Experimental Investigations Of Propellers At Low Reynolds Numbers

Yakov Sh. Flaxman*, Al. V. Lipin†, Stanslav P. Ostroukhov‡, Maxim V. Ustinov§, Andrey V. Shustov** and Alexandr V. Kornushenko††
Central Aerohydrodynamical Institute(TsAGI), Zhukovsky, Russia,140180

and

Sergey V. Serokhvostov‡‡
Moscow Institute of Physics and Technology (MIPT), DAFE, Zhukovsky, Russia,140180

Characteristic Reynolds number *Re* for MAV propeller is about Re~10^4, which is much more lower than the so-called "self-similarity" region for propellers ($Re>10^6$) but there is practically no data concerning propeller characteristics for $Re=10^4$-10^5. A systematical experimental investigation for the propeller characteristics at low Reynolds numbers was made in wind tunnel. Thrust coefficient α, power coefficient β and efficiency η for various angle of pitch were measured. The results obtained show that maximum of propeller efficiency decreases with the decrease of *Re*, angle of pitch corresponding to the maximum propeller efficiency increases with the decrease of Reynolds number, high rotational frequencies correspond to Mach numbers that are sufficient for air compressibility influence on propeller efficiency. The method of investigation and the characteristics obtained will be presented.

Nomenclature

b	=	propeller blade profile width
$\overline{b}$	=	dimensionless relative propeller blade profile width
c	=	propeller blade profile thickness
$\overline{c}$	=	dimensionless relative propeller blade profile thickness
C_L	=	profile lift coefficient
C_D	=	profile drag coefficient
D	=	propeller diameter
f	=	propeller blade profile curvature
$\overline{f}$	=	dimensionless relative propeller blade profile curvature
M	=	torque produced by propeller
P	=	force produced by propeller
r	=	radius, coordinate along the blade
$\overline{r}$	=	dimensionless relative radius
Re	=	Reynolds number
V	=	velocity of the flow
α	=	dimensionless force coefficient
β	=	dimensionless power coefficient

* Sector Chief, Division of Hypersonic Aeromechanics.
† Sector Chief, Division of Hypersonic Aeromechanics.
‡ Leading Researcher, Division of Powerplants.
§ Vice Chief of Division, Department Name, ustinov@stb.aerocentr.msk.su
** Vice Chief of Division, Division of Advanced Aircrafts, shustov@tsagi.ru
†† Sector Chief, Division of Aerodynamics, korshun@progtech.ru.
‡‡ Associate Professor, Department of Aeromechanics and Flight Engineering, serokhvostov@aviel.ru

λ	=	advanced ratio
η	=	propeller efficiency
μ	=	dynamic viscosity coefficient
ρ	=	air density
φ	=	propeller blade profile inclination
$\varphi_{0.75}$	=	propeller blade profile inclination at $2r/D$=0.75
φ^0	=	propeller blade profile inclination relative to $\varphi_{0.75}$
ω	=	angular velocity of propeller

I. Introduction

The propeller blade of airplanes, speed-boats works at Reynolds numbers Re>10^6. This case corresponds to the so-called self-similarity region for which the dependence of propeller characteristics on Re is very slight.

MAV propellers' blades work at Re=10^4-10^5. Data about the behavior of propeller characteristics at these Re are practically absent. But it is well known that the characteristics of wing profiles in this Re range are worse in comparison with the self-similarity region[1,2]. The main reason for these changes is the transition from turbulent to laminar flow in the separation bubble on the upper surface of profile near the leading edge. It leads to the separation propagation all over the upper surface. The flow near the propeller blade differs from the flow near the profile because of pressure gradient along the blade, centrifugal force and Coriolis force which leads to the transversal flows in the boundary layer.

Investigated in this work is the characteristics dependence of the two-blade propeller AV-31 on the Reynolds number in the region $5\cdot10^3$<Re<$1.2\cdot10^6$. In the cross-sections the profiles were П-105. The geometrical parameters of this propeller such as the dependences of profile inclinations $\varphi^0=\varphi-\varphi_{0.75}$, relative width $\overline{b}=b/D$, relative thickness $\overline{c}=c/b$ and relative curvature $\overline{f}=f/b$ as the function of relative radius $\overline{r}=2r/D$ are given in Fig. 1.

