TWENTY FIRST EUROPEAN ROTORCRAFT FORUM

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THEORY AND EXPERIMENT SHOW A 44% INCREASE IN THE ROTOR LIFT/POWER RATIO

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Abstract :

Earlier work on rotor speed and lift limitations have shown that considerable gains can be achieved by stabilizing the divergent pitch-up of the articulated rotor. One of the stabilizing means, easily reproduced in the wind tunnel are elastic restraints of the blade flapping motion. The rotor thus becomes semi-rigid.

The paper relates recent wind tunnel experiments performed on a 1.5 m diameter semi-rigid rotor having as objective the verification of theoretical work showing wide enlargement of the operational envelope of the conventional helicopter. The test results correlate closely with the theory, thus bringing an experimental evidence to the analytical studies done. The maximum increase in the rotor lift/power ratio obtained was 44 %, at advance ratio of 0.3.

1. Notation

$Czm = 6C_T/\sigma$	Lift coefficient $Czm = \frac{3}{100}\overline{Z} = \overline{C}_L$
$Cxm = 8Cp/\sigma$	Power coefficient $Cxm = \frac{4}{100}\overline{C} = \overline{C}_D$
$\overline{S}_f = f/A\sigma$	Reduced flat area
ω_o	Frequency of first flapping mode ($\Omega = 0$)
ω	Frequency of first flapping mode ($\Omega \neq 0$)
α_Q	Shaft angle
me (ψ)	Experimental flatwise bending moment, Nm
mt (ψ)	Theoretical flatwise bending moment, Nm
EDY A	Articulated configuration of EDY rotor
EDY R	Semi-rigid configuration EDY rotor

2. Introduction

The research investigation presented in this paper is an outcome of an effort to analyse the main helicopter limitations which appear to be due to stall appearance on the retreating blade at high lift and high speed rotor working conditions (Refs. 1 and 2). A deep dynamic analysis of these conditions has permitted to trace the origin of the limitations of the articulated rotor to an instability that can be described as divergent pitch-up (Ref.2). The characteristics of this instability are practically unknown. The current literature does not mention how the tendency of the rotor to tilt back limits its performance.

The work presented is the outcome of theoretical and experimental research done on contracts of the French Government Research Agency, DRET, Direction des Recherches, Etudes et Techniques, on active control of stall effects.

The results of our studies indicate that there exist at least three ways to overcome this high speed and high lift instability.

1. Firstly, above the stall barrier, the human pilot is able to stabilize the rotorcraft (as he does in hover) and maintain roughly correct flight conditions. This action, however, encounters severe control difficulties.

   Remark : It should be mentioned that the pitch-up divergence is of a mild type (as the instability in hover), but can not be demonstrated by a wind tunnel experiment without special precautions.

2. Secondly, as described in Ref. 2, artificial means can be used to render rotor stable. The active control of the advancing blade, based on flapping angle and lift detection, permits to overcome the tendency of the rotor disc to tilt back. The gain in performance, expressed in terms of lift/power ratio, give 62 % increase at advance ratio of 0.5 (Ref. 3).

3. Thirdly, the stabilizing effect can be produced by elastic means. In this case the rotor becomes rigid in flapping with a high flapping angle frequency. The present paper gives an experimental evidence of this stabilizing effect.

   Remark : It should be emphasized that this principle has been used on the ABC rotor. However, the advantages of this rigid rotor of the ABC type did never appeared clearly in the technical papers. More particularly, the pitch-up divergence was left theoretically unexplained.

   Our early theoretical investigations showed that the rigid rotor had significant performance advantages compared to the articulated rotor. The gains stem from the fact that the elastic moments at the blade roots prevent the rotor to tilt back.

   This results have been confirmed experimentally on a 1.5 diameter rotor, in the S2Ch ONERA wind tunnel, having flapping angle articulations elastically fastened. The stabilizing moments at the blade roots exercise a down-force on the advancing blade, thus reducing the rotor tilt. The recorded bending moments correlate closely with the theory (Ref. 4).

3. Wind Tunnel Configuration and Rotor Characteristics.

The ONERA S2Ch Wind Tunnel used for the tests has a 3 m diameter test section. The highest wind velocity can reach 120 m/s.

