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Contemporary problems of designing engines for military drone propulsion systems, taking into account their unforeseen mechanical failures and technical protection

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Abstract. The operational range and payload of military unmanned aerial vehicles (UAVs) depend strongly on the selected propulsion system. While electric multirotor drives are well suited to shortrange reconnaissance, longrange missions increasingly rely on propellerdriven piston engines. This article examines the suitability of two and fourstroke piston engines for military UAVs and identifies the most frequent failure modes affecting propulsionsystem reliability. The research niche addressed is the reliability-oriented design of small UAV piston propulsion systems based on componentlevel damage analysis. The purpose of the research was to assess whether piston internal combustion engines can meet longrange mission requirements while maintaining acceptable reliability, and it was hypothesised that reliability is primarily constrained by propellerrelated vibration and thermal overload of key engine components. The study combines a literature review with experimental bench and airframemounted tests conducted in the Aircraft Propulsion Laboratory, including thrust and temperature measurements and posttest inspection of components. Damage analysis covered the propeller and hub connection, drivetrain, crank–piston mechanism and exhaust mounting. The results indicate that the propeller, its mounting and transmission elements are the most failureprone parts; defects such as delamination, imbalance and resonant vibrations rapidly propagate loads to bearings, rings and cylinder surfaces, and may contribute to overheating of cylinder heads above 200°C. The paper outlines practical design and technicalprotection measures to mitigate these risks, supporting the use of piston engines for UAVs with ranges of approximately 2000 km and above.

Keywords: military drones, propulsion system, propeller, thrust, thermal load of engine heads

Introduction

Nowadays, in the era of various armed conflicts, military drones are increasingly used on the battlefield. Their nature of use in military missions is diverse, which requires the use of different aircraft designs and propulsion system solutions. More and more often, various authors are taking up the challenge of analysing the military use of various types of aircraft. The paper (Kopeć et al., 2021) presents very broadly aspects of the use of unmanned aerial vehicles in armed conflicts. The authors analyse various designs of drones for military purposes in great detail. This paper also included a detailed assessment of the possibility of using unmanned aerial vehicles for logistics, evacuation and aerial refuelling. Extensive actions taken in the scope of Priority Tasks of Technical Modernization of the Polish Armed Forces under operational programs are indicated. In particular, the authors presented the emergence of an increasingly wide group of various drones in the Polish Armed Forces. This has seen a great potential of Polish companies involved in the construction and design of unmanned aerial vehicles.

The article (Sajduk, Orłowski, 2025, pp. 1–9) analyses in detail the incident involving aircraft on 9/10 September 2025, during which Polish airspace was violated. The authors point to the rapid need to introduce anti-drone systems on a larger scale to air defence. It is pointed out that this incident showed how dynamically the battlefield is changing and how important it is to introduce innovative design solutions in the field of airspace defence as well as the introduction of such systems to combat small aircraft. In turn, the paper (Kupiecki, 2015) presents the Russian aggression in Ukraine and its impact on the international situation of the European Union countries. In particular, the challenges related to control logistics and armaments technology and mutual support for the creation of advanced defence systems are described. Currently, interest in the designs and possibilities of using drones in relation to the war in Ukraine in the conflict with Russia continues to grow. In the paper (Rochowicz, 2022), the great importance of the use of unmanned aerial vehicles in offensive and defensive missions is rightly indicated. The author describes how effective unmanned aerial vehicles are and how both sides have been developing the technology of various aircraft designs since the beginning of the conflict. Similar research on aircraft readiness and operation has been undertaken in the paper (Ziółkowski, 2022, pp. 2751-2762).

The paper (Kasprzycki, 2022, pp. 79–107) uses a critical analysis of available source materials and a historical analysis that allowed to assess the evolution of the Russian concept of next-generation war. In particular, it was established that Russia did not use the full potential of the concept of next-generation war, and the operation itself was carried out in a manner contrary to the principles of the art of war. It has also been shown that the key to the failure was the miscalculation of the potential of the Ukrainian forces and the overestimation of their own capabilities, the improper allocation of funds under the State Armaments Programme 2020, as well as the ubiquitous corruption and waste resulting from the authoritarian system of power in Russia, which led to a falsified picture of the state of the Russian Armed Forces. Modern weapons were not used in this.

This is an example of how important it is to develop new technologies in the field of warfare, in particular operations in the airspace.

The paper (Magiera, 2025, pp. 259–269) analyses the significance of the mass use of drones in the Russia–Ukraine war after 2022, focusing on their role in the acquisition and aggregation of battlefield data. The author has shown that unmanned aerial vehicles (UAVs) and, to a lesser extent, naval aerial vehicles (UAVs) enable ongoing, detailed monitoring of enemy activities. Such actions radically change the nature of dynamic confrontation. Research has confirmed that through the constant collection and processing of large data sets, unmanned aerial vehicles (UAVs) increase the effectiveness of both defensive and offensive operations. The audiovisual materials obtained serve not only military but also political purposes, influence social attitudes and become a propaganda tool. The author points out that these experiences will also be used by states and armed groups in future conflicts. Research (Volkov et al., 2025, pp. 137–158) has shown that the integrated use of air defence radars and electronic warfare systems significantly increases the effectiveness of protecting key objects from air attacks. The analysis confirmed that the synchronization of the operation of both systems allows for faster detection of threats and more precise neutralization of them, especially thanks to the ability to interfere with the navigation and control systems of enemy air attack means. Modelling attack scenarios has shown that rapid, real-time data exchange increases operational agility and the ability to respond to complex, dynamically changing threats. In addition, it was established that the use of modern EW technologies and automatic coordination systems significantly shortens the time of detection and neutralization of targets, increasing the resilience of the entire air defence system. However, these systems have limited performance for analogue propulsion systems in small aircraft with internal combustion engines.

