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Fan – in – Fin
Performance at Hover
Computational Method

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KAMOV Company has developed the Fan-in-Fin configuration for the multipurpose single rotor Ka-60 helicopter KASATKA which has flown the first flight on December 24, 1998.

This paper presents a computational method of the performance data (thrust, figure of merit) of Fan-in-Fin configuration at hovering. The method is founded on the theory of Prof. Shaidakov V.I. (MAI) for Fan-in-Fin configuration with the conical duct and completely expanded output air flow. The Fan-in-Fin configuration consists of inlet lip, rotor, duct and internal fittings in a duct which create drag. The total pressure losses are determined as a sum of local losses. The rotor itself operating in a duct is considered as rotor under modified Joukovsky-Vetchinkin disk vortex theory. The correction factors are input which allow to take into account additional inductive air flow in a rotor plane effected by a shroud. Influence of blade tip clearance to shroud is taken into consideration.

The method is realized in "ROTOR_FAN" code. The "ROTOR_FAN" code is used both at Fan-in-Fin development and supporting efforts of the Ka-60 helicopter flight tests.

Notation

Symbol	Unit	Description
$F = \pi R^2$	m^2	rotor disk area
R	m	rotor radius
Кл	-	number of blades
b	m	rotor blade chord
$\sigma = \text{Кл} \cdot b \cdot R/F$	-	rotor solidity
r , $(\bar{r} = r / R)$	m	blade radial station
r_K	m	lip radius
δ , $(\bar{\delta} = \delta / R)$	m	blade tip clearance
L	m	diffuser length
n	-	diffuser expansion coef.
ξ	-	drag of shroud coef.
$\alpha_{\text{Д}}$	deg	diffuser angle
α	deg	attack angle
β	deg	flow rotation angle
φ_o	deg	blade collective pitch
$\Delta\varphi$	deg	blade twist
Cx_P	-	blade section drag coef.
Cy	-	blade section lift coef.

æ	-	blade tip load losses
Γ, $(\bar{\Gamma} = \Gamma \cdot \text{Кл} / (4\pi \cdot \omega \cdot R^2))$	m^2/s	circulation of blade section
v_1 , $(\bar{v}_1 = v_1 / \omega R)$	m/s	axial inductive velocity
u_1 , $(\bar{u}_1 = u_1 / \omega R)$	m/s	circular inductive velocity
ωR	m/s	rotor tip speed
T , $(\bar{T} = T / T_\Sigma)$	kg	thrust
$C_T = \dfrac{16 \cdot T}{\Delta \cdot (\omega R)^2 \cdot F}$	-	thrust coefficient
N	h.p.	rotor power
$m_K = \dfrac{1200 \cdot N}{\Delta \cdot (\omega R)^3 \cdot F}$	-	power coefficient
$\eta_O = A \cdot \dfrac{C_T \sqrt{C_T}}{2 \cdot m_K}$	-	rotor figure of merit
A	-	rotor plane velocity increase factor
$K_{\text{И}}$	-	ideal quality of system
ρ	$kg \cdot s^2/m^4$	air density
Δ	-	relative air density
M, Re	-	similarities criterion

Subscripts

в - rotor
к - shroud
кол - inlet
д - diffuser
и - ideal
Σ - total

MAI - Moscow Aviation Institute, Russia
TsAGI - Central Aerogydrodynamics Institute named after Joukovsky N.E., Russia

Introduction

In Russia the lagre development of the theory and practice of axial-flow fans belongs to TsAGI, which is engaged in this subjects since 1930. Activities of Ushakov K.A. [1], Struve E.E. [2], Brussilovsky I.V. [3,4] etc. become the basis of Russian industrial aerodynamics.

The large contribution in theoretical and experimental researches of a configuration "rotor in duct" are introduced by the Russian helicopter aerodynamic school Prof. Youriev B.N. Among activities of the Russian scientifists it is necessary to mark the works by Ostoslavsky I.V. [5], Vildgrube L.S. [6], Tarasov N.N., Yakubovich V.N., Zhabin V.A. [7], (TsAGI); Kurochkin F.P. [8], Zavalov O.A., Shaidakov V.I. [9 ÷ 17] (MAI).

In MIL PLANT the research of "rotor in duct" were engaged by Nekrasov A.V., Lepilkin A.M., Barshay M.M. In 70 years the "rotor in duct" vortex theory was developed by Barshay M.M., and the "ink-jet" theory was developed by Lepilkin A.M. The tests "rotor in duct" on the Mи-24A helicopter was conducted by MIL PLANT in 1975 [18]. The helicopter Mи-24A with "rotor in duct" has tested successfully, but serially was not let out.