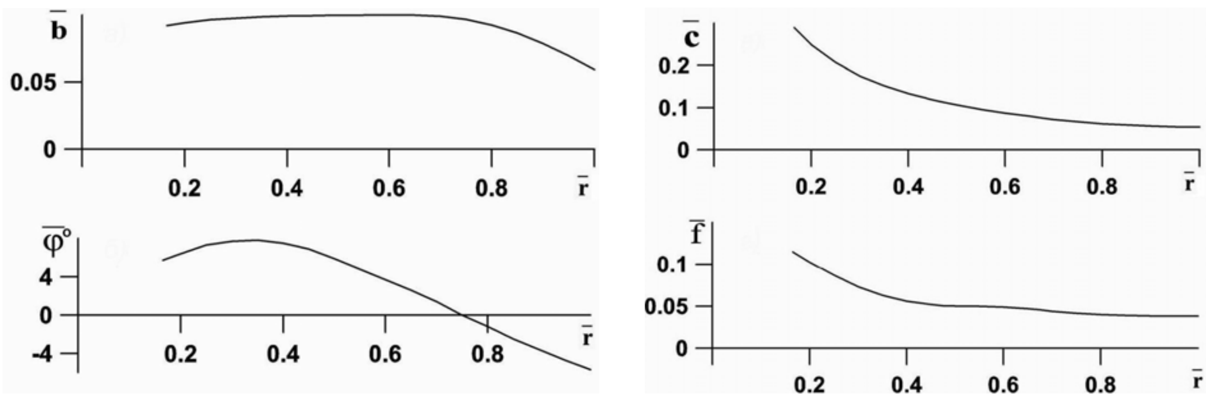

Figure 1. Geometrical characteristics of propeller investigated.

II. Measurement methodic and results processing

In the case when all other similarity criteria are the same, the Reynolds number is proportional to the square of the propeller force. In the present investigation the maximal difference between the results is 10^4 times. The same is the difference for torque. So, it is impossible to obtain all the results at the one unique plant. So the measurements were made at three plants. One of them is a propeller device VP-107 in wind tunnel T-104 (TsAGI), a device in wind tunnel T-129 and the dynamometer with floating sensitive element (only for measurements without the flow).

The propeller device in T-104 allows to obtain the power of 600 kW, maximal rotational frequency of 12000 revolutions per minute, the maximal force that could be measured is 2 kN, maximal torque is 480 N·m. The accuracy is ±0.4N for force and ±0.06 N·m for torque.

The device in T-129 was made specially for the investigation of MAV propellers. It allows to obtain maximal power of 500 W, maximal rotational frequency of 15000 revolutions per minute, the maximal force that could be measured is 40N, maximal torque is 0.6 N·m, the accuracy is ±0.03N and $\pm 6\cdot 10^4$N·m, respectively.

For the measurements without the flow the dynamometer with floating sensitive element (DFSE) was used. The maximum power available was 10W, maximal frequency was 3000 rev/min, the maximal force was 4H and torque was 0.05 N·m.

The accuracy of frequency measurements was about 1%, the accuracy flow velocity measurement was 0.5-1%.

In the wind tunnel T-104 a two-blade propeller AV-31 of 1.1m in diameter there was investigated. At other devices the model of this propeller with the diameter of 0.2m was investigated. This model was made by the method of stereo-lithography. The accuracy was 003-0.05 mm for the 0.2m propeller and 0.1 mm for 1.1m propeller. The construction of both the propellers allows to vary the pitch angle, and the accuracy was $0^0 20'$. The propeller of 1.1m had cock of 200mm diameter, propeller of 0.2m had cock of 38mm diameter fort-129 and 35 mm for VAT. Relative diameters of non-working part of the blade were practically identical (0.18, 0.19, 0.175, respectively).

