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THE EB-3 FLY-LAB OF THE WARSAW UNIVERSITY OF TECHNOLOGY

The authors describe the program undertaken at the Warsaw University of Technology (WUT), aimed at developing mobile aerodynamic laboratories to be used for investigation into aerodynamic properties of airfoils or lightweight propulsion systems – in natural scale and in natural atmosphere. The enterprise was named the EB-program, and has both: research and educational aspects; in all phases of the program (i.e. design, manufacturing and testing) the WUT students are involved. As the result of work, three mobile aerodynamic laboratories were build: EB-1 – which was tested on the car roof, EB-2 – unique flying laboratory based on the PW-6 glider, and EB-3 – a new generation of flying wind tunnel to be used on the AOS-71 glider, which currently is under preparation to the flight tests. The authors present in detail the measurement systems and procedures supported by the LabView software.

1. Introduction

Despite the fact that currently several advanced numerical tools have been developed specifically for aircraft airfoil design (like X-Foil, Fluent, CFX, etc.), the need to validate the results of computer analysis in an experimental way still exists. Aerodynamic characteristics of the airfoil depend on such issues, as a boundary layer profile and the phenomena of transition to turbulence flow on the airfoil surface. Several parameters have influence on that transition, especially the Reynolds number and turbulence of free stream. Thus, the aerodynamic characteristics being measured in different wind tunnels can also differ. Moreover, they can vary from those measured under natural atmosphere conditions. That is why validation of airfoil characteristics in a natural atmosphere has a big importance. The first flying labs designed for measurement of glider airfoil characteristics in a natural

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atmosphere were built in the 80s of the last century. They are represented by the German fly-lab based on Schemp-Hirth "Janus" glider, and the Lithuanian fly-lab, which has been constructed from two Czech "Blanic" gliders (Fig. 1).

Fig. 1. Schemp-Hirth Janus glider as a fly-lab and Lithuanian fly-lab based on Blanic glider [1]

In 2002, the Institute of Aeronautics and Applied Mechanics (IAAM) of Warsaw University of Technology (WUT) established a new concept of a flying laboratory for airfoils testing. Its project founder was (RIP) Dr. P. Sierputowski, Ph.D. A leader of design-team was one of the authors of this paper, Dr. M. Rodzewicz (currently Ph.D., D. Sc.). Since then, the program has been perpetually developing. The program was named EB (abbreviation of Polish words "Element Badawczy" which can be translated as a "Research Element", which refers to the specimen of the wing-segment to be investigated in the fly-lab). From the beginning, the aspects of both research and education have been exposed in the program.. Thus, the students of the WUT were involved in all stages of the program; especially the second author of this paper: Mr. D. Głowacki (currently M. Sc.). At present stage of the EB-program development the range of works was increased on aerodynamic testing the wing-segments as well as on performance testing of lightweight propulsion systems. It is planned that, for the first mentioned aim, there will by applied the method of pressure measurement along the airfoil and change of momentum of the air stream behind the wing-segment. For the second aim, there will be applied the system of load-cells. As both measurement systems are not fully finished yet, the test-results presented in this paper concern a present status of instrumentation development.

The idea of EB-program is illustrated in a schematic way in Fig. 2.

2. EB-1 – the mobile wind tunnel

The 1^{st} phase of this project was the design of moveable wind-tunnel stand, fixed on the car roof (Fig. 3).

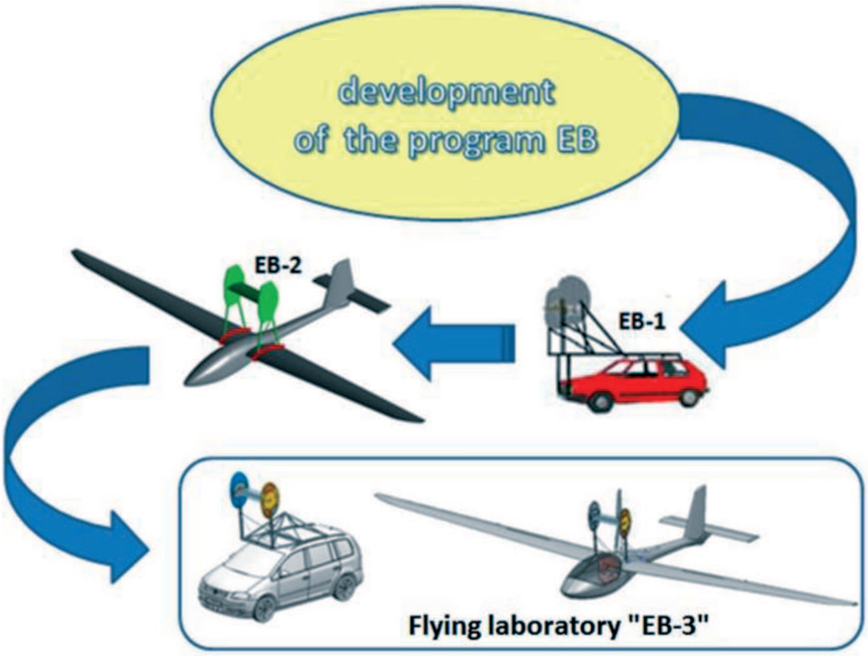

Fig. 2. Development of the EB – program

Fig. 3. Testing the EB-1

A research element comprised of a segment of the wing together with the flap, which was fixed between two large perpendicular side-plates - was marked as EB-1. Outside the side-plates, an electronic measurement system was installed, which allowed recording of the pressure changes simultaneously in 32 points on the wing's surface. The angle of incidence (AoA) of the wing and deflection of the flap were adjustable. The experiments were performed on a 3 km long runway of an airfield. Sample of registered time courses of a pressure signal (without filtration), measured at chosen points of the wing, is shown in Fig. 4. The first half of the chart refers to the car acceleration phase (up to 100 km/h), and the second half refers to the deceleration. On the basis of several records, the images of pressure distribution for the specific airspeed and AoA's values have been derived.

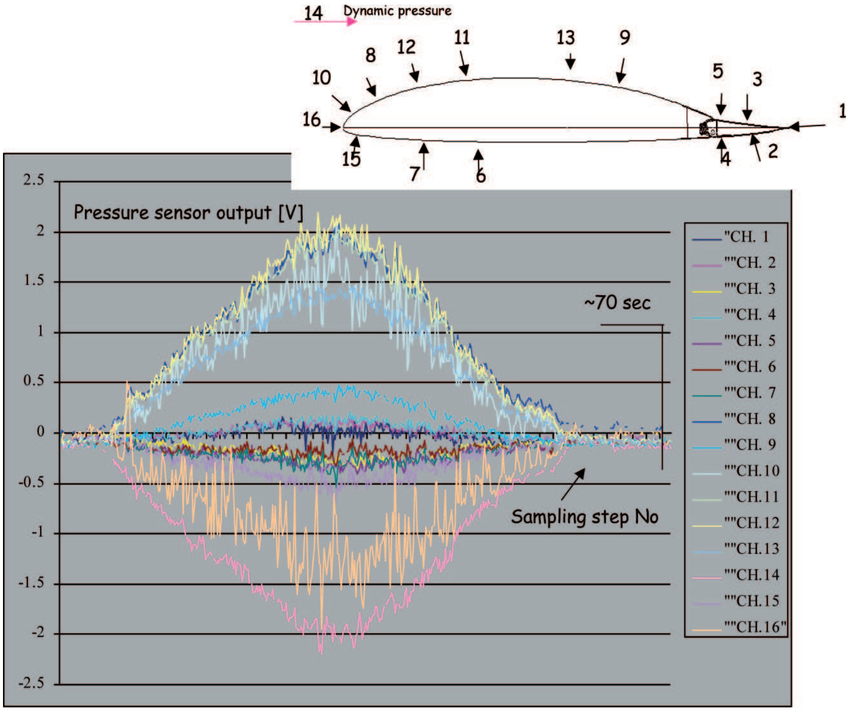

Fig. 4. Example of registered pressure signals

The EB-1 was used mainly for testing the hardware and procedure of pressure distribution measurement and for preparation of the next EB-program phases.