The total pressure is atmospheric. The tunnel is equipped with special Rotor Test Bed seen on Fig.1. The rotor drive is hydraulic permitting stabilized rotor angular velocities of 200 to 3000 r.p.m.

The shaft axis can be inclined to ± 24°.

The rotor, called EDY, has the particular feature to work either articulated or semi-rigid. Mechanical means permit to fasten the articulations and to pass from one configuration to the other.

The main characteristics of the EDY rotor are the following :

- Rotor diameter	$2R = 1.474$ m
- Cord of the blade	$c = 0.050$ m
- Number of blade	$b = 3$

The rotor was tested up to speeds of 1300 r.p.m. The highest advance ratio reached was μ = 0.6.

- Blade section :	NACA 0016
- Weight of the blade	0,245 Kg
- C.G. location	28 % of the cord
- Blade planform	rectangular
- No twist	

The EDY rotor was tested in two configurations : articulated and semi-rigid. From dynamic point of view the semi-rigid configuration is characterized by the reduced frequency of the first flapping mode. This frequency depends on the rotor rpm according to the following law :

$$(\omega / \Omega)^2 = (\omega_0 / \Omega)^2 + 1.19$$

During the tests, the first flapping mode of the blade had the frequency of 1.27 Ω at 1200 rpm.

Special load cell balance system composed of 3 vertical and 3 horizontal thermostatically stabilized load cells measured the 6 load components at the rotor head.

Stain gauges sensed the blade flapping stresses, control loads and the rotor torque moment.

The analog signals of the above sensors were subsequently converted to digital signals and computer treated in real time, so that the results could be available as the tests run and compared with theoretical predictions.

4. Test Procedure and Presentation of Results

The main objective of the tests was the experimental evidence of the high performance gains theoretically predicted for the semi-rigid rotor. The second objective was to acquire the understanding of rotor working conditions mainly by sensing the stabilizing flapping moments on the blade roots. These objectives had necessitated two series of tests, performed practically in identical conditions on both configurations of the EDY rotor.

The two series of tests were preceded by drag measurements of the rotor hub done in the entire test envelope (Ref. 4).

Curiously, the rigid rotor introduces a redundance of control inputs. There are four control inputs instead of the usual three. The additional input comes from the attitude angle of the hub. In the tunnel we had to optimize the hub angle to get the maximum performance.

As can be seen in Fig.2, the rotor power is highly sensitive to the shaft angle α_Q at high $\overline{C_L}$ values. Generally, four tests points were necessary to define the optimum conditions.

A particular attention was given to insure the required precision of rotor load and torque measurements. The comparatively high rotor regime, 1200 rpm, was chosen to reduce the scatter of test results and maintain the rotor inside the safe rotor working envelope.

The scatter of test results was of the order of ± 5 to ±10 %. To reduce discrepancies the tests were repeated several times.

More particularly, the semi-rigid rotor had to support high rolling moments, primarily in 1P, introducing a typical sine component of stress (Fig.3). Most of the results were obtained at advance ratio 0.3 and shown on Fig.4.

Thoughout the entire test envelope, the rotor was running at a unique reduced flat area drag parameter, $\overline{S_f} = 0.1$.

The rotor performed as predicted and no abnormal behaviour was observed during the tests.

5. Analytical Simulation of Test Conditions

The analytical method used was based on the computer program established for full scale rotor working conditions, the K27 code. The blade, in present simulation, was assumed infinitely rigid in articulated rotor configuration and flexible in semi-rigid rotor configuration. Unsteady stall effects were taken into account by using the ONERA unsteady stall model for lift, drag and twisting moment (Ref.5). The blade was assumed infinitely rigid in twist and chordwise. The 2-D airfoil data were corrected according to corresponding Reynolds and Mach numbers. The computations used constant inflow. For very high lift coefficient, $\overline{C_L} \rangle 1.25 C_L$ max and advance ratios higher than 0.6, the K27 code gave divergent results. However, the test envelope was well covered by the computer program used. As shown in Figs. 3 and 4, the correlation with test results was highly satisfactory. The discrepancies are of the order of 10 %.

The presentation of results uses a polar diagram recalling 2-D airfoil polar diagram. We remark, in Fig. 4, the rotor characteristic traced with lift coefficient as abcissa. The optimum rotor working conditions are given by the highest slope the rotor characteristic curve shows. Thus the comparison between two different rotors is simplified and the highest Lift/Power Ratio attained is taken as performance criterium (rotor optimum working condions).

