FEM analysis of the opposed-piston aircraft engine block

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Abstract. An important aspect of aircraft engine design is weight minimization. However, excessive weight reduction may reduce mechanical strength of the engine. This is especially important for aero-engines due to consequences of engine failure in flight. The article presents the results of the FEM opposed-piston diesel engine block model tests. The tested engine is a PZL-100 two-stroke three-cylinder aircraft engine with two crankshafts and six pistons. Air is supplied via a mechanical compressor and a turbocharger. Stress in the engine block is induced by the operating process of the engine block. The pressure in the combustion chamber of the analyzed engine is 13 MPa. The pistons in one of the cylinders are then near their TDC, the deflection angle of the connecting rods is small so almost the entire piston force is transferred to the crankshafts and then to the main bearing supports. This results in the occurrence of a tensile force for the engine block applied in the bolt holes of the shaft supports. The calculation results are presented as stress and displacement distributions on the surface and selected block sections. The maximum values on the outer surfaces of the block occurred in the area of the compressor attached to the block and reached 39 MPa. Maximum stresses were, however, observed inside the block on the air and exhaust flow separators between the cylinder liners. The stress value on the outlet side reached 44 MPa.

1. Introduction
In recent years, more and more diesel-powered engines have been launched onto the aviation engine market. The development of aviation diesel engines is a response to the demand to reduce fuel consumption, as these engines have better efficiency than gasoline engines. A comparison of aviation diesel engines with piston gasoline and turbine engines of similar power shows that diesel engines have a worse power to weight ratio, but their average fuel consumption is 237 g/kWh. However, for the Rotax 912-UL gasoline engine, it is 332 g / kWh and for the PBS TP100 turboshift engine is 548 g/kWh [1].

Opposed-piston two-stroke engines have been around for over 100 years. From 1890, they were first produced in Germany, and then in the USA, Great Britain and France. They are used to propel civilian and military vehicles, ships and even aircraft [2]. Such engines were used in the automotive and aviation industries decades ago but were not widely used due to numerous imperfections, mainly as a result of stricter exhaust emission standards, especially for piston engines, so manufacturers have gradually abandoned their production [3]. The advancement of modern engine technology has led to the resumption of work on opposed-piston engines. Currently, several companies manufacture opposed-piston engines, also for aviation applications. One of the most advanced designs among opposed-piston engines are engines developed by Achates Powers. The first engine was a three-cylinder engine with a capacity of 2.7 dm³, dedicated to delivery vans. This engine was presented for the first time at the Detroit show in 2015. Its mass production is to start in 2024 [4].
Opposed-piston engines have many advantages over other piston engines. These engines have no cylinder head or valves. Their combustion chamber is formed between two pistons so heat generated is not lost through the head. The engine has fewer parts and its design is less complicated, so it is more reliable and does not waste energy on the timing drive. The pushing action of pistons also results in good engine balance. The main disadvantages are the need to connect two crankshafts and the installation of injectors directly in the cylinder liner [5,6].

Downsizing in the design of internal combustion engines has been developed in recent years. It consists in reducing engine dimensions and weight but increasing its power by using a supercharger. Such methods are particularly desirable in aviation [7,8]. In addition to modifying the structure, new materials are introduced, their geometry and mechanical, thermal and fatigue strength are improved [9-11]. To optimize the design of engines, numerical methods of engine design are widely used and developed [1].

The PZL-100 engine was designed in AVL Boost which is a type of software for a one-dimensional modeling of combustion engines. A similar process of engine simulation tests is described in [12] and [13]. The flow of air and cooling liquid in the PZL-100 was modeled using the CFD Ansys Fluent method, whereas AVL Fire and CATIA v5 were used to model its combustion and the geometry and mechanical strength of selected parts, respectively. Solid models of the individual parts of the assembly of the crank-piston system were developed in CATIA v5 and then were assembled. In addition, the MSC Adams software was used to calculate the dynamics of the crank-piston system [14].

The article presents the results of the engine block strength calculations using the FEM method. The Calculations of engine blocks were carried out by many researchers and mainly for in-line and V-type car engines. These calculations focused on, for example, the influence of the size of the cooling jacket [15], the material used [16] and the combustion pressure [17] on stress, heat flux and deformation of the engine block [18]. Single- [19] and multi-cylinder [20,21] air-cooled engines were also investigated often to optimize cylinder deformation in order to reduce mass and improve cooling as well as to compare block load at the moment of maximum pressure in different cylinders [22]. The work [23] is noteworthy because of the described method of optimizing a block of a row engine, and FEM calculations were mainly carried out using Ansys, Abaqus and Patran.

