PROGRESS ON THE DESIGN OF A COMPOSITE FISHBAC MORPHING DEVICE FOR SPANWISE LIFT CONTROL

A. Rivero[1], P. Weaver[1,3], J. Cooper[2] and B. Woods[1*]

[1] Bristol Composites Institute (ACCIS), University of Bristol, Bristol, United Kingdom
[2] Department of Aerospace Engineering, University of Bristol, Bristol, United Kingdom
[3] Bernal Institute, University of Limerick, Limerick, Ireland

* Corresponding author (andres.riverobracho@bristol.ac.uk)

Keywords: Morphing Wings, Plate Structures, Aerodynamics, Fluid-Structure Interaction

ABSTRACT

The Fish Bone Active Camber (FishBAC) is a compliance-based morphing trailing edge device that represents an alternative to traditional trailing edge hinged control surfaces. Capable of generating large, smooth and continuous changes in camber (i.e. without gaps and/or surface discontinuities), the FishBAC has the potential to reduce aircraft fuel consumption and noise. To predict the structural and aerodynamic behaviour of this device, a fluid-structure interaction (FSI) routine – based on a Mindlin-Reissner Plate structural model and a coupled, viscous corrected 2D panel method and 3D lifting line aerodynamic model – has been developed. This paper presents a design case study where this FSI model is used to study the FishBAC's capability to control spanwise aerodynamic loads.

1 INTRODUCTION

Variable camber morphing wings represents an efficient alternative to traditional hinged trailing edge flaps. They vary airfoil camber distribution in a smooth and continuous way, without generating any gaps or surface discontinuities. Because the wing surface remains smooth —unlike when hinged control surfaces are deflected— the freestream flow remains attached, resulting in a lower drag penalty when compared to flaps. This reduction in drag directly translates into a reduction in fuel consumption and noise. Previous work has shown that camber morphing has the potential to reduce fuel consumption between 3% and 6% in fixed-wing aircraft [1].

One promising morphing trailing edge concept is the Fish Bone Active Camber (FishBAC) [2], which is capable of producing large, smooth and continuous changes in camber. The FishBAC (Figure 2) already showed promising drag reductions of about 25% in a preliminary wind tunnel test [3] —when compared to a hinged flap.

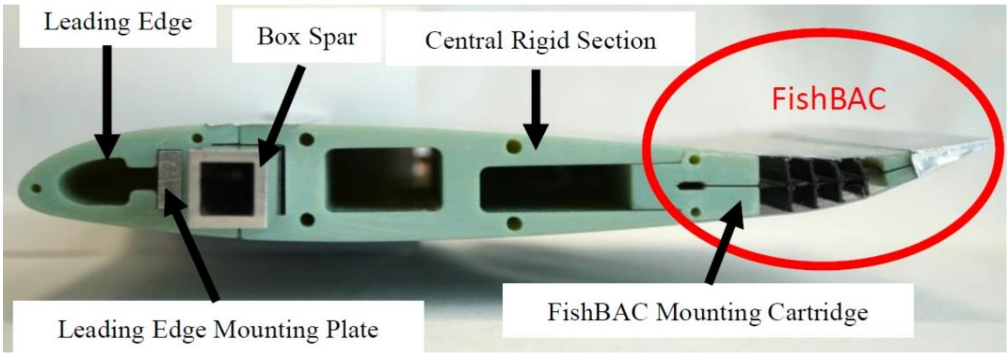

Figure 1: Composite FishBAC wind tunnel model

The FishBAC can achieve these large, smooth and continuous changes in camber due to its compliant nature, highly anisotropic stiffness, and combination of different types of materials. The structure is composed by a central bending spine, which acts as the main load bearing member; a series of spanwise stringers, which provide additional spanwise stiffness, without significantly increasing the chordwise stiffness; an elastomeric skin, which acts as a flexible aerodynamic surface and a pair of tendons, which transfer the actuation loads from servo actuators to the morphing device.

