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Composite additive manufacturing of morphing aerospace structures

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ABSTRACT

Continuous carbon fibre composite additive manufacturing opens up new possibilities for automated, cost-effective manufacturing of highly-loaded structures. This is achieved by the high design freedom of the process, allowing to tailor the fibre placement and by thereby fully exploiting the anisotropy and strength of the composite material. On the other hand, compliant or so-called morphing mechanisms – exploiting the elastic properties of the material to achieve shape changes – show great potential in improving the flight performance of aerospace structures. Such structures exhibit complex internal topologies, making them prohibitively expensive to manufacture with conventional processes. Combining additive manufacturing of composites with the utilization of morphing mechanisms has the potential to concurrently reduce manufacturing cost whilst greatly improving the flight performance of aerospace structures. The applicability of composite additive manufacturing to morphing aerospace structures is discussed in this letter. For the first time, the complete composite primary- and morphing-structure of a fixed-wing drone was additively manufactured. The drone was successfully flight-tested, evaluating the potential of combining these two emerging technologies.
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1. Introduction

The development of 3D printers capable of producing composite components has opened up new possibilities in the field of prototyping and product development [1–3]. By utilizing the high design freedom of the process, the manufactured parts can be tailored to exploit the anisotropy and strength of the material. In contrast to previously employed manufacturing techniques for composites such as automated fibre placement, more complex geometries with higher tow path curvature and higher loading conditions through more optimal fibre placement can be realized. Additionally, additive manufacturing of composites allows better process-automation and waste-free manufacturing, potentially leading to drastic cost savings.

Aerospace structures, such as drone and aircraft wings, are designed to fulfil particular requirements of stiffness, strength, and stability under certain loading conditions. Compliant or so-called morphing structures can satisfy these requirements while being hinge-less and nevertheless possessing functionalities attributed to mechanisms. This is realized by exploiting the elastic properties of the material through introducing controlled flexibility in the structure. Such structures show great potential in increasing the systems performance compared to structures equipped with hinged mechanisms. Potential benefits range from greater adaptability to different flight and environmental conditions [4,5] to reducing the aerodynamic drag [6] due to the smooth aircraft wing surface without discontinuities. Additionally to the direct performance gains of morphing structures, eliminating the use of any moving parts entails decreasing the wear in the structure and therefore improves its maintainability and durability.

Currently, morphing structures, such as the distributed compliance wing structure by Molinari et al. [7], have complex internal topologies that are difficult to manufacture using lightweight composite materials and conventional manufacturing methods. At present, they are manufactured using conventional single material fused deposition modelling printers. However, for larger and highly-loaded aerospace structures, it is vital to use and exploit the superior properties of composite materials. Additive manufacturing of composites permits manufacturing such structures and will therefore be a critical enabler for the adoption of morphing structures. Additionally, the technology has the potential to be extremely cost competitive by allowing the aforementioned process-automation and waste-free manufacturing, and by drastically reducing the number of parts and complexity of the system compared to conventional hinged-structures.

To demonstrate the applicability of composite additive manufacturing to morphing aerospace structures and to build a first

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platform to evaluate its potential, a continuous carbon fibre 3D printer [2] was extended, and the complete load carrying structure, including the morphing components, of a 2 m wingspan fixed-wing drone was manufactured. The drone solely relies on morphing to achieve the control moments around all its three axes. The manufactured drone was flight-tested, showing its outstanding manoeuvrability and thereby demonstrating the potential of combining composite additive manufacturing and morphing aerospace structures.

In this letter, first, morphing aerospace structures and their benefits in terms of flight performance are reviewed. Second, the 3D printing process, which enables cost-effective, automated manufacturing of complex, composite structures is introduced. Finally, as a proof of concept of the proposed combination of composite additive manufacturing and morphing structures, the resulting demonstrator drone and the flight tests are discussed.

2. Background and methods

Morphing wings have been widely researched for several years and are first introduced, before presenting the specific morphing concept and the additive manufacturing method used in this study.

2.1. Morphing wings

Morphing wing research has mostly focused on adaptive trailing edge and wing-camber morphing. By adapting the camber of the wing, the local lift coefficient can be changed to control and manoeuvre the aircraft or to actively alleviate loads. An extensive review of morphing and especially on camber morphing wings was recently published by Li [8]. Three important contributions are briefly reviewed here, dealing with numerical optimizations, flight tests, and concept development of morphing wings.

