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MASS, TIME AND COST REDUCTION IN MAV MANUFACTURING

JACEK MIELOSZYK, ANDRZEJ TARNOWSKI

Warsaw University of Technology TLiMS, MEiL, Pl. Politechniki 1, 00-661 Warsaw, Poland

Abstract

The article investigates concepts of utilization of different materials and detail design concepts which could reduce mass, cost and time of low-volume MAV (Micro Air Vehicle) manufacturing and prototyping. Mass reduction in MAV could be crucial since volume and mass should decrease eight times when linear size of an airplane is halved. There are already examples of EPP (expanded polypropylene) application in MAV manufacturing as a core material – its durability, light weight and extremely low cost of mass production makes it a perfect choice. The drawback of this technique, however, lies in a high cost of design and preparation of production line, especially of high durability mass production molds for extrusion and injection molding. Therefore, authors of this article focused their efforts on investigating other material and methods more suitable for low-volume, MAV fast manufacturing with a possibility of simple structure modification essential in the prototyping phase.

Keywords: MAV, structure, prototyping, foam materials.

1. INTRODUCTION

MAV according to their size requires very light structures. Today's typical composites could be used for light structures, but they have significant disadvantages in a micro scale. The first problem is availability of fabrics with very small yarn. Those used for manned airplanes, which are considered having small yarn, are still too strong and heavy for MAV structures. To stiffen composite structure sandwich materials are used ,which are often porous foams. Resin is sucked by the porous sandwich material that also increases mass. This might be acceptable for manned airplanes, but is a significant disadvantage in the case of small size MAV. There were few composite MAV structures without sandwich materials [1, 2] but, on the other hand, those structures are sensitive for buckling. This behavior may not be critical for flight conditions with small aerodynamic loads on MAV, but without careful maintenance of operators this fragile structure might be easily damaged. Carbon fabrics might be a solution here, but it introduces new problems. MAV-s should be capable of a realization of useful missions. This requires communication with ground station and the needs for the antenna integration. Unfortunately, carbon has unfavorable electromagnetic properties, which can cause electromagnetic wave shielding and communication jamming. MAV in battlefield conditions are also considered as cheap disposable objects. This calls for mass production for which composite structures might not be the best choice. An ideal material for MAV structure should be capable of absorbing high energy during impact (e.g. during less than a perfect landing maneuver). This is important because of safety reasons for people and expensive onboard MAV electronics. The size, in most cases, implies high wing loading and relatively high speeds of flight even during a landing maneuver. The use of parachute as a landing device would increase mass of the MAV and decrease payload space. In the case of MAV collision with people injuries should be highly limited. The energy absorbed during hard landing will save the equipment. For comparison, the original structure of MAV was made using the sandwich composite structure, with the lightest available fabrics. The structure was made as a sandwich configuration consisting of: 25 g/m2 glass fabrics, 1,2 mm foam core 80 kg/m3, 25g/m2 glass fabrics. A modular carbon fabric was used only for spars (details can be found in [3]).

Another significant mass saving can be achieved by a careful design of equipment arrangement and wire connections between payload components. Equipment arrangement is another significant problem, which have to be considered simultanously[8]. The placement of the motor causes different propulsion system design and a possible center of gravity displacement, which will be considered in detail later. The wrong placement of equipment and wire arrangement causes electromagnetic jamming. This problem is not trivial since on MAV-s there is no place to significantly separate the equipment.

The authors of this article designed and flown MAV [4, 5] shown in Fig. 1, experiencing some of the described problems, which were the direct motivation for the research described. Having in mind the outlined problems examples of solutions are presented.

Fig. 1. Flight tested MAV with composite structure

2. COMPOSITE STRUCTURE MODIFICATION

The MAV shape has many unfoldable surfaces. Complex curvature with differing radiuses makes it difficult or even impossible to put stiff foam sandwich material on it. Thermoforming technology was therefore developed to form the foam into the shape of an airplane. The first forming tests on foam samples were performed with different temperatures and times of annealing. Two types of material were tested, 3 mm thick depron[1]) and 1.2 mm thick herex[2]).

Useful samples had to maintain appropriate shape with small radiuses, and could not break or melt. The best results were achieved for temperatures between 100°C to 110°C and annealing time between 5 to 10 minutes. Appropriately shaped samples are presented in Fig. 2.