KAMOV company is engaged in development of the Fan-in-Fin concept for multipurpose single rotor Ka-60 helicopter KASATKA (Fig.1). The experimental researches of Fan-in-Fin in the KAMOV company were conducted under a management of Anikin V.A., the computational methods were developed by Bourtsev B.N., Kvokov V.N., Raikhlin Y.A., Selemenev S.V.

The majority of activities of Russian scientists on research of configuration "rotor in duct" were not published in West.

This paper presents a easy computational method of the performance data (thrust, figure of merit) of Fan-in-Fin configuration at hovering. The method is based on the modified theory of Prof. Shaidakov V.I., published in 1980 [11]. The theory was developed for "rotor in duct" with the conical diffuser and completely expanded flow on an output. The rotor itself is considered under the modified Joukovsky-Vetchinkin disk vortex theory [19] with using of two new correction factors of "influencing" of a shroud. The blade strip hypothesis is accepted. The experimental researches of a TsAGI are also utilized.

It is notable, that for the first approach to the definition of the perfrormance of a "rotor in duct" as to calculation of the rotor performance on a vortex theory with corrective action on influencing of a shroud, was offered in activities: Ostoslavsky I.V. (1935, [5]) and Ushakov K.A. (1936, [1]) TsAGI.

Formulation and method of the solution

The aerodynamic of configuration Fan-in-Fin is more difficult, than of the isolated rotor one. Advanced precise computational methods [20,21,etc.] are accordingly difficult and are expedient for detailed aerodynamic analyses. For calculation of Fan-in-Fin performance data it is sufficient to use "simple" mathematical models basing on appropriate experimental data.

The experimental characteristics "rotor in duct" are measured as a rule by model tests. The aerodynamic test dimensionless factors are enumerated on full-scale rotors.

However, usage of the aerodynamic test dimensionless factors are not always correct, as modeling accuracy depends on relation of model dimensions and full-scale configuration. The test similarity guesses equality of all dimensionless parameters: geometrical, aerodynamic and inertial. It is known, for example based, on Frud criteria (Fr), Reynolds criteria (Re), that the full similarity is impossible because of a scale effect.

The substance of present method is explained by the lines of Table_1 for ideal models only. The basic formulas of the momentum theory for isolated rotor, "rotor in a tube" (with sharp edges) and "rotor in duct" (with "lip") are shown in the Table_1 for hovering. But, real presented method includes the pressure losses for actual shroud geometry. The rotor blade loads are calculated under modified Joukovsky-Vetchinkin disk vortex theory with taking into account flow velocity effected shroud.

To the present method, the Fan-in-Fin configuration consists of a inlet "lip", rotor, duct (diffuser) and internal fittings in a duct creating drag. The pressure losses ($\xi_{КОЛ} + \xi_{Д}$) in shroud ("lip" + diffuser), are based on calculations of experimental data (Fig.4,5) for actual shroud geometry (r_K /R, L/R, α_K). It results in increase of relative rotor thrust ($T_B / T_\Sigma = \overline{T}_B$) of a system (rotor+shroud) (Table2).

Blades in duct, are considered as the rotor working under the modified Joukovsky-Vetchinkin disk vortex theory. At calculation of the inductive velocities we use the Prof. Shaidakov’s "influencing" correction factors of a shroud. The correction factors is included a additive air flow induced of a shroud. The correction factor $A = f\ ((1/\overline{T}_B), K_V)$ is entered into vortex model determining increase of induced velocities in cross-section of a rotor blade, which are created by shroud thrust ($\overline{T}_K = 1 - \overline{T}_B$)

and expansion ratio of a flow in a shroud $(K_V = F / F_2)$ (Table_2).

The blade tip clearance (δ) acts on a blade load distribution to a Prandtl - Shaidakov function (æ_{SH}) [22, 12].

So, the blade loads are calculated on a modified disk vortex theory.

The basic details of present method

The calculation of Fan-in-Fin aerodynamic performance data consists of two phases, namely:

- the rotor and shroud interaction calculation (**1**);
- the blade loads calculation (**2**).

1. The rotor and shroud interaction calculation with the help of correction factors of "influencing". The following factors are to be determined for the given geometrical layout of a shroud and the values of a tip clearance:

$(1/\overline{T}_B)$ - increase factor of rotor thrust because of effect of the shroud;

A - increase factor of axial and circular inductive velocities in a rotor plane.

The increase factors $((1/\overline{T}_B), A)$ of "influencing" are calculated under the momentum theory [11, 23] (Table_2).

