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Preliminary Concept of an Unmanned Aerial Vehicle for Patrolling of Water Basins

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Abstract. The paper presents a preliminary concept of an unmanned aerial vehicle (UAV) designed with a form of the Kasper wing (known in Polish as the 'Kasprzyk wing') and intended for aerial patrolling and monitoring of large water basins, mass gatherings, ground traffic, state borders, and other applications. Considering the potential uses resulting from the applications, the UAV defined in this preliminary concept would have to operate with high-value onboard data acquisition equipment. This is why this paper focus specifically on the problems of security and protection of the onboard data acquisition equipment the purchase costs of which can be several times higher than the costs of building the UAV airframe.

This work has been compiled from the paper presented during the 12th International Armament Conference on Scientific Aspects of Armament & Safety Technology, Jachranka, Poland, September 17-20, 2018.

This problem brought the authors to the main assumption of the work presented herein: to develop an UAV design which would provide maximum security and protection of the onboard mission loadout even in conditions of complete loss of propulsion and guidance control. The capability of safe emergency unpowered landing of the UAV enabled the application of an reflex airfoil based on the Kasper wing design.

In the event of a propulsion power loss, the UAV could automatically begin a low advance velocity flight to reduce the risk of UAV failure upon touchdown. This was how the objective of this work was identified: to study the design criteria and select the materials for the fabrication of the UAV. The fabrication materials were selected to minimise the risk of failure or sinking of the UAV and its high-value onboard loadout in the event of emergency alighting on water. The behaviour of an UAV model at various loads which simulate real-life flight conditions required a multi-faceted analysis; the second part of the work discusses a selection of experimental methods (including an optically active layer method and a digital image correlation method) which will enable testing the strength properties of the fabricated structural elements of the UAV.
Keywords: mechanical engineering, unmanned aerial vehicle, airframe.

1. INTRODUCTION

The monitoring of environmental conditions of large water bodies is often based on satellite imaging. Satellite imaging, however, has several drawbacks. A satellite passes the area to be imaged every few days. There is also no 100 per cent certainty that the weather conditions (cloud coverage) will be favourable enough to enable satellite imaging. In terms of long-term monitoring, both factors are rather negligible — unlike situations which demand urgent monitoring of the effects of an environmental disaster. An event like this may occur when the affected site is outside the range of observation of any orbital vessel. The maximum resolution of regular satellite images is too low (approx. 10 m) to monitor rivers from orbit. Yet another drawback is the presence of the Earth's atmosphere between the monitored area (like a water body) and the satellite onboard instruments. The composition (and pollution levels) of the atmosphere need to be considered when analysing satellite imaging outputs. An alternative to satellite imaging and monitoring is UAVs outfitted with multi-spectrum cameras. This type of craft and its mission loadout would enable observation of ground and water at any time, without any errors in imaging from pollutants in the atmosphere; this solution is also a viable method for monitoring of rivers.

2. THE KASPER WING

Witold Kasper (real name: Witold A. Kasprzyk), a Polish design engineer and pilot, discovered a unique phenomenon while testing the BKB-1 experimental tailless glider in flight. Kasper managed to fly the BKB-1 with a low descent rate (0.5 m/s) at a low speed (32 km/h) and a high angle of attack (AOA = 35°).

A detailed investigation into this finding revealed that its root cause was stable lift-inducing vortices over wings that would emerge at high AOA values (following a stall) and generate lift of the airfoil. Special features of the Kasper wing embodied in the BKB-1 were the back sweep of the wing at approx. 20°, an reflex airfoil profile and wing tip stabilizers. The unique feature of the Kasper wing was the ability of flight with an extremely low or zero advance velocity with the manoeuvrability of the aircraft retained [1]. Witold Kasper applied the findings in successive designs, which included the BKB-1A glider or the Kasperwing ultralight flying wing motorglider (Fig. 1.a) [5].

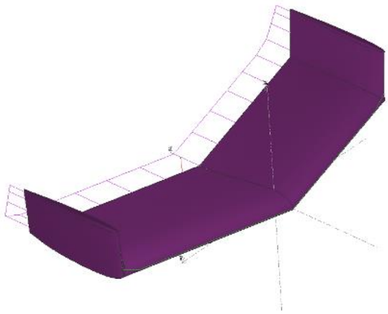
(a)  (b) 

Fig. 1. (a) Kasperwing ultralight flying wing motorglider [6]; (b) Model of the UAV being developed in Xflir5 software

These unique features of an aircraft designed with the Kasper wing will be used by the authors to reduce the risk of damage to high-value onboard instrumentation of the UAV during landing (at a low advance velocity) and a potential failure of propulsion in flight. In the event of a propulsion power loss, the UAV could automatically begin a low advance velocity flight to reduce the risk of UAV failure upon touchdown. During the work discussed herein, the first models of the UAV were developed.