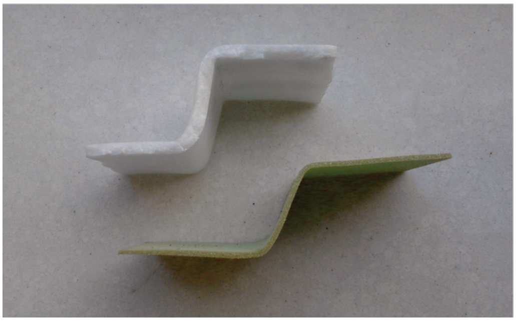

Fig. 2. Thermoformed samples formed from depron and herex material

3. THERMOFORMING MOLD FABRICATION

Utilizing the results of the tests of the thermoformed samples, full size molds for the whole airplane had to be prepared. Because of the size and the number of the molds needed they had to be cheap. In the first attempt plaster was used which performed well during tests with samples. Unfortunately, bigger molds had more air bubbles trapped inside which was a source of cracks and caused mold disintegration. In the second attempt fine quality concrete was used. During the process of production the concrete was vibrated and reinforced with fine steel net Fig. 3.

Fig. 3. Thermoforming molds during manufacturing process on the left and final result on the right

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(1) Depron® is a type of extruded, closed-cell polystyrene foam (XPS) originally developed as heavy-duty flooring insulation. The density range is about 28–50 kg/m^3.

(2) Herex is a closed cell, cross-linked polymer foam that combines excellent stiffness and strength to weight ratios with an elevated temperature resistance. The density range is about 40–250 kg/m^3.

Four different molds have been manufactured – two per the top and the bottom side of the airplane – for uniform foam thermal saturation in thermoforming process Fig. 4a. There were positive and negative impressions of the originally milled molds. The concrete molds went through many thermal cycles without any noticeable wear. Foam formed in the shape of the airplane is presented on Fig. 4b.

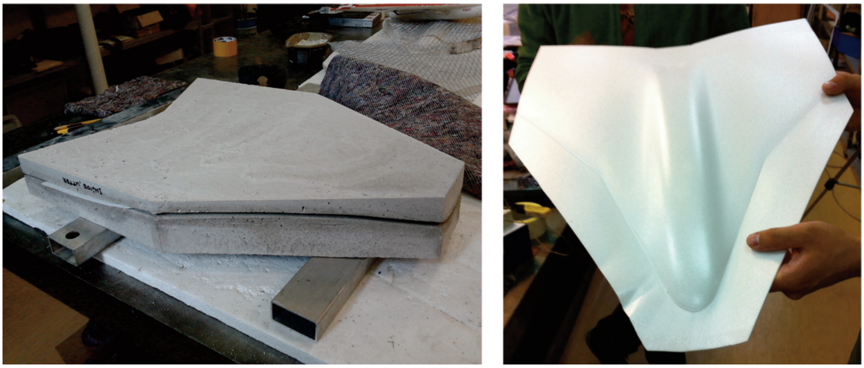

Fig. 4. a) Thermoforming foam in hot molds and b) final result

Although the used material is cheap, manufactured molds are quite heavy (up to 16 kg) and therefore may not be optimal for bigger MAV dimensions.

3.1. Reduced mass Sandwich Structure

The original composite sandwich structure had plies of glass fiber on each side of the sandwich material. The structure seemed to be overstiffened and some mass savings could be gained by using a single glass ply only on the outer surface of the airplane. In full scale aircrafts such a structure is unacceptable, because of surface buckling danger, but for small MAV with lightly strenuous structures this solution could work. After assembling lower and upper surfaces of the airplane the structure creates a closed section, with good capabilities from the strength point of view. All openings cut in the skin of the airplane had to have reinforced edges Fig. 5.

