Study on torque of tangential fan in three operating mode

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Abstract. This paper is dedicated to the load moment calculation on the shaft of the tangential fan that is used with an electric motor to control the flight of an aircraft. The tangential fan can act as a propulsor and as an actuator for a gas-dynamic drive. In the latter case the tangential fan can work in three operating modes: compressor, generator and mixed mode because of different constructive compositions. In compressor mode the torque of an electric drive is transmitted to the tangential fan, which generates the thrust. In generator mode the tangential fan spins because of the incoming flow and the electric drive induces a current. In mixed mode the tangential fan spins because of the incoming flow and the electric fan additionally slows or fastens the flow. Load moment equations for the said modes are obtained using vector diagrams and the law of energy conservation. Solving the equations showed the load moment characteristics. It was observed that the increment of the load moment with increasing velocity of the incoming flow is non-linear. The obtained results enable the developers to estimate the power characteristics of an actuator based on a tangential fan at the design stage.

1. Introduction

General trends in the development of aviation and rocket technology are aimed at stricter requirements for actuating mechanism, including weight, dimensions and power density.

Weight, size and power characteristics are determined based on the parameters of the energy source for all types of drives. Efficient use of the incoming flow could satisfy the increased requirements.

The incoming flow usage requires implementing a special impeller machine, which makes it possible to accelerate the flow and reduce the braking pressure losses.

The base element of such impeller machines are impellers or rotors. The placement of a rotor with an electric motor inside of an aircraft leads to restrictions of their dimensions and the tangential direction of the air flow. With this direction of the incoming flow, it is preferable to use a tangential fan as it’s shown in figure 1, which consists of rotating drum-like rotor 4 with forward curved blades placed in a housing. The housing consists of an air-flow inlet 1, main cavity 2 and an air-flow outlet 3. Rotor is propelled by an electric motor.

At the moment, there are a lot of design schemes for aircraft actuating mechanisms including a tangential fan.

In some cases, the proposed schemes are classic propulsion. For example, FanWings [1], jetcraft (Stryelet) [2], etc. In other cases the proposed schemes works like propulsion and gas-dynamic drives at the same time that control the flight of an aircraft by creating thrust.
impulses, as well as reducing flow separation and reducing drag as a result. A typical example is a propulsion wing [3].

The advantages of the considered methods are low power consumption, the ability not only to create a control or driving force, but also to change the aerodynamic characteristics of the entire aircraft.

However, despite the existence of various design schemes and control principles, there are no methodology and design recommendations for similar devices. Research is carried out exclusively by numerical simulation or experimentally. Any change entails a large amount of numerical calculations and new experiments. Moreover, the main attention is paid to aerodynamic performance, while the method of designing an actuator with tangential fan and selection of an electric motor for it have been less of an interest.

Due to the complex nature of the flow no mathematical model has been presented that describes the parameters of air in the airflow inlet and outlet, main cavity in dependence of geometry of the rotor, housing and operating conditions. Therefore, determining equations describing dependence between the torque on the shaft of the rotor and the operating mode, external conditions and geometric parameters of the impeller is an urgent task.

2. Description of the tangential fan torque

The operating conditions of the tangential fan when it is installed on an aircraft are significantly different from the traditional operating conditions of the fan in terms of pressure drop, changes in air density, the possibility of an incident flow freely entering the air flow inlet. This specificity allows to consider the tangential fan’s work in three modes of operation [4].

The first mode is compressor. It is characterized by the absence of an incoming flow in the airflow inlet. In this case, a control signal is applied to the electric motor, the electric motor spins the rotor and the drive operates as a compressor, creating a high-speed flow and increasing the thrust of the outflowing stream. This mode is the most studied and it is represented in the propulsion wing.

The second mode is generator mode. The flow freely enters the impeller and spins it. Tangential fan with an electric motor in this case is used as a wind turbine generator.
The third mode is called mixed or combined mode and demonstrates the features of the first two modes. In this case, the flow falls freely on the rotor, but the speed of its rotation is regulated by an electric motor. Depending on the flow rate, the rotor can additionally accelerate the flow (at low values of the incident flow), level it (rotating in the direction of the flow) or slow it down (counter-flow or low rotation speeds at high flow rates).