Research (Tsyrfa et al., 2024, pp. 217–232) has shown that despite the existence of an extensive legal framework for the management of strategic resources, their effectiveness in wartime conditions is limited by bureaucracy, lack of transparency and weak interinstitutional coordination. The results confirm the need for legislative changes, the introduction of a uniform monitoring system and the approximation of Ukrainian regulations to EU standards in order to increase the country's defence resilience. Research (Zheng, 2023, pp. 55–72) has shown that Ukraine's trade with China, despite the dynamic changes caused by the war with Russia, remains strategically important. Such activities are particularly important in the case of increasing production potential, including the creation of new technologies. The article (Madej, 2024, pp. 113-133) analyses how the experience of using drones in the war in Ukraine affects international discussions about their role in armed conflicts and the directions of development of unmanned and autonomous combat systems. The author presents the level of advancement of drone technologies from before the war, and then discusses the scale and method of their use in Ukraine, from

Turkish Bayraktars, through Iranian Shaheeds, to American Switchblades. Research has shown that the conflict has confirmed the growing importance of combat drones and loitering munitions as key elements of modern combat. At the same time, real-world applications of these systems have verified previous predictions about their effectiveness and operational capabilities. The author points to clear trends: the mass use of low-cost drones, the combination of reconnaissance and combat functions, and the development of autonomous systems. On this basis, conclusions were formulated regarding the future of military drones, including the potential transition to fully autonomous combat systems and changes in the operational doctrines of states, as exemplified by the American *Replicator program*.

The paper (Sajduk, 2016, pp. 148–156) indicates that small and medium-sized unarmed platforms will be the main direction for the development of unmanned technologies, which is confirmed by the experience of the conflict in Ukraine. The conflict in Ukraine proves the effectiveness of cheaper, numerous drone systems, which can compensate for the numerical or technological limitations of the armies of countries such as Poland. The paper presents that new drone manufacturers, especially China, will accelerate the proliferation of this technology in second and third world countries, affecting the global military balance. This means that for Polish it is necessary to accelerate the development of its own unmanned systems and invest in defence against them in order to adapt the armed forces to the new reality of the battlefield.

Analysing the available literature sources on armed conflicts and trends in the construction and construction of aircraft, it should be clearly stated that in the production of small aircraft for military purposes, it is necessary to focus, mainly on propulsion with the use of piston engines. It is this propulsion that provides a sufficiently long range in long-range missions, in particular in hybrid warfare and long-range targets. While electric drives have their advantages in the form of low noise emissions, their main disadvantage is their low ability to achieve long flight distances. Each attempt to increase the range is associated with a significant increase in the weight of the power source, which already results in additional losses in the loss of operational range. In addition, electric rotor drives do not produce a relatively high thrust force with low energy consumption. They are also susceptible to damage in difficult flight conditions.

In view of the above, it must be stated that the future of cheap and simple aircraft structures, in particular small aircraft, belongs to internal combustion propulsion. The main advantage of these solutions is a simple and compact design, relatively high useful power (including the ability to produce high thrust values), uncomplicated technology for the production and manufacture of components of the drive system. The disadvantage of these solutions is mainly the problem with the durability and reliability of the transmission system and the piston combustion engine. In these lists, two-stroke engines are preferred. They produce much more usable power compared to four-stroke engines with less curb weight. In addition, these solutions significantly simplify the lubrication system, cooling system and power system control. An effective solution from the point of view of enemy defence is the use of analogue control systems and a mechanical system with fuel injection and ignition of the fuel-air mixture. In this case, the navigation system itself is associated with the use of electrical components less resistant to interference by air defence systems, but the propulsion system itself is significantly more difficult to neutralize.

The purpose of this article is to evaluate the applicability of two and fourstroke piston internal combustion engines in military UAV propulsion systems and to identify the dominant failure mechanisms limiting reliability. The research problem addressed is: which propulsion system components and operating conditions most critically affect the durability and mission readiness of longrange, propeller-driven military drones? The main hypothesis is that, in such UAVs, reliability is primarily limited by propeller-induced resonant vibration and associated thermal loads, and that targeted design measures and technical protection can significantly reduce the incidence of premature failures. The research strategy combines a critical literature review with experimental bench and airframe mounted tests (including thrust and temperature measurements) and posttest inspection of damaged components. The scope of the analysis is limited to small propeller-driven UAVs powered by piston engines; electric multirotor systems are referenced only as a background comparison.

