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EXPERIMENTAL STUDY OF THE CHARACTERISTICS OF FANS FOR SMALL UAVs

The subject *of this study is the determination of the performance characteristics of small UAV fans across a wide range of rotor speeds.* ***The objective*** *of this work is to improve the accuracy of flow-parameter measurements in the inter-blade passage of a tandem fan with a combined toroidal-spiral blade tip by digital modeling and verification of the results on a specially designed experimental test bench.* ***The task:*** *to propose an experimental test bench for studying the power characteristics of UAV thrust fans of both enclosed and open types. The problem of selecting a fan for a power plant is quite complex, given the wide range of aircraft for various purposes, especially small-sized ones. Sometimes it is necessary to choose from a wide range of model fans that can be produced quite quickly using a 3D printer. Therefore, the development of an experimental setup that, while featuring simple design solutions, would meet the necessary operational requirements and specified metrological characteristics is undoubtedly a pressing task.* ***The following results were obtained.*** *The experimental test bench proposed (and tested) by the authors is technologically simple and enables rapid determination of comparative and operational characteristics of fans in the relevant model range, with the aim of selecting the optimal option from the customer's perspective. A method for determining the main energy-efficiency characteristics of fans for small UAVs is presented (the experiments were conducted primarily on tandem fans; in which both rows of blades are connected by a toroidal-spiral tip). A distinctive feature of the method and the developed experimental setup is that it allows for the separation of the thrust and torque measurement channels, which ensured their independent measurement. This made it possible to obtain* ***scientifically sound simulation results*** *through practical verification. During the design of the setup, particular attention was paid to the channels for recording efficiency and power factor, as these parameters were measured indirectly—their values were calculated from other measured parameters rather than determined directly. It should be noted that the experimental test bench was designed to allow for the study of both open and enclosed fans. Another distinctive feature of the setup is that it allows one to obtain fan performance characteristics, such as the thrust dependence T=f(n), power – P=f(n), and efficiency η=f(n) over a wide range of rotor rotational speeds (n=0…50,000 rpm), which is very important for small UAVs. The results obtained were used to derive comparative characteristics of a model series of fans for a UAV engine with a thrust of 50 kH, which are currently the most prevalent, especially in combat conditions. Further expansion of the system's functional capabilities is planned. Therefore, during its design, reserve channels for measuring parametric information were incorporated.*

Keywords*: unmanned aerial vehicle; fan; aerodynamic characteristics; thrust; power; experimental setup; parameter.*

Introduction

Experience shows that bench testing has a significant impact on the design process and the selection of the optimal power plant for UAVs. Bench tests provide a wealth of information about the test object and help validate design assumptions. Furthermore, the results of field tests can be used to improve prediction methods, such as computational fluid dynamics (CFD), control algorithms, and empirical or semi-empirical methods [1].

Data from real-world tests allow for improving the accuracy of numerical calculations when modeling in the ANSYS simulation environment.

To verify numerical calculations when modeling in the ANSYS simulation environment and to accurately assess the characteristics of the fan and motor used in UAVs, a reliable test bench is required. Therefore, special attention is paid to the design and construction of test benches for measuring fan thrust and evaluating its characteristics [2, 3, 4].

Fan testing typically involves evaluating their performance under various operating conditions [5, 6, 7]. Fan performance (its energy efficiency) is most easily assessed by changes in aerodynamic parameters using normalized coefficients, such as efficiency (η), power coefficient (C_p), thrust coefficient (C_t), and efficiency (η) [8]

$$C_T = \frac{T}{\rho n^2 D^4}, \qquad C_P = \frac{P}{\rho n^3 D^5}, \qquad \eta = \frac{TV}{P},$$

where P is power (W); T is thrust (H); D is fan diameter (m); n is rotational speed (rpm); ρ is air density (kg/m³); V is air velocity (m/s). One must add a parameter that is very important for UAVs to this list: acoustic power level. The approximate acoustic power level (APL) can be calculated using the formula

$$APL=10\log\frac{kA_b(V_{0,7})^6}{10^{-16}},$$

where A_b - blade area; $V_{0,7}$ - speed at 0.7 times the blade radius; k - proportionality coefficient.

It follows that the greatest noise is generated by the tip of the fan blade (noise intensity depends on the blade tip speed to the sixth power). That is, noise can be reduced by decreasing the lift force near the blade tips (thereby reducing its efficiency), or by using a combined toroidal-spiral blade tip in a tandem configuration [9, 10].