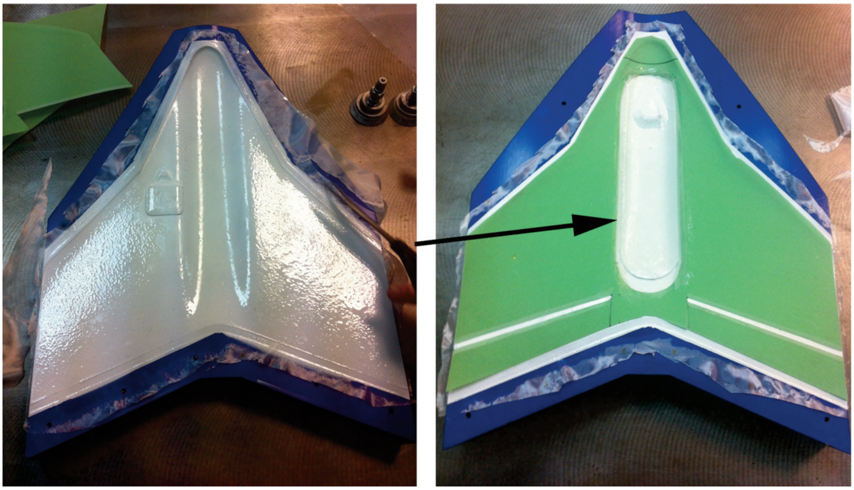

Fig. 5. Reduced mass sandwich structure, with reinforced edges marked

A single side laminated composite was used for manufacturing of the entire aircraft structure. Before making composite the molds of the airplane were covered with thin layer of white epoxy paint and left for 24 hours for curing. The final composite product after getting out from the mold would already have an external white cover. It appeared that the thermoformed sandwich structure, which was manufactured a few months earlier, recovered partially to the straight shape of the prefabricate. The limited vacuum of -0.4 bar couldn't press enough the foam to the mold. As a result the final product had numerous air cavities between composite and the foam Fig. 6. This defect can be easily eliminated by thermoforming sandwich structure shortly before composite manufacturing and with the usage of higher underpressure, which was proved while manufacturing the original composite structure.

Fig. 6. The single ply composite structure with air bubble defects

3.2. Integrated composite hinges

Additionally integrated composite hinges were planned to be built. Such a solution provides more structural strength [6], a lack of elevon gap and allows for manufacturing time reduction.

Fig. 7. Set of composite structure samples with integrated hinges

The main issue was to make the line of the hinge vulnerable for bending and resistant for fatigue. A number of samples with herex foam of size 10 x 15 cm were created Fig. 7. On every sample integrated composite hinge was made. The edges of foam in the place of the hinges had a chamfer. The gap in the hinges between sandwich materials had a spacing of 2–5 mm. The hinge had additional narrow ply of glass or Kevlar fiber. The samples were laminated on one side or both.

The results are gathered and presented in Tab. 1. In each cell the mass of samples is written and the cell is marked with a color indicating, if the integrated hinge was working well. Red color shows that the hinge was not working at all. In those cases too much resin in the hinge gap created meniscus and stiffened the hinge. The second reason of the unacceptable result was fatigue cracking of the hinge Fig. 8. Yellow color indicates that the hinge works well under condition of limited control surface deflection angles Fig. 9a. Green color indicates that the hinge works well in all conditions. The control surface has high angles of deflection, even 180deg and no cracks are observed Fig. 9b. Substantial mass savings are observed for single side laminated composites.

Tab. 1. Composite samples properties

		number of fabrics			
		single side		double side	
hinge		glass	kevlar	glass	kevlar
gap spacing	2mm	4,2g	4,6g	6,5g	7,5g
	3,5mm	4,2g	4,6g	6,3g	6,9g
	5mm	4,3g	4,4g	6,3g	6,7g

