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Mechanical Engineering

Study of Characteristics of Coaxial Propeller Systems

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The paper reports on coaxial propeller system which is placed in a guide tube and has two independent shafts, unlike traditional and existing coaxial propeller systems. The stand was prepared during the research process. The experiments were conducted on the mentioned stand and on the basis of the obtained results the modes in which coaxial propeller system is the most effective were defined. The results of the theoretical and experimental studies show the regularity between the number of the propeller revolutions, the distance between them and the produced thrust force. The efficiency of the research mechanism was evaluated. Difference between the useful spent power per unit during the operation of single-prop and double-prop systems was revealed. In terms of practical application, the goal of the research is to improve UAVs and their power units, because engines are the main components of any aircraft. *© 2024 Bull. Georg. Natl. Acad. Sci.*

aviation, coaxial propeller, optimization, efficiency

Initially, coaxial propeller systems were designed to enhance aircraft speed and engine efficiency, thereby reducing fuel consumption. However, throughout various periods of the last century, scientists encountered several challenges related to the effective utilization of coaxial propellers on various types of aircraft [1].

The developmental phases of coaxial propellers are categorized into five distinct stages: pioneers (before 1940), golden years (1940-1950), Western aircraft (1950s onwards), Soviet-Russian aircraft (1950s onwards), and modern development onwards 1980s [2].

While the coaxial propeller system and its attributes have been subject to some degree of study, the question remains whether there exists further room for enhancement and refinement of its various features. This question has become especially relevant with the rise of unmanned aerial vehicles [3]. unmanned aerial vehicles (UAVs), which are rapidly gaining drag within the aviation domain. Consequently, it is vital for their development to reassess all research endeavors to determine areas that could yield greater benefits beyond a mere co-axial propeller system [4, 5].

The primary component of the research involves mathematical calculations and the comparison of the resulting data with the outcomes from practical tests conducted on the mentioned device.

Description of the test device. At the outset of the research, a test device was designed and fabricated specifically for conducting experiments on the coaxial propeller system. This device comprises a tube with a diameter denoted as *D*, within which two separate electric motors and propellers are positioned on each motor. The device allows for the adjustment of the distance, denoted as d, between the propellers. This feature facilitates the study of the relationship between the drag force coefficient, represented as $\alpha\left(d\right)$, and the distance d between the propellers during the research phase (Fig. 1).

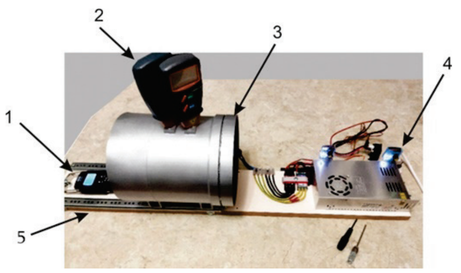

Fig. 1. Description of co-axial propeller test device.

A pipe with a diameter *D* is affixed to a stationary surface using a guide, designated as 5, which mirrors the dynamometer 1 on the opposing side of the drag force vector. Additionally, the test device is equipped with two independent tachometers, denoted as 2, enabling the measurement of the rotations per minute (RPM) of each engine. For the determination of efficiency and performance coefficients, the test device incorporates two independent volt-ammeters, marked as 4, which are linked to each motor. These instruments display the current (in amperes) and voltage (in volts) during various modes of motor operation, aiding in the calculation of power consumption by the engines throughout the research process.

Materials and Methods

To estimate the pulling force of a single propeller enclosed within a guide tube, we examine a propeller consisting of *N* wing segments. For simplicity, let's assume that each wing has the same width, denoted as *b*, and diameter, labeled *D*, along with an identical lifting force coefficient C_y throughout the entire section (refer to Fig. 2). The propeller rotates at a fixed frequency of *n* rotations per minute (rpm).