The flatwise bending moment is another important parameter in our search of means to prevent the rotor divergent pitch-up. In fact, it is this flapping moment that stabilizes the semi-rigid rotor. This moment corresponds to the rolling moments shown in Fig.3. Typically, this moment has a sine form, and acts downwards on the advancing blade (and, of course upwards on the retreating blade). This moment imposes a forward tilt to the rotor and in consequence improves considerably the rotor general performance, defined in our study by Lift/Power Ratio.

6. Tests Results.

Earlier in the present paper we mentioned the similarity between the ABC rotor and a semi-rigid rotor of EDY type. Also the tests we performed have, to a certain extent, been done some 25 years earlier and related in Ref.6. The main result reproduced in Fig.5 demonstrate the much greater lift capability of the ABC rotor when compared to a conventional rotor. However, the power gains of the ABC rotor, did not appear clearly in Réf.6. Neither there is an explication of the superiority of the blade rigidity in the ABC. The characteristic rolling moment of sine form is presented in Fig.11 of Ref.6 and well correlated with theoretical results as we have found it too (Fig. 3 of the present paper).

The general remark concluding the Ref. 6 is fully applicable in our case. Let us cite it here :

"This test was the last in the series of small-scale experimental investigations of the ABC rotor. It is believed the primary objectives of the tests were achieved. These were (1) to establish experimentally that the ABC system offered a means for improving helicopter performance and eliminating the classical speed limitations of conventional rotor systems, and (2) to gain confidence in the ability of the theory to predict rotor performance and blade stress characteristics."

The similarity between the two tests stops here. Our objectives go beyond the test. They target the understanding of the helicopter rotor limitations in lift and speed as well as the search of means to improve the rotor performance by use the active control rather than elastic blade stabilization of pitch-up divergence as done in ABC (Ref. 2).

The results obtained are most encouraging and explain the deep nature of the limitations of the articulated rotor. They pave the way to new approach that can bring considerable performance increase to the conventional rotor equipped with active control means.

7. Conclusions

From the experimental and theoretical research reported in this paper we can draw the following conclusions :

1. The test has brought an experimental evidence to previous theoretical investigations of helicopter rotor lift and speed limitations.

2. The time history of flatwise bending stresses in the blades shows that the rotor limitations stem from pitch-up instability.

3. The pitch-up divergence can be stabilized by elastic means, leading to a semi-rigid rotor, solution tested in the wind tunnel.

4. Experiments show a 44 % increase in the Lift/Power Ratio at rotor advance parameter 0.3, well correlated with theory of the semi-rigid rotor.

5. Theoretical simulations show the possibility of further expansion of conventional helicopter flight envelope : Lift/Power Ratio increased over 60 % and the lift capability highly improved. Optimal $\overline{C_L}$ increases more than 60 %.

The field of future investigations seems very wide and, it is believed, that it can bring an important advancement in the general performance of the conventional rotor, more particularly be use of active control.