Research Methodology

In the durability tests of small piston internal combustion engines, various types of test benches are used, mainly using the supporting frame or the entire aircraft assembly. The publication (Świątek, 2015, pp. 2159–2162) indicates that with the dynamic development of the ultralight aircraft segment, it becomes necessary to implement tools enabling the analysis and comparison of performance parameters of aircraft engines with internal combustion engines used in passenger cars. It was also emphasized that it would be particularly valuable to monitor engine operation continuously, in real time. The author presents the difference in the operating conditions of both classes of propulsion The attention is drawn to the much higher requirements in the field of technical control and safety in relation to aircraft engines, as well as to the differences in the selection of elementary operating parameters (such as crankshaft rotational speed or unladen weight), resulting from different specifics of use and different legal regulations.

The experience gained from the operation of piston internal combustion engines in tourist flights and in intensive, burdensome combat operations of unmanned aerial vehicles clearly indicates that mechanical damage to propellers and related failures of the propulsion unit remain one of the most serious operational challenges

(Chachurski, 2007, pp. 91–98). In practice, it is rotating elements exposed to vibrations, variable aerodynamic loads, foreign body impacts or material degradation that most often initiate dangerous damage, leading, among m.in other things, to unsealing of bearings, loss of crankshaft axiality or reduced engine efficiency.

In order to reduce the risk of such failures, the design of propellers with aerodynamic profiles resistant to overloads resulting from operation at low Reynolds numbers, where the airflow is unstable and the forces acting on the propeller disc show high variability over time, is of particular importance. A properly selected propeller disc profile reduces the amplitudes of torsional and bending vibrations, reduces local material overloads and minimizes the risk of fatigue cracks, which in extreme cases can even lead to the breakage of a fragment of the blade. In addition, aerodynamically optimized propellers reduce shock loads on the shaft, bearings and crank set, reducing the frequency of mechanical failures of the entire powertrain. Although the development of such propellers is associated with higher production costs, it provides a significant increase in system reliability both by reducing the risk of damage to the propeller itself and by reducing the adverse dynamic effects on the internal combustion engine. As a result, properly designed propeller blade profiles are an important element in improving the safety of operation and durability of propulsion systems used in light and unmanned aviation (Johnson, 2003).

Examples of damage to propulsion system elements presented in the paper were based on tests carried out as part of research work in the Laboratory of Aircraft Propulsion.

In the work (Wróblewski et al., 2025a, pp. 165-175), a prototype test bench was used to test two-stroke aircraft piston engines and to evaluate the properties of new anti-wear and thermal coatings used in their components. The construction of the station is based on a steel, anti-corrosion frame equipped with a vibration damping system, which allows for stable installation of small piston internal combustion engines and work at various tilt settings. The measuring system used includes a strain gauge force sensor CL14 combined with a CL450 recorder, so that it is possible to accurately measure the thrust produced by the drive system with different propeller configurations. Additional equipment of the station includes K-type thermocouples and SBS-01T telemetry sensors for measuring cylinder head temperatures, an optical speed sensor, a throttle position sensor and a system for recording engine operating parameters in real time. The station also provides controlled cooling conditions thanks to the use of forced air supply and allows the composition of the fuel mixture to be regulated by the membrane carburettors used. The whole allows for conducting operational tests in a wide range of loads from idle to maximum speeds, as well as for analysing the durability of materials, the impact of propeller geometry on the performance of the power unit, as well as reproducing engine operating conditions similar to real aircraft loads. The workstation is therefore a versatile tool for assessing engine operating parameters, material properties and component behaviour under dynamic conditions.

In the most recent work (Wróblewski et al., 2025b, pp. 119-131), the research stand was significantly expanded and supplemented compared to its previous version, which allowed for a wider and more precise scope of research (Fig. 1). First of all, a complete calibration procedure for the thrust measurement system was added, including the determination of the kG correction factor and experimental verification of the correctness of measurements using standard loads. A detailed uncertainty budget was also developed for all sensors, including thrust, temperature and propeller mass measurements, which had not been done before. The station was then used to carry out a full test procedure involving six different propellers, both two- and three-bladed, made of wood, composites and carbon fibre composite materials. This made it possible to determine the characteristics of the relationship between thrust force, rotational speed and cylinder head temperatures over the entire engine operating range, as well as to analyse the impact of the blade profile, angle of attack, weight and stiffness of the propeller on its performance. The study also assessed for the first time the influence of propeller geometry and material on thermal loads and wear of a piston internal combustion engine, and compared the use of different propeller designs in manned and unmanned aviation. In addition, the scope of research was expanded to include aerodynamic analysis and evaluation of the efficiency of the propellers, which made it possible to determine their suitability for various types of flying platforms.

The research carried out as part of the research also included tests using the OSA 3 aircraft (Fig. 2), which included measurements of the thrust force of the entire system with a piston internal combustion engine mounted on the fuselage of an unmanned aircraft. This stand is based on the actual aircraft design and not on a laboratory test bench, a rigidly fixed frame system. This approach makes it possible to acquire data under conditions much closer to real operation, taking into account the dynamics of the entire powertrain, the displacement of the hull under the influence of thrust and the actual methods of mounting the engine-propeller unit. In contrast to typical measuring stations, the station presented in Figure 2 allows for direct, linear measurement of thrust without the need for correction factors. This is due to the use of a strain gauge force sensor CL14 mounted to the thrust axis, connected to the aircraft fuselage by means of special belts to prevent lateral forces. This allows for measurements with high repeatability and accuracy, not found in traditional, more simplified experimental systems. Such a station allows you to accurately analyse the operating conditions of the engine, especially after it is installed on the aircraft. Such a system makes it possible to significantly reproduce the load of the piston internal combustion engine, changes in air flow, cooling conditions and the obtained thrust values depending on the geometry of the test propellers.