Let's calculate the drag force generated by the propeller. Based on the established aerodynamic ratio, the force exerted on the wing element with a width b and a length dr will be equal to

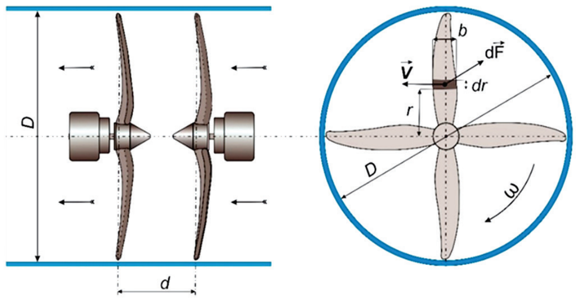

Fig. 2. Parameters of the propeller placed in the guide tube.

$$dF = C_y \cdot \frac{\rho_{air} \cdot \upsilon^2}{2} \cdot dS = C_y \frac{\rho_{air} \left(\omega \cdot r\right)^2}{2} \cdot b \cdot dr, \quad (1)$$

where ρ_{air} represents the air density, v is the rotational speed of the given element given by $\upsilon = \omega \cdot r$, and $\omega = \frac{2\pi \cdot n}{60}$ denotes the angular speed of the propeller. Considering formula (1), the total drag force exerted by the propeller will be equal to:

$$F = \frac{1}{2} \cdot N \cdot C_y \cdot \rho_{air} \cdot \omega^2 \cdot b \cdot \int_0^{D/2} r^2 dr = \frac{1}{48} \cdot N \cdot C_y \cdot \rho_{air} \cdot \omega^2 \cdot b \cdot D^3. \quad (2)$$

If we introduce the propeller coverage coefficient:

$$\lambda = \frac{S_{prop.}}{S_{\sec.}} = \frac{N \cdot b \cdot D/2}{\pi \cdot D^2/4} = \frac{2 \cdot N \cdot b}{\pi \cdot D}. \quad (3)$$

Then, equation (2) will take the form:

$$F = \frac{C_y \cdot \pi^2}{21600} \cdot \rho_{air} \cdot n^2 \cdot \lambda \cdot S_{\text{sec.}} \cdot D^2 = \alpha \cdot \rho_{air} \cdot n^2 \cdot \lambda \cdot S_{\text{sec.}} \cdot D^2, \quad (4)$$

where $S_{\text{sec}} = \pi \cdot D^2 / 4$ represents the cross-sectional area of the guide pipe, and $\alpha = \frac{C_y \cdot \pi^2}{21600}$ stands as the dimensionless coefficient of the lifting force. The resultant equation fully conforms to the form $F = \alpha \cdot \rho \cdot n^2 \cdot D^4$, as proposed by [6].

Considering a system comprising two coaxial propellers enclosed within a guide tube rotating in opposite directions at the same number of revolutions, the anticipated image of the lifting force of the system should mirror the equation (4), with the sole distinction lying in the coefficient of the lifting force, which will be a function of the distance between the propellers. Other additional parameters unrelated to the geometric characteristics of the propellers themselves will remain independent. Thus, the pulling force will be expressed as:

$$F = \alpha(d) \cdot \rho_{air} \cdot n^2 \cdot \lambda \cdot S_{\text{sec.}} \cdot D^2 \quad (5)$$

One of the objectives of the conducted experimental research was to ascertain the nature of the lifting force coefficient $\alpha(d)$ and to assess its degree of consistency across various numbers of revolutions.

An experiment was undertaken to explore the relationship of the coefficient) $\alpha(d)$ with the distance between the propellers. Force values corresponding to specific propeller spacings (comprising 13 distinct points) were meticulously measured. The coefficient $\alpha(d)$ was derived from equation (5) as $\alpha(d) = F / \left(\rho_{air} \cdot n^2 \cdot \lambda \cdot S_{\text{sec.}} \cdot D^2\right)$.

Utilizing the method of least squares [5], a continuous curve was fitted to the data points, approximating a 2nd-order polynomial. (Although coefficients for 3rd and 4th order polynomials were also calculated, the significantly limited number of data points led us to halt at the 2nd order.) The resulting polynomial takes the form:

$$\alpha(d) = a_1 \cdot d^2 + a_2 \cdot d + a_3 \quad (6)$$

where $a_1 = -6.0075 \cdot 10^{-8} mm^{-2}$, $a_2 = 9.5623 \cdot 10^{-6} mm^{-1}$ and $a_3 = 1.2594 \cdot 10^{-3}$, The graph depicting the relationship between the lifting force coefficient and the distance between the propellers is provided in Fig. 3.