3. EB-2 – flying wind-tunnel

Based on the knowledge gathered from the EB-1 experiments, the next part of research program was aimed at the fly-lab design. The authors decided to use the PW-6 glider. This glider was elaborated and built in the IAAM about the year 2000, and the first prototype has been available for research programs undertaken by the WUT [2]-[5]. The design concept of the fly-lab is shown in Fig. 5.

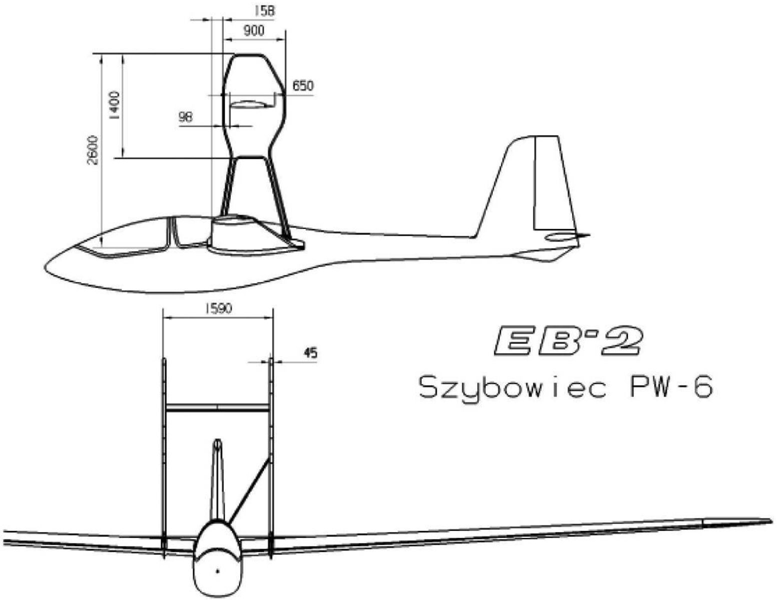

Fig. 5. EB-2 fly-lab of Warsaw University of Technology

This time the stand for measurement of the pressure distribution over the tested wing-segment, which consisted of two composite side plates integrated with the beam-legs and special composite ribs, was fixed high above the glider's wings. All electronic equipment was placed inside the side-plates (see Fig. 6). This concept of flying wind-tunnel was named EB-2.

Fig. 6. Structural design of EB-2

During the design and manufacturing process, the designers were obliged to fulfill plenty of airworthiness requirements for example flight stability, strength and flutter analysis (Fig. 7). Fig. 8 presents examples of critical load-cases for the strength test. Aerodynamic forces are represented by bright color vectors, while inertial forces are represented by dark color vectors.

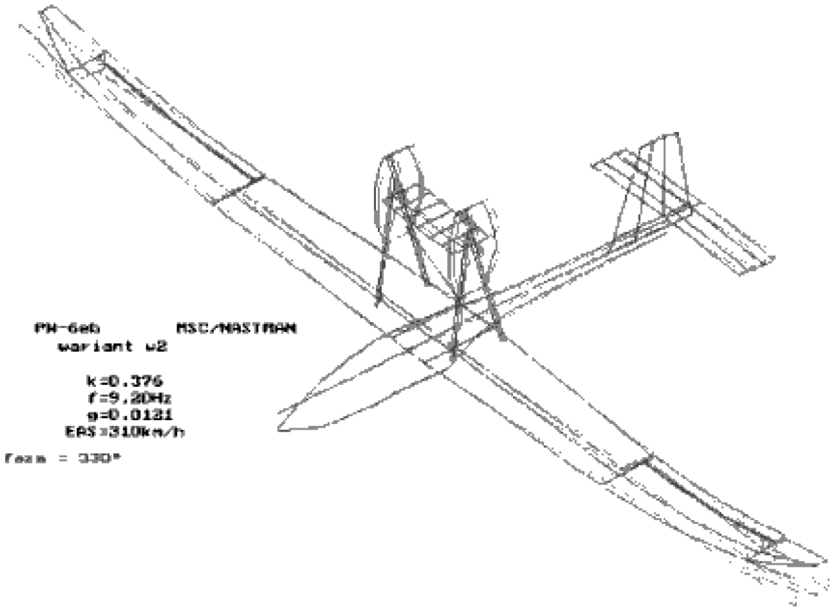

Fig. 7. Example of flutter analysis of the PW-6 glider with EB-2 on top

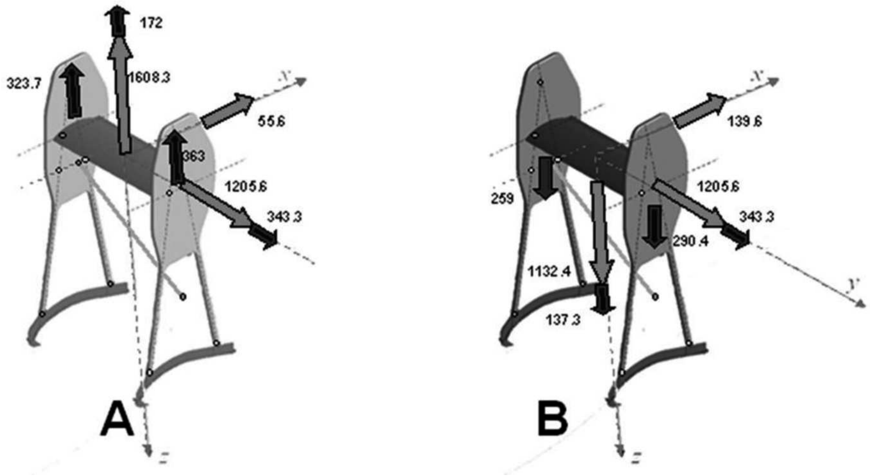

Fig. 8. Critical load-cases for strength testing of EB-2

The maiden flight was made in summer 2006 (Fig. 9). The main aim of the first EB-2 try was to check stability of the glider with the wind tunnel stand on the top. As the safety aspect was crucial in this event, the authors decided to use a towing car for launching the glider. The car was equipped with a 600 m long polyester rope and special release system to be able to control launching process during the towing. The 200m altitude gained above the ground was high enough for confirmation of good stability and proper dynamic behavior of the glider, which were necessary to continue the program. Further tests of the fly-lab were planned to be conducted using aero towing as a common launching method, like in the case of normal gliders. Unfortunately, they were stopped due to budget problems.