Based on the list of tasks to be solved during the experimental determination of fan characteristics and the list of parameters required for this, the main design features and characteristics of the test stand itself were determined, particularly its electronic components, with regard to the need to account for the requirements of prospective research tasks. Therefore, two-channel and four-channel electronic devices (with the necessary redundancy) were used in virtually all measurement channels.

Experimental setup

The experimental setup (Fig. 1) consists of: a system of levers and structural elements for the fan drive, a system of sensors for measuring the main parameters of the setup, and an automated system for collecting and processing information.

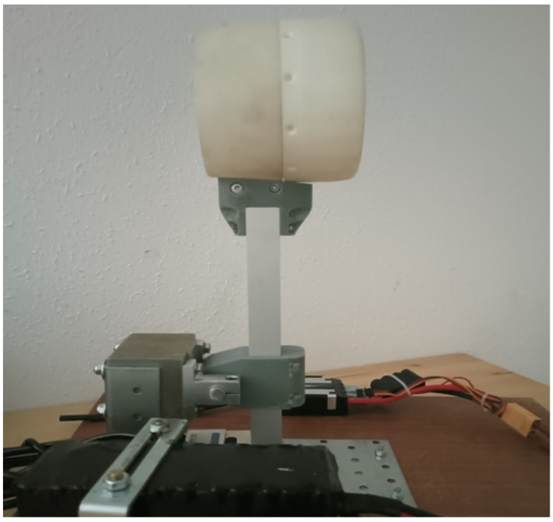

Fig. 1. Experimental setup for studying fan characteristics

Measurements of the main parameters (torque and thrust, fan rotor rotational speed, and relative wind velocity) were performed with an accuracy of ±1% across all operating modes. That is, measurement errors should have been smaller than the errors introduced by modifying the fan (based on the 3D printer's specifications).

The thrust and torque measurement channels were also separated. This would limit the influence of one channel on another during the measurement process and minimize recording errors. The technical requirements for the experimental setup are given in Table 1.

Table 1

Technical specifications of the experimental setup

№	Parameter Name	Value
1	Rotor speed, rpm	0 to 50000
2	Maximum Fan Thrust, H	200
3	Torque, H·м	0 ÷6
4	Fan diameter, mm	70 ÷150
5	Motor power, W	5000

The kinematic diagram of the setup is shown in Fig. 2. The experimental setup includes: a support platform 1; a vertical stand 2; a ball-and-socket joint 3; an enclosed fan 4; a brushless electric motor 5; as well as strain gauge sensors for measuring the fan's thrust and torque. A battery was used to power the electric motor.

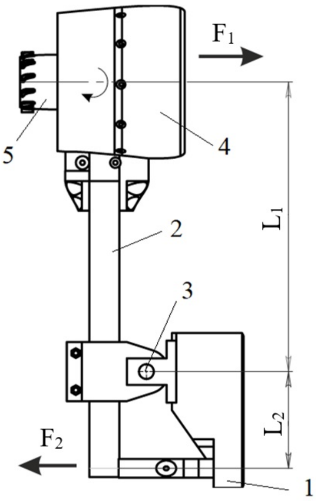

Fig. 2. Kinematic diagram of the experimental setup

Fan 4 (Fig. 2), which is the subject of this study, is mounted on a vertical stand using mounting screws. The fan is driven by an electric motor shaft connected to the flange of a strain gauge torque sensor. The sensor itself is mounted on the flange of the vertical stand. When voltage is applied, the electric motor begins to rotate, driving the fan rotor.

During operation, propeller thrust and reactive torque are generated, the magnitude of which equals the torque required to rotate the fan rotor.

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The thrust is measured by a strain gauge sensor, and the torque, in turn, is also determined by a strain gauge sensor, to which flange the electric motor is attached.

The fan thrust is measured using a lever system (Fig. 2). This ensures that the torques F_1 and F_2 are balanced about the point of rotation. The thrust F_1 is determined from equations (1) and (2):

$$F_1 l_1 = F_2 l_2 \qquad (1)$$

$$F_1 = \frac{l_2}{l_1} F_2 = k_1 F_2 \qquad (2)$$

Equation (2) shows that the pulling force is directly proportional to the force F_2 acting on the sensor and the proportionality coefficient k_1 (gain coefficient). The proportionality coefficient depends on the ratio of the lengths of the levers l_1 and l_2. The greater the length of lever l_2 relative to l_1, the greater the value of the gain coefficient k_1.