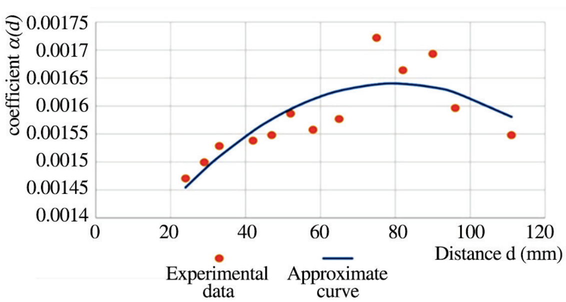

Fig. 3. Dependence of the lifting force coefficient on the distance between the propellers.

The maximum value of the coefficient $\alpha(d)$, and therefore, the maximum drag force, is reached when $d' = -\frac{a_2}{2 \cdot a_1} = 79.5860$ mm.

The corresponding value of the coefficient is $\alpha(d') = 1.6909 \cdot 10^{-3}$ and the maximum drag force, according to the formula $F_{\max} = 1.6950N$.

A practical experiment was conducted for varying values of propeller rotation numbers and distances between them. The experiment yielded measurements of lift force and ejected air velocity. Theoretical values of the $\alpha(d)$ coefficient, determined by formula (6), and experimental values derived from (5), were calculated. Subsequently, to compute the coefficient of action of the experimental device, the current forces on the electric drives were determined, maintaining a constant voltage throughout the experiment at $U_1 = U_2 = 12V$. The data are presented in Table 1.

Table 1. Various experimental data

$\rho_{air} = 1.225$ kg/m^3, $D = 150$ mm, $b = 10$ mm, $N = 2$, $\boldsymbol{d = 20}$ **mm**, $\boldsymbol{U_1 = U_2 = 12}$ **v**						
	F_{exp} (N)	v_{air} (m/sec)	$\alpha(d)_{exp} \times 10^3$	$\alpha(d)_{th} \times 10^3$	I_1 (a)	I_2 (a)
$n = 4000\ rpm$	0.85	6.3	1.2850	1.4266	0.86	1.15
$n = 6000\ rpm$	2.25	9.4	1.5117	1.4266	2.18	3.00
$n = 8000\ rpm$	4.30	12.0	1.6250	1.4266	4.21	6.00
$\rho_{air} = 1.225$ kg/m^3, $D = 150$ mm, $b = 10$ mm, $N = 2$, $\boldsymbol{d = 35}$ **mm**, $\boldsymbol{U_1 = U_2 = 12}$ **v**						
	F_{exp} (N)	v_{air} (m/sec)	$\alpha(d)_{exp} \times 10^3$	$\alpha(d)_{th} \times 10^3$	I_1 (a)	I_2 (a)
$n = 4000\ rpm$	0.90	6.5	1.3605	1.5204	0.83	1.15
$n = 6000\ rpm$	2.35	9.2	1.5789	1.5204	2.18	2.96
$n = 8000\ rpm$	4.40	12.5	1.6629	1.5204	4.45	6.47
$\rho_{air} = 1.225$ kg/m^3, $D = 150$ mm, $b = 10$ mm, $N = 2$, $\boldsymbol{d = 50}$ **mm**, $\boldsymbol{U_1 = U_2 = 12}$ **v**						
	F_{exp} (N)	v_{air} (m/sec)	$\alpha(d)_{exp} \times 10^3$	$\alpha(d)_{th} \times 10^3$	I_1 (a)	I_2 (a)
$n = 4000\ rpm$	0.95	6.3	1.4361	1.5873	0.83	1.16
$n = 6000\ rpm$	2.35	9.4	1.5789	1.5873	2.18	2.97
$n = 8000\ rpm$	4.40	12.0	1.6629	1.5873	4.36	6.00

It is noteworthy that, based on the experimental data, a slight increase in the coefficient $\alpha(d)$ can be observed with the increase in the number of rotations of the propellers. This observation warrants further investigation. In this regard, let's average the experimental data of this quantity for each specific number of rotations and compare it with the corresponding theoretical values:

- For $n = 4000\,rpm,\ \alpha(d)_{\text{exp.}} = 1.4739 \cdot 10^{-3}$, which is 3.32% higher than the corresponding theoretical value.
- For $n = 6000\,rpm,\ \alpha(d)_{\text{exp.}} = 1.5341 \cdot 10^{-3}$, which is 0.90% higher than the corresponding theoretical value.
- For $n = 8000\ rpm,\ \alpha(d)_{\text{exp.}} = 1.5593 \cdot 10^{-3}$, which is 1.76% less than the corresponding theoretical value.