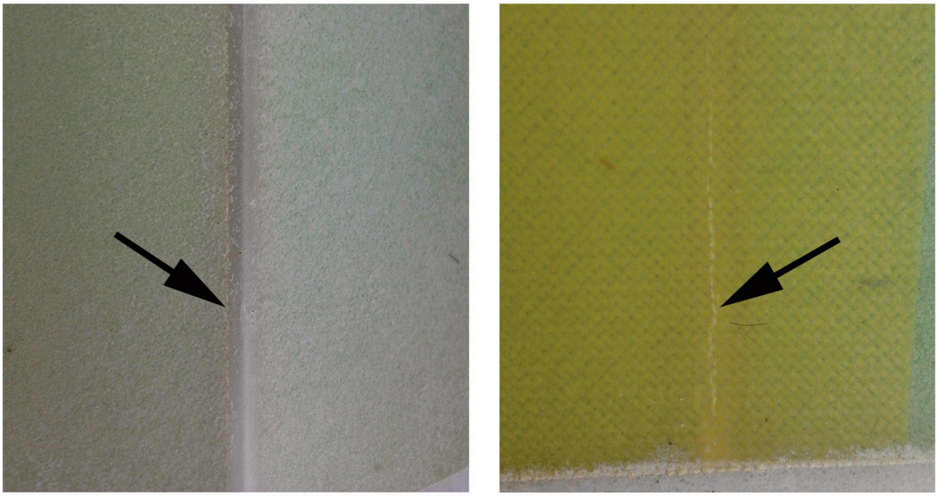

Fig. 8. Hinge fatigue cracking

Fig. 9. a) Limited hinge deflection, and b) 180 deg range deflection

4. THERMOFORMED SHELL STRUCTURE

Another method tested is based on a shell structure made out of two thermoformed depron upper and bottom surfaces of an airframe. Although resulting structure is not as robust as composite sandwich or two-component foam, it is extremely light – up to ten times (see Tab. 2). As it has been proven in fly tests Fig. 10 such a structure has enough durability to withstand aerodynamic loads.

Fig. 10. MAV with foam shell structure in flight

The process of thermoforming has already been described in paragraph 3. Although the structure is fragile, it can provide enough protection for expensive electronic components (e.g. autopilot, video feed, etc.) during impact which can be reused if necessary.

Although shell preparation is very quick, thermoforming molds manufacturing takes much time, but the material cost is very low. To take advantage of such a light structure, equipment parts including power source should be chosen carefully to maintain the light weight of the aircraft [8]. In this case ducted fan propulsion system was used, which allows for much safer operation during hand launching and overall utilization due to a lack of exposure to open propeller Fig. 11.

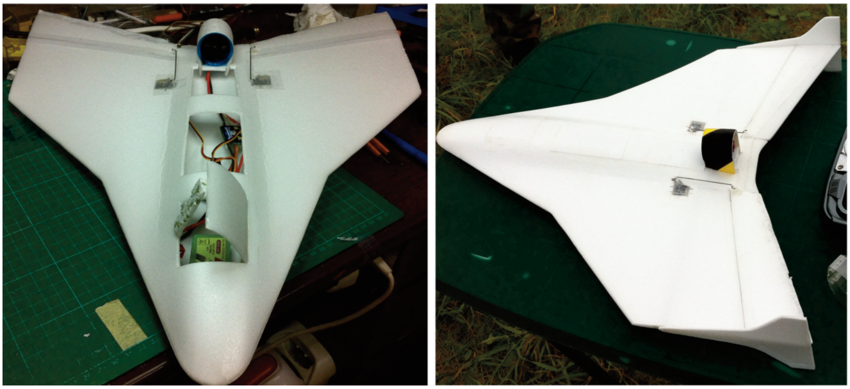

Fig. 11. Shell structure with ducted fan propulsion system ready to fly

5. TWO-COMPONENT FOAM STRUCTURE

The reduced mass composite structure allowed for airframe weight lowering, but manufacturing time was not significantly decreased. On the other hand, thermoformed shell structure mass was one order lower from other structures, but also fragile for field operation. Therefore new materials and methods had been investigated to reduce manufacturing time and improve ground maintenance [7]. This technology was based on two-component, self-expanding ready-to-use polyurethane foam which is easily available.

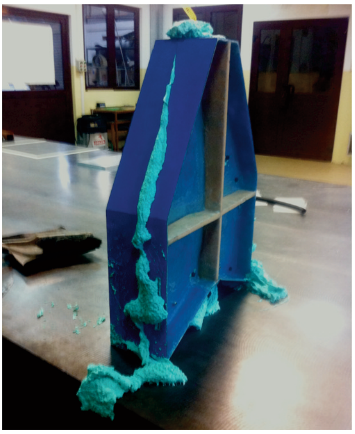

Fig. 12. Composite molds with two-component foam injected

This material is almost as good as previously mentioned EPP, but can be processed without the need for a complicated and expensive production line. This solution can be good for short manufacturing series and well suited for MAV application due to its high strength, fast curing time, resistance to atmospheric moisture, high form stability (no shrinking or post expansion) and low density ca. 35 kg/m3. Additionally, instead of manufacturing four thermally resistant molds (see Fig. 3) the production of only two molds, made for manufacturing composite structures, can be used Fig. 12.

