PHENOMENON OF A COAXIAL HELICOPTER HIGH FIGURE OF MERIT AT HOVER.

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Abstract

The paper presents the results of figure of merit analysis for single and coaxial main rotors at hover as well as for a helicopter with a tail rotor and a coaxial helicopter. The analysis has been performed using a simple physical model based on the results of numerical simulation, wind tunnel tests and full scale flight tests.

It is demonstrated that coaxial rotors have an approximately 10% higher maximal figure of merit at hover compared to a single rotor and that a coaxial helicopter figure of merit exceeds that of a helicopter with a tail rotor by approximately 20%.

The paper also names and briefly describes the main methods of numerical simulation (analysis) developed in Russia to predict coaxial rotors performance at hover.

Notation

c	- main rotor blade chord, m;
$C_T = \dfrac{16 \cdot T}{\Delta \cdot (\omega R)^2 \cdot F}$	- thrust coefficient;
D	- main rotor diameter, m;
D_{EFF}	- effective diameter, m;
$F = \pi R^2$	- main rotor swept area, m^2;
K	- total number of blades;
$m_K = \dfrac{1200 \cdot P}{\Delta \cdot (\omega R)^3 \cdot F}$	- power coefficient;
M	- blade tip Mach number;
P	- power (brought to the rotor shaft or to the main rotor shaft plus tail rotor), hp;
Re	- Reynolds number;
T	- main rotor system thrust, kg;
y	- distance between upper and lower co-axial rotor hubs, m;
Δ	- relative air density;
$\Delta\varphi$	- blade geometrical twist, deg;
$\sigma = \dfrac{K \cdot c}{\pi \cdot R}$	- total coaxial rotor solidity;
$\eta = \dfrac{C_T^{3/2}}{2 \cdot m_K}$, or $\eta = \dfrac{T^{3/2}}{33{,}25 \cdot D \cdot P \cdot \Delta^{1/2}}$	- figure of merit;
ωR	- blade tip speed, m/s;

TSAGI	- Central Aerohydrodynamics Institute named after N. E. Zhukovsky, Russia;
F.R.I.	- Gromov Flight Research Institute, Russia;
MAI	- Moscow Aviation Institute, Russia.

Subscriptions:

s	- single;
c	- coaxial.

Introduction

Helicopter flight performance at hover determines its take off/landing performance and its application scope from the take off/landing safety point of view. These characteristics , in their turn, depend upon the main rotor system aerodynamic efficiency at hover and the efficiency of the powerplant power utilization. The main rotor system aerodynamic efficiency at hover is usually described by the figure of merit (FOM). A FOM tendency for a constant growth is a pronounced objective process. The ways of FOM improvement may be different. One of them is to make use of coaxial rotors as a helicopter main rotor system that also ensure minimal losses of the engine power. Coaxial rotor FOM advantage over that of an alternate equivalent single rotor is well explained by simple physical notions based on the results of numerical simulation or flight test results.

Physical Notions

The physical notions are expressed with the simplest ideal graphs shown in Fig. 1.

The graph for coaxial rotors with extra "active" area δF located outside the constricted upper rotor wake in the lower rotor plane is made similar to the notion of "active disk" for a single isolated rotor having a square area of $F_{EFF}=F$. In accordance with experimental data on tip vortex visualization of a coaxial Ka-32 helicopter at hover, obtained in the beginning of 1990 by FRI jointly with Kamov (ref. 1), the upper rotor wake radius is equal to 0.85R in the lower rotor plane at y=0.1D . It follows from this fact that the coaxial rotor extra active area is $\delta F=0.28F$. The total "active area" is $F_C=(1+\delta F)F_S=1.28F_S$ that is equivalent to an active disc of $D_{EFF}=1.13D$, i.e. the effective diameter of a coaxial main rotor system exceeds the physical by 13% due to suction of additional air by the lower rotor.

We use a known formula for the main rotor at hover connecting, through the notion of figure of merit, the thrust developed by this rotor with the diameter and the input power in the specific atmospheric conditions:

$$T=(33.25\cdot\eta\cdot D\cdot P\cdot\Delta^{1/2})^{2/3}. \tag{1}$$

Substituting the values of single/coaxial rotor physical diameters we correspondingly obtain:

$$T_S=(33.25\cdot\eta_S\cdot D\cdot P\cdot\Delta^{1/2})^{2/3};$$
$$T_C=(33.25\cdot\eta_C\cdot D\cdot P\cdot\Delta^{1/2})^{2/3}. \tag{2}$$

Using the above mentioned notion of an equivalent active disk we may write the following for coaxial rotors:

$$T_C=(33.25\cdot\eta_S\cdot D_{EFF}\cdot P\cdot\Delta^{1/2})^{2/3}. \tag{3}$$

Comparing the expressions of Tc (2), (3) it may be seen that a ratio of coaxial/single rotor figure of merit values, with the input power values being the same in the same atmospheric conditions, is equal to the ratio of effective/physical diameters:

$$\eta_C/\eta_S=D_{EFF}/D=1.13. \tag{4}$$

Comparing the expressions of Tc and Ts considering the above ratio we get:

$$T_C/T_S=(\eta_C/\eta_S)^{2/3}=(1.13)^{2/3}=1.09. \tag{5}$$

The obtained ratios should be understood as an estimation of the magnitude of the results expected from the actual experience.