Fig. 9. First take-off EB-2

4. EB-3 – a new generation of the fly-lab

New development opportunities were offered as in 2009 two Polish universities (Rzeszów University of Technology and the WUT) launched a large research program ”Multifunctional two-seater motor-glider with an electric propulsion”. That program aimed at the design of a special, self-launching glider (AOS-71) to be used as a multifunctional flying laboratory. One of the function of this new fly-lab was a flying wind-tunnel, designated mainly for educational and demonstration purposes (i.e. training the students in observations and measurements of the airflow and dynamic phenomena of the tested objects under real flight conditions). The objects to be tested would be, for example, segments of the wings (like in previous EBs) as well as different kinds of lightweight aircraft propulsion systems integrated with the wing-segment. The AOS-71 was designed and manufactured by the IAAM-team. The authors of the paper were responsible for the task aimed at the design of flying wind tunnel. The concept of such a wind-tunnel, named EB-3, is shown in Fig. 10.

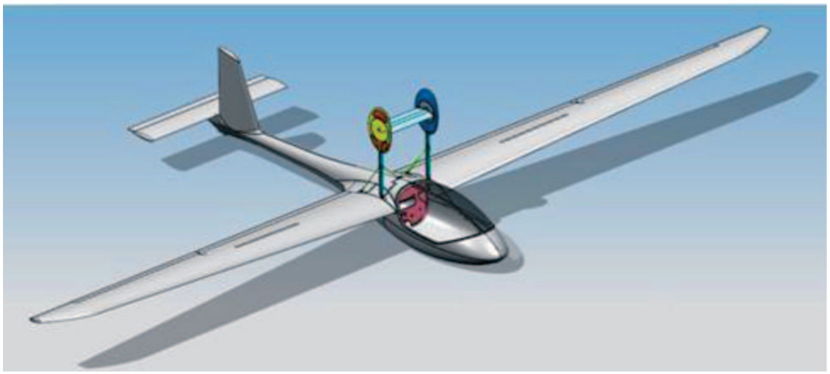

Fig. 10. Flying laboratory AOS-71 with EB-3 on the top

Beside an advanced pressure measurement system, the main difference between the elements of EB-2 and EB-3 consist in the installation of electronic balances, i.e. the load cells for aerodynamic and inertial forces measurement (see Fig. 11).

4.1. Description of the EB-3 hardware

The design of testing stand is shown in Fig. 12 and 13. Like in previous EBs – a researched wing-segment is fixed to the side-plates. This time each side-plate is divided into three structural parts: main body (1), and two circular discs: the outer (2) and the inner one (3). They are integrated in the turnable manner by the system of 3-rollers (4) and by the bolt for fixing the turn-angle (5). The examined wing-segment is connected with the outer disc (2). The aerodynamic forces (and the inertial once) are transferred from disk (2) to disk (3). Disc (3) is suspended on three load cells (6) from the main body of the stand (1). Such a solution allows for testing of the wing-segments in a wide range of AoA's, to be changed in a continuous way.

The load cells and equipment necessary for aerodynamic forces measurement are shown in Fig. 14. Each balance consists of a special aluminum alloy ring and the Wheatstone bridge – consisting of 4 strain gauges, glued on the ring-surface. The balances are connected to signal amplifiers, which are stored in the side-plates. All signals are transmitted to the signal-conditioning system As the measurement of aerodynamic forces on the moving wind-tunnel is affected by variable acceleration generating increments of inertial

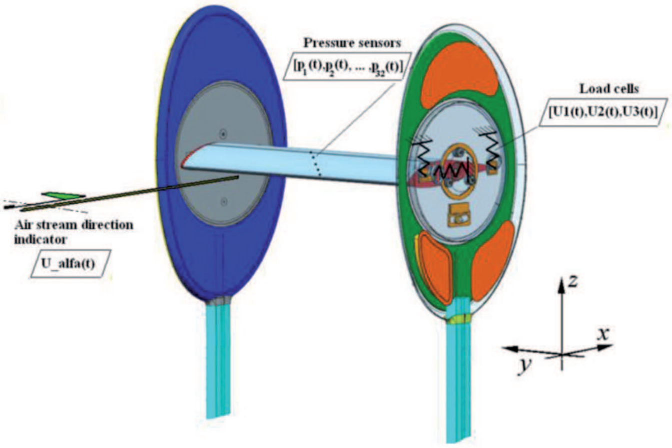

Fig. 11. EB-3 – load cells and voltage outputs (U_1, U_2, U_3) used for measuring loads induced on the tested wing-segment

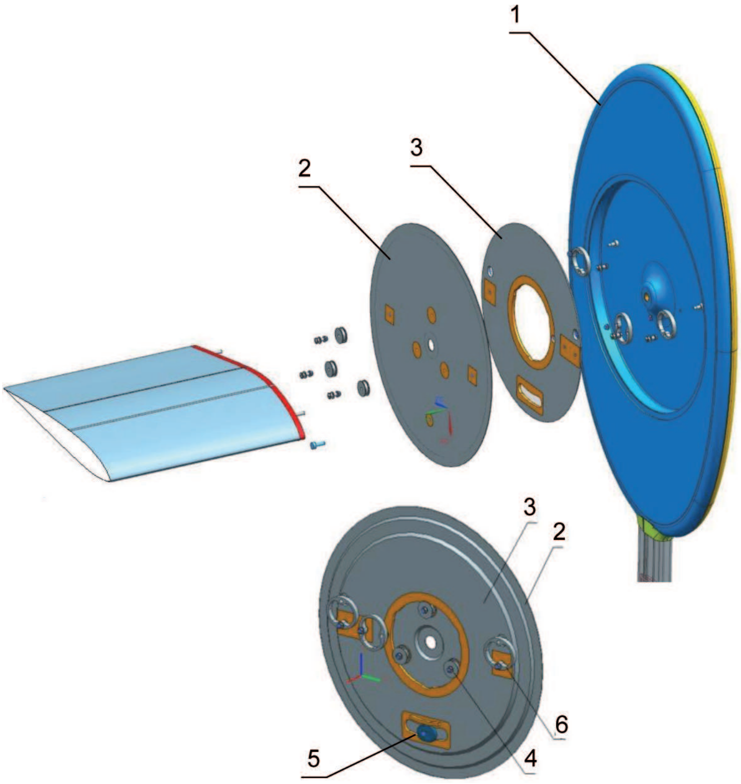

Fig. 12. EB-3 – design of the testing-stand

forces – the system of load cells is supplemented by an electronic accelerometer, which is fixed close to the center of gravity of the tested wing.

Fig. 13. Photos of EB-3 structural elements

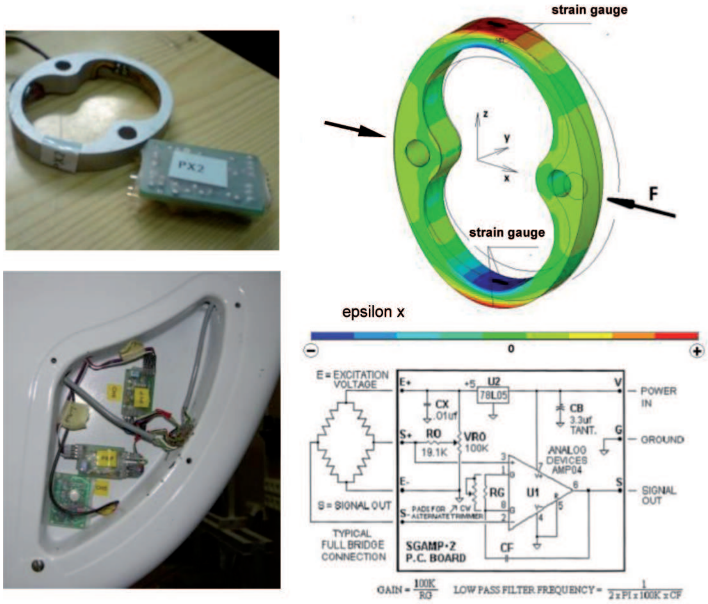

Fig. 14. Load cells and amplifiers for forces measurement on theEB-3 wing

Another element of the measurement system is the electronic AoA-indicator (Fig. 15). The device used in the EB-3 is based on an electronic chip containing an array of Hall sensors, and small magnet, which is integrated with the axis of rotation of an arrow-idicator self-allignable to the air stream.