In order to further develop the FishBAC from its initial prototypes which were primarily manufactured using 3D-printed plastic, a second-generation composite device has been designed [3], manufactured and tested [4]. The composite prototype was designed for a 2D wind tunnel test, which will provide further information on the aerodynamic benefits of the FishBAC device. Another characteristic of this composite prototype is the ability to vary its camber distribution along the span. Since the morphing device has two independent actuation points, the two actuation torque inputs can differ, giving the ability to change camber in a non-uniform way (Figure 2)

Furthermore, besides moving towards using aerospace-graded materials, the use of composite materials on the spine allows for further tailoring of the FishBAC's stiffness variation to reduce actuation energy requirements and to control deformed shapes. In order to model and design the composite FishBAC, a plate-based structural model capable of capturing the static behaviour of discontinuous composite plate structure has been developed [5,6]. The latest discontinuous plate model, based on Mindlin-Reissner plate theory, is capable of accurately modelling the static behaviour of the a highly anisotropic and discontinuous FishBAC device using a single system of linear equations. However, to properly model a morphing structure that experiences large deformations and significant changes in shape, both structures and aerodynamics must be studied together as large changes in shape induce significant changes in aerodynamic loads and vice versa. These coupled models are known as Fluid-Structure Interaction (FSI) routines, and these can be classified in main groups: strongly coupled (explicit algorithm) and loosely coupled (implicit algorithm) [7]. The former one consists of a single model that solves both aerodynamics and structures using a single system of equations, whereas the latter one implements independent structural and aerodynamic solvers that are coupled through an iterative process. On one hand, strongly coupled models are generally more stable but they are normally difficult to develop as fundamental aerodynamic and structural equations need to be modified. On the other hand, loosely coupled models may take longer to converge and are not as stable, but they allow to implement fully independent and previously validated structural and aerodynamic solvers. Since the FishBAC generates large deformations and it is subjected to aerodynamic loads, it is of importance to develop a fluid-structure interaction (FSI) routine for design and analysis of composite FishBAC structures.

Previous work by Woods and Friswell (2014) [8] developed an FSI model of the FishBAC, however, this model focused on the 1-dimensional (chordwise) deformation of the FishBAC —captured using an Euler-Bernoulli beam model— and is unable to model any deformation along the spanwise direction. Moreover, the aerodynamic solver only modelled 2-dimensional aerodynamics (i.e. airfoil level) and was unable to capture any 3-dimensional aerodynamic effects, ubiquitous to finite wings. Therefore, new FSI routine must be capable of analysing composite laminates and of capturing both chordwise and spanwise deformations and must be capable of capturing 3-dimensional aerodynamic effects.

Consequently, a 3D FSI model of the composite FishBAC is developed to study both structures and aerodynamics of a FishBAC-based camber morphing 3D wing. To take advantage of the already validated plate-based composite FishBAC's structural model, a loosely couple approach is followed, and an aerodynamic solver based on Lifting-Line Theory with 2D viscous corrections[9,10] is implemented.

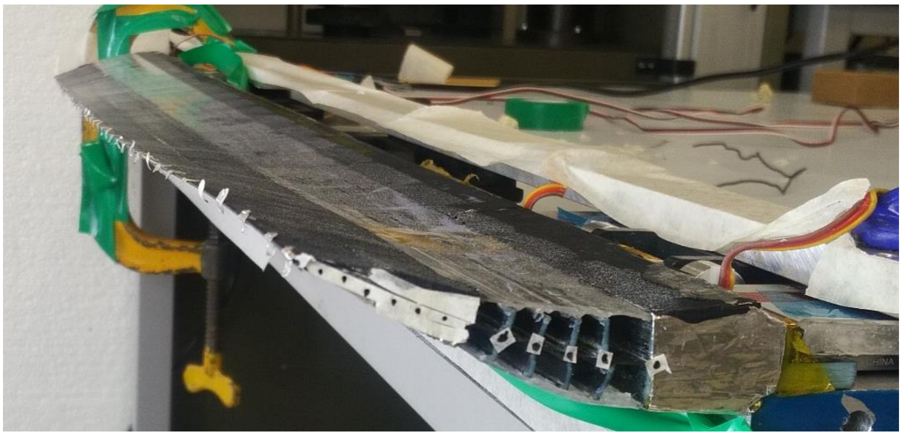

Figure 2: Composite FishBAC under non-uniform actuation inputs. Image shows non-uniform variations in camber along the span

This FSI routine will then be validated against an ABAQUS/CAE (Finite Element Method) & ABAQUS/CFD (Computational Fluid Dynamics) coupled routine, as well as against experimental wind tunnel aerodynamic and displacement measurements. The resulting FSI model is intended to be a robust tool for future analysis, design, and optimisation of the FishBAC, where large variations of camber along the span can be achieved for spanwise aerodynamic load control.