Numerical Experiment

A comprehensive numerical experiment (analysis) is based on much more complex mathematical models than those discussed above.

The survey of theoretical and experimental research developments on coaxial rotors aerodynamics published by Colen P. Coleman (ref. 2) includes research developments made in Russia but is not exhaustive enough in this respect. So we shall list and give a brief description of certain numerical analysis techniques developed in Russia permitting to predict the coaxial rotors performance at hover.

Three main developments were undertaken in Russia in this field by TSAGI, MAI and Kamov.

TSAGI developments are described in (ref. 3). In addition to those described in (ref. 3), developments made by I.A.Serov and V.S.Vozhdayv should be pointed out.

In MAI good results were obtained by V.I.Shaidakov and his colleagues (ref. 4).

Kamov company have paid a lot of attention to the development of numerical techniques. At first we calculated coaxial rotors as a single rotor of total solidity. There we used a blade element momentum theory to determine induced velocity in the disk plane. The drag power was calculated using the blade airfoil data obtained in wind tunnel tests (ref. 5).

Evaluation of an extra air suction by coaxial rotors upon hover performance was made by L.A. Potashnik within the framework of an ideal rotor model (ref.6). That result demonstrated that a coaxial rotor figure of merit exceeds that of an isolated single rotor by 3%.

Among other coaxial rotor analytical models developed at Kamov the following may also be pointed out:

1. E. A. Petrosian's (ref. 7) and V. N. Kvokov's (ref. 8) models correspondingly based on the blade element momentum theory and blade disc vortex theory. They assume a rigid form of the upper/lower rotor wake as an input parameter. Numerical experiments with such models also demonstrated a positive effect of the air suction upon the rotor figure of merit. The amount of this effect depends upon the upper rotor wake contraction (Fig.1).

2. Disc vortex theory by V.A. Anikin (ref. 9);

3. Nonlinear rotor vortex theory by B.N.Bourtsev (ref. 10) applied to coaxial/single rotor aeroelasticity problems solution.

<u>Experiments with models</u>

Experiments aimed at determination of the main rotor model aerodynamic characteristics at hover have not once been initiated at TSAGI. Certain results were obtained by A.D.Levin and V.F.Antropov comparing characteristics of coaxial and equivalent single rotors. These experiments demonstrated that coaxial rotors are advantageous from the figure of merit point of view. Experiments recently made by V.F.Antropov deserve more detailed discussion. He tested a geometrically similar model (D=2.52m; σ=0.15) of coaxial rotors corresponding to a real coaxial helicopter and models of single equivalent rotors, i.e. having solidity equal to the total solidity of the upper/lower coaxial rotors. Figs. 2, 3 and 4 illustrate the results of these tests in the form of figure of merit versus C_T/σ curves. Each coaxial rotor has three blades and single rotor has three blades (Fig.2) or six blades (Figs.3, 4 and 5) with solidity unchanged. Fig.2 illustrates the result obtained for coaxial rotors and single 3-bladed rotor - the maximal coaxial rotor figure of merit value exceeds that of a single rotor by 7...8%. Experiments with 6-bladed models of coaxial and single rotors, that are of special interest, were performed with participation of V.A.Anikin (Kamov company). In these experiments the blades of all rotors were similar geometrically thus automatically providing for comparable results at equal Re, M, ωR and other parameters . Fig.3 contains results of three independent experiments. Coaxial rotor models designated as Variant 1 and

Variant 2 in Fig.3 differed only by replacing the upper rotor blades with the lower rotor blades and changing the direction of rotation. Fig.4 presents the results of other two experiments that were carried out at a little smaller ωR value (53 m/s instead of 60 m/s) in comparison to the experiments presented in Fig.3. Fig.5 presents the results of processing the data presented in Figs.3 and Fig.4 - coaxial/single rotor model figure of merit values versus C_T/σ for corresponding combinations. It may be seen from Fig.5 that the minimal ratio of coaxial and equivalent single rotor model figure of merit values is 1.08...1.11. Fig.6 demonstrates considerable favorable effect of the geometrical twist of the coaxial main rotor model blades in the range of 0 to -14 degrees upon the figure of merit. With the blade twist increase the maximal figure of merit raises from 0.73 to 0.80.

Full Scale Flight Tests

In view of the above we may assume that a high figure of merit is an inherent feature of coaxial main rotors. Along with this, as well as for single rotors, there exists a possibility for a further figure of merit increase by way of selecting blade parameters as well as application of advanced airfoils.

Fig.7 presents the results of production coaxial rotor figure of merit versus C_T/σ evaluation. These results were obtained by measuring the thrust in full scale flight tests using seven coaxial helicopters (Ka-15, Ka-25, Ka-26, Ka-32 production model ; Ka-32 development model, Ka-50 prototype and Ka-50 production model).

