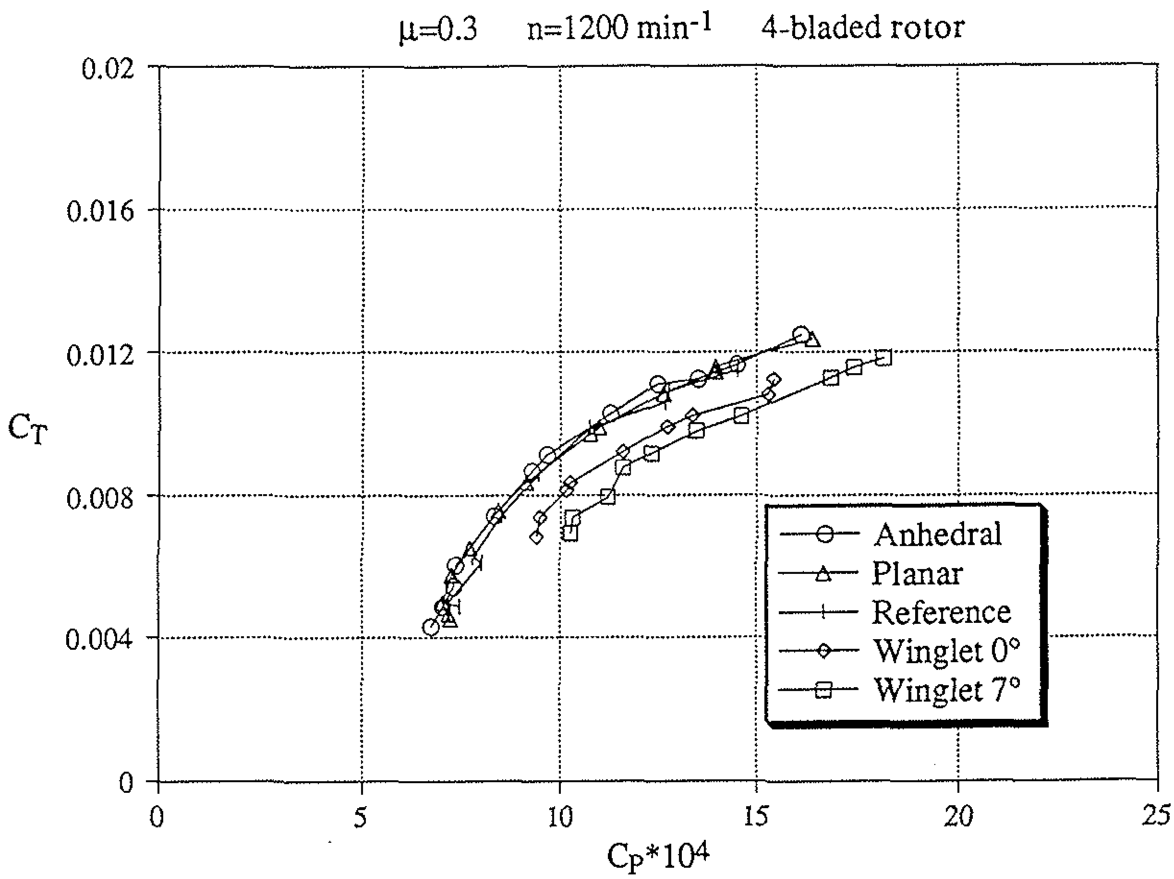

Fig.12 High speed performance measurement

The power requirement for both winglet configurations is higher than for the other three blades. The untwisted winglet requires about 15%, the twisted winglet about 20% more power to produce the same thrust.

3.3 Variation of blade number

Tests were performed with two-bladed rotors and with four-bladed rotors, but since two blades are no longer state of the art and winglets are supposed to be more efficient in noise reduction at four-bladed rotors (due to stronger BVI), just a few results of two-bladed rotors are presented in Fig.13 for the hovering case.