In the first two modes, the control force created by the fan depends on the power of the electric motor. The required power of the electric motor depends on the rotation speed of the tangential fan and the load moment created by the flow on the blades. In generator mode, in order to estimate the generated voltage, it is necessary to have an idea of what range of moments will be created on the rotor of the tangential fan at different flight speeds.

Figure 2 shows the velocities on the impeller on a vector diagram. Zones I and II are emphasized corresponding to the steps through which the flow passes. Zone I represents the inlet zone in the rotor and zone II corresponds to the outlet.

In figure 2 are designated: $C$—absolute velocity; $U$—linear velocity; $V$—relative velocity; $C_{u1,2}$—the projection of the absolute speed into the normal direction of rotation; $C_r$—radial direction of the velocity; $\beta_{1,2}$—angles of the blades from the outer and inner sides of the impeller; $\alpha$—absolute flow angle.

![Figure 2. Velocity diagram on the rotor blades.](image)

The torque generated by the flow can be calculated using the equation for the amount of motion on the rotor [5]:

$$\frac{d(r\Delta mc_u)}{dt} = \Delta M,$$  \hspace{1cm} (1)

where $\Delta M$—the moment of all forces acting on the element with mass $\Delta m$ of the air flow relative to the center of rotation, $r$—the radius at which the element with mass $\Delta m$ is located from the center of rotation of the rotor, $C_u$—the projection of the absolute speed of the element with mass $\Delta m$ into the normal direction of rotation.

Bringing the expression (1) to the entire air flow inside the rotor:

$$\Sigma(\Delta md(rC_u)) = Mdt,$$  \hspace{1cm} (2)

where $M$—moment acting on the flow.
Assuming that the flow is steady and the flow passes through the blades of the impeller only once, the momentum in the air intake and in the air discharge channel (arbitrary sections in both regions) is invariable and equals to:

$$\Sigma(\Delta md(rC_u)) = dm(r_2C_{u2} - r_1C_{u1}) \Rightarrow M = \frac{dm}{dt}(r_2C_{u2} - r_1C_{u1}).$$

(3)

The difference signs in the last expressions depend on operating mode in consideration. If the compressor mode is considered, the rotor acts on the flow, transferring motion to it and accelerating the flow, which means it should be $(r_2C_{u2} - r_1C_{u1})$. In generator mode, the flow acts on the rotor blades and spins it, thus the moment is transferred from the flow to the rotor, which means it should be $(r_1C_{u1} - r_2C_{u2})$.

Equation (3) corresponds to the moment acting on the flow passing through one stage of the blade. In tangential fan, the flow passes through two stages, so equation (3) converts to:

$$M = \frac{dm}{dt}((r_2C_{u2} - r_1C_{u1}) + (r_1C_{u4} - r_2C_{u3})).$$

(4)

Absolute velocity projections are expressed from the velocity diagram:

$$C_{u1} = C_1 \cos \alpha_1 = V_1 \cos \beta_1 - U_1, \quad C_{u2} = C_2 \cos \alpha_2 = U_2 + V_2 \cos \beta_2,$$

$$C_{u3} = C_3 \cos \alpha_3 = U_2 - V_3 \cos \beta_2, \quad C_{u4} = C_4 \cos \alpha_4 = V_4 \cos \beta_1 + U_1.$$  

(5)

Output relative speeds correspond to the input ones according to the equation:

$$V_2 = \mu_T V_1; \quad V_4 = \mu_T V_3,$$

where $\mu_T$—coefficient of speed loss on the blades.

For the next step, the speed velocity must be solved at the input to the first stage, where two speeds are unknown. Since for the selection of an electric motor it is enough to know the maximum values of speeds and based on the analysis of the results of numerical modeling of tangential fans, an assumption was made $C_1 = 0.75U_1$.