The formulae of ($\overline{T}_B$) and of (A) factors are shown in Table_2 and in a Fig.4,5 [24], both for positive rotor thrust and for reverse rotor thrust.

The Table_2 presents numerical values calculated for TsAGI model tests:

- rotor positive thrust:

$$(1/\overline{T}_B) \approx 1.8\,, \qquad A \approx 2\,;$$

- rotor reverse thrust:

$$(1/\overline{T}_B) \approx \sqrt{2} = 1.41\,, \quad A \approx \sqrt[4]{2^3} = 1.68\,.$$

Having estimated a correction coefficient $(1/\overline{T}_B)$ and knowing rotor thrust (T_B) from consequent aerodynamic calculation (see is lower than item **2**), we shall estimate total thrust factor of Fan-in-Fin: $T_\Sigma = (1/\overline{T}_B) \cdot T_B$.

Fig.6 presents the $(C_{T_\Sigma} / \sigma = (1/\overline{T}_B) \cdot C_{T_B} / \sigma)$ experimental data approximation obtained on algorithm,which is shown in Table_2. The satisfactory conformity of calculation and experiment data is visible.

2. The rotor blade loads are calculated on algorithm on the basis of disk vortex theory, modified by correction "influencing" (rotor + shroud) factors $((1/\overline{T}_B), A)$.

The calculation is made from the blade end $(\overline{r} = 1)$ to blade root $(\overline{r} = \overline{r}_o)$. The circulation is determined by the coupling equation [25]:

$$8 \cdot \overline{\Gamma} = \sigma \cdot C_y \cdot \overline{W}_1\,,$$

where: $\overline{W}_1 = \sqrt{\overline{v}_1^{\,2} + (\overline{r} + \overline{u}_1)^2}\,.$

The performance data of Fan-in-Fin are further calculated.

It is assumed, that the factor $(A = \text{const})$ does not depend from $(\overline{r})$ in the algorithm.

Modified formulas for circular and axial inductive velocities are used:

$$\begin{cases} \overline{u}_1 = -A \cdot \dfrac{\left|\overline{\Gamma}_1\right|}{\overline{r}}; \\ \overline{v}_1 = -A \cdot \operatorname{Sign}(C_y) \sqrt{\left|\overline{\Gamma}_1\right| \cdot \left(1 - \dfrac{\left|\overline{\Gamma}_1\right|}{\overline{r}^{\,2}}\right) + 2 \displaystyle\int_{\overline{r}}^{1} \dfrac{\overline{\Gamma}_1^{\,2}}{\overline{r}^{\,3}} d\overline{r}} \end{cases}$$

where: $\overline{\Gamma}_1 = \overline{\Gamma} / \text{æ}_{SH}$.

Influencing of a tip clearance (δ), number of blades (Кл) is determined under the formula Prandtl - Shaidakov (for transformation from average inductive velocities to true inductive velocities):

$$\text{æ}_{SH} = 1 - \frac{F\left[\arcsin\left(\exp(-f)\right),\ \exp(-f_\delta)\right]}{K\left[\exp(-f_\delta)\right]},$$

where:

- elliptic integrals:

$$F(k, \varphi) = \int_o^{\varphi} \frac{d\varphi}{\sqrt{1 - k^2 \cdot \sin^2 \varphi}},\ K(k) = F(k, \frac{\pi}{2});$$

- Prandtl factor [22]:

$$f = \frac{\text{Кл}}{2} \cdot \frac{R - r}{r \cdot \sin\beta} = \frac{\text{Кл}}{2} \cdot \frac{1 - \overline{r}}{\overline{r}} \cdot \left|\frac{\overline{W}_1}{\overline{v}_1}\right|;$$

- Shaidakov factor [12]:

$$f_\delta = \frac{\text{Кл} \cdot \delta}{r \cdot \sin\beta} = \frac{\text{Кл} \cdot \overline{\delta}}{\overline{r}} \cdot \left|\frac{\overline{W}_1}{\overline{v}_1}\right|.$$

It is notable, that

$$(\ \delta \to \infty,\ K \to \pi/2,\ F \to \arcsin\left[\exp(-f)\right]\ ),$$

(æ_{SH}) - formula, transforms to the isolated rotor Prandtl formula [22]:

$$\text{æ}_{SH}(\delta \to \infty) = \text{æ}_{PR} = \frac{2}{\pi} \cdot \arccos\left[\exp(-f)\right].$$

The present method is realised in "ROTOR_FAN" code. The modeled aerodynamic phenomena and functional capabilities of "ROTOR_FAN" code are shown in the Table_3.

Comparision of calculation and experimental data

The "ROTOR_FAN" code practice presents full conformity of calculation and experimental data both for Fan-in-Fin, and for the isolated rotor.