Measuring of helicopter thrust characteristics is a separate problem and we shall not dwell upon it here (ref. 11, for example). The helicopters belonging to the generation of 1955-1965 (Ka-15, Ka-25, Ka-26) had a comparatively low power-to-weight ratio. The thrust characteristics were determined by their flying weights ensuring their hover in still air out of ground effect. For the 1970-1980 generation helicopters (Ka-32, Ka-50) that feature high power-to-weight ratios, thrust characteristics were measured using a load gauge tie-up arrangement.

The helicopter thrust was measured as a sum of its hover weight and the tie-up rope tension force. At the same time the parameters characterizing the engine power were measured (cylinder head temperature, air compression ratio in turbocompressor, engine output shaft torque etc.) . Transfer from a helicopter thrust to a main rotor thrust was made with consideration of thrust losses for the fuselage inflow and power mechanical losses in transmission as well as in the auxiliary unit operation. Fig.7 shows that the results presented may be divided into three groups:

1. Rotors of production Ka-15, Ka-25, Ka-26 and Ka-32 helicopters having blades based on NACA-23012 airfoil. The maximal figure of merit value of these rotors reached 0.77 (Ka-32).

2. Rotors of Ka-50 helicopters with the blades based on advanced airfoils have an optimal twist and a swept tip. The maximal figure of merit value obtained for them was 0.8...0.82. An apparent difference in figure of merit values can be explained by differences in blade geometrical twists.

3. Advanced main rotors of a Ka-32 helicopter are a further development of the Ka-50 rotors. The maximal by now figure of merit values were obtained for them (0.86...0.87). However the maximum of $\eta_C = f(C_T/\sigma)$ is not yet obtained (ref. the upper curve in Fig.7).

Helicopter figure of merit at hover

In view of the above it may be concluded that coaxial main rotors figure of merit has an advantage over that of a single equivalent rotor up to approximately 10%.

When we calculate a figure of merit of a rotor we use a rotor shaft power value. When we calculate a figure of merit of a helicopter we use an engine power value.

However, a single main rotor, in difference from coaxial rotors, if installed on a helicopter with a mechanical drive, cannot exist without an additional tail rotor compensating for the reactive moment of the main rotor and ensuring directional control. Additional power consumption of the powerplant amounts to approximately 10% from the power consumed by the single main rotor at hover.

Fig.8 can be examined as an illustration of the above stated.

So, additional power consumption of a helicopter with a tail rotor determines an extra advantage in figure of merit for a coaxial helicopter. So, the total excess in figure of merit for a coaxial helicopter in comparison to a helicopter with tail rotor is around 20%, i.e. $\eta_C/\eta_S = 1.2$.

Making use of the formulas (2) at equal engine power, equal rotor diameters and in equal weather conditions we get:

$$T_C/T_S=(\eta_C/\eta_S)^{2/3}=(1.2)^{2/3}=1.14. \qquad (6)$$

This means that in the above conditions a coaxial helicopter has a 14% larger free thrust than a helicopter with a tail rotor.

To provide for an equal thrust in equal conditions a helicopter with a tail rotor must have the following main rotor diameter:

$$D_S=(\eta_C/\eta_S)\cdot D_C=1.2\cdot D_C, \qquad (7)$$

i.e., 20% more that a coaxial rotor diameter.

Conclusions

1. A characteristic feature of coaxial main rotors is their high aerodynamic perfection at hover caused by an additional amount of air being sucked in by the lower main rotor.

The coaxial rotors at hover demonstrate a 10% larger figure of merit value in comparison with a single rotor unbalanced by torque.

2. Absence of tail rotor power losses provides a 20% larger figure of merit for a coaxial helicopter as a rotorcraft.

3. At equal main rotor diameters and equal engine powers a coaxial helicopter has a 1.14 times larger rotor thrust in comparison to a helicopter with a tail rotor.

To provide for an equal thrust at hover a helicopter with a tail rotor must have an approximately 1.2 times larger main rotor diameter and 1.5 times larger length.

