Determining aircraft aerodynamic characteristics of regular and non-linear airframes and evaluating the efficiency of the applied methods

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Abstract. This paper discusses three methods of determining aerodynamic characteristics and compares the research results. The research cases are two planes selected by the authors, i.e. EM-10 Bielik and YOKOSUKA MXY7 OHKA and investigated as an airframe with the so-called non-linear aerodynamic flow and a classical design. Aerodynamic characteristics was determined by the following methods: aerospace engineering formulas, CAD simulation of the airflow around the object and examining the prototype in a wind tunnel. The last section of the paper compares the obtained results and evaluates the efficiency of all methods to examine both types of the aircraft. The compared parameters are lift and drag versus angles of attack and aircraft polars.

1. Introduction

The study [1] presents tests of aerodynamic forces and moments generated on individual autogyro elements. The effect of a sideslip angle on load of the gyrocopter stabiliser with an inverted twin tail is examined in the work [2] and aerodynamic forces acting on vertical and horizontal stabilisers and pressure distributions on their surfaces are obtained. Gyroplane longitudinal static stability for the selected stabiliser angles was also studied [3].

The CFD method is widely used for aircraft aerodynamics research (Computational Fluid Dynamics) [4]. It is capable of determining general aerodynamic characteristics of a designed aircraft [5], examining more specific issues such as the stability of aircraft [6] or aerodynamic interference [7-8] or the whole aircraft [9] or its selected parts like wings [10-11]. Aerodynamic characteristics obtained in numerical research can be validated by wind tunnel tests [12-13]. Tunnel tests allow a general analysis of aerodynamic performance of the aircraft [14], an analysis of stability characteristics [15-16] or aero-flexibility [17]. Wind tunnel research can also use the Particle Image Velocimetry (PIV) method [18] and [19] to visualise the velocity field around the gyroplane. When a design process of a new aircraft for a previously assumed performance begins, it is essential to decide on such an airfoil that could fulfil its assigned tasks in the future. The foundation for all further calculations is a wing lift-to-drag ratio which can be obtained by selecting a previously defined and calculated airfoil or by calculating it independently [20]. Aerodynamic performance of the wing can also be changed by using additional movable [21] or fixed elements [22] that change its geometry. Despite its tremendous impact on a lift-to-drag ratio of the entire aircraft, the impact of other elements of the airframe cannot be disregarded. The differences between a wing lift-to-drag ratio and lift-to-drag ratio of the whole plane show that a skilful design of fuselage, stabilisers, canopy, inlet, undercarriage can prove equally
important. This means that an efficiently designed aircraft should have its lift-to-drag ratio accurately predicted at an early stage of its designing to determine the shape of all airframe parts [24].

An aircraft lift-to-drag ratio can be determined by different methods:

a) the method using aerospace engineering formulas based on data to describe a used airfoil, wing parameters and other airframe parts. This method uses two-stage calculations, i.e. computations of a wing lift-to-drag ratio and then a lift-to-drag ratio of the whole aircraft.

b) the method which exploits testing in a wind tunnel. Created in a given scale, examined models are tested in a wind tunnel and results are converted appropriately to obtain values corresponding to airframes of real dimensions.

c) the method which uses computer simulation in a programme intended to conduct parametric 3D modelling (CAD 3D) and design solid models, sheets of metal, welded constructions, moulds, surface models. Such a programme should have a fully integrated package to simulate flow of liquids and gases in real conditions and efficiently analyse the impact of fluid flow (heat exchange or the impact of forces) [23].

In addition, polar drag can be determined from flight data [25] or a novel stochastic total energy model that employs Bayesian computing [26]. Drag polar prediction methodologies during aircraft design phases are discussed in [27].

The first method is based on making calculations after entering a great deal of geometrical data (describing the size of airframe components) into appropriate formulas. In addition, graphs are used to determine certain parameters and data are stored as tables. This method assumes certain simplifications (to simplify too sophisticated calculations) that lead to inaccurate findings, especially at larger angles of attack. Despite its inaccuracies, the method of engineering calculations offers a quite precise and quick analysis of airframes. The second method uses special, often expensive, technical equipment such as the above-mentioned wind tunnel so it is primarily used by aircraft manufacturers or research centres capable of allocating sufficient resources for such a purpose. This method is being increasingly superseded by the third method that uses computer simulation due to the fact that its accuracy and computing power are constantly growing. It also allows simulating flows, forces and performance of an aircraft during a flight [28].

This article compares the efficiency of the above-mentioned methods applied to determine the lift-to-drag ratios of the EM-10 Bielik having a distinctive non-linear aerodynamics generated from leading-edge extension and the simple and classical YOKOSUMA MXY7.