Automated Control and Information Processing System

The Automated Control and Information Processing System (ACIPS) is designed to collect and process information according to specified algorithms.

The processing, analysis, systematization, and visualization of information received from the sensors of the experimental setup are performed by an open-architecture industrial PC controller (Personal Computer) (Fig. 3).

According to the block diagram shown, analog information from the sensors is transmitted to an SDI-ATC-type object communication device (manufactured by Saturn Data Int) [11, 12].

Next, the analog signal from the device is fed to the input of a digital-to-analog converter, and from there directly, in the form of a digital signal, to the PC controller for further processing, visualization, and report generation. The following devices were used as primary information converters (Table 2):

Table 2

Primary transducers of physical quantities

No	Parameter	Type
1	Current and voltage	CW20 DC0-420V
2	Temperature	Resistance thermometer RT 1000
3	Force	Strain gauge sensor TAL 220
4	Torque	CALT DYJN-104-10NM
5	Rotor speed	Hall effect sensor KY-024
6	Relative wind velocity	Differential pressure sensor MPXV5004GVP

The rotational speed of the fan rotor was monitored by a Hall effect sensor located inside the housing.

To generate a signal, a magnet was attached to the motor rotor; as it passed by the Hall effect sensor, it produced a pulse. As a result, one pulse was generated for every full rotation of the rotor.

Communication with the sensors was provided by "SDI-ATC" galvanic isolation modules.

The SDI interface devices perform conversion and normalization of analog signals. The output signal was normalized in terms of current.

Four-channel modules were used, which provided conversion of the input signal, generation of a normalized output voltage signal, and galvanic isolation of the channels.

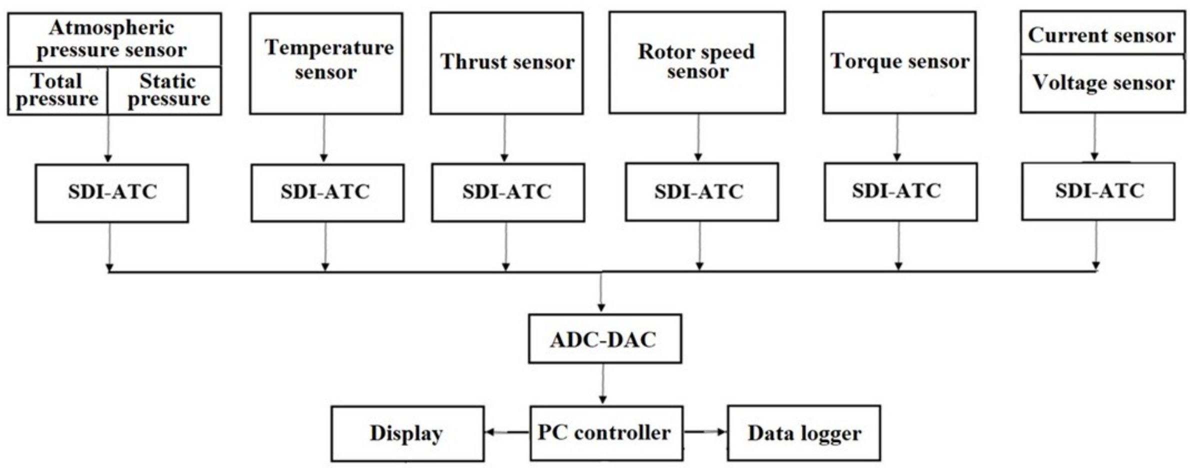

Fig. 3. System block diagram

Four-channel modules were used, which provided conversion of the input signal, generation of a normalized output voltage signal, and galvanic isolation of the channels. The SDI module also provides multiplex switching of output channels (Fig. 4). Eight such channels are used in the experimental setup.

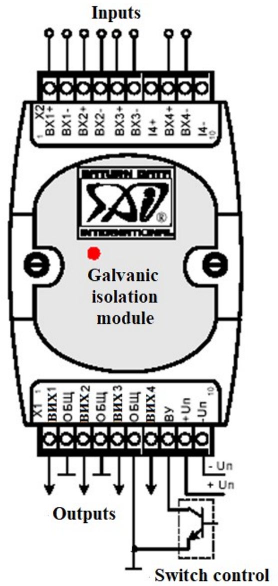

Fig. 4. Connection diagram for a four-channel module

The SDI ADC-32FVL ADC/DAC is used as the digital-to-analog converter to which the SDI modules are connected.