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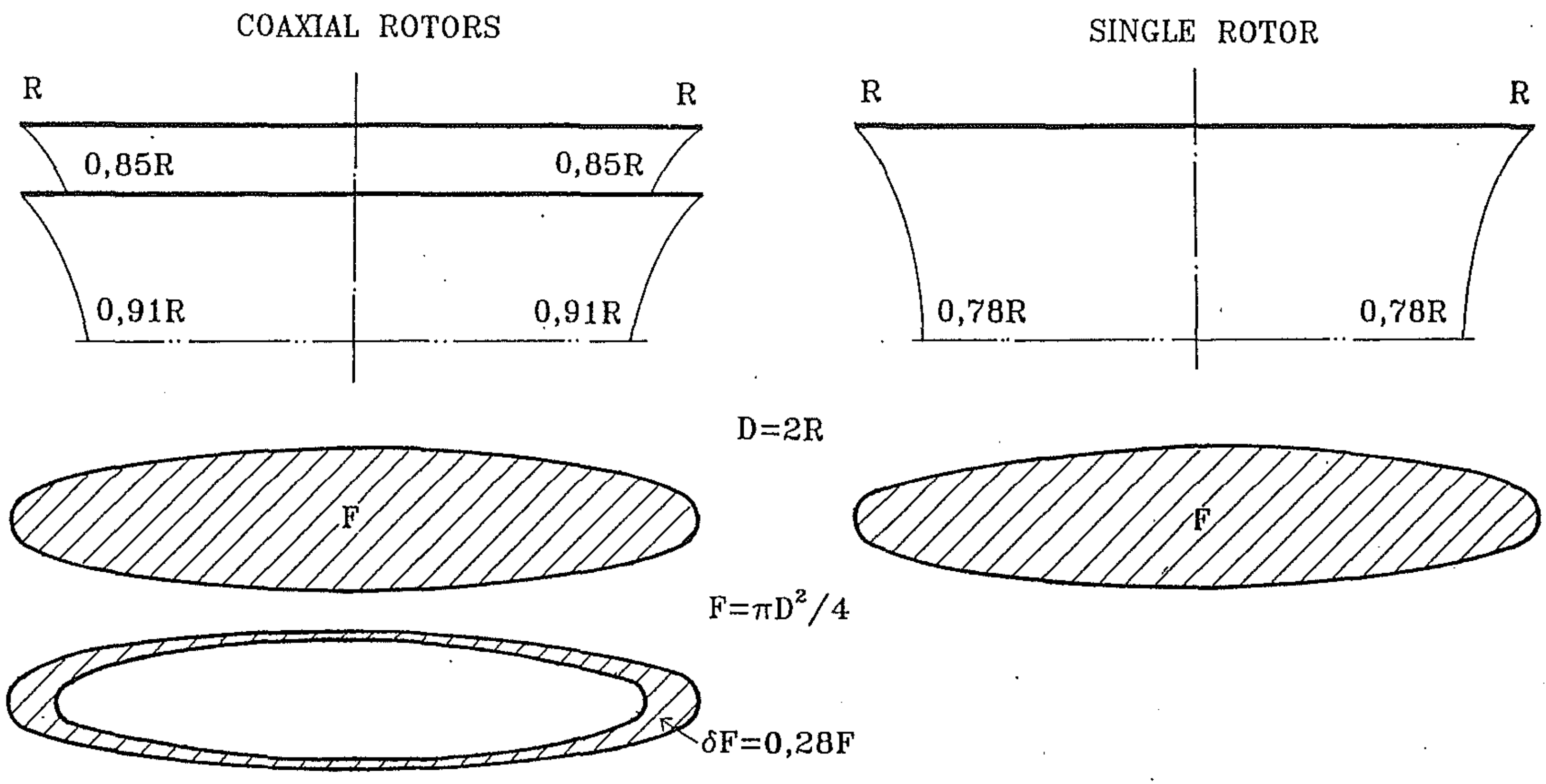


$F_C = F + \delta F = 1{,}28F = \pi D^2_{EFF}/4$ $\quad D_{EFF} = 1{,}13D$ $\qquad F_S = F$

$T_C = (33{,}25 \cdot \eta_C \cdot D \cdot P \cdot \Delta^{1/2})^{2/3}$ $\qquad T_S = (33{,}25 \cdot \eta_S \cdot D \cdot P \cdot \Delta^{1/2})^{2/3}$

$$\eta_C/\eta_S = D_{EFF}/D$$

Ideal rotor: $T_C = (33{,}25 \cdot D_{EFF} \cdot P \cdot \Delta^{1/2})^{2/3}$ $\quad T_C = (1{,}13)^{2/3} T_S = 1{,}085 T_S$ $\quad T_S = (33{,}25 \cdot D \cdot P \cdot \Delta^{1/2})^{2/3}$

Fig.1. Relations between ideal single and coaxial rotors active disc areas, effective diameters and thrusts at hover.