The most thorough results were obtained for the investigation of Reynolds number influence without flow. In all the devices the pitch angle was varying from 10^0 to 30^0 by the step of 5^0. For each value of pitch force *P* and torque *M* were measured, and the frequency was changed from its minimal to maximal value. Then dimensionless force and power coefficients α and β were calculated, which are defined as

$$\alpha = \frac{(2\pi)^2 P}{\rho\omega^2 D^4};\ \beta = \frac{(2\pi)^3 M}{\rho\omega^3 D^5}.$$

In the absence of flow the propeller efficiency is defined as

$$\eta = \sqrt{\frac{2}{\pi}}\frac{\alpha^{3/2}}{\beta}.$$

During the measurements the force and torque were measured separately, to obtain the efficiency data were approximated by the polinoms of second order that were obtained by the minimal squares method. The value of Re were calculated for the blade chord at 0,75 of maximal radius:

$$\mathrm{Re} = \frac{0.75}{2}\frac{\bar{b}_{0.75}\omega D^2\rho}{\mu}. \qquad (1)$$

For the fixed blade geometry Re depends on force as

$$\mathrm{Re} = \frac{0.75\pi\bar{b}_{0.75}}{\mu}\sqrt{\frac{\rho P}{\alpha}}.$$

In this formula Re is independent of the diameter and rotational frequency. So, from this, the range of Re that can be realized at the device defines mainly by the force range. As a whole all the devices provide forces form 0.1N to 3N at third device, from 3N to 12N at the second device and from 8N at the first device. The range of Re was $\mathrm{Re}=5\cdot 10^3\text{-}2\cdot 10^4$ at the third device, $\mathrm{Re}=2\cdot 10^4\text{-}10^5$ for the second device and $\mathrm{Re}= 10^5\text{-}1.2\cdot 10^6$ for the first device.

The investigation in the flow was conducted for pitches from 10^0 to 35^0 by the step of 5^0. The force and torque at fixed values of rotational frequencies by the varying the flow velocity were measured. This enables to find α and β as function of advanced ratio λ:

$$\lambda = \frac{2\pi V}{\omega D}.$$

At several practically constant values of Re was defined by (1).

It should be noted that Re must be defined through the total velocity rather than rotational velocity. But defining through the rotational velocity gives an error only of about 20% and the significant change in the characteristics corresponds to 3 times change of Re.

The values of efficiency for the propeller in the air flow were also calculated, which is defined as

$$\eta=\lambda\alpha/\beta.$$

III. Measurements results

The results of measurements for α, β, η without the flow as the functions of Re are shown in Figure 2. As Re varies in the wide range, the graphs are made in logarithmic. Results obtained at different devices are shown with different markers. The characteristics obtained at the second and third devices are in good coincidence with each other, but for the first device they differ very sharp. The reason of this fact is not clear. But we can make several assumptions. One of them is that in the first device the 1.1m propeller was used, and in the other devices 0.2m propeller was used. The surfaces of both the propellers have nearly the same smoothness but the surface imperfections can influence on the flows in the boundary layer in different ways. The boundary layer on the bigger model was 5 times thicker, so higher relative imperfections can cause earlier laminar-turbulent transition and increase turbulent friction. Both these factors lead to β increase. Such a characteristic change was observed in the experiments. The exceptions from this rule are results for the pitches of 10^0 and 35^0. For 35^0 it can be explained by a slight influence of roughness on the flow near the profile at supercritical angles of attack. For 10^0 its can be explained by the insufficient accuracy of a small torque measurement.