3. UAV MATERIALS AND STRUCTURE

The first stage of work was to model the UAV in Xflir5 software (Fig. 1.b) and run CFD simulations in OpenFOAM (Fig. 2). The analyses of the model and the simulation confirmed that stable lift-inducing vortices over wings could form at high AOA values in flight.

A significant part of the analyses was the selection of building materials and the wing structure, guided by the primary design condition of minimising the risk of the UAV sinking following emergency alighting on water.

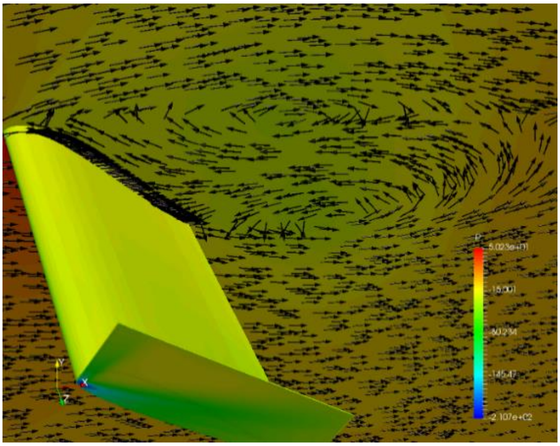


Fig. 2. Over-wing lifting vortices forming at 35° AOA (simulated in OpenFOAM)

The wing of the UAV was developed from the MH78 reflex airfoil [7] (Fig. 3). To endow the structure with unsinkability, the wing airfoils were made from rigid PUR (polyurethane) foam, commercial name EKO PRODUR CP 4090, with the following characteristics [8]:

- apparent core density: 92 kg/m^3 (PN-EN 1602:1999);
- compressive strength: 560 kPa (PN-EN 826:1998);
- water absorption (24 h), V/V: 0.2% (PN-93/C-89084).

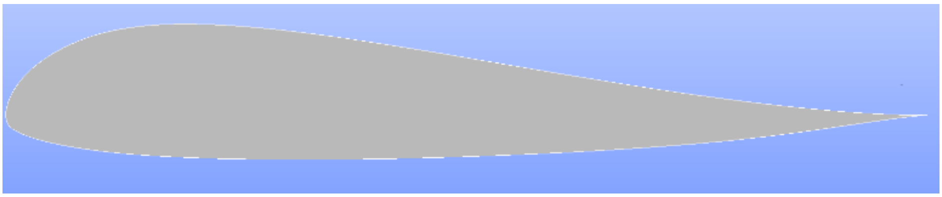
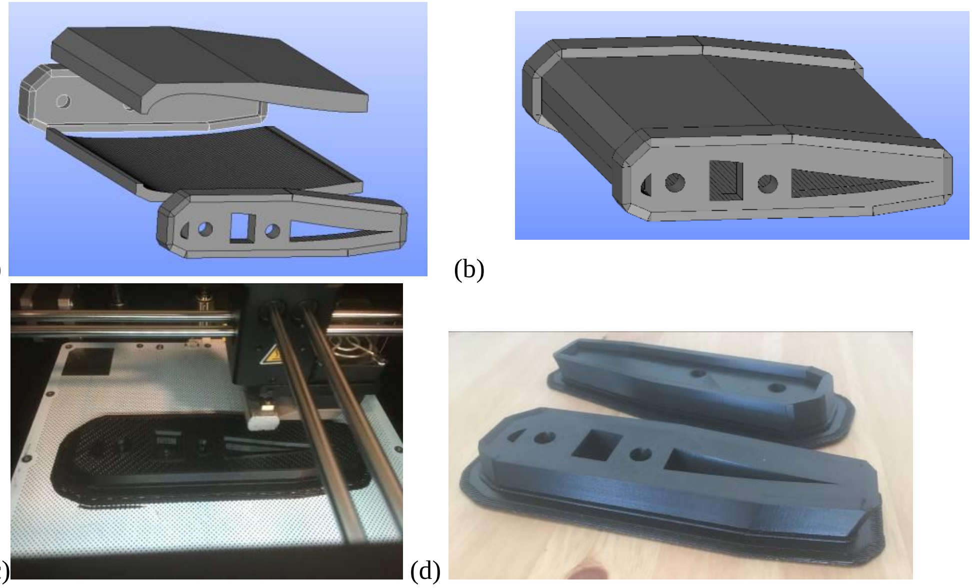


