FANS/PROPULSION UNITS AND FANS FOR HELICOPTER POWER PLANT COOLING SYSTEMS

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Basic approaches to development of aerodynamic projects of axial-flow fans to provide cooling for helicopter power plants, as well as fan/propulsion units and fenestrons are presented.

FANS FOR COOLING HELICOPTER POWER PLANTS

All Mil and Kamov helicopters are equipped with fans whose aerodynamic projects were developed by the TsAGI State Research Institute. These fans (Fig. 1) are of sophisticated design concept; they comprise the inlet guide vanes (IGV), impeller (R) and outlet guide vanes (OGV). The inlet guide vanes can have different setting angles thus regulating, i.e. obtaining the required air flow. The slot anti-surge device serves to widen the range of stable operation. The fan equipped with this device was installed in the V-12 helicopter. This fan (Fig. 2) had impeller flow meridional acceleration which made it possible to obtain very high pressure coefficients and to provide the required operating conditions at relatively low tip speeds. Fig 3 shows the fan from the Mi-6 helicopter. It also has a high pressure coefficient and incorporate the anti-surge device. Its modifications are installed in many other Mil and Kamov helicopters.

The fan aerodynamic projects are carried out by using the method developed by the TsAGI State Research Institute [1]. It is based on the method of determining optimal design parameters providing maximum efficiency, method of selecting airfoil cascade solidity and design angles of attack along the blade ring height obtained by generalising the results of experimental investigations of the air flow structure in relative motion. Shaping of blade rings, i.e. the definition of distribution of setting angles and radial airfoil camber, is carried out by using the airfoil cascade theoretical characteristics.

To obtain high efficiency and to widen the range of operating conditions with this particular efficiency, methods aimed at obtaining special options for impeller blades and outlet guide vanes have been developed.

FAN/PROPULSION UNIT THEORY

The FPU is used in subsonic aircraft to develop thrust and produce control forces. Executive aircraft powered with the FPU and manufactured in Great Britain and Germany are well known. Projects incorporating the FPU are being developed for other types of aircraft as well.

Here a method of determining parameters of a low-speed FPU is offered. New notions, such as a generalised external flight efficiency (GEFE) and hydraulic quality (hq) of the duct accommodating the FPU, are introduced. Equations expressing the FPU maximum GEFE and other optimal parameters have been obtained. It is shown how any deviation from optimal parameters affects the FPU power consumed and diameter. It is of particular importance in the matter of reducing the overall dimensions and weight of the FPU in particular and the aircraft in general. The decisive parameter in all the expressions is the hydraulic quality (hq). As in all other similar cases, the task is solved for one-dimensional flow.

Velocities, static pressure and air density are assumed to be constant in the air flow inlet and outlet sections (Fig. 4) of the FPU first blade ring as well as in the outlet section of the FPU duct from which the air flow is discharged; in this case, only velocities perpendicular to those sections are available. Air compressibility is ignored.

In our case the energy equation can be as follows:

$$p_v + б\frac{c\,v^2}{2} = \zeta\frac{c\,c_a^2}{2} + \frac{c\,v_2^2}{2} \qquad (1)$$

where p_v is the energy transferred to the air flow by the fan per air flow rate per second, it is equal to the fan total pressure; α is a coefficient of the air flow kinetic energy recovery determined by the airspeed v; ζ is the pressure loss factor of the duct accommodating the FPU; c_a is an average air flow velocity in the fan outlet section; v_2 is the air flow velocity leaving the FPU nozzle. In Equation (1) the left-hand portion expresses the total energy spent to overcome the duct hydraulic pressure and to produce a jet.

The flow rate equation is as follows:

$$Q = c_a \cdot \frac{\pi D^2}{4} (1 - \nu^2) \qquad (2)$$

where Q is the capacity of the fan having the diameter D and relative diameter ν = d/D, d being its hub diameter.

The momentum and thrust equation is as follows:

$$T = \rho\, Q\, (v_2 - v) \qquad (3)$$

Let us transform Equations (1), (2), (3) and present them as follows:

$$p_v = \frac{c\, v^2}{2} = \left[\left(\frac{v_2}{v} \right)^2 + \zeta \left(\frac{c_a}{v} \right)^2 - \text{б} \right] \qquad (4)$$

$$Q = \frac{\pi D^2}{4} (1 - \nu^2)\, \frac{c_a}{v} \cdot v \qquad (5)$$

$$T = c\, v^2 (1 - \nu^2) \left(\frac{v_2}{v} - 1 \right) \frac{c_a}{v} \cdot \frac{\pi D^2}{4} \qquad (6)$$

Let us introduce the FPU GEFE:

$$\eta_{out} = \frac{T \cdot v}{p_v \cdot Q} \qquad (7)$$

It is a ratio of the useful power determined by the vehicle flying at a speed V under thrust T to the FPU hydraulic power equal to p_v . Q transferred to the air flow. If p_v and T in Equation (7) are substituted by those in Equations (4) and (6) respectively, the following expression is obtained after simple transformations:

$$\eta_{out} = \frac{2\left(\frac{v_2}{v} - 1 \right)}{\left[\left(\frac{v_2}{v} \right)^2 - 1 \right] + \left[1 + \zeta \left(\frac{c_a}{v} \right)^2 - \text{б} \right]} \qquad (8)$$

It should be noted that for ζ=0, α= 1

$$\eta_{out} = \frac{2v}{v + v_2}$$

is a propeller perfect GEFE.