This article presents the results of testing an opposed-piston engine block using CATIA v5. Such an engine arrangement is rare and there is no research on stress distribution in such a specific design.

2. Computational model
The CAD model of the PZL-100 opposed-piston engine was created with the use of CATIA v5 and in cooperation with the aircraft engine manufacturer WSK "PZL-KALISZ" S.A. It is a 100 kW diesel engine intended for the propulsion of light aircraft (figure 1).

![Figure 1. PZL-100 opposed-piston engine model in CATIA v5.](image-url)
The purpose of the FEM analysis was to identify the places in the engine block where maximum stresses may occur and specify whether they could lead to engine failure. The greatest stresses may arise at the moment of the maximum combustion pressure. When determining the assumptions for the engine design, it was assumed that this pressure would not exceed 13 MPa. The pistons in one of the cylinders are then close to TDC, the deflection angle of the connecting rods is small and almost all the piston force is transferred to the crankshaft and then to the main bearing supports. This results in a tensile force for the engine block applied in the holes of the bolts of the crankshaft supports.

To determine the stresses in the engine block caused by the gas force, the FEM analysis was performed. The PZL-100 engine has 3 identical cylinders, however, the stress distributions are not the same in each of the three engine parts. This is because they are positioned at different locations in the block, which includes the coolant, air, exhaust and oil passages, and because of the need to mount various attachments to the block.

Three cases with different places of load application were analyzed separately. The calculations were made for the occurrence of the maximum gas force successively in three cylinders. It is assumed that the block is rigidly restrained in the bolt holes of the bearing supports on the outlet side. On the inlet side, a force of 44 kN was applied, resulting from the assumed maximum pressure acting on the piston crown with a diameter of 65.4 mm. Additionally, the screw holes were stiffened in pairs to simulate the operation of the main bearing supports (figure 2).

The models use parabolic computational mesh elements. The global size of the mesh was set at 5 mm, and local mesh densities up to 2 and 3 mm were applied in the location of the highest stresses.

![Figure 2. Engine block model with the distributed boundary conditions.](image)

3. Results
The stress distributions were obtained on the block surface and in its most loaded cross-sections (figures 3 – 5 and 7).
Figure 3. Stress distribution on the outer surface of the engine block.
Figure 4. Stress distribution in the longitudinal section of the engine block.
Case I

Case II

Case III

Figure 5. Stress distribution in the cross-section of the engine block.
**Figure 6.** Sections of the engine block in the locations of the crankshaft supports.

**Figure 7.** Stress distribution in the block cross-section passing through the crankshaft supports.
Case I

Case II

Case III

Figure 8. Displacement distribution of the engine block.

On the outer surfaces of the block, the maximum values occur in the area where the compressor is attached to the block, and their values reach 23 MPa, 24 MPa and 39 MPa (figure 4). The maximum
stress concentration was observed inside the block. It occurs on the elements separating the flow of air and exhaust gases, located between the cylinder liners. The stress values on the outlet side reach 40 MPa, 43 MPa and 44 MPa (figures 4, 5, 7). Despite extremely high loads, the stresses do not exceed the permissible values for the material used, amounting to approx. 190 MPa [24], [25].

Figure 6 shows the position of the sections of the engine passing through the crankshaft supports. These cross-sections also pass through the locations of the greatest stresses, i.e. the block connections between the engine cylinders. It should be added that in the case of the connections on the exhaust outlet side, these areas are also exposed to high temperatures, which reduces the strength of the material from which the engine block is made. The stress distributions in sections 2 and 3 are presented in figure 7. The maximum stresses amount to approx. 40 MPa, which is a safe value.

Figure 8 shows the displacement distribution. The maximum displacements occur where the force is applied and are respectively 0.067 mm, 0.073 mm and 0.078 mm. The stiffness of the block is important due to the risk of contact of the crankshaft journals with the shells. In the analyzed case, the difference between the deformations of the shaft supports is approx. 0.04 mm. It is a safe value.

4. Summary
A numerical modeling of structure strength allows you to quickly find potentially dangerous areas in the geometry that could lead to failure of a designed machine. At an early stage of design, it is a method that saves time and research costs, but it is necessary to verify the structure on the test stand afterwards. A construction of an opposed-piston engine block differs from engines where one piston moves in one cylinder. Also, the necessity of placing two crankshafts and a specific charge exchange system results in areas of high stress concentration in the block.

Stress distributions of up to 44 MPa were recorded in the tests. The maximum stresses in the block are much lower than the allowable stresses of the material from which it will be made. However, given the fatigue nature of the loads, the weakening of the material due to high temperatures and inaccuracies in the casting process, it may be necessary to adjust the geometry to improve the strength of the engine block.

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