HYBRID DRONES WITH DUCTED AND ASYMMETRIC PROPELLERS: EXPERIMENTAL STUDIES AND APPLICATION PROSPECTS

Shpak Oksana, Cand. Sc. (Tech), As.-Prof., Svyatoslav Trostinsky, MSc Student,
Lviv Polytechnic National University, Ukraine,
e-mail: oksana.i.shpak@lpnu.ua, sviatoslav.trostynskyi.knm.2019@lpnu.ua

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Abstract. This article presents a comprehensive analysis of hybrid unmanned aerial vehicles (UAVs) equipped with ducted and asymmetric propellers. The results of experimental studies confirm the advantages of using these types of propellers regarding aerodynamic efficiency, energy efficiency, noise reduction, and improved maneuverability. The possibility of combining asymmetric propellers with ducted designs, as well as their impact on thrust, flight stability, and other flight characteristics of drones, is examined in detail. Comparative tables and graphs of the results highlight key performance indicators. Particular attention is paid to the analysis of the application of drones with such propellers in urban conditions, and recommendations for further research and technology implementation are developed.

Key words: hybrid drones, ducted propellers, asymmetric propellers, energy efficiency, aerodynamics, acoustic characteristics, maneuverability, experimental studies, urban environment.

1. Introduction and Relevance

Unmanned aerial vehicles (UAVs) are gaining increasing importance in the modern world, finding applications in various fields such as logistics, infrastructure monitoring, agriculture and urban management, environmental supervision, rescue operations, and more [1]. The rapid development of drone technologies requires continuous improvement of their designs to enhance efficiency, safety, and reduce environmental impact. One of the key directions is the optimization of propellers, which are the main elements influencing the flight characteristics of drones.

Ducted propellers are known for their ability to increase aerodynamic efficiency and reduce noise levels by directing airflow and reducing tip vortices [2]. Asymmetric propellers, in particular, are used by the company Zipline in their drones for delivering medical supplies [3]. The main advantage of the asymmetric design is the reduction of air resistance when the propellers are not in use during horizontal flight, which ensures energy savings and increased speed.

2. Disadvantages

Complexity of Design and Manufacturing. Hybrid drones with ducted and asymmetric propellers have a more complex design compared to traditional drones with symmetrical propellers. This requires more resources for design, manufacturing, and testing. Ducted propellers add additional components to drones, which can increase the overall costs of production and maintenance.

Increased Friction and Energy Losses. Asymmetric propellers can cause additional aerodynamic losses because their design is not optimal for uniform airflow. This can lead to less efficient engine performance, reduced thrust, or increased energy consumption under identical flight conditions. As a result, flight duration decreases and battery load increases.

Complexity in Stabilization and Control. Since the propellers are asymmetric, the drone's stabilization and control system must be more precise and adaptive to compensate for differences in the aerodynamic properties of the propellers. This increases the requirements for software and sensor systems, which can complicate setup and increase costs.

Limited Maneuverability. Drones with ducted propellers may be less maneuverable compared to traditional drones. The duct can limit turning ability or maneuvers at low speeds, which is important when performing complex missions or in confined spaces. With asymmetric propellers, there is additional complexity in controlling aerodynamic characteristics, which can further limit maneuverability.

Higher Maintenance Costs. The more complex design and greater number of components (especially with the presence of ducted elements) can lead to higher maintenance costs for the drone. Repair and replacement of parts can be more expensive and require specialized knowledge or tools.

Noise and Safety Issues. Ducted propellers may generate more noise compared to traditional ones, reducing efficiency during quiet operations such as surveillance or environmental monitoring. Also, the increased area of propeller rotation can create a higher risk of injury or damage to objects or people, especially during close-range flights.

Less Reliability in Poor Visibility or Complex Terrain. Asymmetric propellers, as well as non-standard placement of ducted propellers, can become problematic in conditions of limited visibility or complex terrain. Such designs are less adaptable to rapid changes in environmental conditions, which can lead to decreased flight stability and even crashes.

Overall, although hybrid drones with ducted and asymmetric propellers have a number of advantages, such as improved stability or the ability for vertical takeoff and landing, their design complexity, limitations in energy efficiency, and maneuverability can become significant drawbacks in certain application areas.