Fig. 3. MH78 airfoil

An innovative solution was the production of a casting mould for the wing by applying 3D printing (Fig. 4). During this stage of work, a proof of concept was made by building a smaller version of the wing casting mould in the form of a four-piece box with PUR inlet holes and embedding spars in the form of carbon or aluminium tubes (Fig. 4).



a) (b) (c) (d)

Fig. 4. Wing casting mould: (a) CAD model; (b) CAD model of the assembled wing casting mould; (c) 3D printing progress; (d) finished 3D-printed parts of the wing casting mould

Unfortunately, the material layer along the trailing edge was too thin, and the test castings would frequently fail during demoulding; sometimes, the cast surfaces revealed moulding defects (Fig. 5).

Fig. 5. Test casting of a wing length with evident defects on the surface and at the trailing edge

The experience from the first stages of work on the production of the UAV wings led to a concept of wing fabrication. It was decided to reinforce the wing surface with a glass fibre laminate produced with existing casting moulds (Fig. 6).

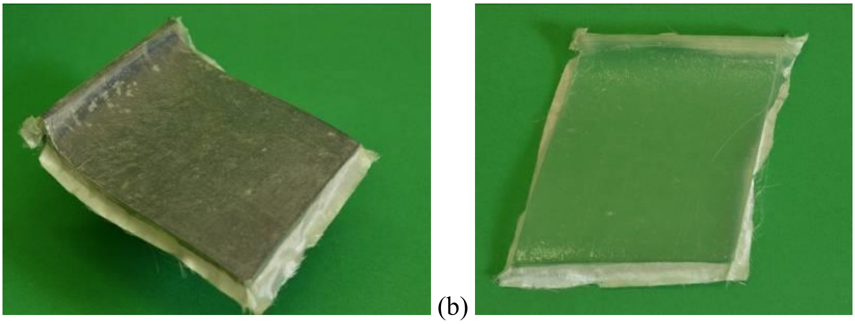


Fig. 6. Thin GFR laminate coat: (a) piece applied to the wing casting mould; (b) finished cast module

The side segments of the wing casting mould were abandoned as they were difficult to separate from the castings; instead, profiles of balsa wood were applied that would be embedded in the as-cast wing airfoil (Fig. 7 a).

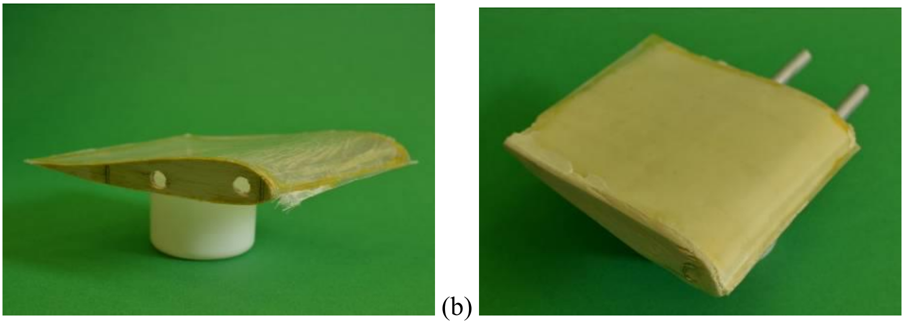


Fig. 7. (a) Bonded GFR coatings with the side balsa wood segments ready for placement in the casting moulds; (b) Test casting of a UAV wing length made in the modified fabrication process

The modifications applied to the fabrication process made test castings of the UAV wing lengths satisfactory to the authors (Fig. 7.b). This enables the next stages of work, which include experimental testing of strength properties of the fabricated structural parts.

4. PREPARATION FOR EXPERIMENTAL TESTING

The behaviour of the UAV model at various loads which simulate real-life flight conditions required a multi-faceted analysis; the second part of the work discusses a selection of experimental methods.

The analytical solutions known to date do not permit an accurate or quick calculation of the strength of parts with complex geometrical features and complex loads, especially when the loads are variable.