Methodology of Experimental Research

During the experimental studies, the following characteristics were determined: the dependence of thrust – T=f(n), power – P=f(n), and efficiency – η=f(n) of open and ducted fans featuring interconnected toroidal-spiral tips of the double-row rotor blades.

Calibration of the primary transducers (sensors) was performed as follows.

Thrust sensor. A ring was welded to lever l_1 (Fig. 2) precisely in the vicinity of the fan drive rotor axis, to which the rod of the reference dynamometer was attached. The dynamometer itself was mounted to the massive support plate of the installation via a manual loading screw mechanism.

Reference load values were set by turning the screw mechanism and recorded by an automated control system. A calibration curve was constructed based on the readings from the reference dynamometer and the electronic channel.

Torque was calibrated using the following procedure.

First, the fan rotor was secured. A reference force (in the form of reference weights) was applied to the fan mounting flange via a corresponding lever arm. The readings of the electric motor flange torque sensor were recorded. A calibration curve was constructed using a proportionality coefficient.

The rotor speed sensor was factory-calibrated as part of the delivery set.

Therefore, subsequently, on the operating unit, interval speeds were set in the range from 0 to 50,000 revolutions per minute, and the results were recorded in the corresponding table for further calibration.

When evaluating fan performance, the question arises as to the reliability of the obtained parameters [13]. First and foremost, this is due to the fact that fan parameters such as the thrust coefficient, the power coefficient, and the propeller efficiency are not measured directly but are indirect values obtained by calculation using specific formulas. The calculation formulas include parameters that are measured directly, each of which has its own error [14].

The calculation method is based on dividing the error into two components – systematic and random. The random component can be neglected if data obtained from measurement channels, in which the random component is already included in the error, are used to estimate the total measurement error.

The results of the error calculations (Fig. 5, Fig. 6, Fig. 7) show that their values vary over a fairly wide range depending on the rotor speed. For example, for the fan efficiency, the maximum error is 4%, and the minimum is 0.1%. Moreover, the minimum error is observed at high rotational speeds, and the maximum at low ones. As the rotational speed approaches 0, the error increases rapidly (Fig. 5). To validate the calculation method, tests of a tandem fan were conducted on the ground under zero incoming flow velocity conditions. As a result of the tests, the fan’s thrust and torque were measured at various rotational speeds, and based on the obtained results, the fan’s coefficients and its efficiency were recalculated.

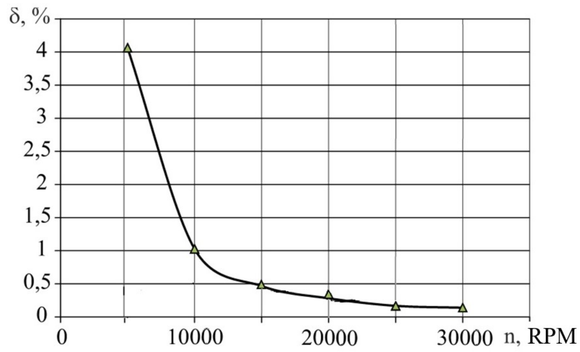

Fig. 5. Dependence of the efficiency error on the rotational speed

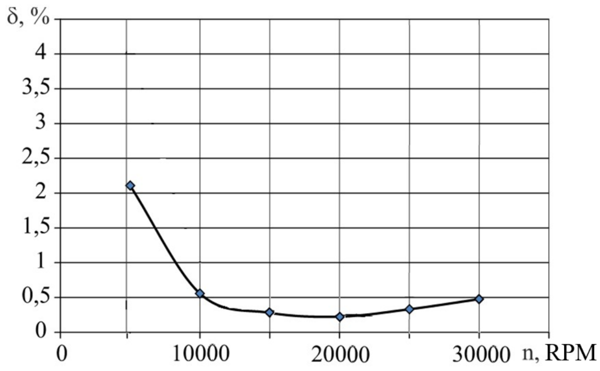

Fig. 6. Distribution of the power factor error

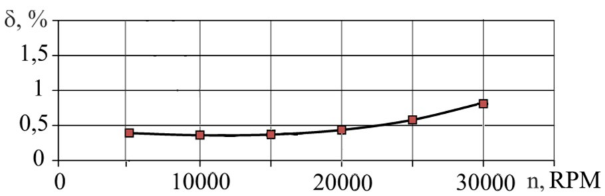

Fig. 7. Distribution of the thrust coefficient error

The error distribution of the fan characteristics obtained from the measurement results, shown in Figs. 5, 6, and 7, indicates that they fall within the limits specified during the experimental design.