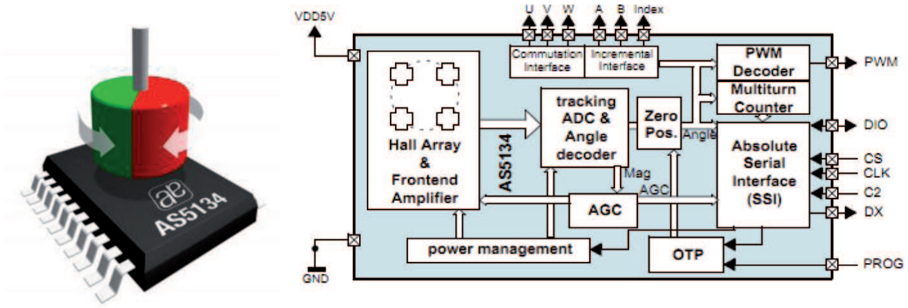

Fig. 15. Angle of incidence (AoA) measuring system

Signals from the load cells, accelerometer and AoA indicator, are transmitted to the analog-digital converter (A/D converter – see Fig. 16.) and then to a mobile computer. All processing of the signals can be performed in the "on-line" mode.

Fig. 16. A/D converter used in EB-3 (NI USB-6009; features: 14-bits resolution, sampling frequency: 48kS/s)

The system for pressure distribution measurement is shown in Fig. 17. Special inserts were applied into composite shells during manufacturing process of the wing structure. The inserts are made to allow for the connection of pressure measurement points (i.e. small holes of 0,4 mm diameter which are to be drilled on the wing-surface) – with the pressure sensors. The main difficulty consist in proper location of those holes, because the drilling operation is usually performed after painting the wings, and the location of the inserts at this phase is invisible from the outside of wing surface. The array of pressure sensors is integrated with electronic amplifiers, and linked with the A/D converter. The USB output of the A/D converter is connected with the PC stored in the glider fuselage. The system is supplemented by a Prandtl tube fixed on the outer disc (2) – (see Fig. 11), which is necessary for measurement of undisturbed air stream velocity insert.

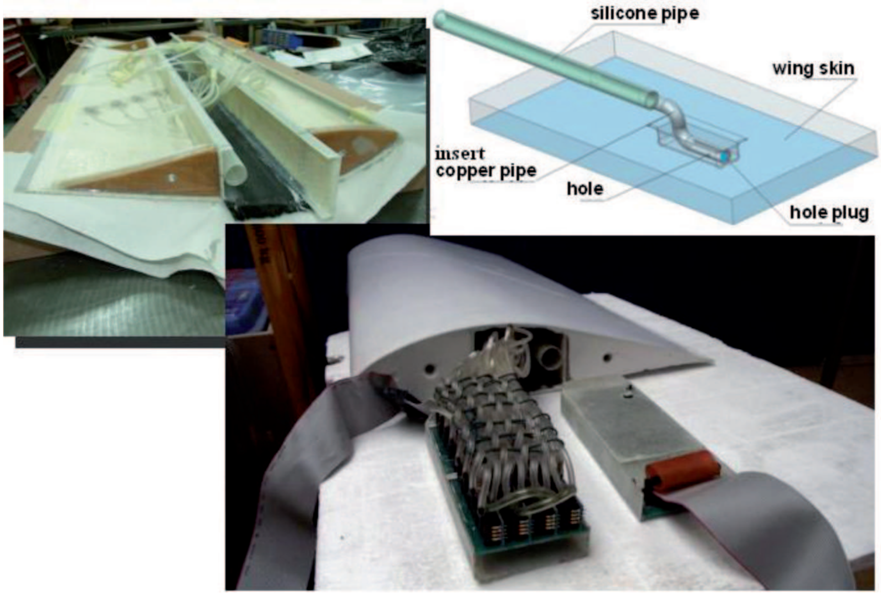

Fig. 17. Arrangement of EB-3 pressure measurement system

4.2. Signal calibration and processing

Before using the EB-3 on the AOS-71 glider – it is necessary to perform several ground tests of the whole system aimed at checking its effectiveness and reliability and calibration of measurement channels. These tests are very important especially for the measurement system of forces acting on the EB-3 wing. For this purpose, the authors designed a special-multifunctional testing stand. This stand may be used for static tests as well as the dynamic once of the EB-3 (to be performed on a moving car – see Fig. 18).

Unlike on the glider, the whole stand can be rotated along the horizontal axis. A special servo mechanism has been used to remotely adjust the tilt of the EB-3.

A block diagram showing the signal processing procedure, drawn specially for testing the EB-3 on the stand, is shown in Fig. 19. At first, each signal is filtered by a low-pass digital filter. The filtered signals are compensated on the basis of calibration-test results (performed before the experiments). In the case of load cells – this compensation comprises two aspects: the influence of tilt angle variation, and the influence of varying acceleration during the

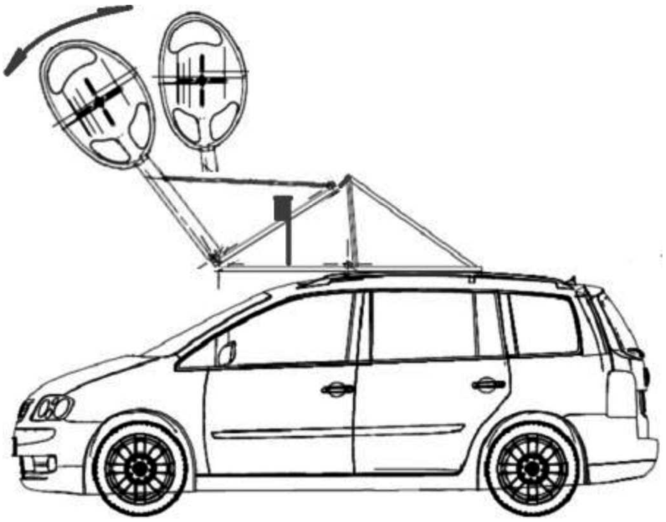

Fig. 18. Testing stand for the EB-3

dynamic test. The procedure of compensation allows for determining x and z components of the resultant aerodynamic force acting on the EB-3 wing – (see Fig. 20) without the influence of inertial forces, generated by varying acceleration or tilt angle changes.

4.3. EB-3 signal calibration procedure

A transformation matrix (marked as **A** at Fig. 19), plays an important role in the signal processing procedure. This matrix contains the coefficients necessary for transformation of voltage signals (i.e. outputs of load cells) into the external loads acting on the EB-3 wing, i.e. tangent and perpendicular (in relation to the wing-plane) components of force vectors together with the pitch moment of force.