The calculated performance data and TsAGI model tests results [7] are shown in Fig.7. It is to good conformity of the aerodynamic rotor blade loads $C_{T\Sigma}(\varphi_o)$, $C_{TB}(\varphi_o)$, $m_K(\varphi_o)$ v.s. collective pitch.

The polygons of velocities and aerodynamic forces acting on blade section are shown in a Fig.8. The outcomes of calculations of blade loads and inductive velocities are shown in a Fig.8: α, β, v_1, u_1, æ, Г, Cx_p, Cy, dT_B / dr, dm_K / dr (r / R). Both for the isolated rotor model and for the same rotor mounted into a shroud, rotor thrusts was equal to: $T_B = 9$ kg ($C_{TB} / \sigma = 0.189$). The axial, circular inductive velocities and the air flow rotation angles are shown in a Fig.8 [7]. The satisfactory conformity of calculated and measured values is shown.

"ROTOR_FAN" code application to Ka-60 helicopter development

"ROTOR_FAN" code is used to calculate:

- aerodynamic performance data;
- balancing collective pitch of blades;
- asymmetrical pedals course for positive and reverse thrust ranges of Fan-in-Fin.

Conclusions

1. "ROTOR_FAN" code allows to calculate aerodynamic performance data of Fan-in-Fin at hovering.
2. "ROTOR_FAN" code is successfully used both for bench and for flight tests of the Ka-60 helicopter.

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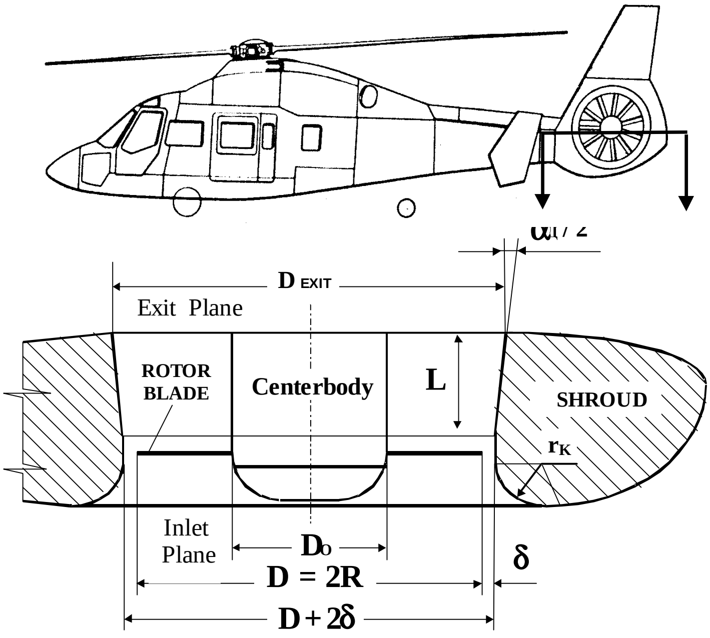
Fig. 1 KAMOV Ka-60 (Kasatka)

Fig. 2 Ka-60 Fan-in-Fin Antitorque System



$$n = \frac{D_{EXIT}^2}{(D + 2\delta)^2}; \qquad \frac{L}{R} = \frac{\sqrt{n} - 1}{tg\,(\alpha_Д / 2)}$$