The rotor angular speed is related to the linear:

$$U_2 = r_2\Omega_r, \quad U_1 = r_1\Omega_r.$$  

(7)

Thus, in the compressor mode, two sides and the opposite angle are known from the velocity triangle at the entrance of zone I, which means that the relative speed $V_1$ is:

$$V_1 = C_1 \frac{\sin(\delta)}{\sin(180 - \beta_2)} = C_1 \frac{\sin(180 - \beta_2 - \arcsin D)}{\sin(\beta_2)},$$

$$\sin \gamma = \frac{C_1}{U_1} \sin(\beta_2), \quad D = \frac{C_1}{U_1} \sin(\beta_2), \quad \gamma = \arcsin D, \quad \delta = 180 - \beta_2 - \gamma.$$  

(8)

From the experimental data obtained for the compressor mode [6], it can be concluded that the flow is accelerated at both stages, but it narrows before entering the second stage. This narrowing corresponds to the ratio $\Delta S$ of the flow cross-sections of the rotor arcs in the area of the air inlet and the outlet. In this case, $V_3$ can be expressed as:

$$V_3 = \frac{C_{r3}}{\sin(\beta_2)} = \frac{C_{r1}D_1}{D_2 \sin(\beta_2)} \Delta S, \quad C_{r1} = C_1 \cos(90 - \alpha_1).$$  

(9)
The angle $\alpha_1$ is found from the parallelogram of velocities:

$$\alpha_1 = 180 - \arccos \left( \frac{U_2^2 + C^2_1 - V_2^2}{2U_1C_1} \right).$$

(10)

The final equation (3) can be written as:

$$M = \frac{dm}{dt} \left( r_2(U_2 + V_1 \mu_T \cos \beta_2) - r_1(V_1 \cos \beta_1 - U_1) \right)$$

$$+ \left( r_1(V_3 \mu_T \cos \beta_1 + U_1) - r_2(U_2 - V_3 \cos \beta_2) \right) =$$

$$= \frac{dm}{dt} \left( r_2(r_2 \Omega_r + V_1 \mu_T \cos \beta_2) - (V_1 \cos \beta_1 - r_1 \Omega_r) \right)$$

$$+ \left( r_1 \left( \frac{C_{r_1} D_1}{D_2 \sin(\beta_2)} \Delta S \mu_T \cos \beta_1 + r_1 \Omega_r \right) - r_2(r_2 \Omega_r - V_3 \cos \beta_2) \right).$$

(11)

Mass flow rate $dm/dt$ could then be determined using flow coefficient $\varphi$:

$$\varphi = \left( \frac{dm}{dt} \right)(D_1 b U_1)^{-1},$$

(12)

where $b$—length of the rotor. For compressor operation, it can be assumed that $\varphi = 1$.

In the generator mode, the incoming flow acts on the rotor. The flow angle $\alpha$ is controllable and depends on the angle of attack. The circumferential force on the rotor blades arises due to the action of the air flow. The flow enters the blade channels along the axis of the air intake and exits tangentially relative to the trailing edge of the blade. Then the flow again passes through the blades and enters the air discharge channel. Accordingly, equation (4) will take the form:

$$M = \frac{dm}{dt} \left( (r_1 C_{u_1} - r_2 C_{u_2}) + (r_2 C_{u_3} - r_1 C_{u_4}) \right).$$

(13)

The flow rate $dm/dt$ in generator mode depends on the parameters of the air intake and is determined as:

$$\frac{dm}{dt} = \rho V_0 S_{in};$$

(14)

$$M = \frac{dm}{dt} \left( (r_1 C_{u_1} - r_2 C_{u_2}) + (r_2 C_{u_3} - r_1 C_{u_4}) \right).$$

(15)