A common solution to this obstacle is numerical methods (including FEM). Numerical methods, however, are often limited in application, usually by the complexity and diversity of geometrical features of test objects, the nature of loads applied test objects, and the challenges in modelling characteristics of materials. The calculations provided by numerical methods always require an ultimate verification (proof) by experimental testing.

NDT (*Non-Destructive Testing*) field experiments are very helpful. It is possible to determine how the test object performs in operating conditions without any need to apply modelling simplifications.

The methods include those qualified for further research into the UAV, i.e. a photoelastic coating method and a DIC (*Digital Image Correlation*) method.

Both methods provide insights into the state of strain and stress on the test object surface, and not only at selected points. The methods enable testing of objects made from any material and operating in all real-life conditions. Another benefit of the methods is that they provide an excellent visualisation of the state of loads; this helps quickly locate points of hazardous stress concentration. The methods are relatively simple in application and insensitive to external factors, which makes them an excellent choice for experimental testing of the UAV.

The photoelastic methods, which include the photoelastic coating method, work by the principle of optical birefrigence; this phenomenon occurs in certain transparent materials (which are the so-called ‘optically active materials’) exposed to loads. Optical birefrigence (which is also known as optical anisotropy) has an explicit and wide-range linear relation to material deformations. A polarized light beam which passes an optically active material is split by refraction into two beams which propagate at different velocities in the plane of principal strains. The velocity differential results in a relative delay between the two beams, and the magnitude of delay depends on the difference between the refractive indices in both planes. The difference between the refractive indices depends on the difference between the principal components of strain. Both beams exiting the optically active material reveal interference, resulting in characteristic fringe pattern - an isochromatic image.

The photoelastic coating method consists in an assumption that a significant relationship exists between the state of strain on the surface of a test object and the strains within a thin layer of an optically active material adhesively bonded to that surface. When the test object is loaded, the resulting strains are transmitted to the layer of transparent material integrally bonded to the test object. The layer becomes then birefrigent and maps the state of strain present on the surface of the test object. The effects of birefrigence can be observed with a polariscope, in which light passes twice through the optically active layer and is reflected from a reflective layer. The resulting isochromatic image (of interference fringes) provides information on the state of strain of the tested surface.

Figure 8 shows (a) an optical path diagram of a reflection polariscope and (b) an overview of a polariscope at the Division of Applied Mechanics of the Warsaw University of Technology, Faculty of Mechatronics (Poland). The polariscope will be used in the experimental testing of the UAV.

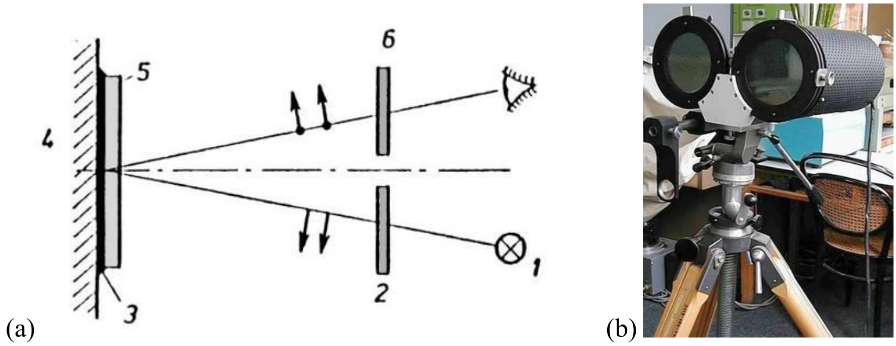


Fig. 8. Reflection polariscope: (a) optical path diagram: 1 – light source, 2 – polarizer unit, 3 – reflective layer, 4 – test object, 5 – optically active layer, 6 – analysing unit; (b) reflection polariscope (at the Division of Applied Mechanics) [2]

The UAV model wing is a non-planar object and will be tested with a flexible optically active coating in the form of gel sheets which easily conform to the shape of the test surface and can be hardened in the state of conformity.

Figure 9 shows examples of isochromatic images of an aircraft landing gear. The images were generated with a flexible optically active coating (Vishay Precision Group, Micro-Measurements).