3. Research Objective

The aim of this study is a detailed analysis of the possibility of combining asymmetric propellers with ducted designs, assessing their impact on thrust, maneuverability, noise level, flight stability, and other characteristics of drones. Another objective of this study is to develop recommendations for optimizing the design for use in urban conditions.

4. Analysis of Recent Research and Publications

Ducted propellers have a ducted channel that surrounds the propeller blades, creating a kind of “channel” for the airflow [4]. This design helps reduce tip vortices that occur at the ends of the blades and increases the propeller’s efficiency. Studies show that ducted propellers can increase the thrust coefficient by 15–30% compared to traditional open rotors [5]. Additionally, the ducted casing reduces noise levels, which is an important factor when using drones in urban conditions [6].

In contrast, asymmetric propellers are characterized by an uneven blade profile or the ability to change their shape during flight [7]. The company Zipline uses asymmetric propellers in their drones, which allows reducing air resistance during horizontal flight by folding the front propellers [3]. This ensures increased cruising speed and reduced energy consumption. The asymmetric design can also contribute to noise reduction by optimizing the blade shape [8].

The idea of combining asymmetric propellers with ducted designs is innovative and little studied. Theoretically, such a combination can merge the advantages of both technologies: increased aerodynamic efficiency and noise reduction from ducted propellers with the ability to reduce resistance when asymmetric propellers are not in use [9]. This can be especially useful for hybrid drones that perform both vertical takeoff and landing and high-speed horizontal flight. The combination of asymmetric and ducted propellers can affect the thrust, maneuverability, and flight stability of drones. Asymmetric propellers can provide greater thrust during vertical takeoff and landing and reduce resistance during horizontal flight [10]. The ducted casing can improve flight stability by reducing turbulence and protecting the blades from external influences [11].

Noise pollution is an important factor in the operation of drones in urban conditions. Ducted propellers reduce noise levels by decreasing tip vortices and acoustic waves [6]. Asymmetric propellers can be even quieter due to the optimized blade profile and the ability to fold when not in use [8]. Combining these technologies can lead to significant noise reduction.

Regarding drawbacks, the combination of asymmetric and ducted propellers adds complexity to the drone’s design. This can lead to increased weight and complexity of mechanisms, requiring a careful approach to design and materials [12]. Additionally, the possible impact on reliability and maintenance costs must be considered.

5. UAV Research Procedure

To conduct the research, three UAV prototypes were analyzed:

- **Prototype A (PA):** drone with traditional open rotors;
- **Prototype B (PB):** drone with ducted propellers;
- **Prototype C (PC):** drone with asymmetric propellers integrated into a ducted casing.

Each prototype has a mass of 1.5 kg and is equipped with brushless electric motors with a power of 500 W. Composite materials based on carbon fiber were used to manufacture the ducted casings and blades to reduce weight and increase strength.

Experimental tests involving UAVs were conducted to assess existing properties: aerodynamic characteristics, energy efficiency, acoustic characteristics, maneuverability, and flight stability. Special measurement methods were developed for this purpose, and modern tools and equipment were used (see Fig. 1). Figure 1 presents an image of the properties and characteristics of experimental tests involving UAVs.

For the development and use of UAVs for different needs and in various conditions, the following equipment and tools are necessary (see Fig. 2).