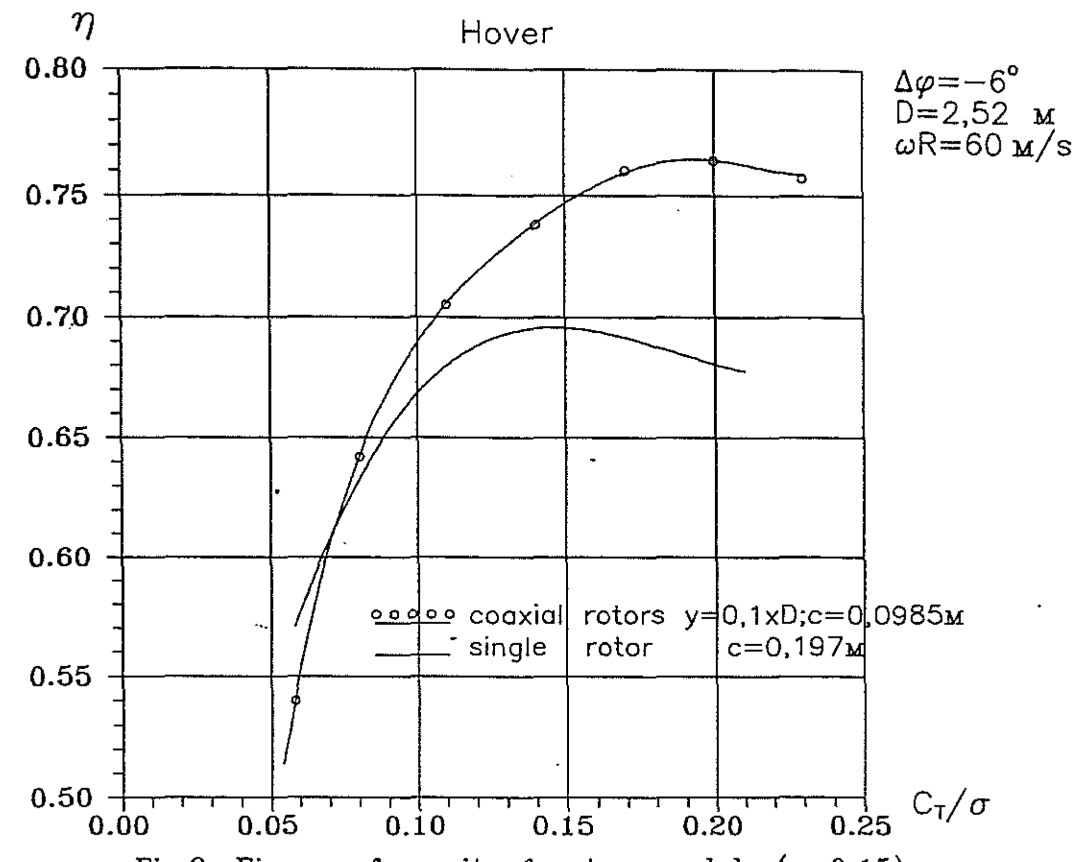


Fig.2. Figure of merit of rotor models (σ=0,15).
Coaxial rotors 2x3 blades; single rotor 3 blades.

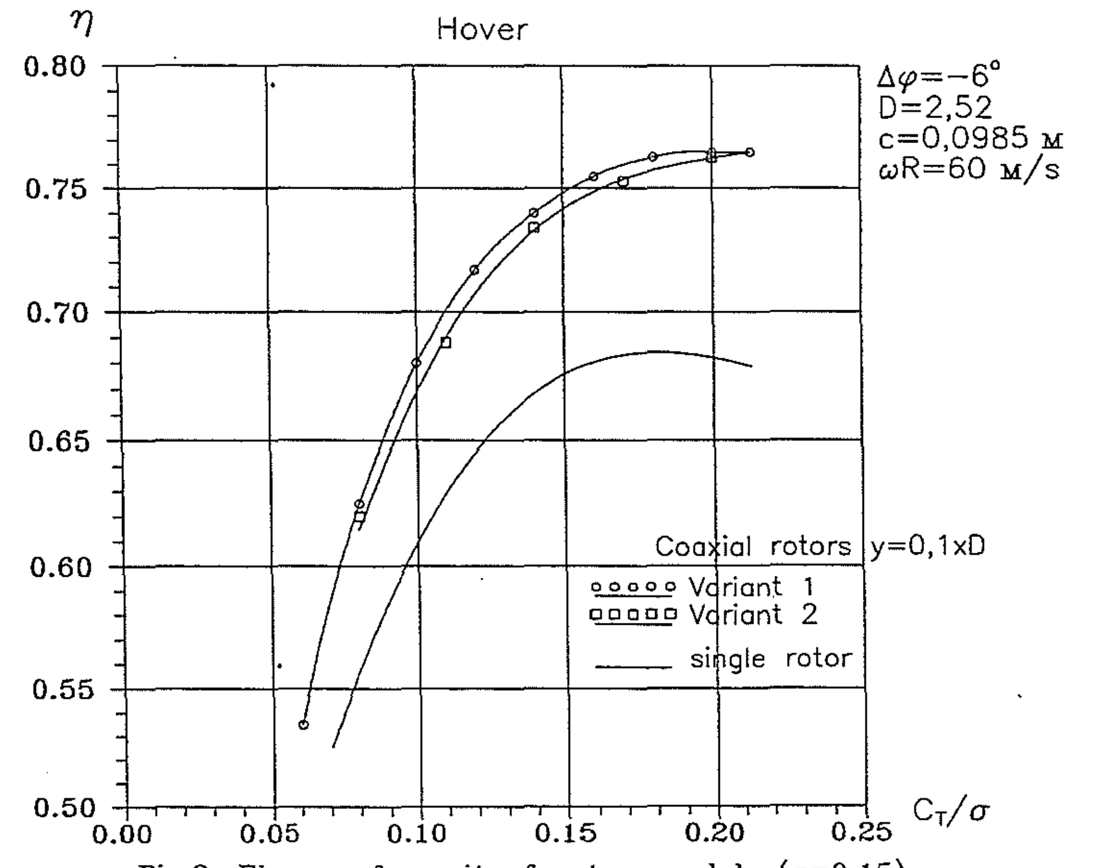


Fig.3. Figure of merit of rotor models (σ=0,15).
Coaxial rotors 2x3 blades; single rotor 6 blades.