Conclusions

An experimental setup was designed and tested for experimental studies of small-sized UAV fans, which allows for testing fans (including tandem fans with a connecting toroidal-spiral blade tip) of both open and enclosed types. The proposed design allows for the separation of the thrust and torque measurement channels, ensuring their independent measurement.

A metrological evaluation of the independent measurement channels was conducted.

Such an experimental setup can be used not only for the direct measurement of the parameters necessary to construct the performance characteristics of UAV fans, but also for the verification of numerical modeling methods and the determination of their operational characteristics.

The experimental setup is simple to operate and has satisfactory metrological characteristics of the measurement channels.

Contributions of the authors: formulation of the problem – **M. S. Kulyk**; review and analysis of information sources – **L. G. Volyanska, I. G. Babichev**; development and verification of the test bench – **M. S. Kulyk, F. I. Kirch**; analysis of test results – **I. G. Babichev, L. G. Volyanska, O. P. Yashchuk**.

Conflict of Interest

The authors declare that they have no conflict of interest regarding this study – financial, personal, authorial, or otherwise – that could influence the study and its results presented in this article.

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The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

All the authors have read and agreed to the published version of this manuscript.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ХАРАКТЕРИСТИК ВЕНТИЛЯТОРІВ МАЛОРОЗМІРНИХ БПЛА

М. С. Кулик, Ф. І. Кірчу, Л. Г. Волянська, І. Г. Бабічев, О. П. Ящук

Предметом дослідження в роботі э отримання характеристик вентиляторів малорозмірних БПЛА в широкому діапазоні частот обертання ротора. **Метою** роботи є підвищення точності вимірювання параметрів потоку робочого тіла в міжлопатковому каналі тандемного вентилятора з об’єднувальною тороїдально-спіральною закінцівкою лопатей шляхом цифрового моделювання і верифікація отриманих результатів на спеціально створеному експериментальному стенді. **Завдання:** запропонувати експериментальний стенд досліджень енергетичних характеристик тягових вентиляторів БПЛА закапотованого та відкритого типів. Проблема вибору вентилятора силової установки є доволі складною, виходячи з широкої номенклатури літальних апаратів різноманітного призначення, особливо малорозмірних. Іноді приходиться вибирати з цілого ряду модельних вентиляторів, виготовлених досить оперативно на 3D принтері. Тому розробка експериментальної установки, яка, при простоті конструктивних рішень, відповідала б необхідним експлуатаційним вимогам і заданим метрологічним характеристикам, є задачею безперечно актуальною. **Отримано такі результати**. Запропонований (і випробуваний) авторами експериментальний стенд є технологічно простим, дозволяє оперативно отримувати порівняльні й робочі характеристики вентиляторів відповідного модельного ряду з метою вибору оптимального, з точки зору замовника, варіанту. Представлено метод визначення основних характеристик енергоефективності вентиляторів малорозмірних БПЛА (експерименти проводилися, в основному, на тандемних вентиляторах, обидва ряди лопатей яких об’єднано тороїдально-спіральною закінцівкою). Особливістю методу та розробленої експериментальної установки є те, що вона дозволяє розділити канали вимірювання тяги та крутного моменту, що забезпечило їх незалежне вимірювання. Це дозволило отримати **науково обґрунтовані результати** моделювання шляхом їх практичної верифікації. Особливу увагу при проєктуванні установки було приділено каналам реєстрації ККД та коефіцієнта потужності, що пов’язано з опосередкованим їх вимірюванням – значення цих параметрів не визначалися напряму, а шляхом розрахунку за іншими виміряними параметрами. Необхідно зазначити, що експериментальний стенд проєктувався з можливістю проводити дослідження як відкритих, так і закапотованих вентиляторів. Характерною особливістю установки є також те, що вона дозволяє отримувати характеристики вентилятора, наприклад, залежність тяги T=f(n), потужності – P= f(n), η= f(n) у широкому діапазоні частот обертання ротора (n=0…50000 об/хв), що дуже важливо для малорозмірних БПЛА. Отримані результати використано при отриманні порівняльних характеристик модельного ряду вентиляторів для двигуна БПЛА з тягою 50 кН, які в данний час є превалюючими, особливо в бойо-

вих умовах. У подальшому планується розширення функціональних можливостей установки. Тому під час її проектування закладено резервні канали вимірювання параметричної інформації.

Ключові слова: безпілотний літальний апарат; вентилятор; аеродинамічні характеристики; тяга; потужність; експериментальна установка; параметр.

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