8. References

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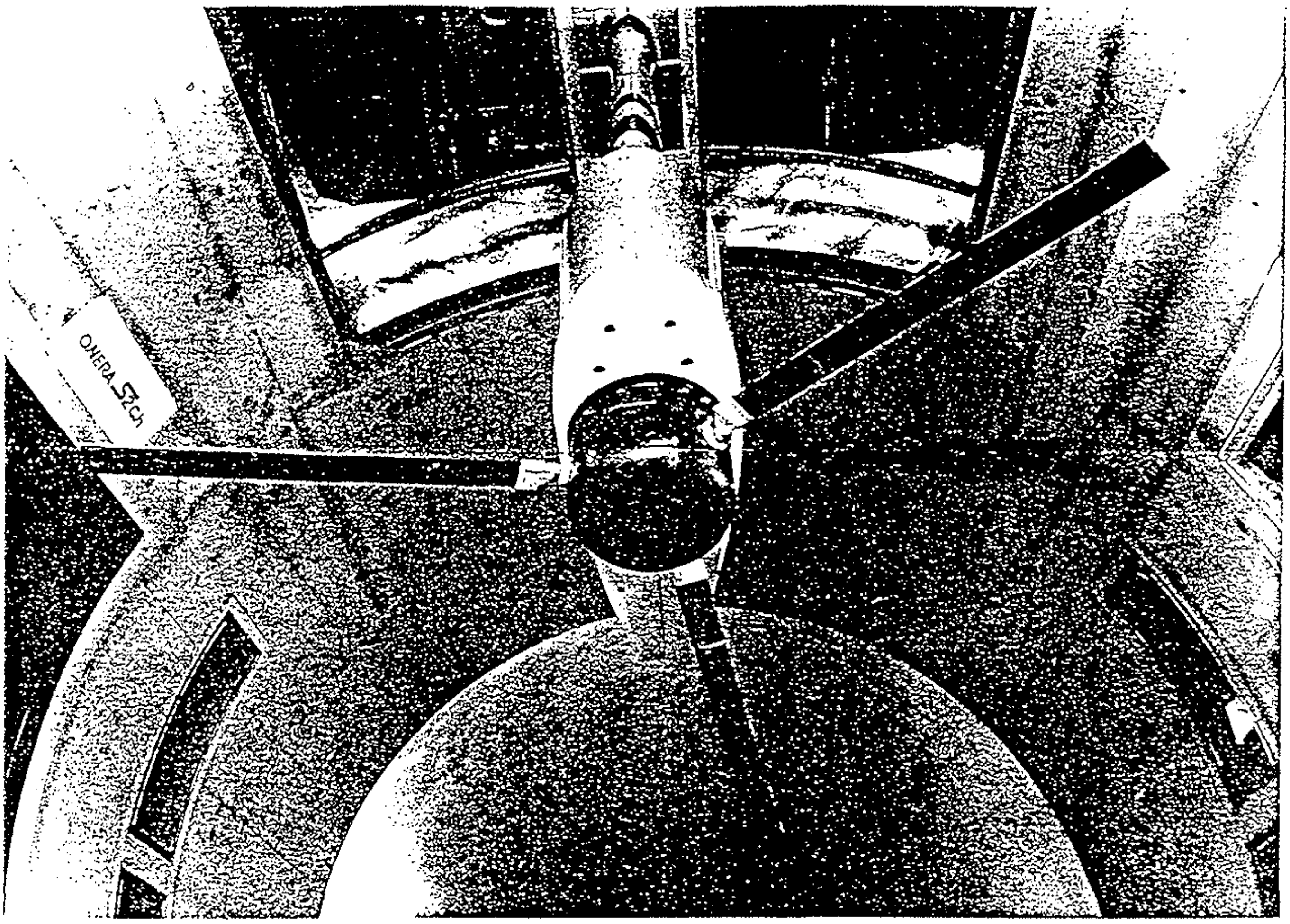