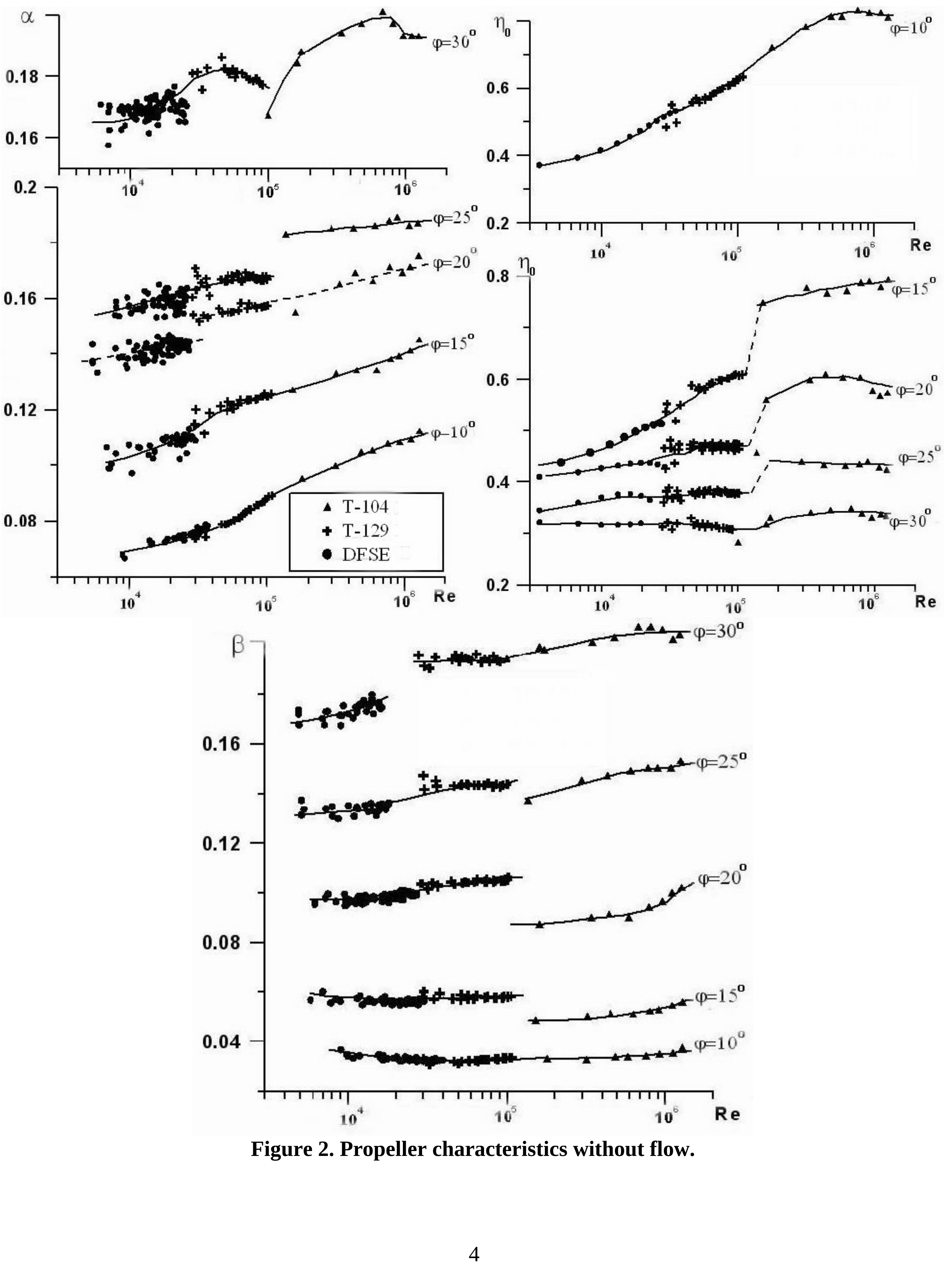

Figure 2. Propeller characteristics without flow.

From all the characteristics, the change of Re affects most strongly on the force coefficient. The value of a decrease is higher at low pitch angles. For example, at $\varphi_{0.75}=10^0$, for Re=$5\cdot10^3$ coefficient α decrease on 35% in comparison with Re=$1.2\cdot10^6$. For the moderate pith angles (for flow without separation) the function β(Re) has minimum. Propeller efficiency decreases significantly with the Re decrease. For example, at $\varphi_{0.75}=10^0$ in the range of Re=$1.2\cdot10^6$-$5\cdot10^3$ efficiency decreases 2 times, from 0.8 to 0.4.

It should be noted that at Re<10^4 coefficients α and β are practically constant.

Results for α and β as function of λ in the case of propeller in the flow are shown in Fig. 3. One can see that Re decrease influenced most dramatically α coefficient. The most abrupt change corresponds to the passage from Re=10^6 to Re=10^5.