Fig. 3 Radial Cross – Section of Fan-in-Fin

Table 1

Comparison of Ideal Models of the Antitorque System

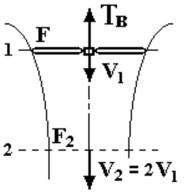
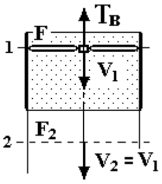
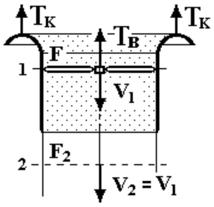
The Formulas of the Momentum Theory			
From : - BERNOULLI EQ - MASS CONSERVATION - MOMENTUM EQ - ENERGY EQ	Isolated Rotor  	" Rotor in a Tube "  	" Rotor in Duct " 
Total Thrust $T_\Sigma = T_B + T_K$	$T_\Sigma = T_B$	$T_\Sigma = T_B$	$T_\Sigma = 2 \cdot T_B$
Rotor Thrust $\overline{T}_B = T_B / T_\Sigma$	$\overline{T}_B = 1$	$\overline{T}_B = 1$	$\overline{T}_B = 1/2$
Shroud Thrust $\overline{T}_K = T_K / T_\Sigma = 1 - \overline{T}_B$	$\overline{T}_K = 0$	$\overline{T}_K = 0$	$\overline{T}_K = 1/2$
Velocities Ratio $K_V = v_2 / v_1 = F / F_2$	$K_V = 2$	$K_V = 1$	$K_V = 1$
Rotor Plane Velocity Increase Factor $A = \sqrt{2/(\overline{T}_B K_V)}$	$A = 1$	$A = \sqrt{2} = 1.414$	$A = \sqrt{2} \cdot \sqrt{2} = 2$
Rotor Plane Velocity $v_1 = A \cdot \sqrt{\frac{T_B}{2\rho F}}$, (m / s)	$v_1 = \sqrt{\frac{T_B}{2\rho F}}$	$v_1 = \sqrt{2} \cdot \sqrt{\frac{T_B}{2\rho F}}$	$v_1 = 2 \cdot \sqrt{\frac{T_B}{2\rho F}}$ or: $v_1 = \sqrt{2} \cdot \sqrt{\frac{T_\Sigma}{2\rho F}}$
Ideal Power $N_{\text{И}} = \frac{T_B v_1}{75}$, (h.p.)	$N_{\text{И}} = \frac{T_B}{75}\sqrt{\frac{T_B}{2\rho F}}$	$N_{\text{И}} = \sqrt{2} \cdot \frac{T_B}{75}\sqrt{\frac{T_B}{2\rho F}}$	$N_{\text{И}} = 2 \cdot \frac{T_B}{75}\sqrt{\frac{T_B}{2\rho F}}$ or: $N_{\text{И}} = \frac{1}{\sqrt{2}} \cdot \frac{T_\Sigma}{75}\sqrt{\frac{T_\Sigma}{2\rho F}}$
Figure of Merit $\eta_o = \frac{N_{\text{И}}}{N} = A \cdot \frac{T_B}{75N}\sqrt{\frac{T_B}{2\rho F}}$	$\eta_o = \frac{T_B}{75N}\sqrt{\frac{T_B}{2\rho F}}$	$\eta_o = \sqrt{2} \cdot \frac{T_B}{75N}\sqrt{\frac{T_B}{2\rho F}}$	$\eta_o = 2 \cdot \frac{T_B}{75N}\sqrt{\frac{T_B}{2\rho F}}$ or: $\eta_o = \frac{1}{\sqrt{2}} \cdot \frac{T_\Sigma}{75N}\sqrt{\frac{T_\Sigma}{2\rho F}}$
Ideal Quality of System by Bendeman – Shaidakov [23 , 11] ($K_{\text{И}} = T_{\Sigma \text{И}} / T_{B \text{ИИЗ}}$)			
$K_{\text{И}} = \frac{1}{\overline{T}_B}\left(\frac{1}{A}\right)^{2/3} = \sqrt[3]{\frac{K_V}{2\overline{T}_B^2}}$	$K_{\text{И}} = 1$	$K_{\text{И}} = \frac{1}{\sqrt[3]{2}} = 0.79$	$K_{\text{И}} = \sqrt[3]{2} = 1.26$
Thrust Formula by Welner $T_\Sigma = K_{\text{И}} \cdot (33.25\sqrt{\Delta}\, D \eta_o N)^{2/3}$ (kg)	$T_B = (33.25\sqrt{\Delta}\, D \eta_o N)^{2/3}$	$T_B = 0.79 \cdot (33.25\sqrt{\Delta}\, D \eta_o N)^{2/3}$	$T_\Sigma = 1.26 \cdot (33.25\sqrt{\Delta}\, D \eta_o N)^{2/3}$

Table 2

Correction Factors for Shroud Geometry		
TsAGI Model Shroud Geometry	$r_К / R = 0.2$, $L / R = 0.7$, $\delta / R = 0.01$, $\alpha_Д = 8°$, $n = 1.1$	
---	**Reverse Rotor Thrust**	**Positive Rotor Thrust**
Velocities Ratio	$K_V = 1$	$K_V = 1/[\,n\,(1+0.4\,(\alpha^{\circ}_Д / 57.3))] = 0.861$
Inlet Drag Factor	$\xi_Д = f(\alpha_Д, L/R) = 0.349$ (**Fig. 5**)	$\xi_{КОЛ} = f(r_К / R) = 0.112$ (**Fig. 4**)
Exit Drag Factor	$\xi_{КОЛ} = 0$	$\xi_Д = 3.2\,[\,tg\,(\alpha_Д / 2)]^{5/4}(1-1/n)^2 = 0.001$
Blade Tip Clearance Factor	$\varepsilon = 1 - 109 \cdot \bar{\delta}\sqrt{\bar{\delta}} = 0.891$	
Rotor Thrust	$\bar{T}_B = 1 + \varepsilon \cdot [\,K_V / 2 + (\xi_{КОЛ} + \xi_Д)/(2K_V) - 1\,]$	
	$\bar{T}_B = 0.71$	$\bar{T}_B = 0.55$
Rotor Plane Velocity Increase Factor	$A = \sqrt{2/(\bar{T}_B K_V)}$ = **1.68**	$A = \sqrt{2/(\bar{T}_B K_V)}$ = **2.06**
Total Thrust	$T_\Sigma = (1/\bar{T}_B) \cdot T_B =$ **1.41** $\cdot T_B$	$T_\Sigma = (1/\bar{T}_B) \cdot T_B =$ **1.82** $\cdot T_B$