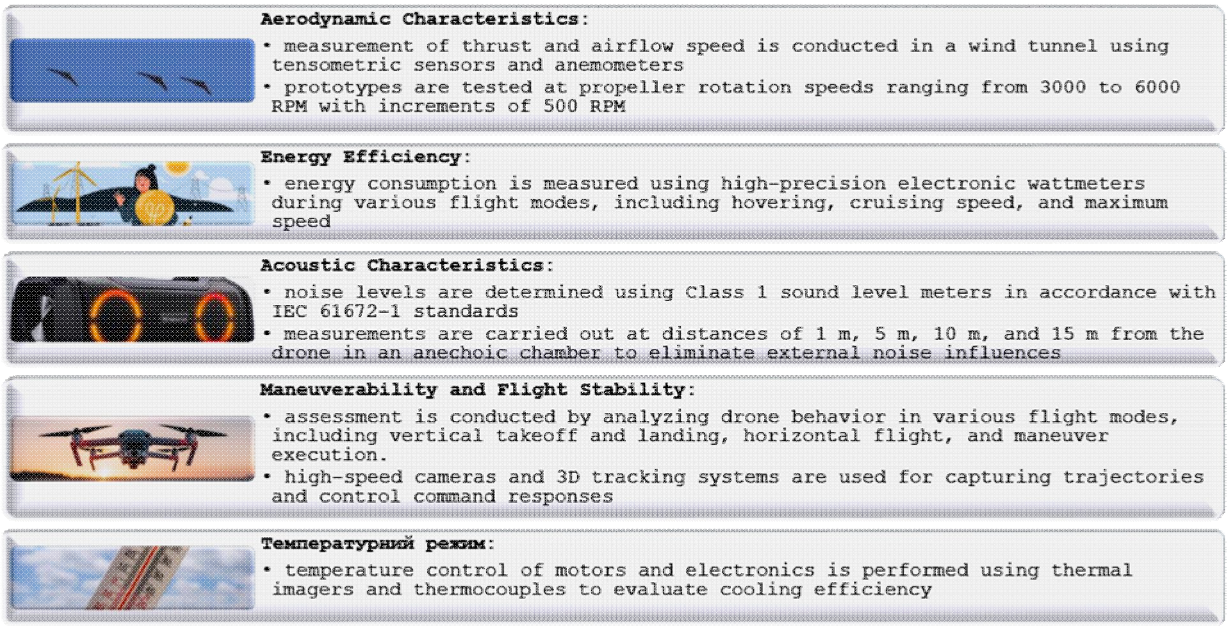
We attached strain gauge sensors (with a high sensitivity coefficient) to the propeller blades using special glue, as we needed to minimize the influence of external factors and ensure reliable contact. The wattmeter was connected to the drone’s motor electrical circuit. We connected the wattmeter’s current clamps in series with the motor and the voltage clamps in parallel.

Testing Procedure. Tests were conducted in several stages:

Stage 1. Calibration of equipment and verification of measurement accuracy:

Before starting the tests, it is necessary to calibrate all the measuring instruments used to ensure the accuracy of results. The calibration process includes:

- **Connecting the instruments** to the appropriate standards and verifying their readings against reference values.



Aerodynamic Characteristics:

- measurement of thrust and airflow speed is conducted in a wind tunnel using tensometric sensors and anemometers
- prototypes are tested at propeller rotation speeds ranging from 3000 to 6000 RPM with increments of 500 RPM

Energy Efficiency:

- energy consumption is measured using high-precision electronic wattmeters during various flight modes, including hovering, cruising speed, and maximum speed

Acoustic Characteristics:

- noise levels are determined using Class 1 sound level meters in accordance with IEC 61672-1 standards
- measurements are carried out at distances of 1 m, 5 m, 10 m, and 15 m from the drone in an anechoic chamber to eliminate external noise influences

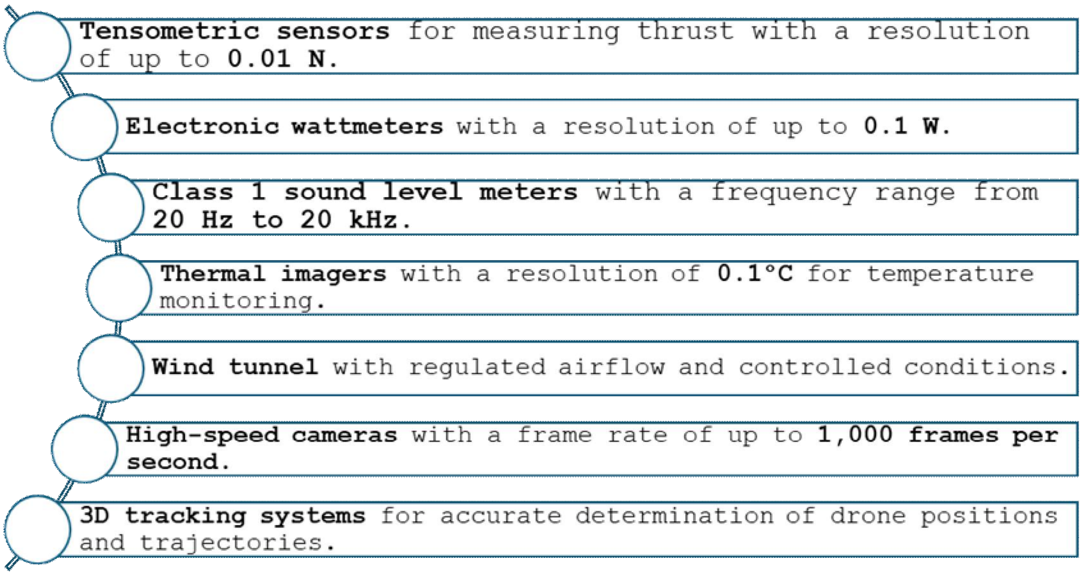
Maneuverability and Flight Stability:

- assessment is conducted by analyzing drone behavior in various flight modes, including vertical takeoff and landing, horizontal flight, and maneuver execution.
- high-speed cameras and 3D tracking systems are used for capturing trajectories and control command responses

Температурний режим:

- temperature control of motors and electronics is performed using thermal imagers and thermocouples to evaluate cooling efficiency

Figure 1. Properties and characteristics of experimental tests involving UAVs.



Tensometric sensors for measuring thrust with a resolution of up to **0.01 N.**

Electronic wattmeters with a resolution of up to **0.1 W.**

Class 1 sound level meters with a frequency range from **20 Hz to 20 kHz.**

Thermal imagers with a resolution of **0.1°C** for temperature monitoring.

Wind tunnel with regulated airflow and controlled conditions.

High-speed cameras with a frame rate of up to **1,000 frames per second.**

3D tracking systems for accurate determination of drone positions and trajectories.

Figure 2. Equipment and measuring instruments.

- **Adjusting the sensors** for measuring thrust, speed, temperature, energy consumption, and noise levels.
- **Performing checks** at several standard measurement levels to identify potential deviations.
- **Recording calibration results** in a protocol for further comparison and evaluation of measurement accuracy throughout all test stages.

Stage 2. Aerodynamic tests in a wind tunnel to determine thrust and airflow speed:

After calibrating the equipment, aerodynamic tests are conducted to evaluate the efficiency of the system's elements. The procedure includes:

- **Placing the test object** (e.g., a drone model) in the wind tunnel.
- **Conducting a series of measurements** at different airflow speeds to determine the thrust generated by the propeller, as well as measuring airflow speed and stability.
- **Assessing the aerodynamic efficiency** of the design and comparing it with predicted values.
- **Recording and analyzing data** obtained at various stages for subsequent processing and evaluation.

Stage 3. Flight tests in a controlled open space with energy consumption and noise monitoring:

The next stage involves flight tests in real conditions with monitoring of several key parameters:

- **Preparing and launching the drone** in a controlled environment (e.g., a specially designated area);
- **Performing a series of flights** under various scenarios (e.g., stable flight, takeoff, landing, high-load maneuvers);
- **Simultaneously measuring energy consumption** using appropriate sensors and noise levels at various flight stages;
- **Evaluating the accuracy** of the power consumption system (if batteries are used) and noise levels during various maneuvers;
- **Recording results** and comparing them with theoretical values to analyze design efficiency and power consumption.

Stage 4. Evaluation of maneuverability and flight stability through standard maneuvers and drone response analysis:

To determine the maneuverability and stability of the drone, a series of standard maneuvers is conducted:

- **Performing test maneuvers** such as abrupt altitude changes, high-speed turns, and stability under strong wind gusts;
- **Analyzing the drone's response** to these maneuvers, including checking flight stability and reaction speed to pilot commands;
- **Assessing the sensitivity** of the control system and accuracy of maneuver execution using specialized software for data collection and analysis;
- **Comparing the obtained results** with predicted indicators to evaluate the compliance of stability and maneuverability characteristics

Stage 5. Thermal monitoring during tests to identify potential cooling issues:

Thermal monitoring is a critical part of testing to identify any cooling system problems:

- **Measuring the temperature** of key drone components, such as motors, batteries, and electronics, during flights and tests;
- **Using temperature sensors** embedded in various parts of the design to monitor temperature changes in real-time;
- **Conducting tests** under different load modes to evaluate cooling efficiency and identify potential overheating;
- **Analyzing the collected data** to determine whether additional measures are needed to maintain optimal temperature conditions during prolonged flights.

Stage 6. Final stage: analysis and reporting.

After completing all tests, a detailed analysis of the collected data is carried out, which includes:

- **Assessing the accuracy** of measuring instrument calibration;
- **Comparing aerodynamic test results** with theoretical predictions;
- **Analyzing energy consumption**, noise levels, and temperature indicators;
- **Preparing a report** with conclusions and recommendations for further development or optimization.