Fig. 1 EDY Rotor installed in the ONERA S2Ch wind tunnel

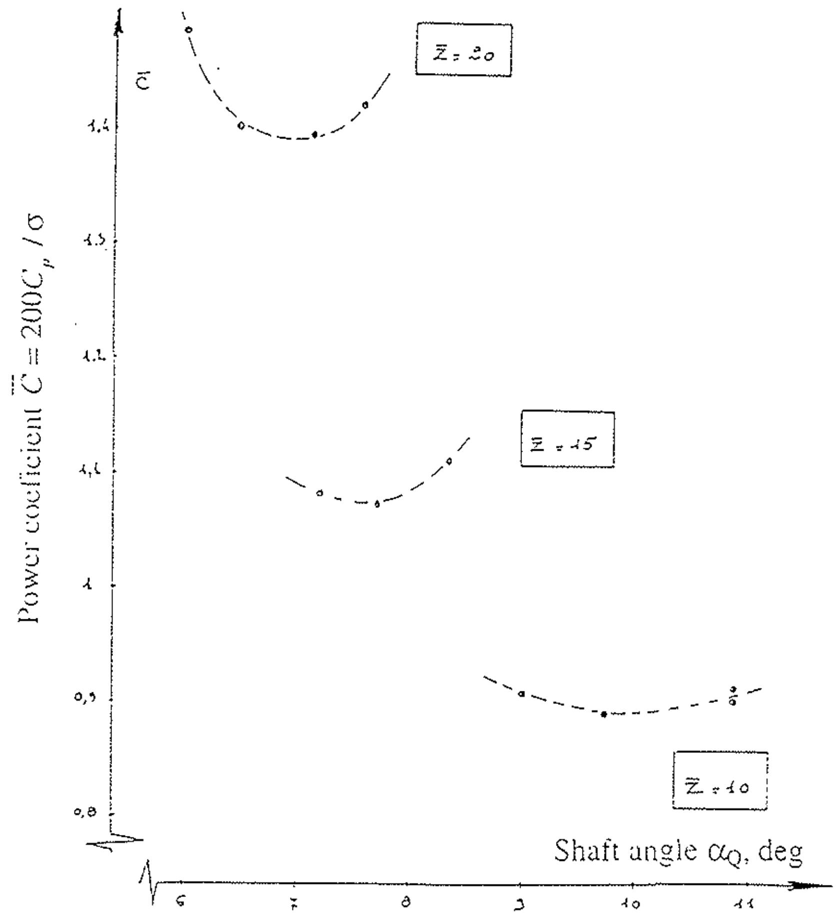

Fig. 2 Experimental optimization of EDY R performance

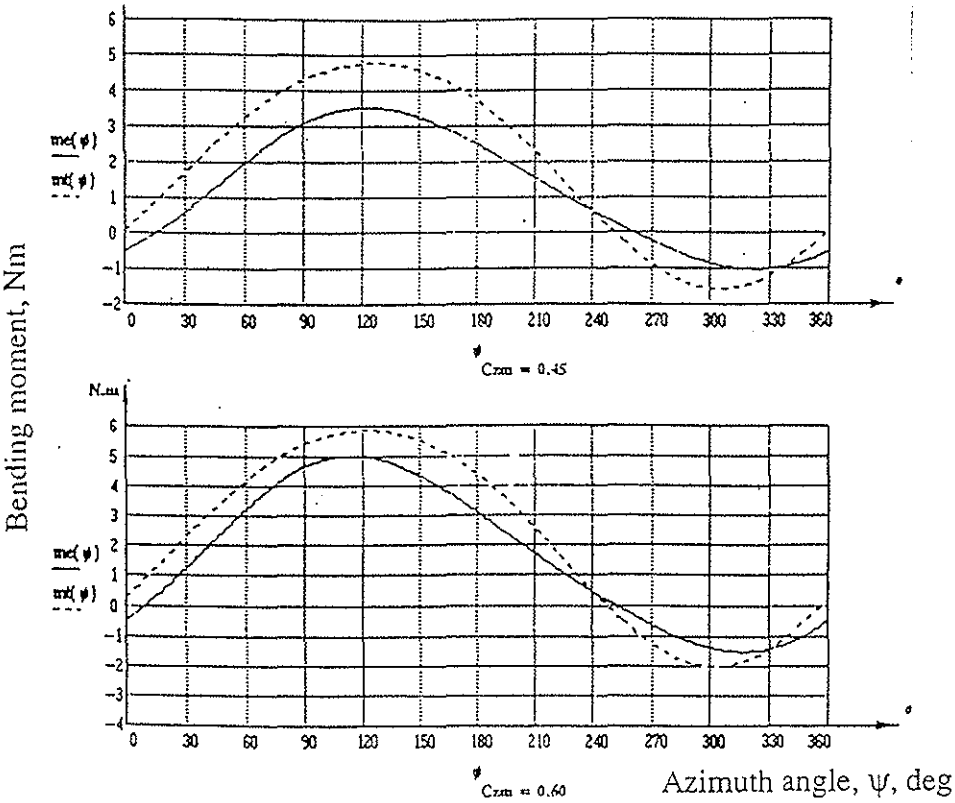