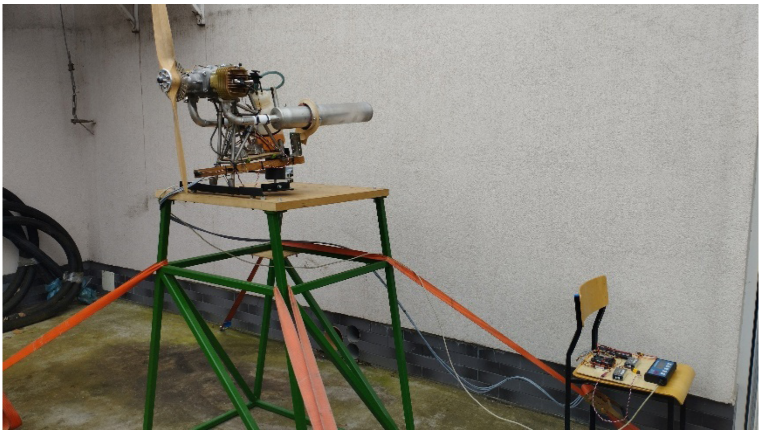

Fig. 1. Frame test bench designed for testing piston internal combustion engines in a frame system
Source: Own study

Fig. 2. Test bench using a real OSA 3 aircraft with an engine mounted on the fuselage
Source: Own study

Discussion of results

Modern propellers used in unmanned aerial vehicles and ultralight aviation are most often made of composite materials reinforced with fibres, primarily carbon fibre and nylon (Tiruvenkadam, 2024). Studies indicate that carbon composites are characterized by higher rigidity, lower susceptibility to deformation and higher thermal resistance at shaft speeds of up to about 6000 rpm. Nylon, on the other hand, is better able to withstand shock loads, so it is mainly used in simpler, commercial unmanned platforms. Examples of the use of various composites in aviation

– also in elements of propulsion systems – are presented in the paper (Piłat, 2009, pp. 111-120), where a number of advantages of such solutions are listed: high resistance to impact and cracking, low dead weight, lack of susceptibility to corrosion, low thermal expansion, electrical nonconductivity, low electrical permeability and very good vibration damping properties. However, these materials also have their limitations, m.in. low compressive strength, difficulties in machining and manufacturing processes, tendency to absorb moisture and a relatively high price. The use of composites, on the other hand, allows to eliminate corrosion-related problems typical of metallic materials (Błachnio, 2023, pp. 191-210).

In the design of multirotors such as quadrocopters, the weight and stiffness of the propellers are essential for platform stability, flight time and energy consumption (El-Sayed AF, 2016). In most small aircraft, the energy demand necessary to generate adequate thrust and the resulting range and time in the air remains an important factor. Any loss of energy means that more fuel has to be taken, which leads to an increase in the overall weight of the platform. Properly selected propeller geometry can therefore not only increase the thrust generated, but also increase the overall efficiency of the aircraft's propulsion system.

Mechanical damage is also an important aspect of the operation of propellers, which can result from both aerodynamic overloads and vibrations generated by the engine and airflow disorders. The parameters of air cyclones and contaminants, which can directly affect the durability of the propellers and the propulsion unit, including the piston-rings-cylinder assembly, are also important (Dziubak, Bąkała, 2021). An experimental study of the possibility of improving the filtration efficiency of return cyclones with a tangential inlet was also investigated in work (Dziubak, 2022). Air flows and parameters such as the degree of particulate contamination, e.g. in difficult terrain conditions (sandy) are very important for the operating parameters of the engine, but also for the generated thrust.

In composite propellers, fatigue cracks caused by multiple load cycles are a common problem. Torsional vibrations of the blades lead to local stresses, which over time can cause delamination of the composite, breakage of a fragment of the blade or its complete destruction. An additional threat is damage resulting from asymmetry of the engine, imbalance of the propeller or its improper installation.

Examples of damage to three-bladed carbon fibre composite propellers are shown in Figures 3-6. A particularly sensitive area is the propeller-to-hub attachment zone. This is where the greatest stresses from the transmission of engine torque via the drivetrain accumulate. Improper selection of screw tightening force, microcracks in composite hubs or deformations in the area of mounting holes can lead to damage, including blade kickback during operation. This poses a risk to both the aircraft and the persons in the immediate vicinity of the aircraft. Resonant vibrations further intensify these loads, causing gradual loosening of the joints or damage to the contact surfaces. If the natural vibration frequency of the main engine system is covered with the torque-forcing frequency of any harmonic, the vibration resonance occurs. This means that at the resonant rotational speed of the engine crankshaft and thus the propeller mounting hub, there may be a rapid increase in the amplitude of the shaft torsion angle under the action of a forced moment of a specific harmonic. If the system does not have additional vibration damping elements in the torque transfer system to the propeller, then as a result of the frictional forces and the resulting moments, the amplitude of vibrations increases indefinitely. In the case of a damping action of frictional forces, amplitudes can increase to significant and dangerous values due to the increase in torsional stress values. The rating of the resonance range in single-crank motors is accurate and can be calculated from simple mathematical equations. In the case of multi-crank engines, computational analysis can lead to erroneous conclusions. In this case, the most effective method of assessing resonant vibrations and determining their range in relation to the rotational speed of the shaft and the propeller is experimental research. This is because a particular harmonic can cancel out for the whole engine, but it can cause a resonance on the shaft section between the crank it loads and any other, up to the crank on which the harmonic can cancel. In order to exclude resonant vibrations for a given engine prototype and the entire transmission system, electronic motor operation limits are sometimes used at given speeds. Such treatments can only be identified during experimental tests for a given engine and a given aircraft. Each change in any parameters leads to a change in the point of rotational speeds of the shaft identified with the point of harmonic vibration.