In order to determine this transformation matrix, it is necessary to apply the calibration procedure.

This procedure is based on the following equation:

$$\boldsymbol{F} = \boldsymbol{U} \cdot \boldsymbol{A} \tag{1}$$

Where:

— $F \in R^3$ is the vector of EB-3 wing external loads, composed of two perpendicular force components and one moment of force: $F = [F_x \; F_z \; M_y]$

— $U \in R^3$ is the vector consisting of voltage outputs of load cells:

$$\Delta U = [\Delta U_1 \Delta U_2 \Delta U_3] \tag{2}$$

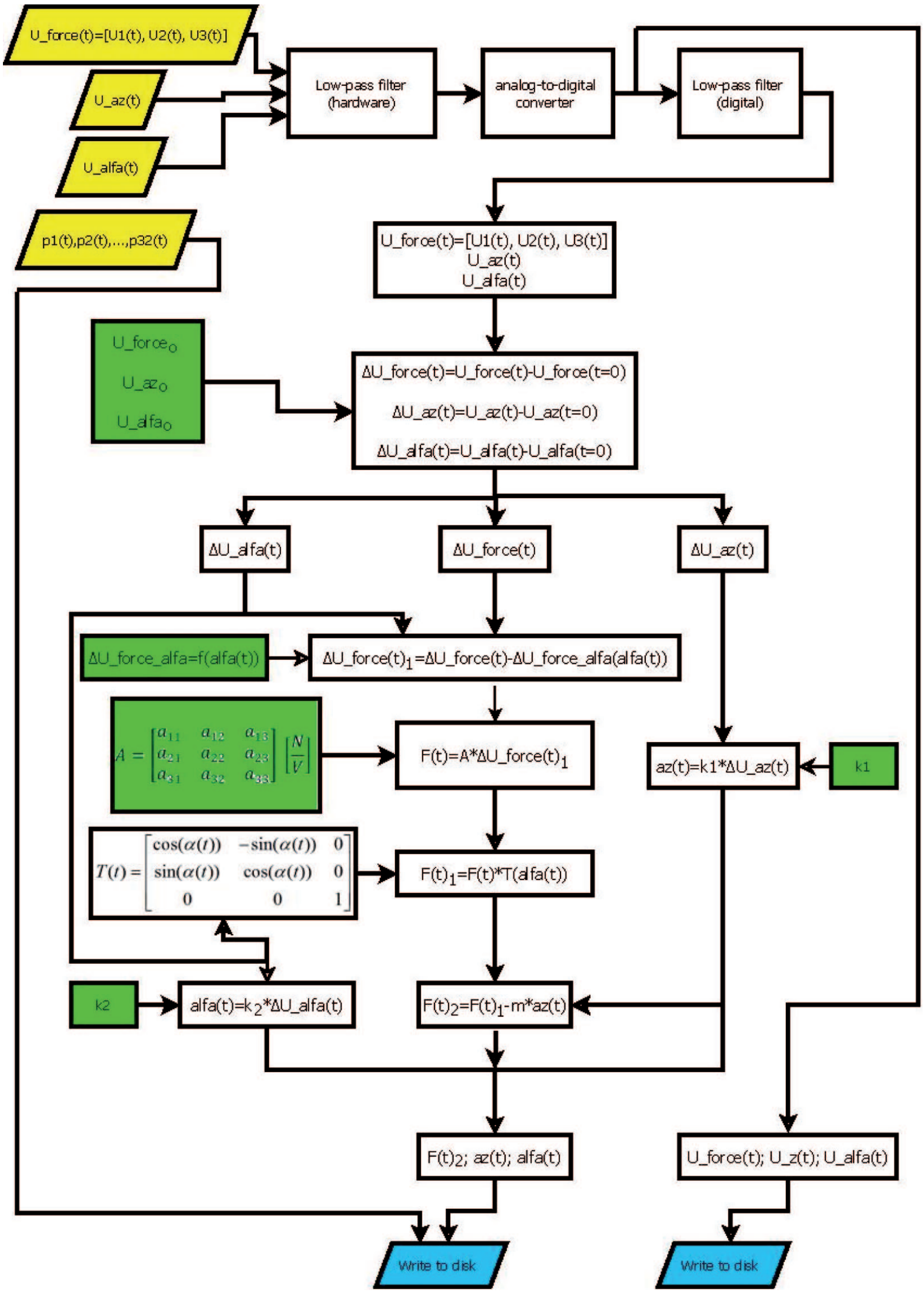

Fig. 19. Block diagram of signal processing

Note: symbol Δ means an increment of force or voltage signal relative to the initial value (which may be different than zero due to wing mass influence, or non-zeroed signal amplifiers).

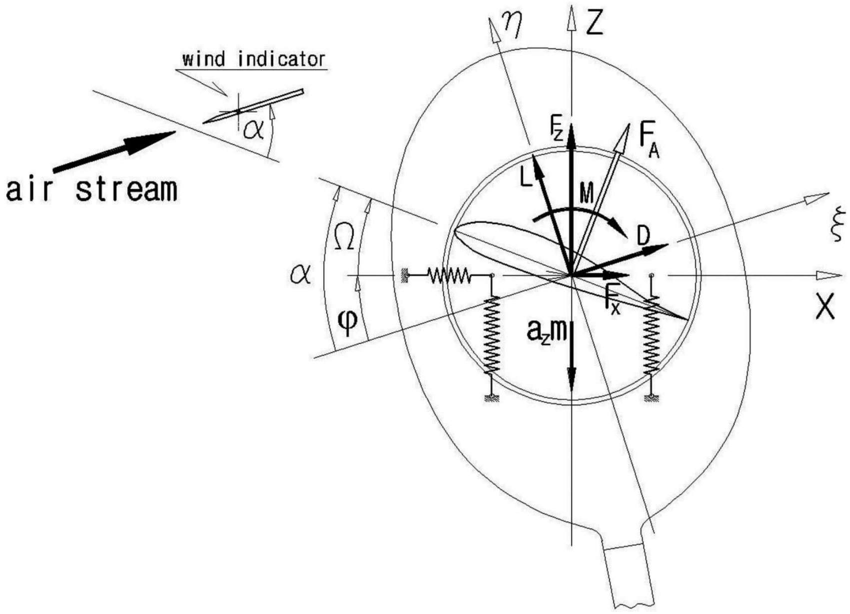

Fig. 20. Illustration of the EB-3 force measurements system

— $A \in M_{3x3}(R)$ is the transformation matrix to be found:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{3}$$

In the case of EB-3 stand – the calibration procedure consisted in application of the loads to the EB-3 wing in three different ways (i.e. applying three linearly-independent vectors of loads – see Fig. 20) and gathering the information about corresponding increments of voltage outputs of load cells.

The result of each experiment (i.e. each loading case) can be written as:

$$\left[F_x^i \, F_y^i M_y^i\right] = [\Delta U_1^i \Delta U_1^i \Delta U_1^i] \cdot \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{4}$$

where i = 1, 2, 3 – is the index of a loading case.