At two-bladed rotors the untwisted winglet is better than the twisted tip. Compared to the reference tip the highest power reduction amounts to 8%, almost equal gains can be achieved by the untwisted winglet and the anhedral tip. Performance improvements are found to be less efficient with a two-bladed rotor than with four blades.

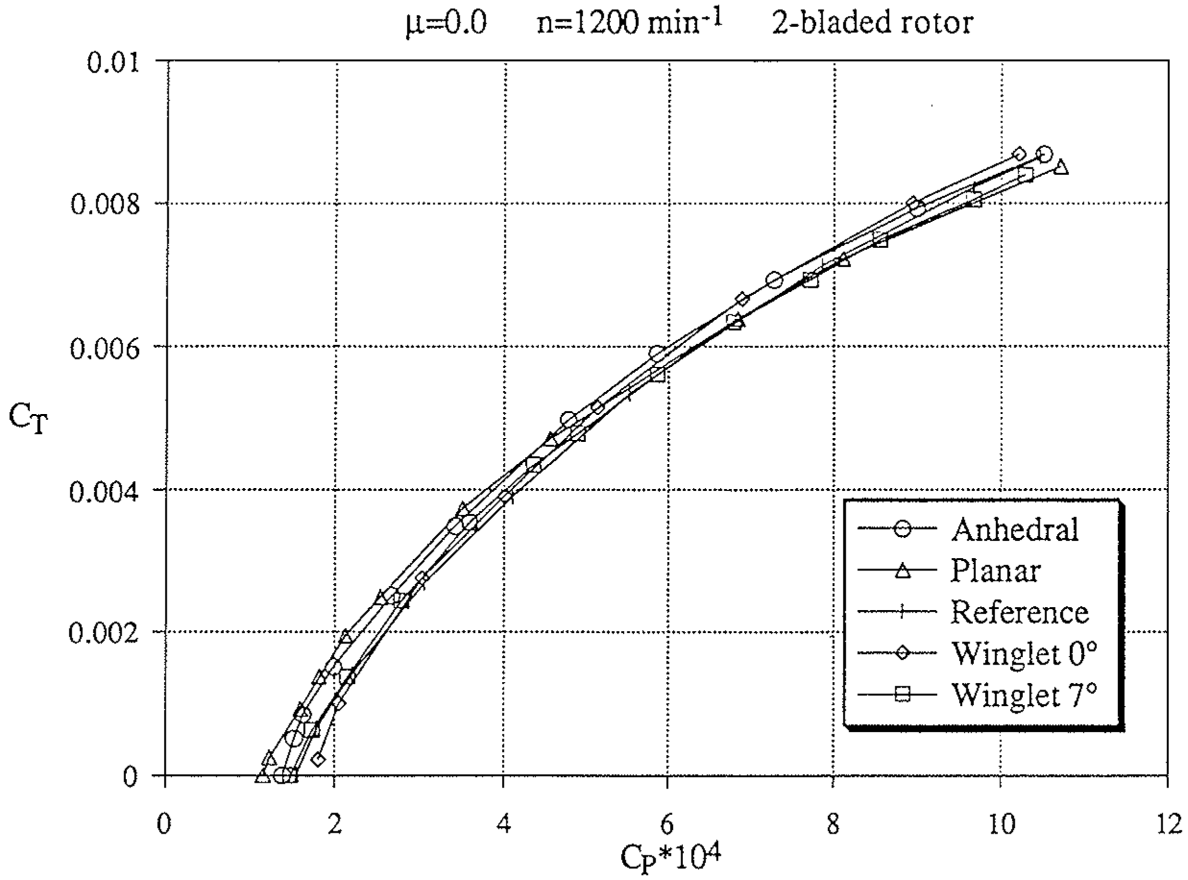

Fig.13 Hover performance measurement (two-bladed rotor)

4. Design aspects

Resuming the results under the aspect of helicopter design, one can say that winglets are favourable as long as hover performance has to be used as design criteria. This will happen with heavy rotorcraft, which reach their maximum range at medium speeds, and fast forward flight is much less important than hover performance.