In terms of the number of propeller blades, two-bladed propellers are currently most often chosen due to their simpler design and lower aerodynamic drag, which makes them particularly effective during long-term flights (Tiruvenkadam, 2024). Three-bladed propellers provide more thrust and better stability, however, they require more power and are more difficult to balance precisely (Tiruvenkadam, 2024). Light helicopters such as the IS-2, on the other hand, use tail propellers with four or six blades, which reduces noise levels and rotor diameter, while increasing thrust (Tiruvenkadam, 2024). In addition, increasing the number of propeller blades increases the rigidity of the rotor, but at the same time enhances the vibrations transmitted to the crankshaft and the drive system. This can accelerate bearing wear, lead to looseness in the drivetrain, and even initiate cracks in the motor body. Therefore, the selection of the number of propeller blades and the material from which they are made must take into account not only aerodynamic performance, but also resistance to overloads and vibrations, which in operational practice are the main cause of damage to the propellers and the power unit itself.

Composite propellers, especially those made of carbon fibre, although characterized by high rigidity, low dead weight and high thermal resistance, are susceptible to specific damage resulting from the nature of the work and the properties of the materials used in their construction. The most frequently observed failures include delamination, i.e. the separation of composite layers, caused by aerodynamic overloads, resonant vibrations, solid particle impacts or manufacturing imperfections. This is a particularly dangerous type of degradation because it initially develops below the surface of the blade, remaining invisible during standard visual inspection, and at the same time leads to structural weakness, loss of rigidity and impaired dynamic balance. Equally problematic are microcracks in carbon fibres resulting from multiple cycles of variable loads. Carbon fibre, despite its stiffness, is a brittle material and prone to the initiation of local cracks, especially around the leading edge of the blade, where stress concentrations are greatest. This edge is additionally exposed to erosion and chips caused by rain, hail, collisions with insects or sand particles, which leads to impaired flow, increased vibrations and accelerated material wear.

A particularly sensitive area of composite propellers is their attachment zone to the hub (Fig. 7), where significant stresses due to the transmission of engine torque accumulate. In this part, there are often micro-cracks around the mounting holes, resin detachment, local crushing of the material due to over-tightening of the screws, as well as chips caused by repeated disassembly. Vibrations resulting from uneven operation of the piston internal combustion engine or resulting from imbalance of the propeller further intensify the damage process, increasing the fatigue of the material and promoting the formation of further defects.

The consequences of such damage are not limited to the propeller itself, but extend to the entire powertrain. In extreme situations, the crank-piston system may become unsealed. Damage to composite propellers, although more difficult to detect in the early stages than in the case of metal or wooden structures, is therefore crucial for the safety of aircraft operation and the durability of the entire propulsion system.

Fig. 3. View of damaged propeller due to excessive angular vibrations

Source: Own study

Fig. 4. View of damaged propeller mount – 3-blade composite propeller
Source: Own study

Fig. 5. View of propeller mount breakage due to overspeed overload
Source: Own study

Fig. 6. View of the damage to the 3-blade carbon fibre composite propeller mount
Source: Own study

Damage to the propeller has a direct and very adverse effect on the operation of the propulsion system. In particular, the technical condition of the transmission system and propeller mount is important (Fig. 7-9). Mechanical damage to this system as a result of resonant vibrations of the entire system or propeller can lead to damage to the main engine assembly and tearing off the propeller during its operation. Imbalance resulting from delamination, microcracks and erosion of the leading edge leads to an increase in vibrations transmitted to the crankshaft, bearings and crank-piston components. Excessive dynamic loads cause intensive wear of main and connecting rod bearings, as well as accelerated lubrication degradation, which can lead to a partial loss of oil film thickness and, consequently, seizure of pistons and breakage of piston rings (Fig. 10-12). This process usually begins with local overheating of the work surfaces, increased friction due to a decrease in the thickness of the oil film, and the formation of scratches on the piston shell, which over time can lead to a complete scratch of the cylinder surface. In the case of fuel-oil mixture lubricated engines, as is the case with two-stroke internal combustion engines mainly used in small aircraft, the selection of appropriate proportions and the use of appropriate construction materials with increased surface hardness, low surface roughness and low friction coefficient value is necessary to maintain the required engine performance parameters in long-haul years. Only the adoption of appropriate construction materials and the proportions and viscosity parameters of the fuel-oil mixture can contribute to increased endurance in long-range flights at increased temperatures of the engine heads and propeller transmission system.