The first important contribution highlights the general potential benefits of applying camber-morphing to large aircraft. The numerical study by Burdette [4] predicts potential fuel burn reductions of airliners equipped with morphing trailing edges of up to 5%, mainly achieved by structural weight reduction achieved through adaptive manoeuvre load alleviation. Another important contributor to the development of morphing wings is the company Flexsys, which develops compliant structure based morphing wings, enabling potential range extensions of high-altitude, long-endurance aircraft of 15% [9]. They recently performed flight tests of their morphing wing and are planning to extend their experimental investigations with NASA and the U.S. Air Force Research Laboratory [10]. More recently, several morphing mechanism concepts were developed and tested at CMASLab. Molinari [7] developed a concept based on distributed compliance structures and piezoelectric actuators, which was extended by Previtali [11] to work with electromechanical actuators, as well as provide control around multiple axis by Keidel [12,13], and applied to highly loaded wings by Fasel [14,15].

The camber-morphing concept utilised in this study is based on the concept of distributed compliance and electromechanical actuators. The concept of the compliant rib is shown in Fig. 1. The rib consists of the carbon fibre reinforced plastic (grey) and Polyamide-12 (green) additively manufactured morphing structure, the actuator (blue), the actuator rod (yellow) and the wing skin (white). Airfoil shape changes are achieved by pushing or pulling the actuator rod and thereby deforming the trailing edge, thus changing the camber of the wing.

2.2. Additive manufacturing of composites

The latest development in additive manufacturing of continuous fibre composite materials allows the automation of the manufacturing process and the mould-less manufacturing of highly complex composite parts [2,3]. Compared to automated fibre placement methods with limited maximum tow curvature or manual-labour intensive state-of-the-art processes, more complex geometries can be realized at lower cost. First cost calculation of continuous fibre additively manufactured composite parts suggest the potential to reduce the production costs up to ten times using the introduced 3D printing technology. Within this study, a dual extrusion (fibre composite and plastic) processing head developed by the company 9T Labs [2] was extended to allow printing parts with a build volume of up to $0.19m \times 1.84m \times 0.10m$ to accommodate the printing of the demonstrator drone. The process is based on the additive fusion technology from 9T Labs and allows printing composite parts with a carbon fibre volume content of up to 60%, a void content lower than 2%, and an interlaminar strength of 48 MPa, comparable to conventionally manufactured compression moulding composite parts. This is achieved in a two-step process, first printing the part followed by a fusion bonding step. The printer is depicted in Fig. 2, showing the printing process of the fuselage truss-structure of the drone and an optical microscopy image of the achievable low porosities after fusion bonding of a sample part. A video of the printing process can be found here: Printing Process Video.

3. Results

To assess the potential of combining composite additive manufacturing and morphing structures, a fixed-wing morphing drone is manufactured and flight-tested. The developed drone consists of a load-carrying truss-structure fuselage, wingbox and V-tail, and morphing ribs manufactured with the introduced composite 3D printer. To provide a smooth aerodynamic surface, a thin thermoplastic skin is folded around the wing and fuselage structure. The concept and the final drone are shown in Fig. 3. The drone was manufactured as multiple components namely the morphing ribs, the wingbox spars and sparcaps, and the fuselage that are assembled in a post-processing step to form the final drone. In the assembly step, the properties of the thermoplastic material can be exploited by welding the single parts together. It can be envisioned that with future extensions of the printing system, the complete internal wing structure can be printed in a single processing step,

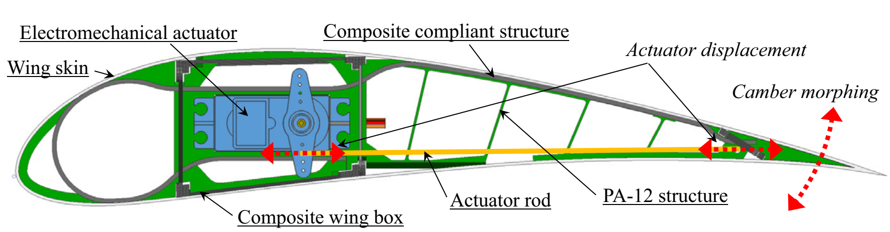

Fig. 1. Camber morphing concept based on compliant composite structure and electromechanical actuator.

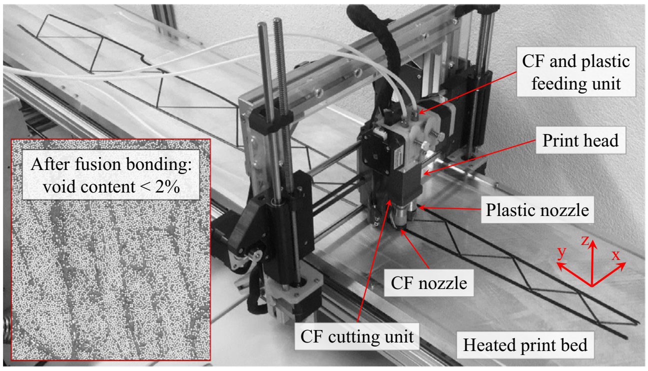

Fig. 2. Continuous carbon fibre (CF) 3D printer, printing the fuselage truss-structure. Box bottom left: Optical microscopy image of the achievable low porosities after fusion bonding of a sample part.