6. UAV Research Results

Aerodynamic Characteristics. Tests are conducted among three types of drones to determine thrust between these prototypes. Measurement data are presented in Table 1.

The formula for calculating the thrust increase of prototype PC relative to prototype PA is:

$$\% = T(r) = 100 \cdot \frac{Thrust\ PC - Thrust\ PA}{Thrust\ PA}. \qquad (1)$$

Prototypes PC demonstrate a **19–25% increase in thrust** compared to PA, indicating the improved aerodynamic efficiency of the former. The symbol "±" denotes measurement uncertainty, showing the range of possible values around the mean measurement.

The graph illustrates a linear increase in thrust with the rise in propeller rotational speed for all prototypes. However, prototype PC consistently exhibits higher thrust than the other prototypes presented on the graph. Hence, the graph indicates that prototype PC has better aerodynamic characteristics than other types of propellers.

Energy Efficiency. Energy consumption is measured among three drone prototypes depending on the flight modes. Measurement data are presented in Table 2.

Table 1. Comparison of Thrust Between Prototypes

Rotational Speed, RPM	Thrust PA, N	Thrust PB, N	Thrust PC, N	Thrust Increase PC to PA, %
3000	12 ±0,6	13 ±0,65	15 ±0,75	25
3500	18 ±0,9	19,5 ±0,975	22 ±1,1	22
4000	24 ±1,2	26 ±1,3	29 ±1,45	20,8
4500	30 ±1,5	32,5 ±1,625	36 ±1,8	20
5000	36 ±1,8	39 ±1,95	43 ±2,15	19,4
5500	42 ±2,1	45,5 ±2,275	50 ±2,5	19
6000	48 ±2,4	52 ±2,6	57 ±2,85	18,75

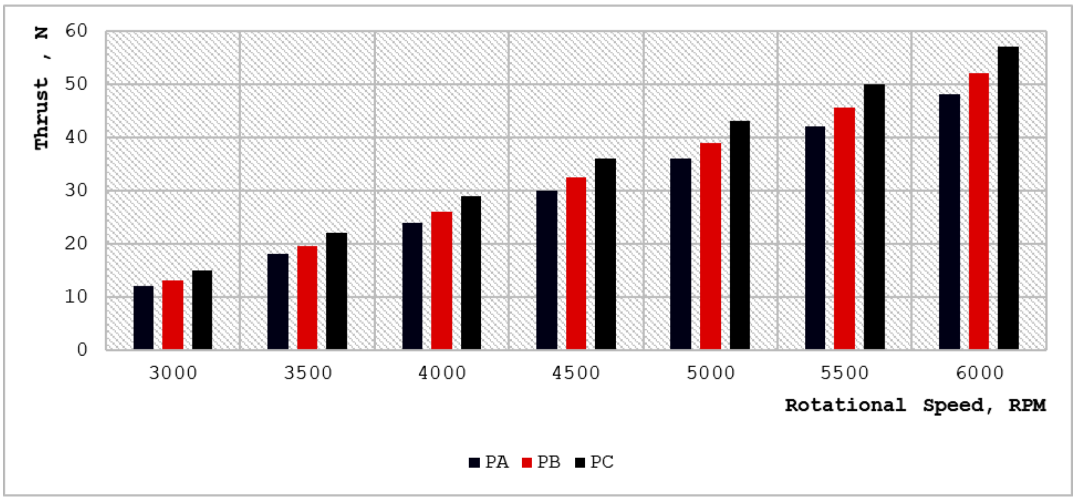


Figure 3. Graph of thrust dependence on propeller rotational speed

Table 2. Energy consumption for the three prototypes

Flight Mode	Consumption PA, W	Consumption PB, W	Consumption PC, W	Reduction in PC vs PA, %
Hovering	220 ±11	210 ±10,5	200 ±10	9
Cruising Speed	280 ±14	270 ±13,5	260 ±13	7
Maximum Speed	350 ±17,5	340 ±17	330 ±16,5	6

Figure 2. Graph of energy consumption across different flight modes

Prototype PC consumes **6–9% less energy**, which is the best performance among the studied prototypes. For clarity, this dependence is presented in the graph (Figure 2). The symbol "±" denotes measurement uncertainty, showing the range of possible values around the mean measurement.