The fan hydraulic power is pv . Q=N . η, where N is the fan shaft horsepower, η is the fan efficiency. Using Equation (7), we shall obtain

$$N = \frac{T \cdot v}{\eta_{out} \cdot \eta} \qquad (9)$$

Taking into account the physical sense of the propeller perfect GEFE and the propulsion unit efficiency, the latter should be called an FPU generalised GEFE.

The analysis of Equation (8) shows that for the given c_a/v, ζ, α there is a maximum GEFE corresponding to $(v_2/v)_{opt}$. It follows from $d\eta_{out}/d(v_2 . v) = 0$ that

$$\left(\frac{v_2}{v} \right)_{opt} = 1 + \sqrt{1 + \zeta \left(\frac{c_a}{v} \right)^2 - \alpha} \qquad (10)$$

Let us call the second term in Equation (10) the reverse hydraulic quality of the duct $(v_2/v)\mu_{hq}$

$$\mu_{hq} = \sqrt{1 + \zeta\left(\frac{c_a}{v}\right)^2 - \alpha} \tag{11}$$

Now

$$\left(\frac{v_2}{v}\right)_{opt} = 1 + \mu_{hq} \tag{12}$$

and the maximum GEFE

$$(\eta_{out})_{max} = \frac{1}{1 + \mu_{hq}} \tag{13}$$

As $(v_2/v)_{opt}$. does exist, there are optimal pressure p_v, fan capacity, flow rate Q and, which is more important, FPU diameter D for the given c_a/v and μ_{hq}. Taking into account the fan efficiency η, the minimum power consumed by the FPU is as follows:

$$N_{min} = \frac{T \cdot v}{\eta \cdot (\eta_{out})_{max}} \tag{14}$$

The dependence of η_{out} versus v_2/v for different μ_{hd} is given in Fig. 5. It was obtained by using Equation (8) with account of Equation (11).

It is quite natural that investigations of how any deviation from the FPU optimal diameter D_{opt} and maximum efficiency can affect the power consumed are of the greatest importance, different values of the μ_{hq}. included:

$$D_{opt}^2 = \frac{4T}{\mu_{hq}\, \pi c\, v^2\, (1-\nu^2)(c_a / v)}$$

Making use of Equation (14), we shall obtain, that

$$\frac{\eta_{out}}{(\eta_{out})_{max}} = \frac{N_{min} \cdot \eta_0}{N \cdot \eta} \tag{15}$$

where the subscript 0 is related to the parameters for N_{min}, D_{opt}. The ratio of the diameters should be obtained from Equation (6), if it is introduced there instead of v_2/v. After some transformations, the following can be obtained:

$$\frac{N_{min} \cdot \eta_0}{N \cdot \eta} = \frac{1 + \mu_{\Gamma K}}{1 + \mu_{\Gamma K} \dfrac{D^2(1-\nu^2)/D_{opt}^2(1-\nu_0^2)}{2D^2(1-\nu^2)/D_{opt}^2(1-\nu_0^2)}} \tag{16}$$

Fig. 6 presents dependences obtained by using Equation (16). As can be seen, the power minimum is expressed quite vaguely, and the higher the hydraulic quality of the duct, the more allowable the deviation from the optimal diameter can be. Many problems inherent in the FPU are considered in Reference [2].The fan aerodynamic project is carried out by using the method described in Reference [1].

INVESTIGATIONS MADE TO WIDEN THE FIELD OF COST-EFFECTIVE PERFORMANCE OF ADJUSTABLE FANS/PROPULSION UNITS

Stringent requirements are imposed on built-in fans/propulsion units concerning the wide range within which the adjustment is provided to obtain high aerodynamic efficiency for aircraft having various operating conditions. Comprehensive investigations of different ways of adjustment of the above fans have been made in the TsAGI State Research Institute:

- Adjustment by changing the impeller blade setting angle
- Adjustment by changing the position of the IGV flaps
- Combined adjustment by changing the impeller blade setting angle and the position of the IGV flaps
- Adjustment by changing the geometry of flexible inlet and outlet guide vanes.

Adjustment by changing the impeller blade setting angle ensures a wide area of cost-effective performance. Fig. 7 shows characteristics of one of investigated fans. As can be seen, when the total fan efficiency remains 0.8, the fan capacity can become more than 3 times higher. However, in some cases, it is necessary to widen the area of the cost-effective performance not only from the point of view of capacity, but that of pressure as well. In this case adjustment by changing the position of the inlet guide vane flaps and combined adjustment by changing the impeller blade setting angles and inlet guide vane flaps can be used.