2. Aircraft characteristics

2.1. EM-10 Bielik

The concept of the EM-10 Bielik dates back to the late 1990s when an aerospace manufacturer, currently known as Margański & Mysłowski Aircraft Company, began to develop a concept of a flying simulator organise a large number of flights for training military pilots and to avoid too high training costs. Their main intention was to create a simple and light (also economical) airplane which would not carry any weapon and could facilitate fighter combat training with simulation.

Figure 1. Orthographic projections of the EM-10.

Figure 2. Graphic depicting of the EM-10 during a flight.
The bulk of its installations and its cockpit layout were taken from the TS-11 Iskra. These parts were mostly used and obtained free of charge or at a minimum price because they were taken from other aircraft. The EM-10 Bielik was completed, mounted on a trailer and transported to Mielec to perform its first test flight on June 4, 2003. After a month, the aircraft climbed as high as 3,000 m during its second one-hour test flight. After these attempts, a demonstration flight for the military was planned. The demonstration was to convince military commanders to use this aircraft in military pilot training. Unfortunately, even before the scheduled date of the flight, it became obvious that the Air Force would not purchase the Bielik so its third flight was not performed.

2.2. YOKOSUKA MXY7 OHKA
During World War II, guided weapons were at an early stage of development even in the most developed countries, and suicide attacks (Kamikaze) increased the probability of hitting a target of a bombing raid because pilots could adjust the flight path until the impact. This idea had been initially rejected, but when Japan was defeated by the United States in the Battle of the Philippine Sea on 19-20 June 1944, it was considered as the only way to improve Japan's situation. The first prototypes and training version of the Ohka K-1 with a landing skid and a front water ballast to make up for weight of its warhead were manufactured in early September and the rocket engine tests also started in the same month. On October 23rd, the Ohka was dropped down pilotless over Sagami Bay from a Mitsubishi G4M Betty bomber, and its first piloted training flight was on October 31st. The flights were successful and series production started immediately. The figures below present the Yokosuka in flight and its orthographic projections.

![Figure 3. Orthographic projections of the Yokosuka MXY7.](image)

![Figure 4. Visualisation of the Yokosuka MXY7 aircraft during a flight [29].](image)

3. Determination of aircraft characteristics

3.1. Analysis of aerodynamic characteristics using aerospace engineering formulas
This engineering method is based on making a number of calculations after entering a great deal of geometrical data (describing the size of airframe components) into appropriate formulas. The method uses two-stage calculations, i.e. computations of the wing lift-to-drag ratio and the lift-to-drag ratio of the entire aircraft. Obviously, the calculated lift-to-drag ratio is burdened with error (as a result of assumptions made to simplify the computations). The higher angle of attack, the larger errors are due to non-linear characteristics, for example an increase in lift by increasing angles of attack. For small angles of attack, the errors are relatively small and results faithfully represent aircraft behaviour and its performance in the air [30]. Figure 5 shows the aircraft dimensions in a vertical projection used to carry out all necessary calculations.
Figure 5. Measurement of the aircraft dimensions in a vertical projection.

The calculations produced the findings depicted in the graphs of the lift and drag coefficients which vary with angle of attack. The polar graph of the aircraft $C_L(C_D)$ was created from these two graphs.

3.2. Analysis of aerodynamic characteristics using SolidWorks software package

A model in the SolidWorks environment was created from technical drawings of the aircraft and additionally supported by the view of the prototype constructed by the aircraft manufacturer in the then version of the UniGraphix programme. The simulation followed the stage of modelling, which was connected with setting up multiple configurations to test all angles of attack in the range between (-40) to 40 degrees with a 1° leap. It was also necessary to specify all flow conditions, detailed grid parameters forming the area of calculations and other quantities necessary to conduct the simulation. Figures 6 and 7 show the prepared 3D models of the EM-10 and Yokosuka MXY7.

Figure 6. Model of the EM-10.  

Figure 7. Model of the YOKOSUKA MXY7.

Before the calculations, the authors determined objectives of the simulation: lift, drag, lift and drag coefficients. The results computed in relevant time periods are given in the tables and diagrams of aerodynamic characteristics of the aircraft. The figures show air direction during the simulations.
3.3. Analysing the aerodynamic characteristics using a wind tunnel
This analysis was carried out for the EM-10 Bielik aircraft only. At the design stage, the aircraft was tested with appropriately scaled models fixed in the wind tunnel on the premises of the Warsaw University of Technology. The wind tunnel aerodynamic characteristics of the EM-10 Bielik were obtained, owing to the courtesy of professor Krzysztof Kubryński, a world-renowned aerodynamics expert who designed modern aerodynamics of the Bielik. Professor Kubryński shared by e-mail the results of his research in the form of polar graphs and lift coefficients correlated with angles of attack. The resulting graphs enabled us to determine the missing graph of the drag force coefficient and the angle of attack. Figure 10 depicts the models used for the wind tunnel testing.