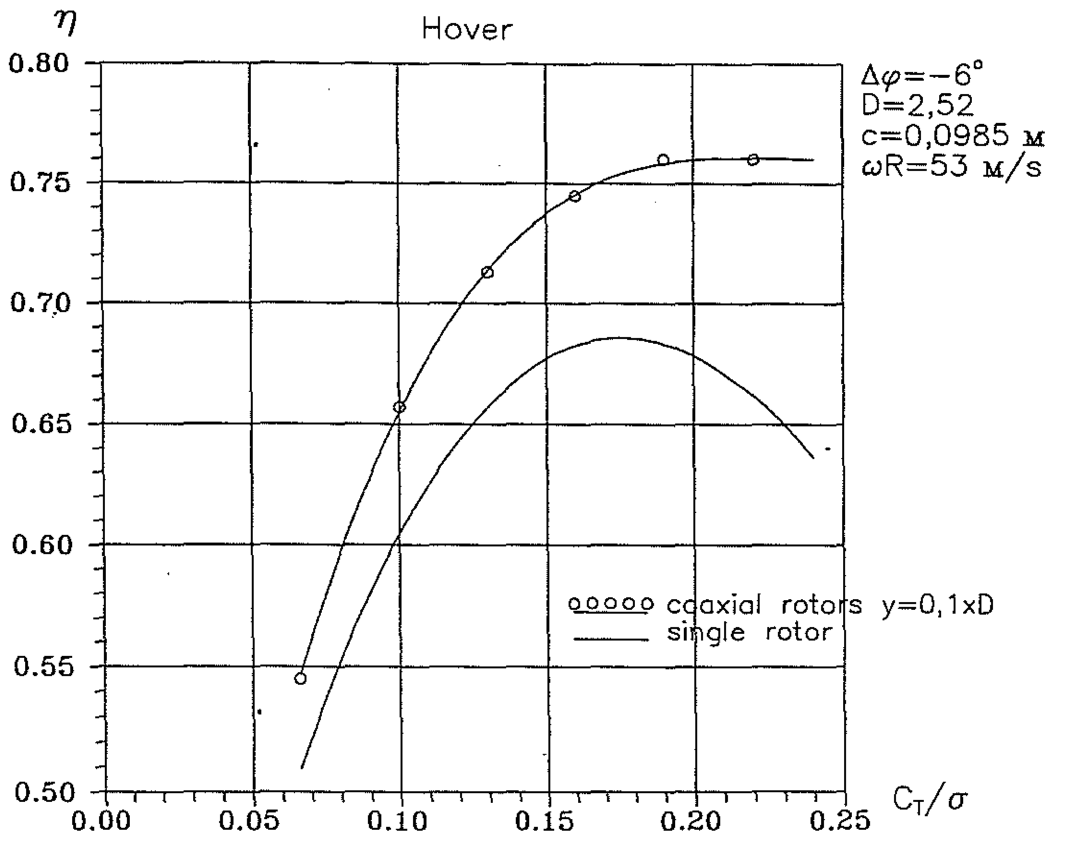


Fig.4. Figure of merit of rotor models (σ=0,15). Coaxial rotors 2x3 blades; single rotor 6 blades.