The rest of the dependencies correspond to the equations presented in (5)–(9). So the final equation (3) for generator mode can be written as:

$$M = \rho V_0 S_{in} \left( C_1 \cos \alpha_1 - r_2(U_2 + V_1 \mu_T \cos \beta_2) \right)$$

$$+ \left( r_2(U_2 - V_3 \cos \beta_2) - r_1(V_3 \mu_T \cos \beta_1 + U_1) - r_2(U_2 - V_3 \cos \beta_2) \right)$$

$$= \rho V_0 S_{in} \left( C_1 \cos \alpha_1 - r_2(U_2 - V_1 \mu_T \cos \beta_2) \right)$$

$$+ \left( r_2(r_2 \Omega_r - V_3 \cos \beta_2) - r_1 \left( \frac{C_{r_1} D_1}{D_2 \sin(\beta_2)} \Delta S \mu_T \cos \beta_1 + r_1 \Omega_r \right) \right).$$

(16)

Mixed mode is the most difficult as it differs in the mutual influence of the rotor and flow. For the sake of simplicity, it was decided to consider two cases.

At low speeds of the incoming flow, it can be assumed that the rotor transmits the moment to the flow, which means that the moment on the rotor shaft is determined by the equation (14).

In the second case at a high flow rate the rotor turns into a load, and the moment on the rotor shaft is presented by the equation (16).
It should be noted that the equation of torque presented in a simplified manner without taking electric motors, geometry of the inlet and the location inside the shaft impeller into account. Considering these factors should be the next step. In general, it could be noted that their influence would be rather negative: a narrow inlet and a large diameter shaft inside the impeller will reduce the value of the mass flow, hence, the moment. Therefore, the real moment on the impeller shaft would be less than the calculated one. However, the proposed simplifications do not interfere with the preliminary calculation of the moment, which means that knowing the parameters of the rotor and velocity of the incoming flow or rotational speed of the wheel, the load torque can be calculated.

The maximum rotational speed of the rotor is calculated based upon the operating modes. In compressor and mixed mode at low velocities of the incoming flow, it corresponds to the maximum rotational speed of the electric motor. In generator mode and mixed mode at high flow velocities, it depends on the speeds at which the aircraft would fly and also on the material of the impeller (on its mass and moment of inertia).

In case of operating in all three modes, the required power is selected as the maximum calculated value.

3. Calculation results
Equations (11), (12), (16) were used to calculate the torque on the shaft of the rotor with the parameters presented in table 1 and figure 1.

| Geometry parameters | Geometry parameters |
|---------------------|---------------------|
| \( Z \), number of blades | 24 |
| \( \beta_1 \), blade angle outer | 30° |
| \( \beta_2 \), blade angle inner | 90° |
| \( b \), length of the rotor | 15 mm |
| \( \Delta S \), arcs inlet/outlet | 0.915 |
| \( D_1 \), impeller outer diameter | 300 mm |
| \( D_2 \), impeller inner diameter | 210 mm |
| \( l \), blade chord length | 52 mm |

As it can be seen, non-linear torque graphs are presented in figures 3 and 4. Partially, the behavior of the graphs relates to the fact that the flow passes through the blades twice, thus accelerating twice. In this case, the obtained graphs correspond to the values of the steady-state

**Figure 3.** Compressor mode’s dependence of torque on rotation speed.

**Figure 4.** Generator mode’s dependence of the torque on the shaft on the flight speed.
moment on the shaft during prolonged rotation of the rotor, and therefore are not suitable for assessing its dynamics. In addition, it has to be noted that the real values of the moments created by the flow should be lower, since the equations do not take into account the friction and a decrease in the flow rate coefficient. Thus, the electric motor selected according to the graphs should be sufficient for operating in the selected mode.

4. Conclusions
This research demonstrates calculation of the load moment on the shaft of tangential fan in three various operating modes that arise during its usage as an actuating mechanism of an aircraft. The main analytical dependencies and accepted simplifications are given. A simplified analytical equation was presented to determine the load moment on the impeller shaft relative to three operation modes and rotor’s geometric dimensions. The obtained equations can be used for choosing an electric motor and for preliminary dynamic parameters evaluation of the tangential fan at the design stage.

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