For light helicopters, which are to be designed regarding the fast forward flight performance, a new design should weigh noise reduction and power penalties. An optimum may be obtained for a non-planarity between those of winglets and anhedrals. Anhedrals are not seen as the optimum blades, because they just reduce the noise by 1 dB [5].

Any progress in reduction of parasite drag will lead to the fact that even lighter helicopters will be designed with respect to the hover performance and might get winglets.

5. Conclusions

Wind tunnel tests have been performed to measure the influence of various planar and non-planar blade tips on rotor performance.

Although non-planar blade tips (winglets) were designed to reduce rotor noise (6 dB reduction of sound pressure level has been measured), they also were found to improve rotor performance in hover and low speed forward flight significantly. Winglets use the two most efficient mechanisms to reduce BVI intensity: an increase of vortex core radius and an enlargment of the blade-vortex miss distance. Using winglets, the Figure of Merit - a measure of rotor hovering efficiency - can be increased up to 13%. Improvements are explained mainly by non-planarity and to a less extend by a suitable shaping of the wing planform in the tip region.

While winglets show improvements up to 9.5% in low speed forward flight (μ=0.1), its performance decrease at higher advance ratios so that they show performance drawbacks at medium and higher speeds (μ>0.2). While performance penalties have to be expected in fast forward flight (μ=0.3) for both winglet configuration, the anhedral tip with less non-planarity based on an ONERA-design does not show a similar deterioration in fast forward flight.

Resuming the results under the aspect of helicopter design, winglets are favourable at heavy helicopters, which have to be designed with respect to hover performance. For light helicopters, a new design of non-planar blades has to weigh noise reduction and power penalties in fast forward flight. An optimum may be obtained for a non-planarity between those of winglets and anhedrals.

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References

1. M.V. Lowson, Progress towards quieter civil helicopters, Forum Proceedings of the 17th European Rotorcraft Forum, Paper No. 91-59, Berlin, Germany, Sept. 1991

2. W.R. Splettstößer, K.-J. Schultz, R. Kube, T.F. Brooks, E.R. Booth, G. Niesl and O. Streby, BVI impulsive noise reduction by higher harmonic pitch control, Forum Proceedings of the 17th European Rotorcraft Forum, Paper No. 91-65, Berlin, Germany, Sept. 1991

3. S.E. Widnall and T.L. Wolf, Effect of tip vortex structure on helicopter noise due to blade-vortex interaction, Journal of Aircraft, Vol.17, No.10, Oct. 1980, pp. 705-711

4. J.M. Galmann, A parametric computational study of isolated blade vortex interaction noise, Conference Proceedings of the 14th Aeroacoustics Conference, Paper No.119, Aachen, Germany, May 1992

5. A. Desopper, P. Lafon, J.J. Philippe and J.Prieur, Effect of an anhedral sweptback tip on the performance of a helicopter rotor, Vertica, Vol 12, No.4, pp. 345-355, 1988

6. R.H.G. Müller and R. Staufenbiel, The influence of winglets on rotor aerodynamics, Vertica, Vol.11, No.4, pp. 601-618, 1987

7. R.H.G. Müller, Winglets on rotor blades in forward flight - a theoretical and experimental investigation, Vertica, Vol.14, No.1, 1990

8. R.H.G. Müller, Special vortices at a helicoptor rotor blade, Journal of the American Helicopter Society, Vol.35, No.4, Oct. 1990

9. W. Johnson, Helicopter theory, Princeton Univ. Press, 1980

10. A. Desopper, P. Lafon and P. Ceroni, Influence of the control law on the performance of a helicopter model rotor, Vertica, Vol.14, No.3, pp. 429-437, 1990