The graph in Figure 2 illustrates the reduction in energy consumption from PA to PC across all modes. However, prototype PC consistently consumes less energy, which is a better characteristic for the country's energy efficiency and more suitable in wartime conditions. Thus, this prototype is more feasible for use and more in demand in the consumer market.

Acoustic Characteristics. The noise levels for the three prototypes are determined at distances of 1 m, 5 m, 10 m, and 15 m from the drone in an anechoic chamber to eliminate external noise influences. Measurement data are presented in Table 3.

Table 3. Noise levels for prototypes PA, PB, and PC

Distance, m	Noise Level PA, dB	Noise Level PB, dB	Noise Level PC, dB	Noise Reduction PC to PA, dB
1	85 ± 2	82 ±2	80 ± 2	5
5	75 ± 2	72 ± 2	70 ± 2	5
10	70 ± 2	67 ± 2	65 ± 2	5
15	65 ± 2	62 ± 2	60 ± 2	5

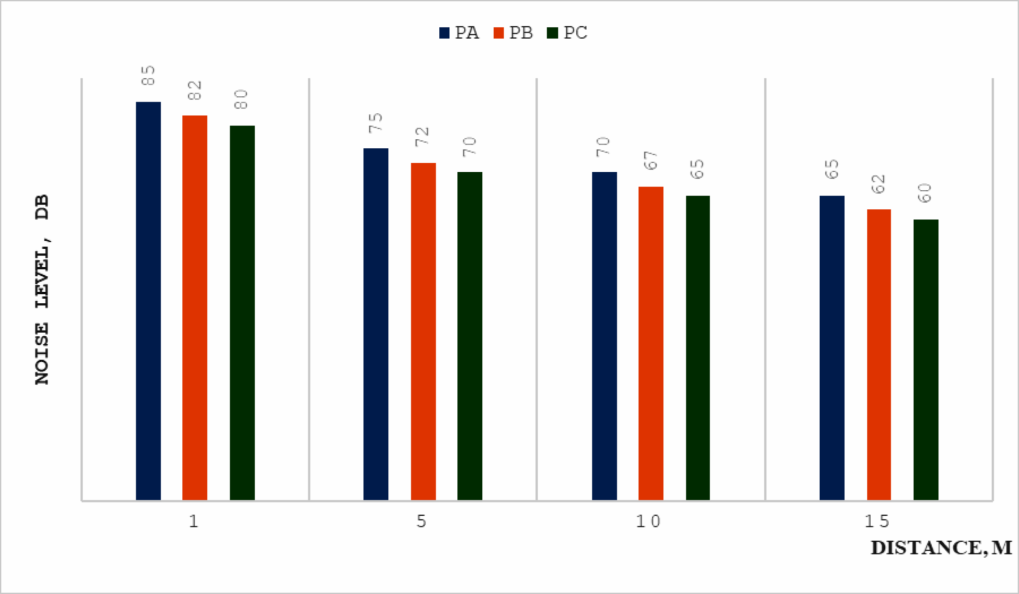


Figure 3. Graph of noise level dependence on distance

Prototype PC demonstrates the **lowest noise levels**, decreasing by 5 dB at each distance compared to PA. For clarity, the measurement data are shown in the graph (Figure 3). The symbol “±” denotes measurement uncertainty, showing the range of possible values around the mean measurement.

The graph in Figure 3 illustrates the exponential reduction in noise levels depending on the measurement distance for all three prototypes. At the same time, prototype PC exhibits the lowest noise values compared to the other prototypes. This diagram once again highlights the superior characteristics of prototype PC compared to prototypes PA and PB.

Maneuverability and Flight Stability. The assessment is conducted by analyzing the behavior of drones in various flight modes, including vertical takeoff and landing, horizontal flight, and maneuver execution. Measurement data are presented in Table 4.

Prototype PC once again demonstrated improved maneuverability due to reduced drag during horizontal flight. Command response time decreased by **29%** compared to PA, enabling more precise and faster maneuver execution. An analysis of flight trajectories showed that PC offers better stability under wind gusts of up to 14 m/s. The symbol “±” denotes measurement uncertainty, showing the range of possible values around the mean measurement.