Fig. 8 shows a comparison of areas with the efficiency ≥0.8 for adjusting by changing the impeller blade setting angles and the inlet guide vane flaps. As can be seen, the range of cost-effective adjustment in pressure has widened upwards. At the same time, due to additional losses in the IGV the range of cost-effective performance in the area of high capacity has somewhat narrowed.

One of the factors limiting the range of cost-effective performance when adjustment by changing the position of the inlet guide vane flaps is used is the flow separation occurring at the joint of the rotatable and fixed portions of the blade at high angles of flap deflection. The range of flap deflection providing attached flow can be increased by using flexible inlet guide vanes having continuously variable camber.

The results obtained from the application of such a blade system are presented in Fig. 9, where a comparison of areas with the efficiency ≥0.8 for two options of adjusting the fans is given: for changing the flap setting angle and inlet guide vane camber. As can be seen, the adjustment by changing the inlet guide flexible vane camber makes it possible to greatly widen upward the area of cost-effective performance.

Another factor reducing the fan efficiency is a wide range within which the angle of attack of the outlet guide vanes changes when the operating point displaces along the fan characteristic. In this case, high positive and negative angles of attack are realised along the upper and lower boundaries of the area of operating conditions respectively. The effect of this factor can be reduced by changing the geometry of the blade ring; to do this, different configurations of the outlet guide vanes, such as those having rotatable blades, blades incorporating a droop nose, or flexible blades, can be used. Fig. 10 presents a comparison of the characteristics of the fan having the same impeller blade setting angle for two versions of the outlet guide vanes, i.e. when use is made of non-rotatable blades of invariable geometry and flexible blades with variable camber. As can be seen, the implementation of the method of changing the geometry of the blade ring makes it possible to essentially increase the fan cost-effectiveness in out-of-tolerance conditions.

ABOUT FENESTRON AERODYNAMIC PROJECT

It is well known that instead of a tail impeller the so-called fenestron is used in some of the helicopters made in France and the US as well as in Russia (Fig. 11). It is designed as a shrouded tail impeller (see, for instance Reference [3]). In this case high tip speed is assumed which results in a high noise level. Here it is suggested that its aerodynamic project should be carried out as that of an FPU. The fenestron calculations are made for helicopter hovering when v=0. Let us transform the equations for the FPU given above by introducing its tip speed u into them as a parameter. In this case, the energy and flow rate equations will become

$$p_v = \frac{c\,u^2}{2}\left[\zeta \bar{c}_a^2 + \left(\frac{v_2}{u}\right)^2\right] \qquad (17)$$

$$Q = u\,\bar{c}_a \frac{\pi D^2}{4}(1-\nu^2) \qquad (18)$$

Let us introduce the speed ratio $n=v_2/c_a$ into Equation (17). After that

$$p_v = \frac{c\,u^2}{2}(ж + n^2)\bar{c}_a^2 \qquad (19)$$

The following equation is used to determine the fenestron thrust:

$$T = u\;\bar{c}_a\,\rho\,Q\,n \qquad (20)$$

Here T, D, ν and u are given. The parameters ζ and n can be assessed in accordance of the fenestron structural and layout arrangement. After that the flow rate.

$$Q = \left[\frac{T}{n \cdot c}\,\frac{\pi D^2}{4}(1-\nu^2)\right]^{1/2} \qquad (21)$$

and average flow rate coefficient can be obtained

$$\bar{c}_a = \frac{T}{n \cdot c\,u\,Q} \qquad (22)$$

The coefficients of pressure and capacity ψ and φ respectively are as follows:

$$\psi = \frac{2p_v}{cu^2} , \quad \varphi = \varphi_a(1-\nu^2) \quad (23)$$

In Equation (23) $\varphi_a=c_a$. This is the way the coefficient of average axial velocity is usually designated in aerodynamic of the axial-flow fan. To carry out its aerodynamic project, it is necessary to know the coefficient of theoretical pressure ψ_t. It characterises the power that should be spent per unit of air flow rate per second. The coefficient of theoretical pressure $\psi_t=\psi/\eta$, where η is the fan efficiency. The value η is assessed [1] by the values ψ, φ_a, ν.

Thus, the design parameters of the fenestron/fan/propulsion unit are obtained. Shaping of its blade system providing high efficiency, minimal overall dimensions and weight should be implemented by using the method described in Reference [1].

For one of the helicopters equipped with a fenestron whose tip speed u=220 m/s the fan whose tip speed u = 150 m/s was projected by using the method described above. The expected reduction in the noise level is 10 dB. When a fenestron is developed, helicopter project designers select its thrust and diameter. The fenestron speed should be determined in co-operation with the specialists in the field of fan aerodynamics.

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