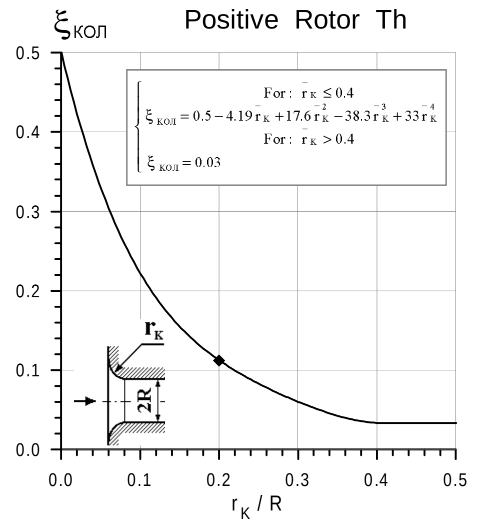


Fig.4 Inlet Drag Factor (Experimental D

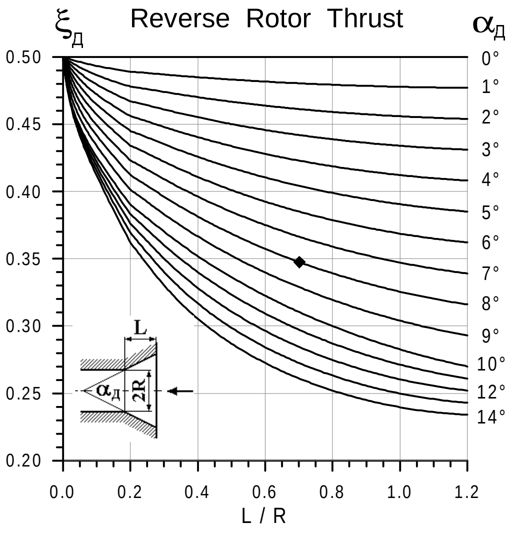
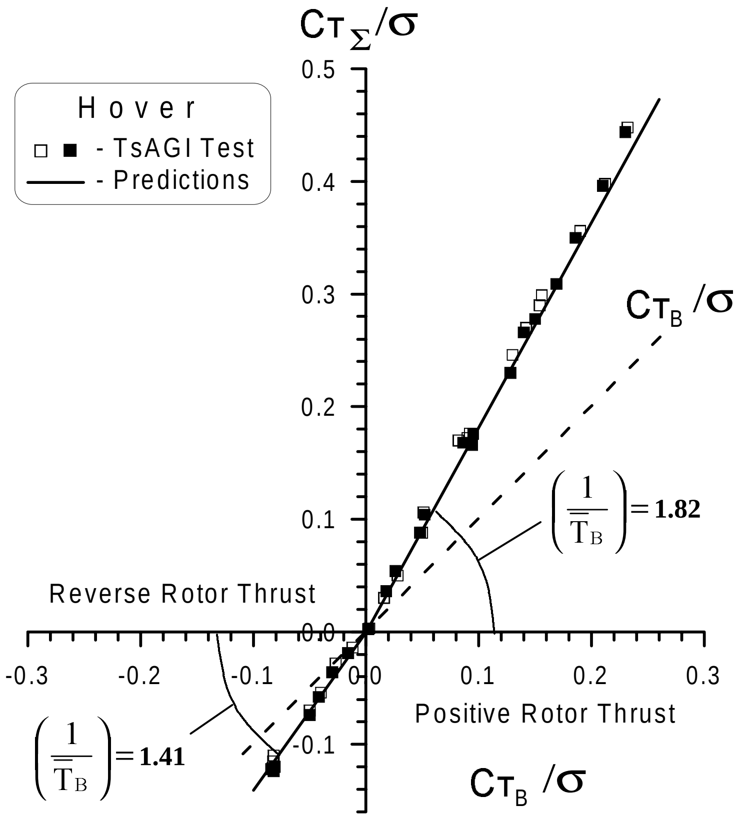
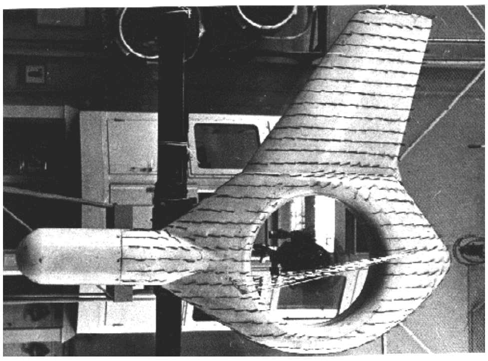