Based on the obtained experimental data, we can calculate the efficiency coefficient of the device. By standard definition, this ratio is the ratio of useful work to total work, or alternatively, the ratio of useful power to total power:

$$\eta = \frac{A_{eff.}}{A_{total}} = \frac{P_{eff.}}{P_{total}}. \tag{7}$$

According to the established methodologies, to compute the useful power for evaluating the coefficient of action of propeller engines installed on aircraft, it is customary to consider the motion of the aircraft as $P_{eff.} \sim F_{drag} \cdot \upsilon_{aircraft}$, where F_{drag} represents the thrust force generated by the engine, and $\upsilon_{aircraft}$ denotes the aircraft speed. In the context presented here, the useful power amounts to zero. Consequently, an alternative qualitative assessment is warranted. In this scenario, the sole energy characteristic deemed as effective work is the kinetic energy of the airflow emanating from the "nozzle," whereby the drag force generated by the machine will be directly proportional to this energy.

If we assume that the machine operates for a duration Δt, then the total energy consumed will be equivalent in magnitude to the electrical energy expended on the propeller drives, representing the total work incorporated in formula (7). We express this as:

$$A_{total} = (U_1 \cdot I_1 + U_2 \cdot I_2) \cdot \Delta t \text{, and power } P_{total} = \frac{A_{total}}{\Delta t} = U_1 \cdot I_1 + U_2 \cdot I_2. \tag{8}$$

As for the kinetic energy of the ejected airflow, it can be calculated as follows. Let's assume that within a time interval Δt, an airflow with a mass Δm will be discharged from the "nozzle". The mass of air $\Delta m = \rho_{air} \cdot \Delta V$, where ΔV represents the volume of a cylinder with a diameter D and a height $h = \upsilon_{air} \cdot \Delta t$, thus $\Delta V = \frac{\pi \cdot D^2}{4} \cdot \upsilon_{air} \cdot \Delta t$. Consequently, the expression for the effective work will be formulated as:

$$A_{eff.} = \frac{\Delta m \cdot \upsilon_{air}^2}{2} = \frac{\pi \cdot \rho_{air} \cdot D^2 \cdot \upsilon_{air}^3}{8} \cdot \Delta t \text{, and power } P_{eff.} = \frac{A_{eff.}}{\Delta t} = \frac{\pi \cdot \rho_{air} \cdot D^2 \cdot \upsilon_{air}^3}{8} \cdot \Delta t . \tag{9}$$

Finally, from formula (7) for the effective coefficient of action is obtained with:

$$\eta = \frac{P_{eff.}}{P_{total}} = \frac{\pi \cdot \rho_{air} \cdot D^2 \cdot \upsilon_{air}^3}{8\left(U_1 \cdot I_1 + U_2 \cdot I_2\right)} . \tag{10}$$

Clearly, formula (10) signifies the efficiency of the presented mechanism rather than the coefficient of action in its strict interpretation. To elucidate the mechanism's efficiency more explicitly, it is advantageous to compare the scenario involving two coaxial propellers with the efficiency of a simpler mechanism consisting of just one propeller. This involves considering the ratio $\eta_{two.prop.} / \eta_{one.prop.}$.

Certainly, based on the data obtained from tests conducted on the single propeller system, we can calculate the ratio of the efficiency coefficients for all points using formula (10). The results will be presented in Table 2.