This paper discusses current progress in the development of this three-dimensional fluid-structure interaction routine and explores the FishBAC's capabilities regarding spanwise aerodynamic load control.

2 MINDLIN-REISSNER DISCONTINOUS PLATE MODEL

A parametric and robust composite Mindlin-Reissner plate model was developed to capture the complex geometry of the FishBAC device using a single system of linear equations. It solves the plate's differential equation by using the Rayleigh-Ritz Method, where the sum of strain energy and potential energy due to external loads is assumed to be constant. Furthermore, this model accounts for the use of composite laminates by implementing Classical Laminate Theory (CLT) for stiffness calculations and correct for transverse shear strains following the First-Order Shear Deformation Theory (FSDT) approach. Both aerodynamic pressure distribution and actuation torque loads are modelled as applied external potential energy on the system.

The FishBAC geometry and stiffness is highly discontinuous due to the presence of stringers, so the structure is modelled as individual plate units of uniform stiffness that are joined together using a series of artificial penalty springs. Lastly, the Rayleigh-Ritz formulation requires the use of assumed shape functions. Therefore, the model implements Chebyshev Polynomials of the Fist Kind as assumed displacement and rotation fields [6]. Validated against Finite Element Analysis, this model can predict the behavior of the FishBAC with a percentage error of less than 10% and using only 1% of degrees of freedom (DOFs). Figure 3 shows an example of the obtained displacement fields using the Mindlin-Reissner discontinuous plate model.

.

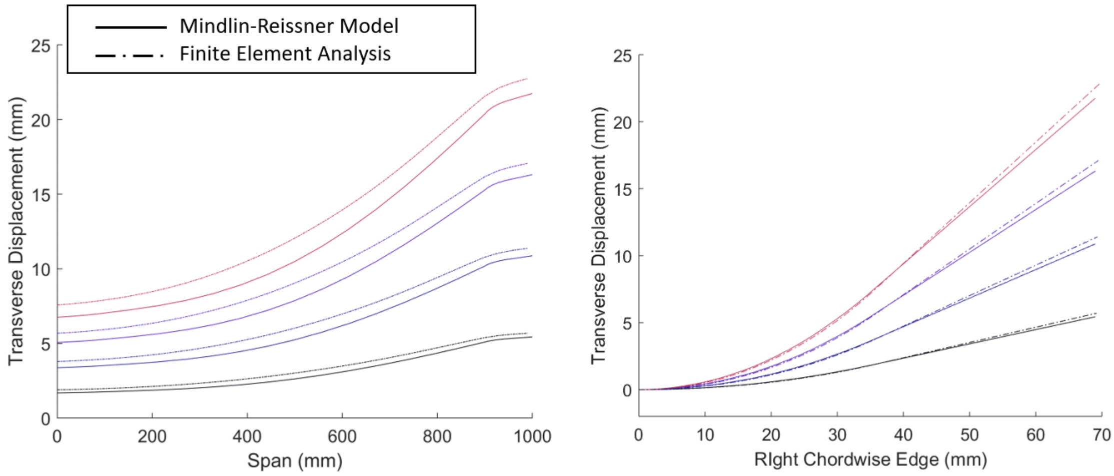

Figure 3: Displacement fields obtained using Mindlin-Reissner discontinuous plate model