Payload bays and other necessary openings can be cut afterwards or the manufacturing molds should have appropriate protrusions. In this particular case specific blocks for bays were placed in mold before foam application and removed after foam was cured Fig. 13.

Fig. 13. Two component foam structure with payload bay

There are still a few challenges to be addressed, though. During foam expansion in curing process gas is produced, which can be trapped between foam and mold leaving undesired holes and dents in aircraft structure Fig. 14. To avoid this, probably special vents should be designed and drilled in the mold to relive trapped gasses.

Fig. 14. Rough surface with holes of the two component foam structure

Maintaining a trailing edge shape is not easy. The trailing edge cannot converge to a very narrow ending, because the expanding foam will not fill the limited space Fig. 15. Too thin a trailing edge will also often break during common field operations. Non uniform force put in the region of the trailing edge also changes trailing edge thickness, which is not appropriate. Motor installation behind the trailing edge will be a demanding design task to prevent the structure from breaking.

Fig. 15. Trailing edge geometry errors

Depending on the requirements, foam structure can be reinforced with a single ply of fiberglass with a very small yarn to provide smooth surface and prevent otherwise delicate surface from abrasions. This method ,as a combination of Two Component Foam Structure with Reduced mass Sandwich Structures, gives very favorable results. Not only does it prevent foam surface from abrasions, but it dramatically increases stiffness of MAV superstructure as well. There is of course additional weight penalty i.e. 18% increase of an empty structure, but this will translate to favorable 5% increase of TOW (take-off weight) as shown in Table 2. Additional time has to be reserved for composite lamination in molds together with its curing time required for laminate to achieve appropriate strength to withstand foam injection. As described in Reduced mass Sandwich Structures, airplane molds can be covered with paint for additional finish as shown on Fig. 16.

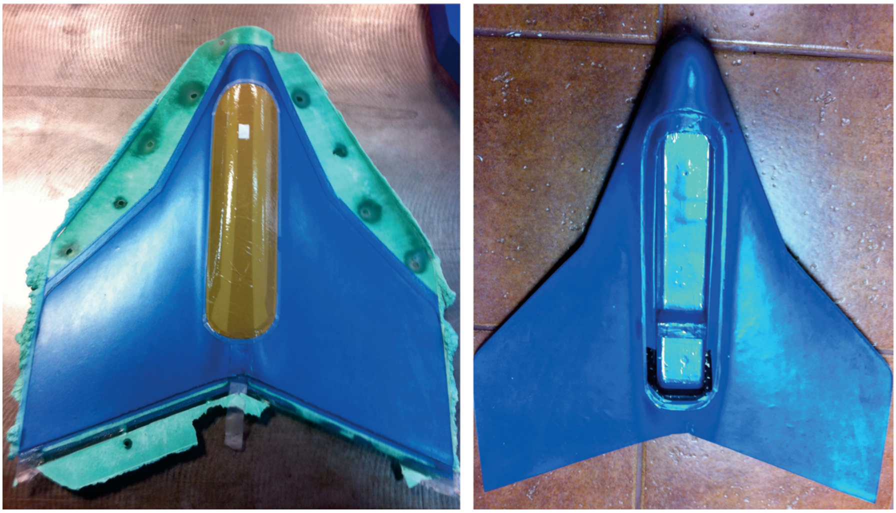

Fig. 16. Two component foam structure reinforced with composite layer and color surface finish

For the proof of concept foam structure without a reinforcing ply of fiberglass was chosen for post processing to make the airframe airworthy. This decision was based on the fact that such a structure is much easier to modify, which is essential in a very early phase of prototyping. To accommodate the motor placement behind a trailing edge, a special motor mount has been designed and fabricated. A relatively simple construction was made of carbon fiber laminate in a form of a tube. An appropriate cavity in the airframe has been easily prepared to accommodate the engine mount and the tube has been glued in place Fig. 17. Due to relatively large contact surface between the engine mount and the airframe, this connection is surprisingly strong. Additionally, the motor mount served as a canopy lock.