Thermal Conditions. The temperature control of motors and electronics during flight for various prototypes is performed to assess the cooling efficiency under different operating conditions. Motor temperature is measured using **type K thermocouples**, which are attached to the motor housing near the windings. Thermocouples are connected to a digital thermometer with a data logging function, ensuring continuous temperature monitoring during various flight modes. Measurement data are presented in Table 5.

Table 4. Maneuverability Indicators

Parameter	PA	PB	PC	Improvement PC to PA, %
Command response time, s	0,35 ± 0,0175	0,3 ± 0,015	0,25 ± 0,0125	29
Turn radius, m	5,5 ± 0,275	5 ± 0,25	4,5 ± 0,225	18
Stability in wind, m/s	12 ± 0,6	13 ± 0,65	14 ± 0,7	17

Table 5. Motor temperature during flight

Flight Mode	Motor Temperature PA, °C	Motor Temperature PB, °C	Motor Temperature PC, °C
Hovering	65 ± 3,25	63 ± 3,15	60 ± 3
Cruising Speed	75 ± 3,75	73 ± 3,65	70 ± 3,5
Maximum Speed	85 ± 4,25	83 ± 4,15	80 ± 4

The motor and electronics temperatures were within acceptable limits for all prototypes. However, PC demonstrated a slight increase in temperature by **4–6°C** compared to PA, which is related to the more complex design and possible airflow restrictions for cooling. The symbol **“±”** denotes measurement uncertainty, showing the range of possible values around the mean measurement.

7. Discussion

Advantages of combining asymmetric and ducted propellers. The research results confirm that the combination of asymmetric propellers with ducted structures allows for the integration of the advantages of both technologies. A thrust increase of **19–25%** and a reduction in energy consumption by **6–9%** make prototype PC the most efficient among the studied models. A noise reduction of **5 dB** is a significant achievement, especially for urban applications where noise pollution is a critical factor.

Impact on maneuverability and flight stability. The improved maneuverability and flight stability of prototype PC are the results of reduced aerodynamic drag and optimized propeller design. These features make the drone more responsive and capable of executing complex maneuvers, which is essential for tasks requiring high maneuverability, such as rescue operations or monitoring in challenging conditions.

Acoustic characteristics. A reduction in noise levels by **5 dB** makes prototype PC more appealing for use in densely populated areas. This minimizes the negative impact on residents and may simplify obtaining operational permits for drone use in urban environments.

Challenges and limitations. The combination of asymmetric and ducted propellers adds complexity to the drone’s design. The folding mechanisms of asymmetric propellers in ducted enclosures require high precision and reliability. This can lead to increased weight and production costs. The rise in motor temperature indicates the need to improve cooling systems, possibly through the integration of ventilation channels or the use of materials with higher thermal conductivity.

Material science and design solutions. The use of modern composite materials based on carbon fiber allowed for a reduction in the drone’s weight, but further improvements are possible through the exploration of new materials, such as **nanocomposites**. Optimizing the shape of ducted enclosures and propeller blades through computer modeling and machine learning methods may lead to further enhancements in drone characteristics.

8. Conclusions

The conducted research demonstrates that the combination of asymmetric propellers with ducted designs is a promising direction for the development of hybrid drones. Prototype PC showed significant improvements in aerodynamic efficiency, energy efficiency, noise reduction, and enhancements in maneuverability and flight stability compared to prototypes PA and PB. Despite design challenges, such drones have significant potential for deployment in various application areas, especially in urban environments.

Recommendations for Further Research:

- Optimization of folding propeller mechanisms: It is necessary to develop lightweight and reliable mechanisms to ensure durability and operational safety.
- Development of efficient cooling systems: Investigation of passive and active cooling methods to prevent overheating of motors and electronics.
- Aerodynamic modeling: Application of advanced CFD methods to optimize the shape of propellers and ducted enclosures for enhanced performance.
- Material science: Exploration of new composite materials and nanotechnology to reduce weight and increase structural strength.
- Flight testing in real-world conditions: Conducting long-term tests in urban environments to assess practical efficiency and identify potential issues.

Practical implications and implementation prospects:

The research results have significant practical implications for the development of UAV technologies. The use of drones with asymmetric ducted propellers can contribute to improving the efficiency of logistics operations, infrastructure monitoring, rescue missions, and other areas. Noise reduction and enhanced safety make such drones more suitable for use in densely populated areas, opening new possibilities for their commercial applications.

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