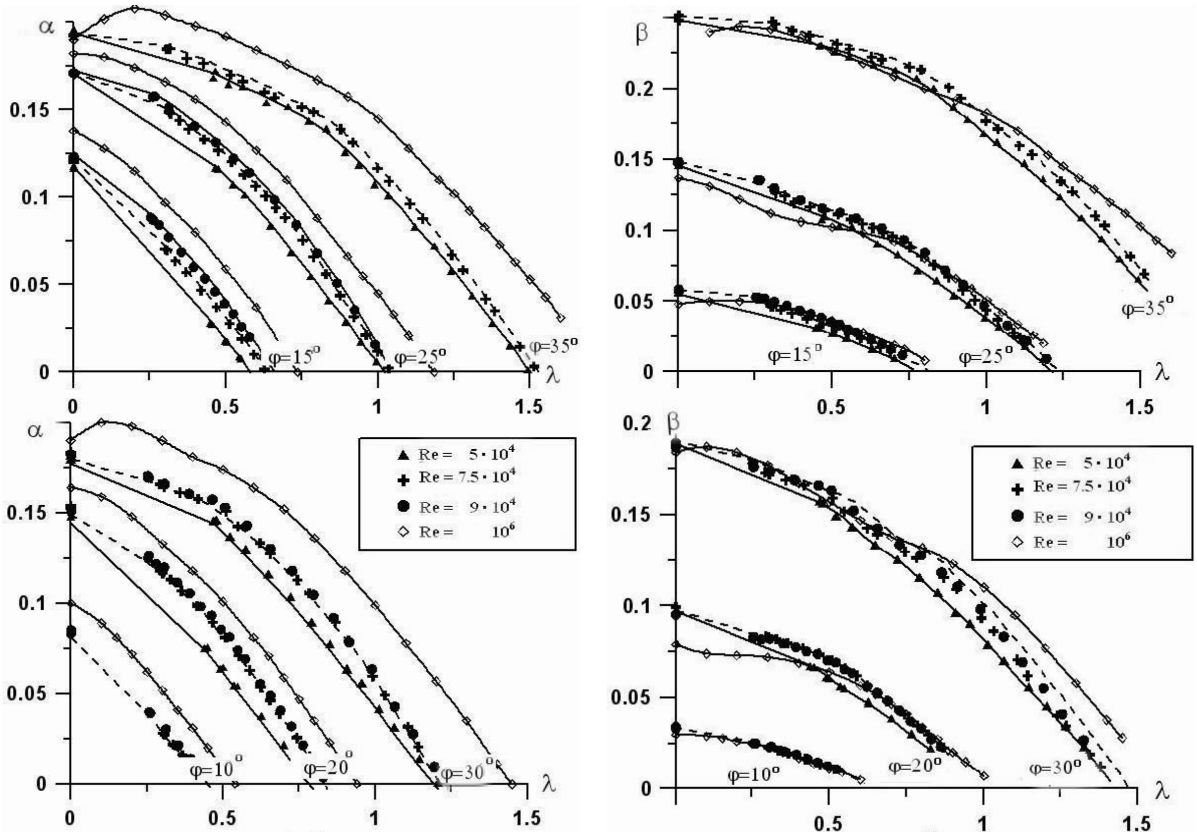

Figure 3. Propeller characteristics with flow

The influence of Re on β coefficient is not so simple. For $\varphi_{0.75}<30^0$ in the case of small λ coefficient β increases, and in the case of high values of λ coefficient β decreases. For intermediate λ values the function $\beta(\lambda)$ is not monotonous and has maximum at Re=(7.5-9) $\cdot10^4$. This “transition range” with non-monotonous β shifts to higher λ with the pitch increase. Such a behavior coincides with the well-known facts about the profile characteristics at low Re. At small λ the main part of β is due to profile drag which increase with the Re decrease. For the high λ a significant part of β is due to profile C_L which decreases with Re decrease. At high λ the blade profiles are at lower angles of attack and the influence of C_L is rather weak. Non-monotonous dependence β(Re) for intermediate λ is probably explained by the difference of “critical” Re corresponding to the abrupt changes of profile C_L and C_D.

Such a complex dependence of propeller characteristics on Re number rejects the possibility of converting the propeller characteristics obtained for Re>10^6 to the small Re numbers. On the other hand, the dependence of characteristics on the Re for the cases of presence and absence of flow are rather similar. So, one can estimate the change of characteristics with flow on the basis of characteristics without flow.

The dependence of efficiency on λ for various Re number is shown in Fig.4. One can see that the efficiency decreases significantly with Re decrease from self-similarity region. For the fixed pitch the maximum of η shifts to smaller λ values with the Re decrease. For the fixed λ the maximum of η shifts to higher values of pitch with the Re decrease. Figure 5 illustrates these facts.