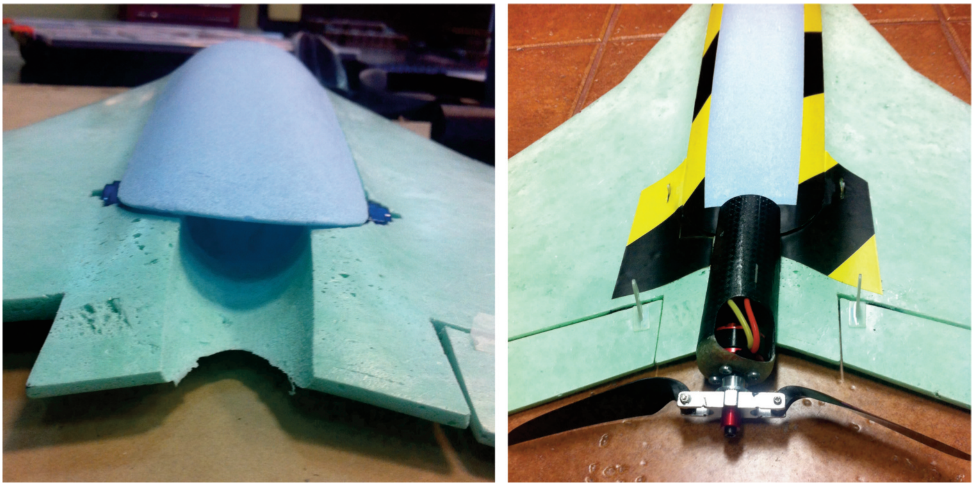

Fig. 17. Motor mount

A similar procedure was implemented for servo fittings. Suitable cavities were cut into the airframe and servos were glued into place. The servo placement was chosen to minimize the pusher length and to minimize the channels for servo cables in the airframe. Although the lightest available electric outrunner motor with an adequate power to provide necessary propulsion has been selected, the center of gravity has been unfavorably shifted rearward. To avoid an increase of MAV weight, by adding necessary led in the nose, the payload bay has been extended (a simple procedure due to the nature of the used materials) in front wise direction as shown on Fig. 18. The forward shifted battery pack resolved the center of the gravity problem by placing it in the right point.