Having outputs of all three loading cases, we can formulate the equation:

$$\begin{bmatrix} F_x^1 & F_y^1 & M_y^1 \\ F_x^2 & F_y^2 & M_y^2 \\ F_x^3 & F_y^3 & M_y^3 \end{bmatrix} = \begin{bmatrix} \Delta U_1^1 & \Delta U_2^1 & \Delta U_3^1 \\ \Delta U_1^2 & \Delta U_2^2 & \Delta U_3^2 \\ \Delta U_1^3 & \Delta U_2^3 & \Delta U_3^3 \end{bmatrix} \cdot \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{5}$$

where $a_{11}, a_{12}, \ldots, a_{33}$ are unknown coefficients.

Hence, the matrix $\boldsymbol{A}$ can be derived by a simple transformation of equation (5).

It was found that in the case of EB-3 those matrices take the shape:

It is worth emphasizing that the experiments and calculations made by the authors were supported by the algorithm written in the LabVIEV program.

4.4. The relative error of measurement

In the case of test performed on the car – the angle $\beta = 0$ and therefore $\varphi = \alpha$ (see Fig. 20), so the system consisted of aerodynamic loads and the reaction forces caused by those loads can be simplified to the form presented in Fig. 21.

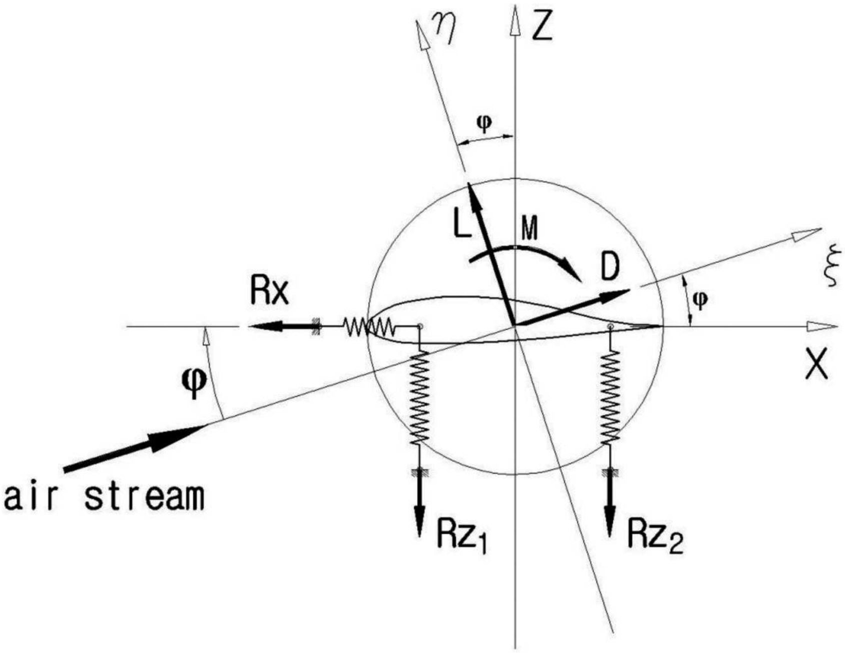

Fig. 21. Aerodynamic loads and reaction forces

Hence the tangential and normal components of an aerodynamic force can be derived from the following equations:

$$L = -R_x \sin\varphi + (R_{z1} + R_{z2}) \cos\varphi \tag{6}$$

$$D = R_x \cos\varphi + (R_{z1} + R_{z2}) \sin\varphi \tag{7}$$

The measurement errors are expressed by equations (8) – (11):

$$\Delta L = |-\sin\varphi|\,|\Delta R_x| + |\cos\varphi|\,|\Delta R_{z1}| + |\cos\varphi|\,|\Delta R_{z2}| + |-R_x \cos\varphi - (R_{z1} + R_{z2}) \sin\varphi|\,|\Delta\varphi| \tag{8}$$

$$\Delta D = |\cos\varphi|\,|\Delta R_x| + |\sin\varphi|\,|\Delta R_{z1}| + |\sin\varphi|\,|\Delta R_{z2}| + |-R_x\sin\varphi + (R_{z1}+R_{z2})\cos\varphi|\,|\Delta\varphi| \quad (9)$$

$$\frac{\Delta L}{L}100 = \frac{\Delta L}{-R_x\sin\varphi + (R_{z1}+R_{z2})\cos\varphi}100\ \% \quad (10)$$

$$\frac{\Delta D}{D}100 = \frac{\Delta D}{D = R_x\cos\varphi + (R_{z1}+R_{z2})\sin\varphi}100\ \% \quad (11)$$

The relative errors of L and D aerodynamic force components depends on the features of the object to be investigated. In the case of the wing segment having typical glider airfoil, those errors can be very significant – especially regarding D component.

For example, taking into consideration the aerodynamic characteristics of the EB-3 system consisted of the wing-segment with Wortmann FX66-17A-II-182/20 and the side plates (Fig. 22), and assuming that the errors of force and angle measurement are as follows: $\Delta R = \pm 0.5N$, $\Delta\varphi = \pm 2^\circ$ – the following values of relative errors can be determined from equations (10) and (11) – see Tab. 1):

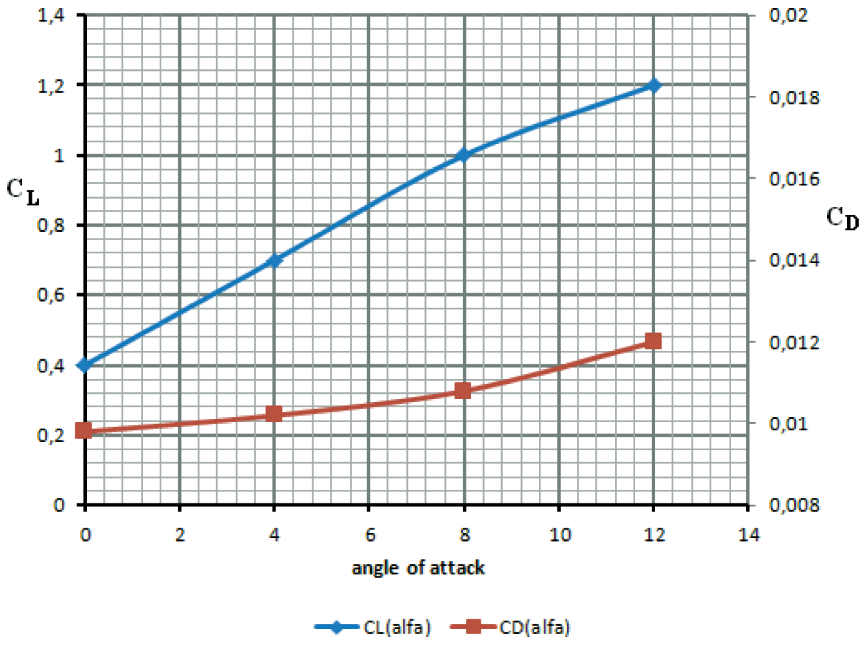

Fig. 22. Aerodynamic characteristics of the wing segment together with the side plates *(Fluent based approximation)*

As it arises from Tab.1 – only L component can be measured with acceptable accuracy for the assumed values of ΔR and $\Delta\varphi$.