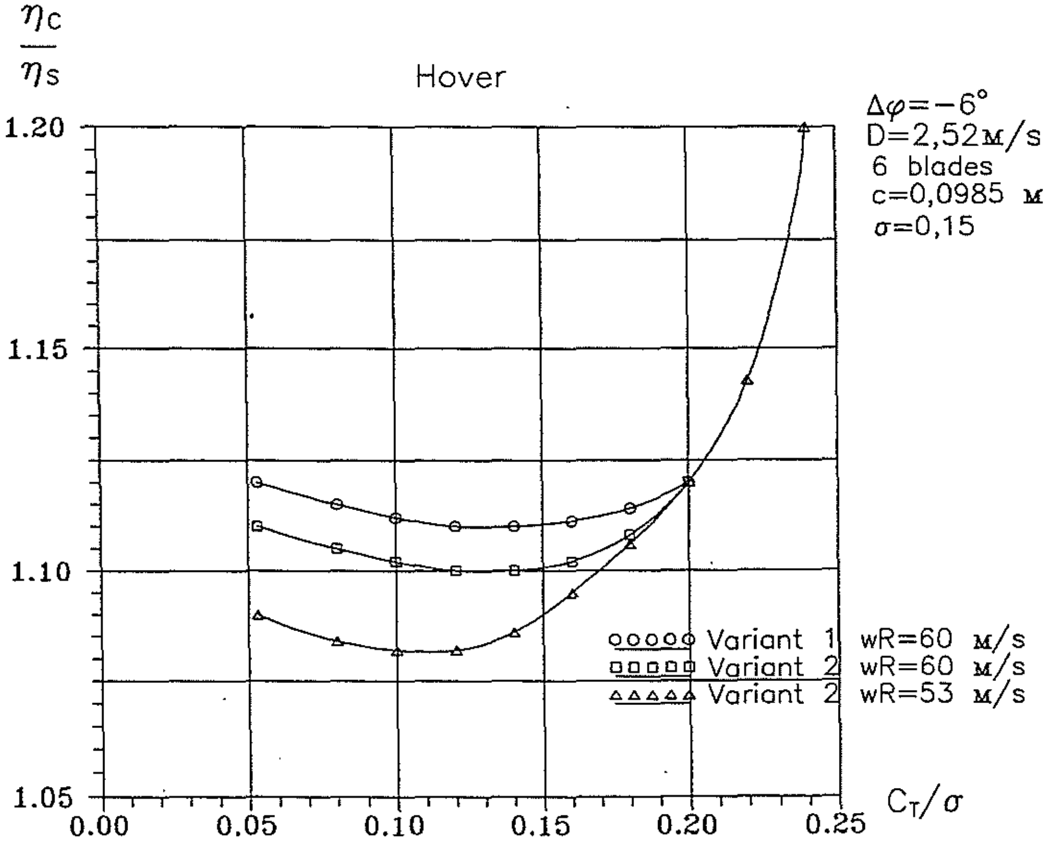


Fig.5. Ratio of coaxial η_c to single η_s rotors figures of merit.

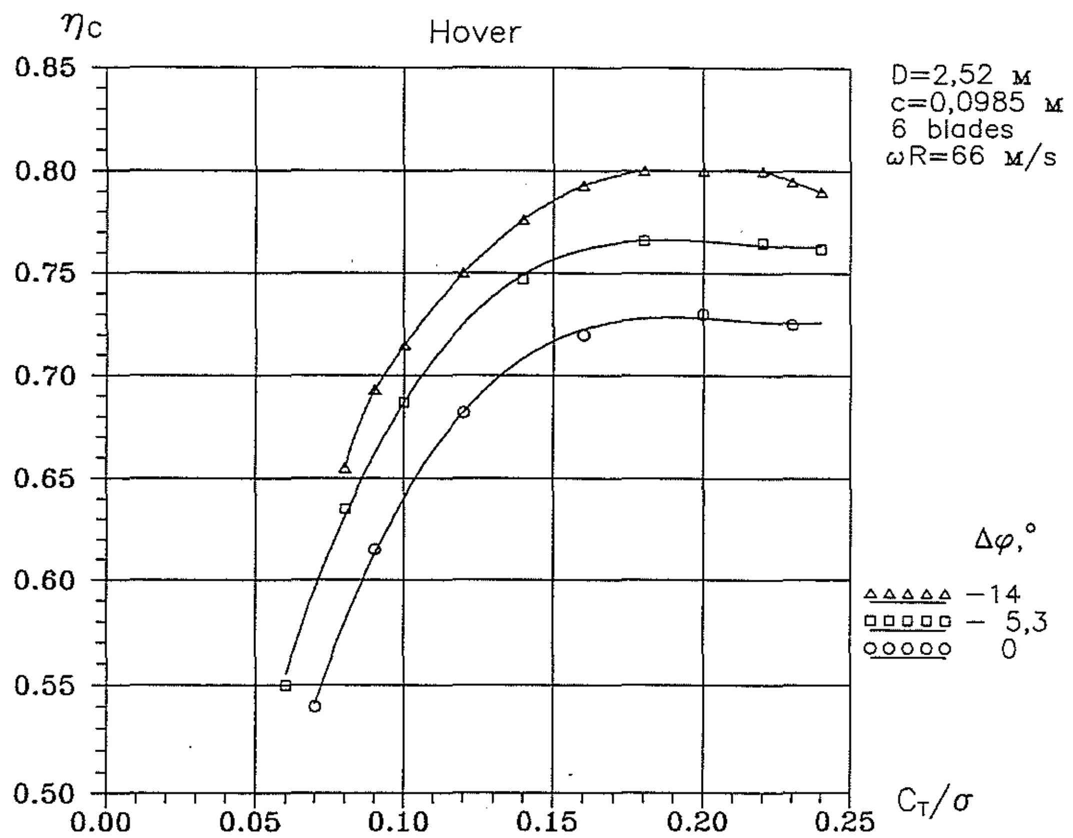


Fig.6. Blade twist effect on figure of merit. Coaxial rotor models.