4. Findings and conclusions
The graphs below show the test results obtained by all three methods for determining the EM-10 aerodynamic characteristics.
The aerodynamics of the EM-10 Bielik is completely different from the one of most aircraft. Its lift and drag forces are created according to a completely different principle. The emerging momentums behave differently. These properties result from detaching the airstream on the swept wing. The consequences of such a detachment are tremendous. There is the so-called non-linear aerodynamics in which the lift force is generated by vortices generating high negative pressure so the aerodynamic characteristics differ significantly - the lift force increases non-linearly and at higher angles of attack. The lift force reduces because the vortices reduce. The main problem in designing this type of aircraft is that the phenomenon of destructive vortices is largely dependent on airframe geometry in an unpredictable manner so the fundamental challenge is a computational analysis of the properties of this aircraft based on typical engineering methods as confirmed by the above-mentioned results - engineering formulas in this case prove to be completely useless because aerodynamic characteristics depend on many elements like wing parameters, shape of leading-edge root extension, the entire fuselage layout, flight controls, etc. They are all interdependent in a non-linear manner, which makes them unpredictable. A classical aircraft can be designed by means of computational methods,

**Figure 11.** $C_L(\alpha)$ graphs.

**Figure 12.** $C_D(\alpha)$ graphs.

**Figure 13.** Lift-to-drag ratio graphs determined by different methods.
unlike this type of aircraft because it is necessary to perform long and complex wind tunnel research and construct its all elements through trial and error.

Figure 14. $C_L(\alpha)$ graphs.  

Figure 15. $C_D(\alpha)$ graphs.

Figure 16. Lift-to-drag ratio graphs determined by different methods.

It can be concluded from the graphs in Figures 14-16 that the aerodynamic relationships determined by the two methods are very similar. The most similar ones are the dependencies of the lifting force and the angle of attack. The maximum difference between the values (not taking into account the angles of attack greater than its critical value) does not exceed -0.18, which is less than 9% of the maximum value of the lifting force coefficient. In both cases, the critical angle of attack is 20 degrees and the maximum load factor values differ by less than 2.5%.

The values of the drag force coefficient correlated with the angle of attack determined by both methods differ slightly more significantly. The graphs almost overlap up to the angles of attack of 15 and -15 degrees. A clear difference is above these angles because the drag coefficient determined in a computer simulation...
continues to increase similarly to a square function, whereas the derivative of the drag coefficient calculated by the engineering method after the increase in the angle of attack clearly decreases.

Due to the fact that the area of the polar diagrams just like the graphs of the drag coefficient is a consequence of the previous ones, they are similar for most of the range, and once it is exceeded, it varies significantly.

5. Conclusions
The conclusions from the EM-10 aircraft test are as follows:

a) The calculations conducted by aerospace engineering to determine the EM-10 aerodynamic characteristics are imperfect. Even though the maximum value of the lift coefficient is approximately the same, the changes in this coefficient and the angle of attack are quite different. In accordance with the computational method, the aircraft stalls if the angle of attack is slightly more than 14°, but in reality the angle of attack needs to be increased up to 40°.

b) The results of the computer simulation in the SolidWorks environment differ from those obtained by the calculations. Their course is more similar to real characteristics (in both characteristics, the change tendencies are similar and stall occurs near the angle of attack of 40°); however, the values of both the lift and drag coefficients are too small, more than twice.

c) Despite a wide range of applications of aerospace engineering formulas in aerodynamic characteristics or CAD computer simulations, it should be remembered that an analysis of different aircraft may produce different results that are far from reality as illustrated by the EM-10 Bielik examination.

The conclusions from the YOKOSUKA MXY7 aircraft test are as follows:

(a) The specified aerodynamic characteristics (highly similar results) confirmed that both methods, i.e. engineering calculation and computer simulation are efficient and highly accurate.

(b) These methods enable a fast analysis of the characteristics of the airframe and the impact of the change of any element on final aerodynamic characteristics of the aircraft.

Final conclusion:
At the stage of designing an aircraft, it is recommended to check aerodynamic characteristics by various methods to reduce errors of findings and to make more efficient changes in an airframe structure.

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