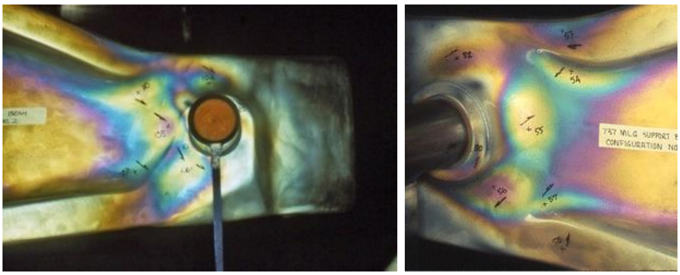


Fig. 9. Isochromatic image of an aircraft landing gear [8]

Another experimental test method to be applied in the research into the UAV is DIC, a technique of contactless optical measurements of real-time displacement. The DIC method consists in a comparison of the test object image before and after its deformation. The image is generated by illuminating the test object with VIS (white) light or (in the case of spot DIC methods) laser light.

The displacement of characteristic points on the test object surface (where the points are most often marks with a dye) allow a determination of the strain values in the area of interest.

The images of the marks recorded in a PC memory before and after deformation of the test object can be correlated by a criterion of the light intensity registered by a CCD array for every image pixel. By processing with interpolation functions, the analytical accuracy can be improved over a strictly digital analysis on a pixel grid. The determination of the displacement magnitudes of the characteristic points (marks) of the test object surface provides an image of strain and stresses of the whole area of interest (Fig. 10).

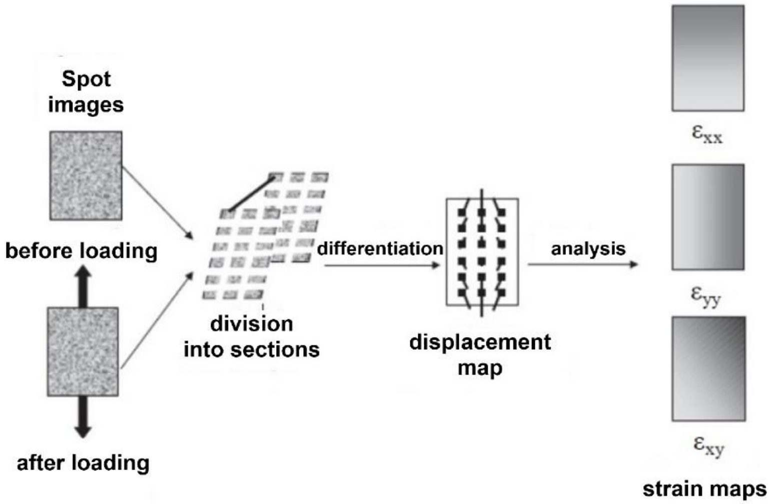


Fig. 10. Principle of displacement and strain determination in the DIC method [3]

The DIC method allows analysing the field of displacement at low (microscopic) or high deformation. Like the photoelastic coating method, the DIC method can be used to test elements made from any material and subject to various loads (both static and dynamic). The sensitivity of the DIC method depends on the image observation method (including the field of view size and the geometric resolution of image).

DIC testing is done with measurement setups which feature systems of two or three digital video cameras, light sources and PC workstations with suitable software. Such a system is designed to record and analyse the digital images (Fig. 11).

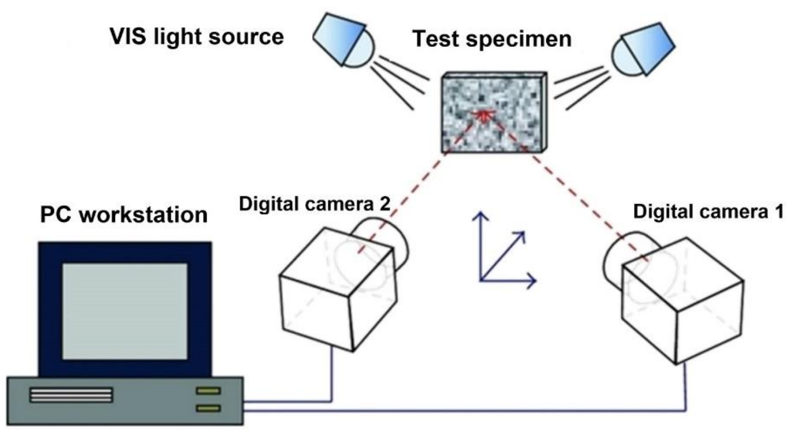


Fig. 11. Operating principle of a DIC measurement system [3]

Figure 12 shows the ARAMIS measurement system (at the Motor Transport Institute in Warsaw, Poland) which the authors intend to use for testing of the UAV.