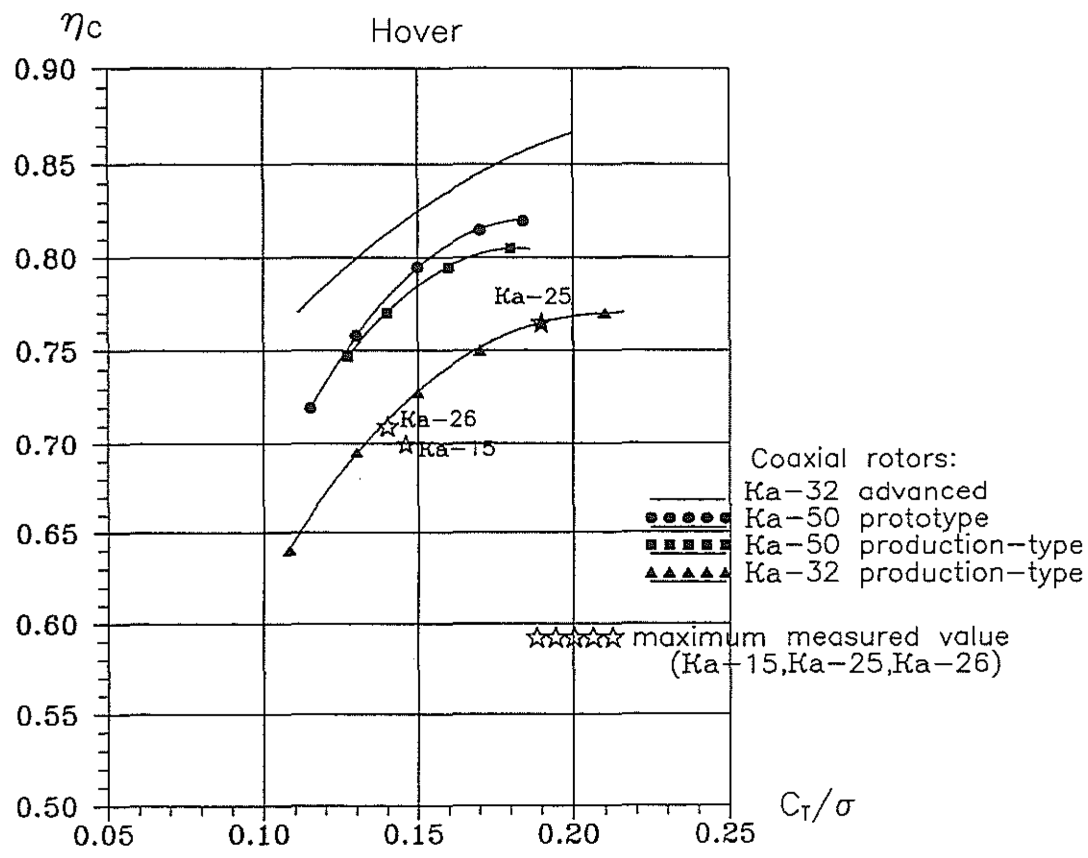
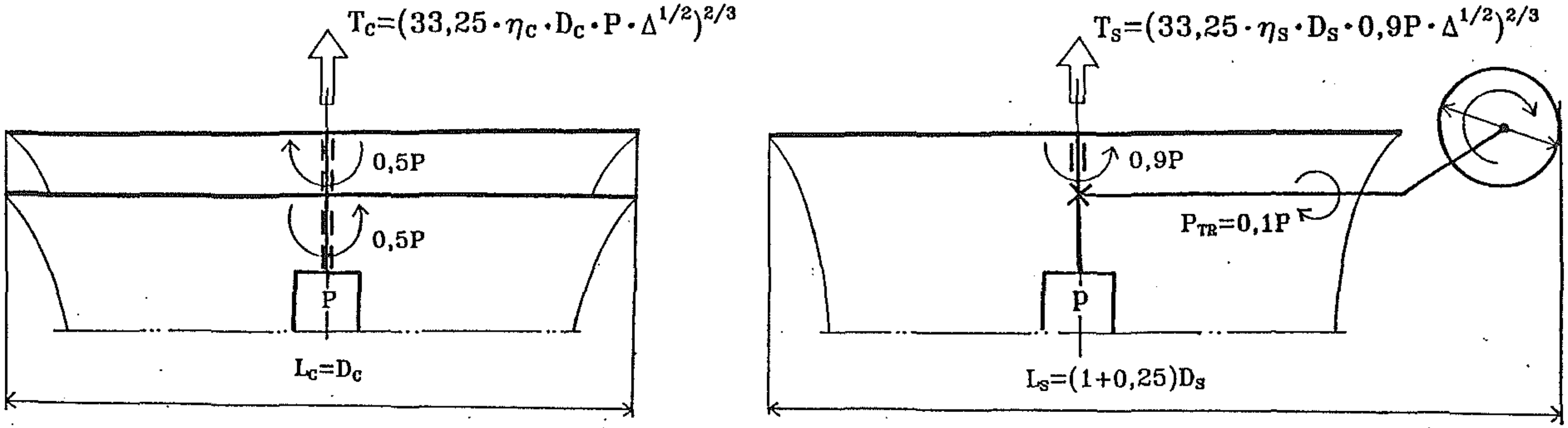


Fig.7. Figure of merit of coaxial helicopter rotors. Flight test based results.

COAXIAL HELICOPTER

HELICOPTER WITH A TAIL ROTOR



From $\eta_C/\eta_S=1{,}1$ and $P_C=P_S=P$ and $P_{TR}=0{,}1P$ hence:

1. At $D_C=D_S$ the thrust ratio is $T_C/T_S=(1{,}1/0{,}9)^{2/3}=1{,}14$;

2. At $T_C=T_S$ the diameter ratio is $D_S/D_C=1{,}1/0{,}9=1{,}22$
   and the length ratio is $L_S/L_C=(1+0{,}25)D_S/D_C=1{,}525$

At equal power and equal thrust of rotors at hover a helicopter with a tail rotor must have a main rotor diameter 1,22 times larger and the helicopter must be 1,525 times longer than a coaxial one.

Fig.8. Relations between main rotor diameter, power and thrust for coaxial and single rotor helicopters at hover.