Table 2. The ratio of the efficiency coefficients

$\rho_{air} = 1.225$ kg/m^3, $D = 150$ mm, $b = 10$ mm, $N = 2$, $U_1 = U_2 = 12$ v			
	$d = 20$ mm	$d = 35$ mm	$d = 50$ mm
$n = 4000$ rpm	1.2779	1.4248	1.2904
$n = 6000$ rpm	1.5067	1.4233	1.5161
$n = 8000$ rpm	1.0871	1.1483	1.0707

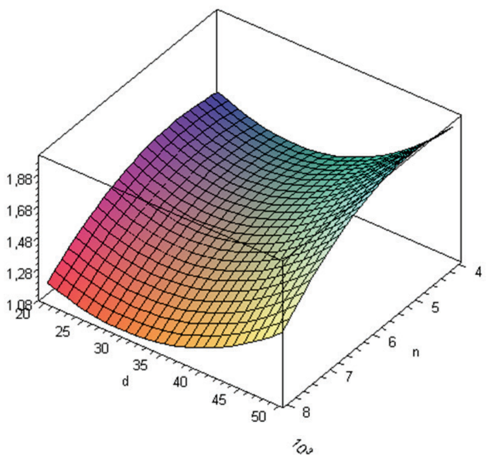

Fig. 4. $\eta_{two.prop.} / \eta_{one.prop.}$ illustrates the correlation between the spacing of the propellers and the corresponding number of rotations.

On the whole, the values of the ratio $\eta_{two.prop.} / \eta_{one.prop.}$ vary with both the distance between the propellers and their number of rotations. To enhance clarity, these data can be represented in the form of a 3D graph, as depicted in Fig. 4. The results of the conducted experiments, it is evident that the maximum efficiency of the mechanism is attained at $n = 6000$ *rpm* and $d = 50$, $\eta_{two.prop.} / \eta_{one.prop.} = 1.5161$.

Conclusions

The results obtained from the conducted theoretical and experimental studies reveal the correlation between key characteristics of air propellers, including the number of revolutions, the distance between them, and the resulting drag force. The theoretical approximation of the dependence of the lifting force coefficient on the distances between the propellers was achieved through a second-order polynomial.

It was observed that at a fixed distance between the propellers this coefficient tends to marginally increase with an increase in the number of revolutions. Throughout the research, the efficiency of the investigated mechanism was assessed, indicating the disparity between the useful power per unit of expended power during the operation of single-propeller and two-propeller systems. The collected data are presented in the form of a 3D graph to enhance the clarity of the research findings. It was discerned that the maximum efficiency of the mechanism within the conducted experiment occurs at $\eta_{two.prop.} / \eta_{one.prop.} = 1.5161$, underscoring the energy efficiency of the two-propeller system.

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მექანიკის ინჟინერია

თანაღერძული საჰაერო ხრახნის სისტემის მახასიათებლების კვლევა

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(წარმოდგენილია აკადემიის წევრის რ. ხუროძის მიერ)

ნაშრომში განხილულია თანაღერძული ხრახნის სისტემა, რომელიც მოთავსებულია მიმმართველ მილში და გააჩნია ორი დამოუკიდებელი ლილვი, განსხვავებით ტრადიციული და უკვე არსებული თანაღერძულ ხრახნთა სისტემებისგან. კვლევის პროცესში დამზადდა სტენდი. ჩატარებულია ექსპერიმენტები აღნიშნულ სტენდზე. მიღებული შედეგების საფუძველზე შეგვიძლია დავასკვნათ, თუ რა რეჟიმებშია მილში მოთავსებული თანაღერძული ხრახნების სისტემა მაქსიმალურად ეფექტური. ჩატარებული თეორიული და ექსპერიმენტული კვლევებით მიღებული შედეგები გამოსახავს საჰაერო ხრახნების ბრუნთა რიცხვებს, ხრახნებს შორის მანძილსა და მიღებული წევის ძალას შორის კანონზომიერებას. კვლევის პროცესში შეფასდა საკვლევი მექანიზმის ეფექტურობა, რაც გულისხმობს სასარგებლო სიმძლავრეებს შორის განსხვავებას ერთეულ დახარჯულ სიმძლავრეზე, ერთ- და ორხრახნიანი სისტემების მუშაობის დროს. პრაქტიკული გამოყენების თვალსაზრისით კვლევის მიზანს წარმოადგენს უპილოტო საფრენი აპარატების და მათი ძალური დანადგარების სრულყოფა.

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