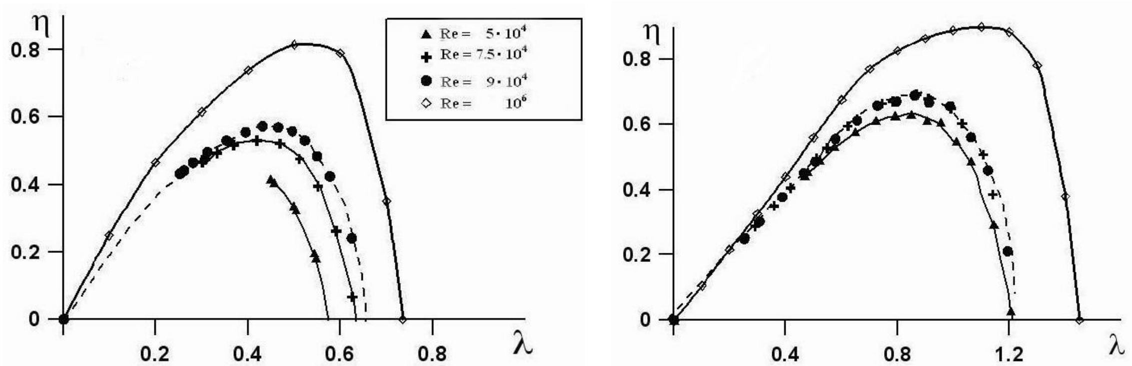

Figure 4. Propeller efficiency as function of λ and Re.

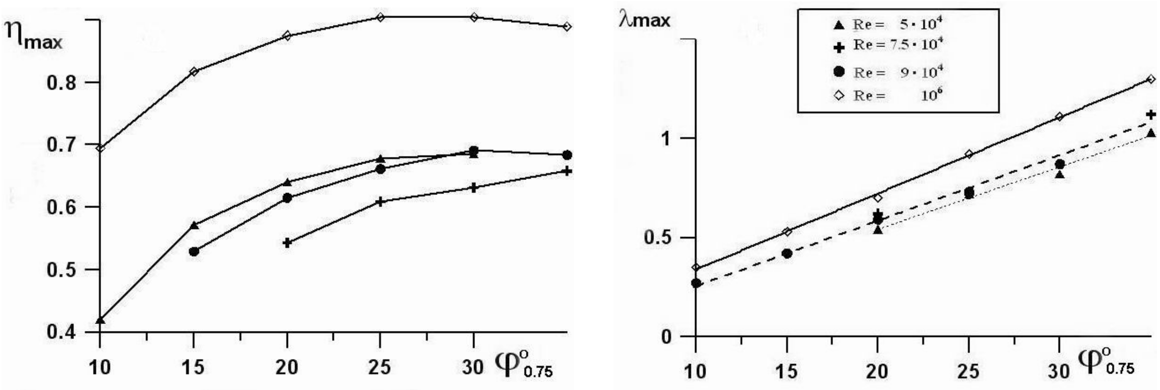

Figure 5. Conditions of propeller efficiency maximum

The results of theinvestigations show that the propeller designed for Re>10^6 and having good characteristics (η_{max}=0.9) at these Re, at low Reynolds numbers has less efficiency (η_{max}=0.67 at Re=$9\cdot10^4$, η_{max}=0.65 at Re=$5\cdot10^4$). So, special propellers for MAVs which are optimized for low Re numbers must be designed. Possible methods of efficiency increase at low Re can be: usage of special profiles, blade width and thickness increase, optimization of profile pitch along the blade, boundary layer control. High potential of efficiency increase was shown during the propeller design for “Black Widow” MAV, which efficiency is about 80%[3].

Acknoledgements

This investigation was conducted under support of RFBR (project N 06-08-01173).

Conclusions

1. The characteristics of propeller AV-31 in the wide range of Reynolds numbers were obtained.
2. The results obtained show that the characteristics become worse with Reynolds number decrease.
3. It is no worth using the propellers that are good enough in the self-similarity region for the low Re numbers.
4. Special methods can be proposed for the improvement of propeller characteristics.

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