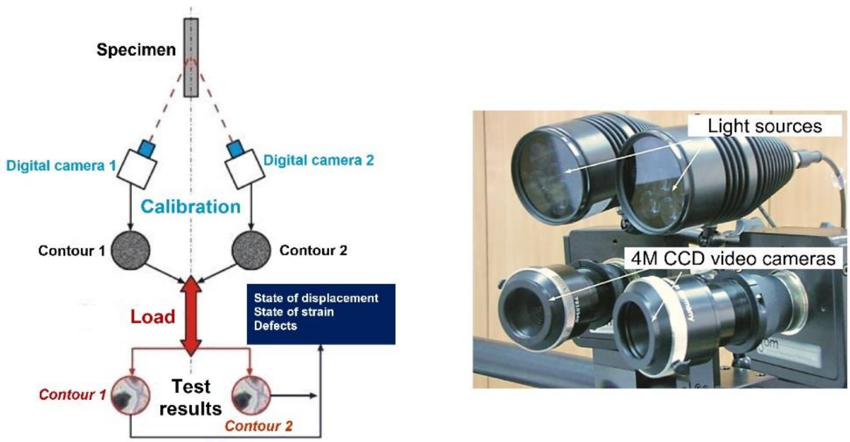


Fig. 12. ARAMIS measurement system: diagram of operation
and the main measurement module [4]

Given their advantages, both experimental methods will be used for the research into the UAV model, a verification of the designed wing airfoil and validation of the numerical strength calculations.

5. CONCLUSION

The objective of the work discussed here is to design and build an autonomous UAV intended for monitoring of large water basins (bodies).

The primary design condition is to develop a UAV design which will provide maximum protection of onboard instrumentation, even if the UAV loses its propulsion power completely. During the work discussed herein, the first models of the UAV were developed. An analysis of the design criteria of the airframe was completed and the structural materials were selected to minimise the risk of UAV and its expensive mission loadout in the event of emergency alighting on water. A method for the fabrication of main structural components of the UAV model was chosen and tested.

The next stage of this work will be a verification of the aerodynamic design criteria of the UAV and a multi-faceted study of the UAV strength properties by applying pre-selected experimental and numerical (FEM-based) methods.

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Wstępna koncepcja bezzałogowego statku powietrznego służącego do patrolowania akwenów wodnych

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Streszczenie. W niniejszej pracy przedstawiono wstępną koncepcję bezzałogowego statku powietrznego (BSP) zbudowanego na planie skrzydła Kasprzyka, którego zadaniem miałoby być monitorowanie z powietrza rozległych akwenów wodnych, a także patrolowanie dużych zgromadzeń, ruchu drogowego, granic itp. Z uwagi na powyższe zastosowania, projektowany BSP miałby transportować drogi sprzęt do akwizycji danych, dlatego też szczególną uwagę zwrócono na kwestie bezpieczeństwa i ochrony przenoszonej aparatury, której cena może wielokrotnie przekraczać koszt budowy samego płatowca. Wynika stąd główne założenie prowadzonych prac, którym jest stworzenie konstrukcji bezzałogowego statku powietrznego zapewniającej maksymalną ochronę sprzętu, nawet wtedy kiedy całkowicie straci on napęd i sterowanie. Możliwość bezpiecznego wylądowania bez zasilania daje zastosowanie profilu samostatecznego, zbudowanego w układzie skrzydła Kasprzyka. Po utracie zasilania BSP mógłby automatycznie przechodzić w lot o małej prędkości postępowej, co zmniejszałoby ryzyko jego uszkodzenia w trakcie przyziemienia. W ten sposób wyłoniono cel pracy, którym była analiza założeń konstrukcyjnych oraz dokonanie doboru materiałów do wykonania bezzałogowego statku powietrznego. Materiały konstrukcyjne dobrano tak, aby w przypadku awaryjnego wodowania zminimalizować ryzyko uszkodzenia lub zatonięcia aparatu latającego wraz z kosztownym wyposażeniem. Zachowanie modelu BSP przy różnych obciążeniach symulujących rzeczywiste warunki jego lotu musi być poddane wszechstronnej analizie, dlatego też w drugiej części pracy zostały omówione wybrane metody doświadczalne (metoda warstwy optycznie czynnej oraz metoda cyfrowej korelacji obrazu), które umożliwią zbadanie właściwości wytrzymałościowych wykonanych elementów konstrukcyjnych.

Słowa kluczowe: inżynieria mechaniczna, bezzałogowy statek powietrzny, płatowiec