Fig. 3 Comparison of analytical and experimental flatwise bending moment results

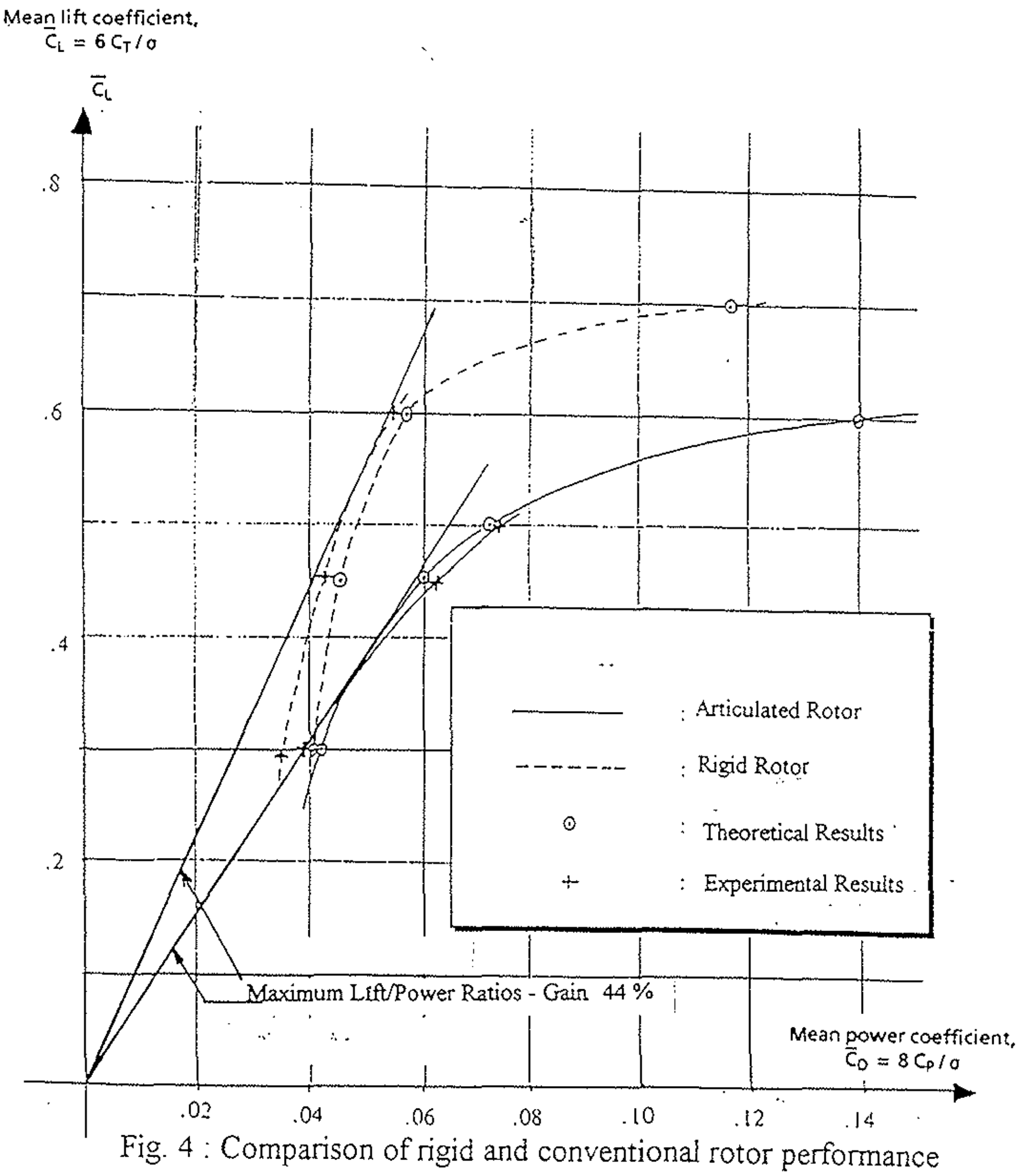

Fig. 4 : Comparison of rigid and conventional rotor performance