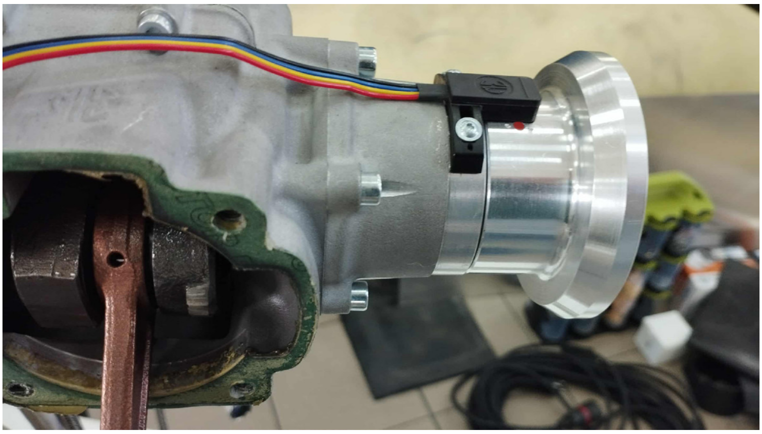

Fig. 7. View of the driveline with speed sensor
Source: Own study

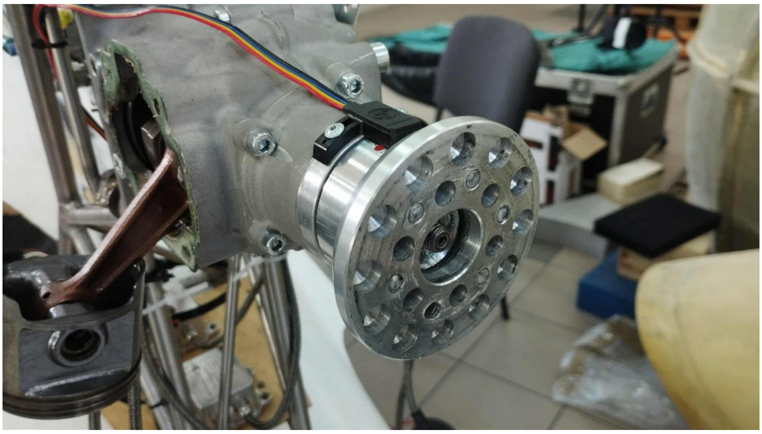

Fig. 8. View of the propeller mount hub
Source: Own study

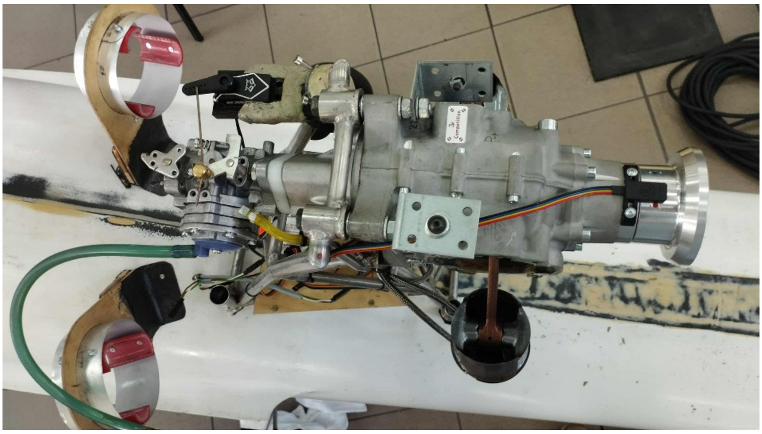

Fig. 9. View of the internal combustion engine block layout with the cylinders removed after the engine seizes
Source: Own study

Under conditions of increased vibrations and overloads, piston rings also break. Rings subjected to variable stresses can undergo micro-cracks, especially in the bonding zones of the ring locks, which impairs their ability to maintain the tightness of the combustion chamber. This results in a drop in compression pressure, overheating of the side surface and piston bottom, increased gas blowing into the crankcase and accelerated wear of the cylinder surface (Fig. 10-12). Cracked rings can further damage the cylinder wall. Two-stroke engines are most often equipped with one ring for a given piston, which not only increases its load resulting from the temperature of the combustion process and the pressure in the labyrinth seal, but also forces its absolute reliability. Damage to such a ring due to excessive unit stresses and compressive forces, as well as the effects of high temperatures and small film thicknesses of the fuel-oil mixture, leads to complete engine damage. Damage to the piston ring in such an internal combustion engine excludes such a power unit from further operation, which is especially important in combat missions.