The chart showing measurement errors of D component for another values of ΔR and $\Delta\varphi$ is shown in Fig. 23. The D-component measurement error

Table 1.
Relative errors of measurement – the case of pure wing segment with Wortmann FX66-17A-II-182/20

	The relative error of measurement			
	φ =0°	**φ =4°**	**φ =8°**	**φ =12°**
$\frac{\Delta L}{L} \cdot 100$	*1.5%*	*0.9%*	*0.6%*	*0.5%*
$\frac{\Delta D}{D} \cdot 100$	*171%*	*270%*	*356%*	*381%*

of about 10% can be obtained only in case when the $\Delta\varphi$ inaccuracy would be under 0,02 deg, which is non-realistic value to be obtained with use of the instrument shown in Fig. 15.

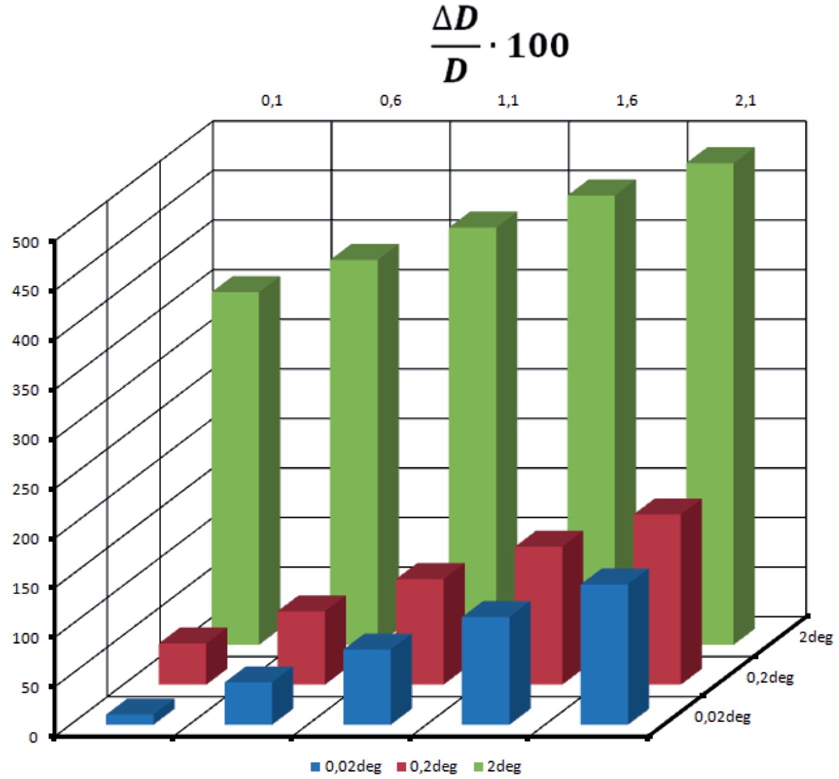

Fig. 23. The dependence of the D component measurement error from the errors ΔR and $\Delta\varphi$

The situation looks much better in the case of testing lightweight propulsion systems. One of the solution of propulsion system to be considered on the EB-3 stand is an oscillating flap in front of the wing (Fig. 24) [7]. Taking into consideration the aerodynamic characteristics of such a system taken from [7], [8] and assuming again that: $\Delta R = \pm 0.5N$, $\Delta\varphi = \pm 2°$, the following measurement errors for L and D components can be derived from the equations (10) and (11) – (see Tab. 2).

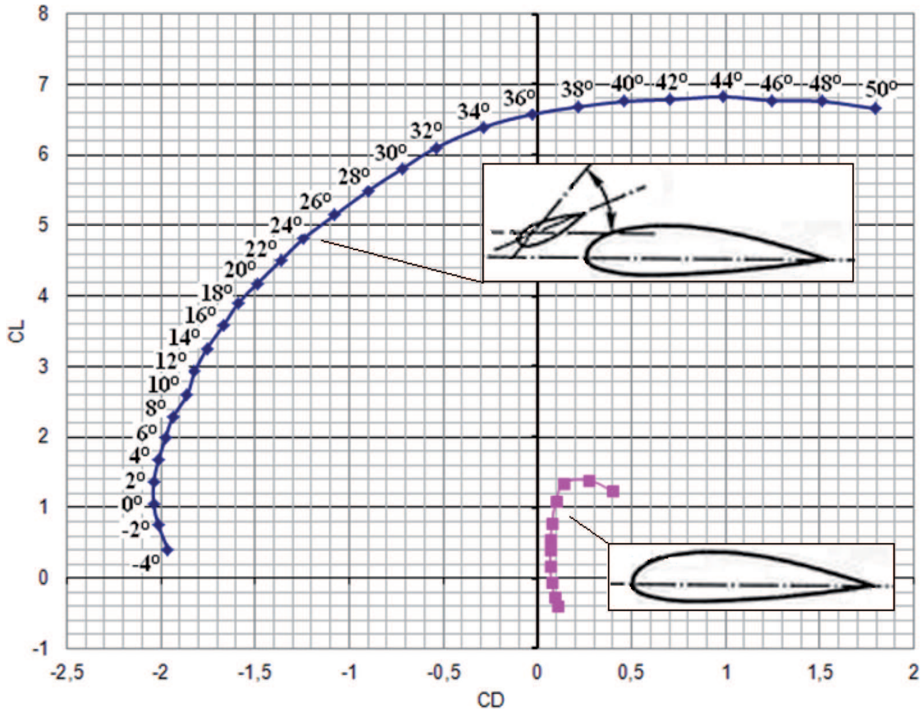

Fig. 24. Aerodynamic characteristics of the wing with an oscillating flap in front of the leading edge [7]

Table 2.

Relative errors of measurement – the case of propulsion system from Fig. 24

	The relative error of measurement					
	φ =0°	**φ =4°**	**φ =8°**	**φ =12°**	**φ =20°**	**φ =30°**
$\frac{\Delta L}{L} \cdot 100$	*7.3%*	*4.5%*	*3.2%*	*2.3%*	*1.4%*	*0.5%*
$\frac{\Delta D}{D} \cdot 100$	*1.9%*	*3.1%*	*4.3%*	*5.8%*	*10.1%*	*28%*

As it arises from Tab. 2, the accuracy of measurement system for such application would be sufficient in large AoA range for both *L* and *D* components.

4.5. EB-3 dynamic testing

Having fully defined the signal processing procedure, the authors passed to the next phase of EB-3 program – the dynamic testing. The aim of those tests was to check all measurement systems under the conditions, which simulated fly-lab surroundings. For this purpose, the EB-3 stand was placed on the roof of the car (Fig. 25).

Fig. 25. Dynamic testing of EB-3

It was supposed that during dynamic tests the car would be driven at a constant speed (100 km/h) and the angle of attack will slowly change between critical negative and critical positive values.

All signals (i.e. from the pressure sensors and load cells should be recorded in the mobile computer disk, and should be processed in "on line" mode. For this purpose, a special tool was design in LabVIEW program, which allows for remote control of AoA as well as graphical presentation of all recorded parameters, including the pressure distribution on the EB-3 wing, and three load components (Fig. 26).

The sample of recorded characteristic of c_L as a function of AoA is shown in Fig. 27.

The curve of lift force coefficient c_L in Fig. 27 is compared with the value of c_L, which was derived in the Fluent program. The Fluent program allows for estimation of aerodynamic characteristics of the system consisting of the wing-segment and two side-plates taking into account effective aspect ratio of this system and 3D- nature of the airflow. As it follows from point Fig. 27 both characteristics are similar.

The sample of pressure distribution on the airfoil, derived from the experiment is shown in Fig. 28.