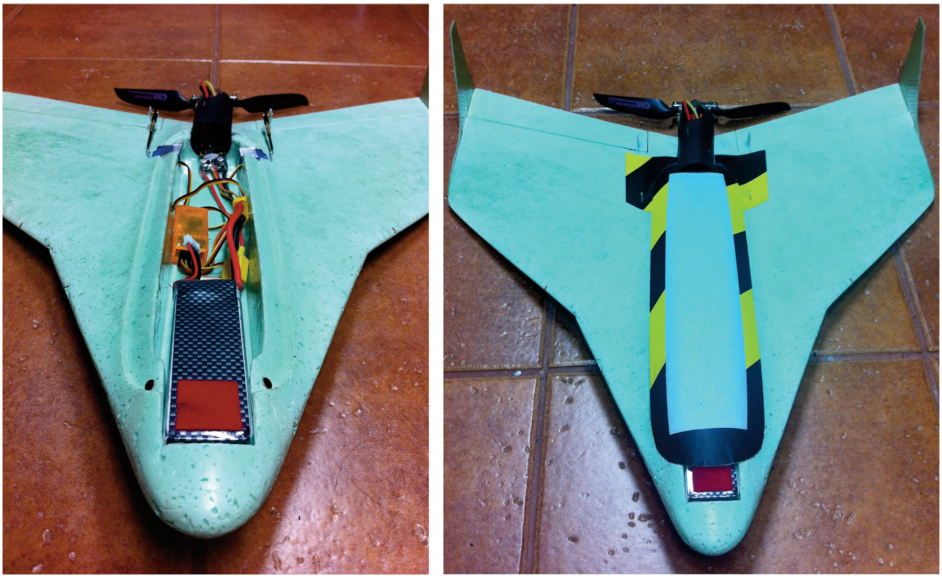

Fig. 18. Payload bay extension

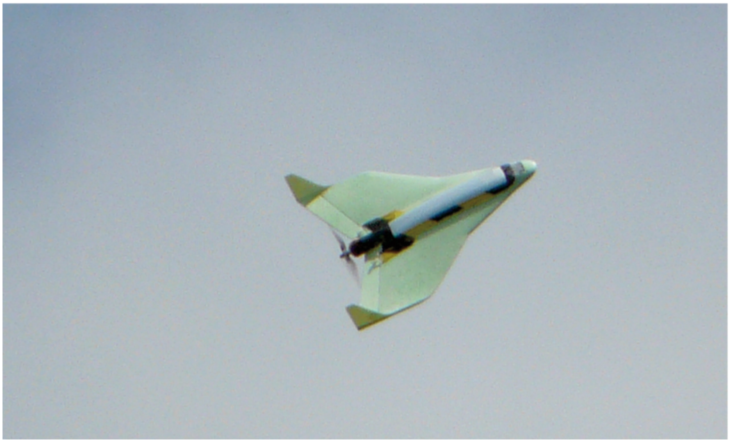

Fig. 19. MAV with two component foam structure in flight

The plane was airborne, without any problems and it behaves in the air properly. Porous wings surface produces little more drag than a fine composite finished. The new material seems to be stiff enough, which is a very important issue for the control surfaces to prevent them from fluttering and an inverse steering behavior.

5. CONCLUSIONS

Three different innovative airframe structures have been presented with a different approach to mass and time reduction in the manufacturing process. The resulting assemblies have different properties in terms of durability and strength (impact survivability), therefore should be carefully chosen to fulfill specific design criteria. All the presented methods offer mass and cost reduction and, to some extent, manufacturing time reduction. The main features are listed below:

- Reduced Sandwich structure offers reduced mass of the airframe, maintaining adequate structural strength and durability but little manufacturing time and cost reduction.
- Thermoformed Shell structure offers the biggest mass reduction but is the most fragile. Components installation still requires more investigation. Very light wing loading, though, can offer promising flight characteristics.
- Two-Component Foam structure offers bigger mass reduction than reduced sandwich structure method and much more manufacturing time reduction. Durability is compromised compared to the reduced sandwich structure, but the installation of the components is the easiest of all three methods.
- Two-Component Foam structure with fiberglass reinforcement provides qualities mentioned above and additionally greatly stiffens MAV structure together with increased wear resistance for very small weight penalties.

Tab. 2. Weight comparison

Description	**Weight [g]**	
	Airframe	**TOW**
Thermoformed shell structure	30	100
Reduced composite sandwich structure	109	n/a
Two-component foam structure	111	403
Two-component foam structure with fiberglass reinforcement	130	422
Classic composite sandwich structure	233	586

Further testing of regular operation should be performed to find application limits of each presented solution.

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REDUKCJA MASY, CZASU I KOSZTÓW W PRODUKCJI MIKRO BEZZAŁOGOWYCH SYSTEMÓW LATAJĄCYCH

Abstrakt

Artykuł omawia zastosowanie nowych rodzajów materiałów do budowy struktur prototypowych Mikro Bezzałogowych Systemów Latających (MBSL). Nowe materiały umożliwiają uzyskanie mniejszej masy, obniżenie kosztów i skrócenie czasu produkcji. Masa w przypadku MBSL może mieć kluczowe znaczenie, ponieważ przy dwukrotnym zmniejszeniu wymiaru liniowego masa i objętość obiektu redukują się osiem razy. Istnieje szereg przykładów zastosowania materiału EPP (expanded polypropylene) do produkcji platform MBSL. Odporność na uderzenia, niska waga, bardzo niskie koszty w produkcji seryjnej czynią ten materiał idealnym wyborem. Wadą jest jednak duży koszt rozpoczęcia produkcji w technologii EPP, związany z uruchomieniem linii produkcyjnej i wytworzeniem wytrzymałych form przystosowanych do wtryskiwania EPP. Dlatego też autorzy artykułu skupili swoją uwagę na zbadaniu nie stosowanych dotychczas materiałów, o podobnych właściwościach do EPP, umożliwiających szybkie wytwarzanie struktur i łatwą obrabialność materiału, niezbędną w procesie wytwarzania struktur prototypowych. Materiały te mogą być zastosowane do budowy pojedynczych egzemplarzy i krótkich serii MBSL.

Słowa kluczowe: *MBSL, struktura, prototypowanie, materiały piankowe*