Fig. 10. Damage to the cylinder smoothing due to the disappearance of the fuel-oil film
Source: Own study

Fig. 11. Damage to the piston side surface due to sudden resonance vibrations of the drivetrain
Source: Own study

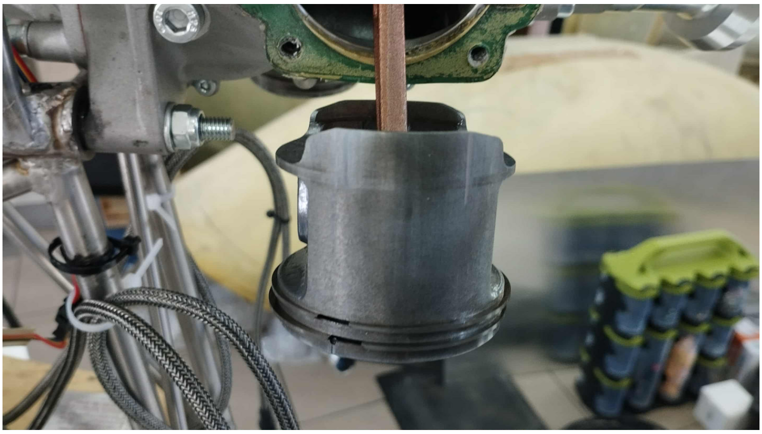

Fig. 12. Damage to the piston ring space due to engine overheating
Source: Own study

Overheating of the cylinder head is also a significant problem (Fig. 13-14). Engines used in light aviation and unmanned aerial vehicles operate for long periods of time under high loads, and the additional vibrations transmitted from the damaged propeller interfere with cooling efficiency, leading to uneven temperature distribution. This can cause deformation of the valve seats, cracking of the bridges between the valves, as well as local overheating of the spark plug and detonation combustion of the mixture. An overheated head also loses its rigidity, which promotes unsealing of the system and deterioration of the operating parameters of the entire drive. Overheating of the cylinder heads of two-stroke aircraft engines is one of the limitations of their permissible operating parameters. Two-stroke engines have twice the frequency of combustion cycles per shaft revolution than four-stroke units, which results in increased heat load on the combustion chamber components, including the head. Studies (Mitianiec, Buczek, 2007) have shown that under conditions of thermal overload and non-uniform cooling, air-cooled spark-ignition engine heads can exhibit pronounced local temperature non-uniformity (with differences exceeding 100°C between hot regions near the combustion chamber and cooler outer finned areas). Such steep temperature differences generate thermal stresses that can accelerate thermo-mechanical fatigue and contribute to the initiation of cracks in the cylinder head.

In a paper (Shalev, 1983) on the fatigue of the heads of two-stroke diesel engines, the author pointed out that microcracks in the area of the spark plug seat and cooling channels develop under conditions of cyclic overheating, and the high frequency of cycles is a key factor in degradation. In the case of this operation, these relationships have been thoroughly confirmed, and even in the case of extreme engine operating conditions at maximum engine speeds, without an additional cooling system, the temperature of the heads can be reached above 200°C, which leads to engine damage in the long term. Therefore, when designing a new engine and choosing the right propeller, it is necessary to additionally design the engine cooling system individually each time and select the appropriate power of cooling fans. The phenomenon of overheating is influenced by, m.in: too poor fuel-air mixture, improper ignition angle, long-term operation at maximum power and difficult heat collection by air or liquid cooling. From a material point of view, the properties of the aluminium alloys used in the heads are important. In the paper (Nelaturu et al., 2020), it was shown that increasing temperature has a clear impact on the fatigue cracking mechanisms in the A356 aluminium alloy, leading to reduced resistance to crack initiation and faster crack growth under cyclic loading. In practical terms, operation at elevated head temperatures can therefore accelerate thermo-mechanical fatigue damage in aluminium castings used in engine components, increasing the risk of permanent deformation, loss of tightness and cracking under overload conditions. Similar symptoms were observed during the tests performed in this work, manifested by engine immobilization when temperatures exceeded about 200°C or by a temporary decrease in thrust force. This indicates that effective cooling of small aircraft engines intended for drones and made of aluminium alloys is necessary to maintain proper performance and ensure structural durability.

Together, the phenomena described mean that even seemingly minor propeller defects can lead to serious mechanical damage to the internal combustion engine. Proper balance, regular inspections and vibration monitoring are therefore crucial to ensure the trouble-free operation of the drivetrain and maintain the durability of the crank-piston assembly and head. When designing and testing new engines and powertrains for aircraft and propeller selection, it is always necessary to conduct experimental endurance tests.

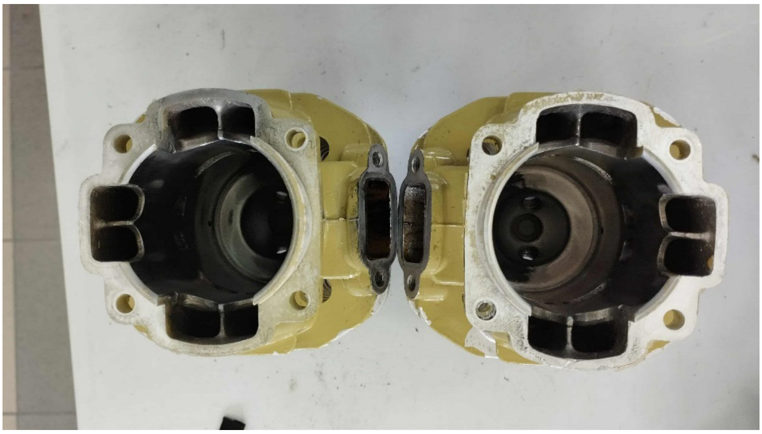

Fig. 13. Damaged inner part of the cylinder smoother due to overheating of the head
Source: Own study