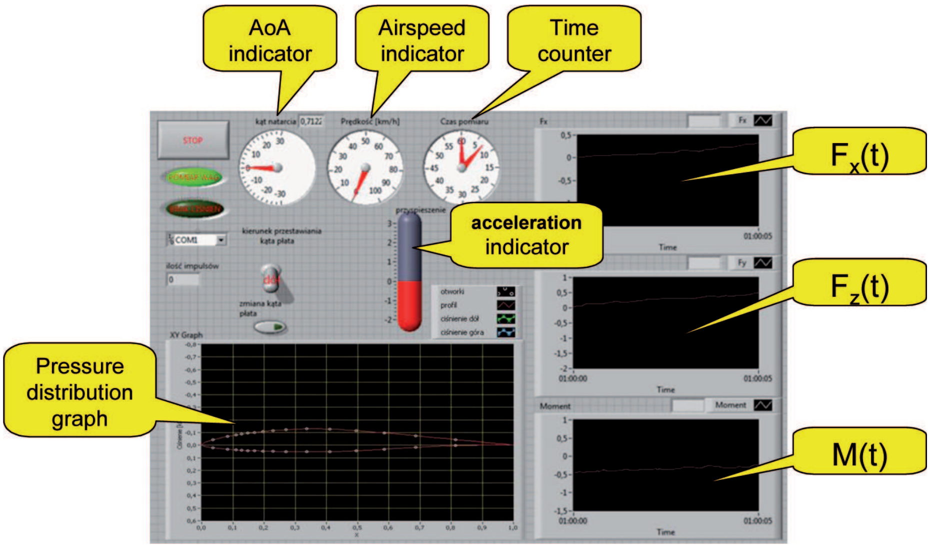

Fig. 26. LabVIEW presentation of EB-3 testing parameters

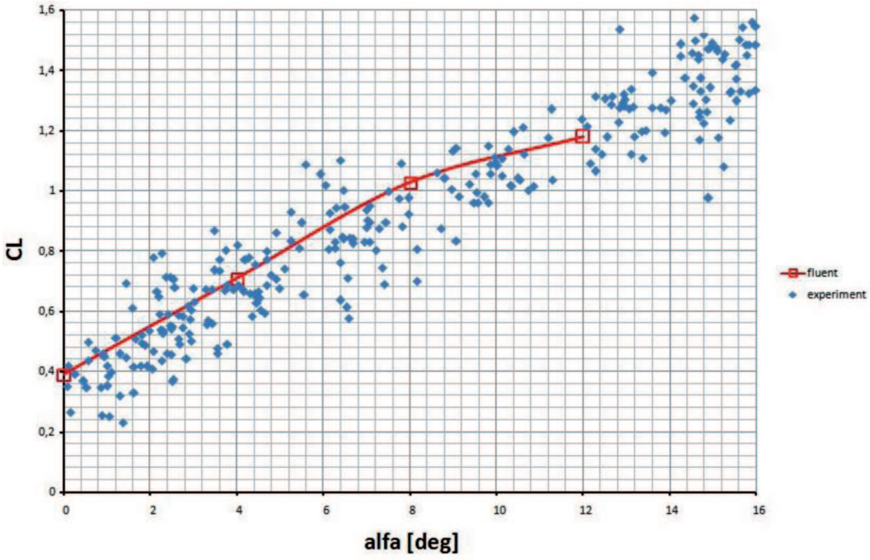

Fig. 27. LabVIEW presentation of EB-3 testing parameters

4.6. EB-3 program current status and plans

The current status of EB-3 program consist in preparations to the tests in the air. A lot of work still has to be done, especially to ensure fulfillment of the airworthiness requirements.

The long-term plans regarding the EB-3 consist of the following application:

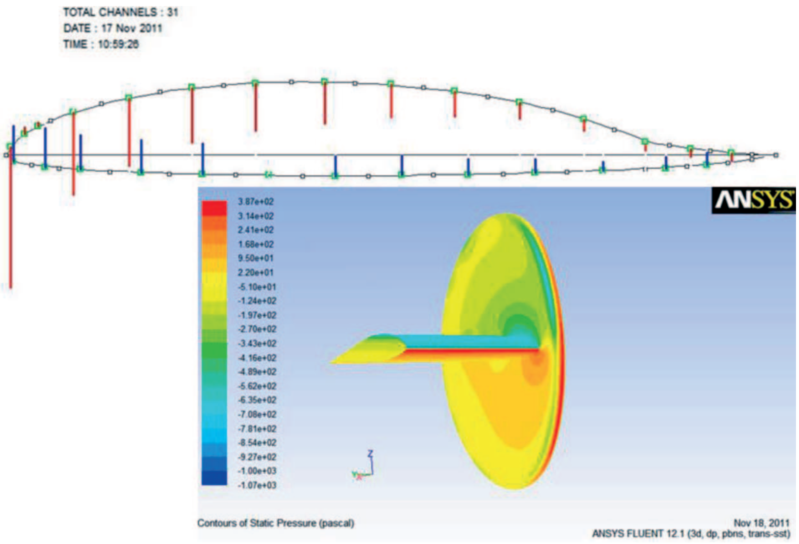

Fig. 28. Graphical presentation of test results

(I) Aerodynamic experiments with the airfoils, for example:

- Multipoint pressure measurements and estimating the pressure distribution over the airfoil and change of momentum of the air stream behind the wing-segment (application of aerodynamic rake)
- Flow visualization
- Research of the airflow phenomena inside the boundary layer (depending on the applied instrumentation). The system is under development

(II) Experiments with the lightweight propulsion systems – (including such untypical solutions as described in the [8],[9]).

5. Summary

The design of flying laboratories requires a knowledge regarding: structural design, mechanics of light, flow simulation, airworthiness requirements, measurement methodology, etc.

It was exciting challenge for the authors (Fig. 29). However, their work was supported by scientists and students from the WUT. The authors would like to express warm thanks to all friends involved in this unique research and educational program.

Fig. 29. The authors and their EB-3

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Program Latającego Laboratorium EB-3 realizowany na Politechnice Warszawskiej

Streszczenie

Autorzy opisują badania prowadzone na Politechnice Warszawskiej (PW), mające na celu rozwijanie mobilnych aerodynamicznych laboratoriów. Przedsięwzięcie zostało nazwane program – EB (od Elementu Badawczego, którym to terminem określono badawczy odcinek płata aerodynamicznego). Program EB ukierunkowany jest na określenie właściwości aerodynamicznych płata nośnego oraz lekkich systemów napędowych w naturalnej skali i w warunkach rzeczywistej atmosfery. Przedsięwzięcie ma zarówno charakter badawczy jak i edukacyjny: we wszystkich fazach programu są zaangażowani studenci PW (projekt, wytwarzanie i testowanie). W wyniku pracy, powstały trzy mobilne laboratoria aerodynamiczne: EB-1 – który był testowany na dachu samochodu, EB-2 – unikalne latające laboratorium zabudowane na szybowcu PW-6 i EB-3. Jest to nowa generacja latającego tunelu aerodynamicznego do wykorzystania na motoszybowcu AOS-71 (który obecnie jest w trakcie przygotowań do prób w locie). Autorzy przedstawiają szczegółowo systemy pomiarowe i procedury obsługiwane przez oprogramowanie LabVIEW.