Fig.5 Inlet Drag Factor (Experimental Data)



Total Thrust : $C_{T\Sigma}/\sigma = \left(\frac{1}{\bar{T}_B}\right) \cdot C_{T_B}/\sigma$

Fig. 6 Rotor Thrust Increase Factor $\left(\frac{1}{\bar{T}_B}\right)$

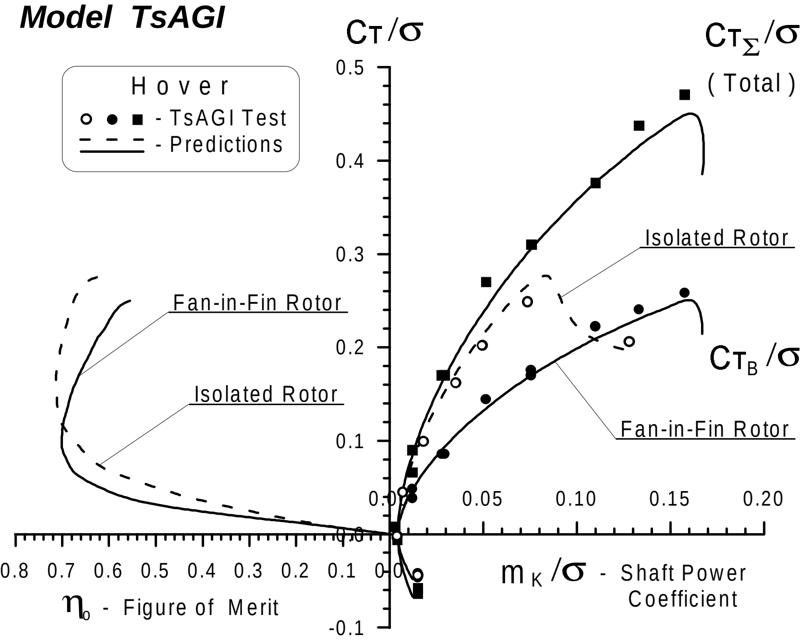


TsAGI Model Geometry

Rotor:
$D = 0.594$ (m), $K_{\text{л}} = 11$, $\sigma = 0.4951$
$\Delta\varphi_{\Sigma} = -12°$, $\omega R = 74.6$ (m/s)
Aerofoil: NACA23012 (r / R = 0.35…1)

Shroud:
$r_K / R = 0.2$, $L / R = 0.7$, $\delta / R = 0.01$
$\alpha_{Д} = 8°$, $n = 1.1$