Fig. 14. View of overheated heads of a small two-stroke aircraft engine
Source: Own study

Technical protection of military unmanned aerial vehicles

Technical protection in unmanned piston-powered aerial vehicles for military purposes should be understood as a set of design and operational solutions aimed at preventing the occurrence of damage, reducing the effects of developing defects and maintaining task capability. Such protection should ensure the durability and reliability of the operation of selected mechanical systems, especially under conditions of high dynamic loads and environmental influences. In the case of small piston-powered unmanned aerial vehicles, the damage mechanisms observed in operational practice are of great importance. These include damage to the propeller and hub connections, torsional vibrations and resonances in the drivetrain, accelerated wear of piston-crankcase components, as well as thermal overloads of cylinder heads. Due to the low curb weight and low production costs for small unmanned aerial vehicles, it will be an effective approach to monitor the technical condition of the propulsion system and airframe structure.

Initial technical protection may be provided by mechanical measures that reduce the likelihood of damage and limit the transmission of vibrations. In real operating conditions, this applies to the use of additional intake air intake covers and effective air filtration (especially in dusty environments with particulate matter), local reinforcement of propeller mounting zones and, where it is structurally possible, the use of damping elements in the torque transmission system. Propeller protection should also include erosion protection of the leading edge and surface solutions to reduce degradation of composite blades. Since a significant part of the damage leading to the decommissioning of an aircraft develops under the surface of various structural components, technical protection cannot be based solely on organoleptic inspection, but also the support of inspections with non-destructive diagnostic elements and consistent control of installation, including bolt tightening moments, the condition of the contact surface and the geometry of the joints, should also play an important role. It is also extremely important to ensure thermal protection by setting appropriate cooling conditions throughout the entire engine operating range. This should include the proper design of the air flow ducts, the selection of the flow forcing capacity, as well as the appropriate fastening and insulation of the exhaust system components.

It is also important to protect the aircraft and its most important components of the powertrain based on measurements, i.e. reading the current operating parameters of the propulsion system. In the propulsion systems of small unmanned aerial vehicles, this mainly concerns the monitoring of the crankshaft rotational speed, changes in the loads associated with the production of thrust, cylinder head temperatures and vibration signals. After exceeding the safety thresholds, a protective action should be taken, e.g. limiting the maximum rotational speed of the engine crankshaft, forcing electronic control of the engine power supply system aimed at bypassing resonant ranges, correcting engine operating conditions in order to reduce heat loads. In addition, it is recommended to introduce a system of controlled engine power and torque limitation while maintaining the minimum required thrust force for a given aircraft type. In systems with a limited degree of automation, some functions can be implemented with simple limiters, thermal protections and mechanical regulators. An element of technical protection is also an absolute continuous record of operating data. Such measurements allow for maintenance depending on the technical condition of the powertrain and aircraft and faster detection of repetitive damage for specific configurations: a given engine type and propeller geometry.

In military conditions, the technical protection of unmanned aerial vehicles also includes the robustness of controllers, sensors and actuators, which remains essential even in simplified control concepts. Filtration of electrical supply systems, basic shielding of signal cables, mechanical protection of electronic connectors of the electrical system and redundancy in the most important measurement paths increase immunity to interference and damage. The purpose of these preventive actions is not to eliminate all defects, but to ensure that, if they occur, remedial actions can be carried out to maintain the combat capability of the aircraft. All such activities are primarily intended to ensure the operational capability of the propulsion system, including the piston, combustion engine and propeller. With such an assumption, a greater combat capability of unmanned aerial vehicles can be achieved. In addition, in the case of monitoring the frequency of occurrence of a given damage and its location, it is possible to make design changes in a given prototype aircraft design. Any such action is necessary in the case of unmanned aerial vehicles for military purposes, in particular those carrying warheads.

Conclusions

1. Damage analysis showed that it is the propeller, hub and transmission system that most often fail. Damage results from resonant vibrations, delamination of the composite, cracks in the mounting zone or improper balance of the propeller. Even small defects lead to significant vibrations and destructive loads on the entire drivetrain, up to the potential detachment of the blade.
2. Excessive vibrations generated by a damaged propeller are transmitted to the crankshaft, bearings and crankshaft and piston. This causes the rings to crack, lubrication degradation, seizure of the cylinder plaster, and complete damage to the unit. This is the main cause of premature failures of two-stroke engines used in drones.
3. Studies have confirmed the possibility of exceeding temperatures of more than 200°C, which leads to deformation of aluminium alloys, a decrease in strength, damage to spark plug sockets and the initiation of fatigue cracks. Overheating is due to both high engine load and vibrations caused by a damaged propeller, which disrupt cooling.
4. The work showed that only a comprehensive approach – including the selection of blade profile, material, number of blades, cooling system and verification under experimental conditions – can ensure stable and sustainable operation of the propulsion system. The advanced test rigs developed in the project enabled precise mapping of aviation conditions and objective assessment of the durability of components.

Overall, the findings support the stated hypothesis that propulsionsystem reliability in pistonpowered military UAVs is primarily constrained by propellerinduced vibration and associated thermal loads. Therefore, mitigation should focus first on propeller design and balancing, mounting integrity, and thermal management.

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