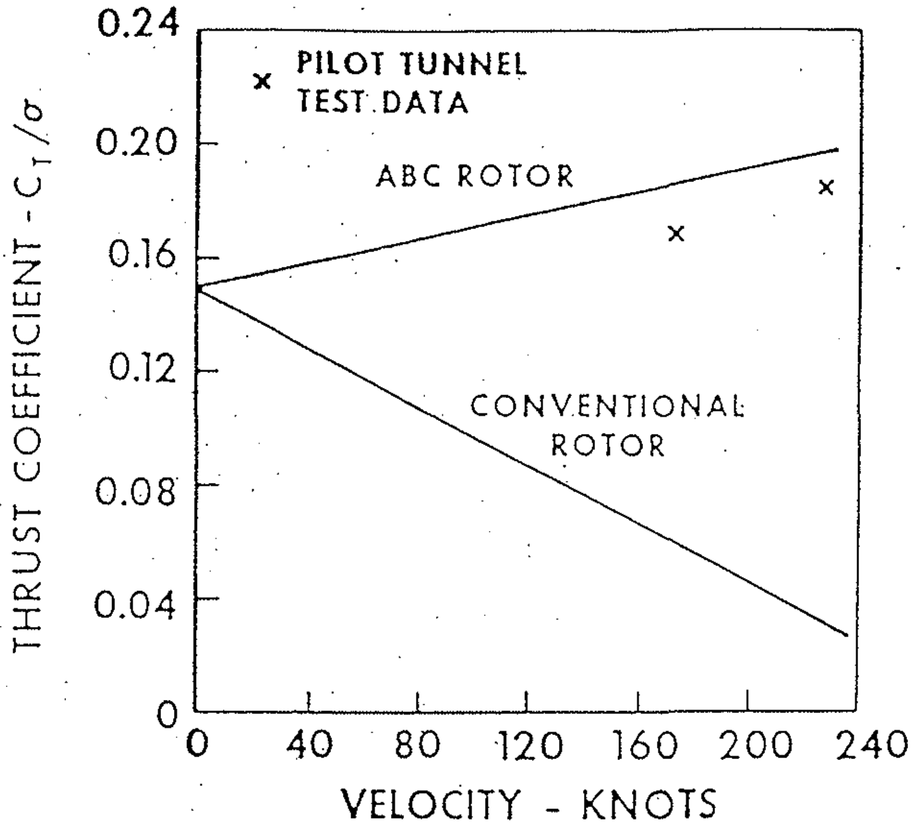

Fig. 5 : Maximum lift coefficient (Ref.6)

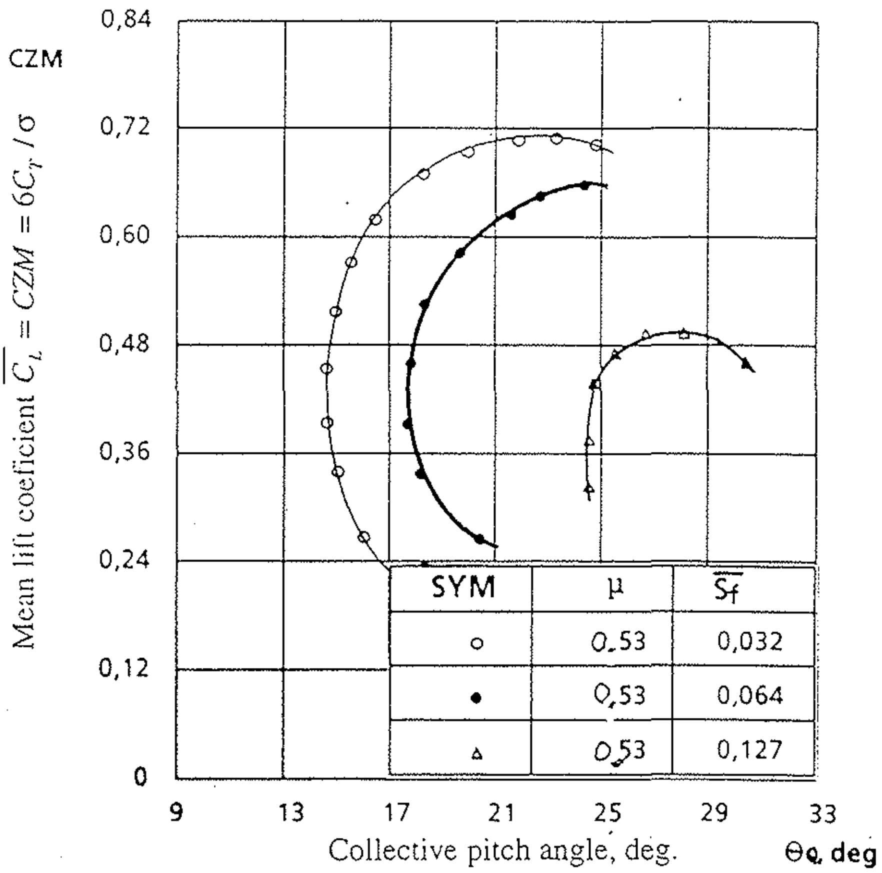

Fig. 6 : Test envelope determination (Ref.7)