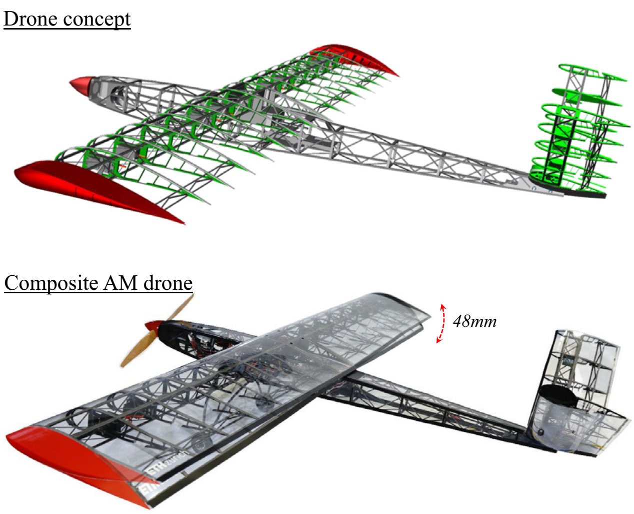

Fig. 3. Top: Camber morphing drone concept with composite fuselage truss-structure and wing box (grey), morphing ribs (green), and morphing wing tips (red). Bottom: Additively manufactured composite drone illustrating morphing actuation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

opening up the possibility to fully automate the manufacturing of the drone structure.

The geometry of the ribs enabled the removal of any hinged control surfaces and were designed to maximize the achievable deformations. By considering aeroelastic interactions in the design of the compliant structure [16], the wing is able to withstand the acting aerodynamic loads, while still generating high deflections leading to an outstanding controllability of the drone. The drone thus relies solely on morphing control surfaces for flight control, by utilizing the introduced morphing concept on the main wing for roll control and on the V-tail for yaw and pitch control. Along the main wing, eight electromechanical actuators were used to achieve a maximum peak-to-peak trailing edge deflection of 48 mm. The individual control of the eight actuators allows the adaptation of the lift distribution along the span. This is mainly used to control the roll of the aircraft, but can also be used to change the spanwise lift-distribution to actively alleviate manoeuvre and gust loads, opening up further potential for weight reduction [4]. A video of the drone showing the morphing of the wing can be found here: Morphing Wing Video.

The introduced drone design and manufacturing concept enabled to automate the production of the composite parts of the drone. Apart from the covering skin and the electronics, all components were additively manufactured, while varying the material combination to achieve the desired stiffness and compliance of each part. The total number of parts was reduced by applying the morphing concept and by manufacturing complex geometries within a single component.

The final aircraft was equipped with a flight control unit and multiple onboard sensors and cameras to record the flight performance. A flight test was performed, testing the controllability of the aircraft and flying various roll and acrobatic manoeuvres. The high deflections of the morphing control surfaces proved to be more than sufficient to control the aircraft, achieving maximum roll rates of up to $240^o/s$. Not only the morphing on the main wing, but also on the V-tail showed excellent performance, making full controllability around the roll, pitch, and yaw axis possible, relying solely on morphing control surfaces. A video of the flight test can be found here: Flight Test Video.

4. Conclusion and outlook

This work presents a proof of concept of the applicability of composite additive manufacturing to morphing aerospace structures. It is a first important attempt towards cost-effective, automated manufacturing of composite morphing structures. On the example of a 2 m wingspan, fixed-wing drone, it is shown that vastly sufficient controllability can be achieved exploiting the proposed design and manufacturing concept. The possibility to automate the process and the waste-free manufacturing indicate a huge potential for cost-effective manufacturing of aerospace structures. This is enabled by exploiting the compliant mechanism concept, relying on flexible structural members instead of hinged structures.

This letter introduces the concept of composite additive manufacturing of morphing aerospace structures and shows its applicability to a first small scale demonstrator. Future studies need to deal with the upscaling of the morphing structure, where the potential of the composite materials can be further exploited. The flight performance gains of these structures need to be compared to existing drone and aircraft designs to validate the performance gains predicted by numerical studies. It can be envisioned that the presented combination of the two emerging technologies of composite additive manufacturing and morphing structures will drastically improve the cost and flight performance of future aerospace structures.

Links to the videos

1. Printing process: https://youtu.be/xdifLkKdAk4
2. Morphing wing: https://youtu.be/JEd3LFBs7eE
3. Flight test: https://youtu.be/J89eSYwC40s

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