Fan-in-Fin Model TsAGI



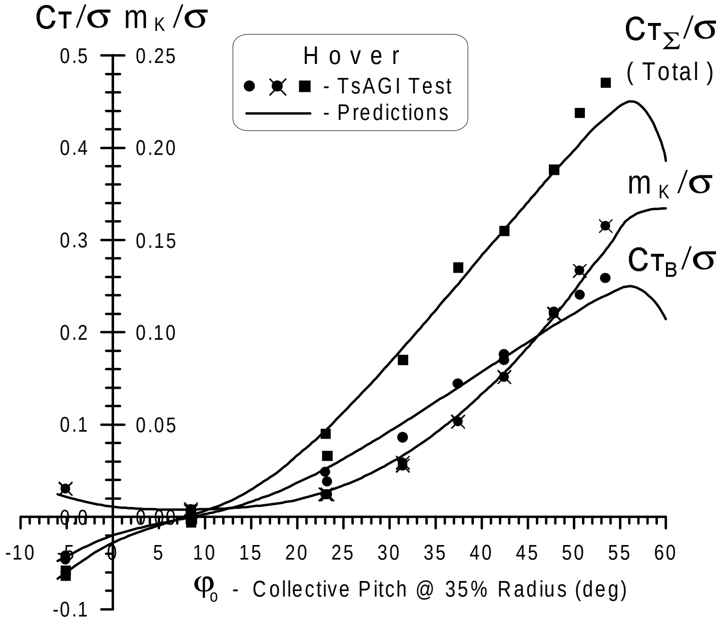
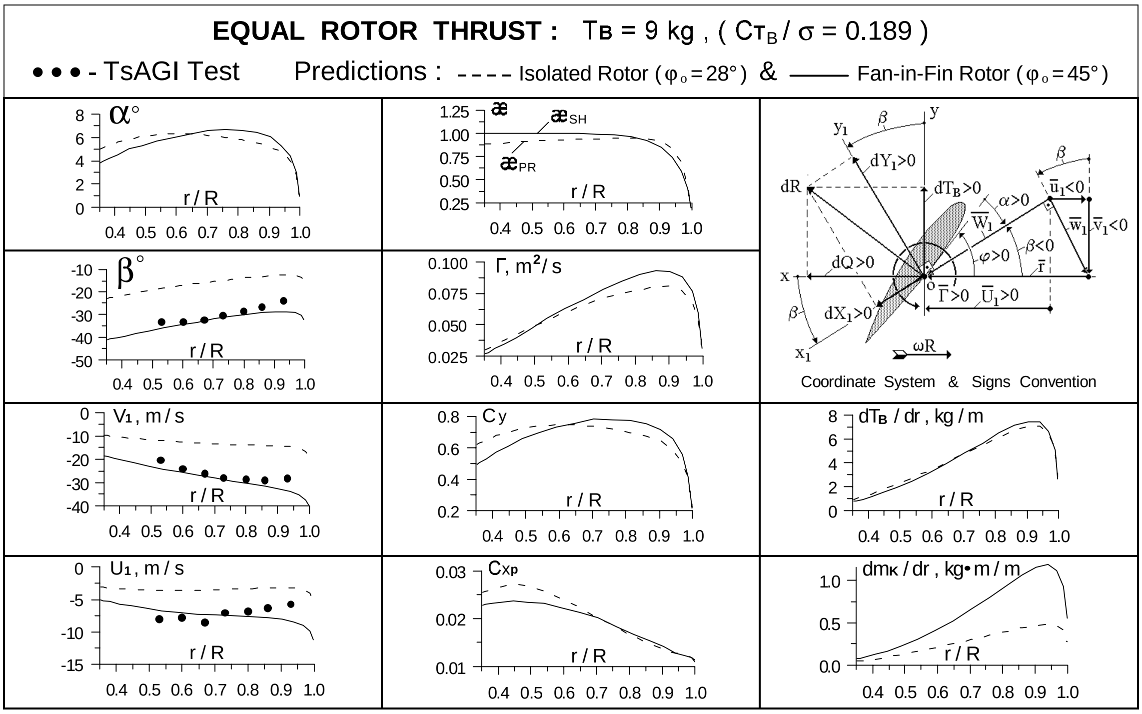


Fig. 7 Hover Performance Correlation



EQUAL ROTOR THRUST : T_B = 9 kg , ($C_{T_B} / \sigma = 0.189$)

● ● ● - TsAGI Test Predictions : - - - - Isolated Rotor ($\varphi_o = 28°$) & ——— Fan-in-Fin Rotor ($\varphi_o = 45°$)

Table 3

The Modeled Phenomena & Functional Capabilities of " ROTOR_FAN " Code

Antitorque System	**Fan – in – Fin**	**Isolated Rotor**
Modeled Phenomena		
Rotor Geometry	$D,\ K_Д,\ \sigma,\ \Delta\varphi_\Sigma,$ Aerofoil : $C_y, C_{XP}(\alpha, M, Re)$	
Shroud Geometry	r_K , L , $\alpha_Д$, n	---
Drag of a Shroud	$\xi_{КОЛ}$, $\xi_Д$	---
Blade Tip Clearances	δ	$\delta \to \infty$
Rotor Thrust Increase Factor	$(1 / \bar{T}_B)$	$\bar{T}_B = 1$
Rotor Plane Velocity Increase Factor	A	A = 1
Blade Tip Load Losses	$æ_{SH}$	$æ_{PR}$
Air Flow Rotation	✓	
Functional Capabilities		
Positive Rotor Thrust	✓	
Reverse Rotor Thrust	✓	
Calculation of Aerodynamic Performance	$C_{T\Sigma}(m_к)$, $C_{TB}(m_к)$, $\eta_o(C_{TB})$ $C_{T\Sigma}(\varphi_o)$, $C_{TB}(\varphi_o)$, $m_к(\varphi_o)$	$C_{TB}(m_к)$, $\eta_o(C_{TB})$ $C_{TB}(\varphi_o)$, $m_к(\varphi_o)$