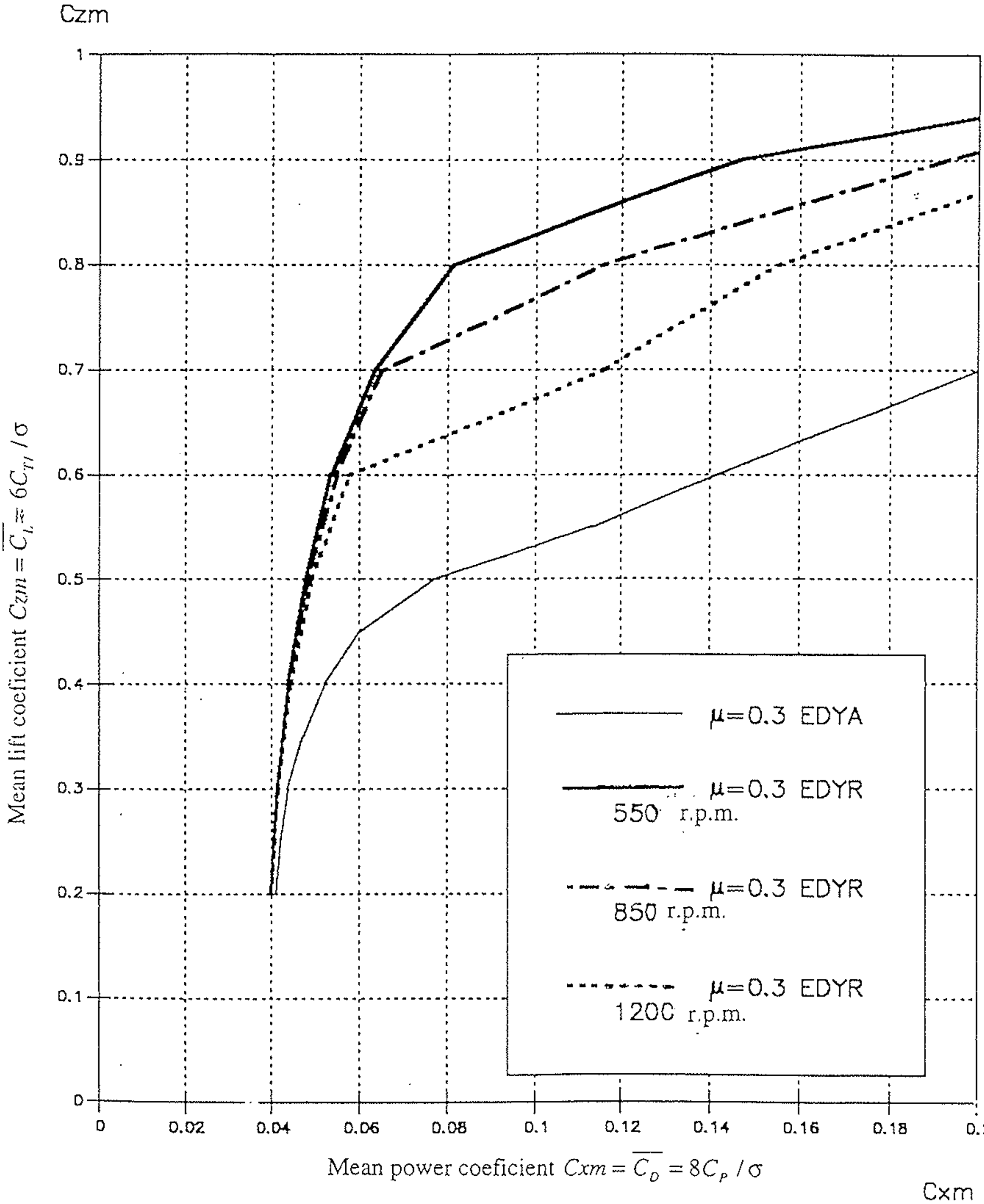

Fig. 7 : Theoretical polar diagrams of EDY R and EDY A rotors at $\mu = 0.3$, $\overline{S_f} = 0.1$