3 THREE-DIMENSIONAL VISCOUS CORRECTED AERODYNAMIC MODEL

The aerodynamic solver used is based on a combination of a 2D viscous corrected panel method (i.e. XFoil [11]) with Weissinger's Lifting-Line Method, which is essentially a Vortex Lattice Method (VLM) horseshoe configuration with a single chordwise panel. The 2D viscous panel method is used to obtain the 2D-airfoil surface pressure distribution, whereas the Weissinger's Lifting-Line Method can capture the spanwise variation in lift and total drag distribution due to downwash [9]. The two s aerodynamic solutions are iterated until they converged, accounting for both 3D and viscous effects. Therefore, the resulting aerodynamic model can capture the aerodynamic changes caused by changes in aerofoil camber, as well as 3D aerodynamic distributions (e.g. induced drag and changes in lift coefficient along the span). Figure 4 shows a schematic of the aerodynamic solver convergence routine.

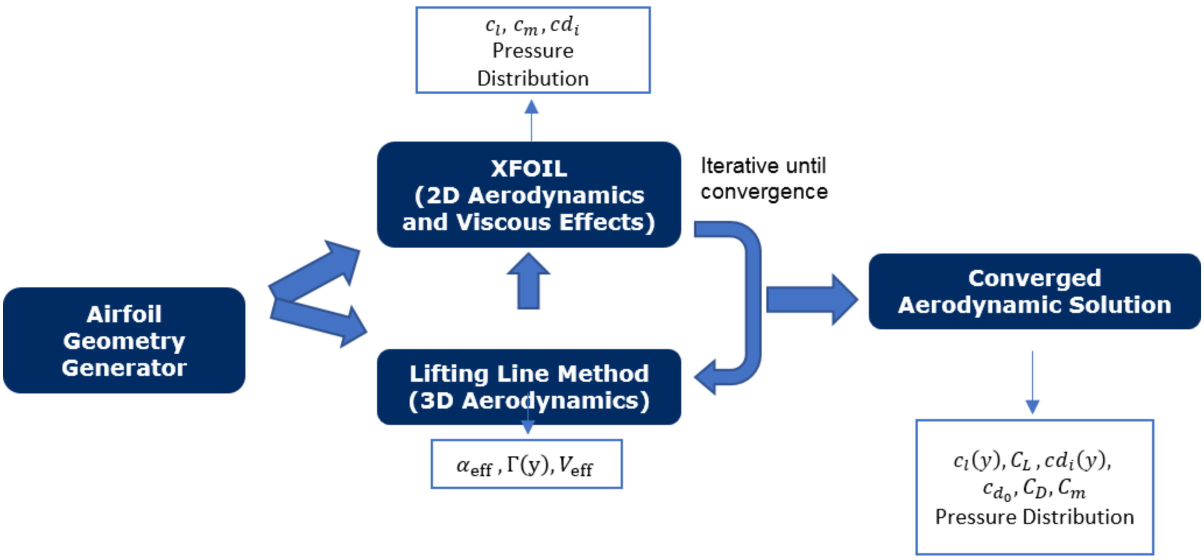

Figure 4: Aerodynamic solver algorithm

4 FLUID-STRUCTURE INTERACTION (FSI): MODEL COUPLING

Once both structural and aerodynamic models have been independently developed, they are both coupled on a loosely basis, which means that both structural and aerodynamic solution are iterated until convergence is achieved.

To assure compatibility between both structural and aerodynamic solvers, the first step is to generate a common set of coordinates (grid) that are used in both structural and aerodynamic models. Once that step is completed, initial undeformed airfoil geometries are generated, followed by an initial set of aerodynamic coefficients and pressure distribution using the aerodynamic model. The obtained pressure distribution, along with the auction torque inputs, become the structural model's input and are applied as external potential energy. The following step is to obtain the FishBAC structural deflection using the Rayleigh-Ritz Method, which results on a displacement field that is then used to generate new set of deformed airfoil geometries.

These new airfoil geometries are used, in a subsequent iteration, as input in the aerodynamic solver and a new set of aerodynamic coefficients and pressure distributions can be obtained. This process is repeated until convergence is achieved —i.e. when the change in 3D lift coefficient is less than 0.5 % for two consecutive iterations. After convergence is achieved, the final aerodynamic coefficients (i.e. 3D lift coefficient, 3D drag coefficient, spanwise lift and drag coefficients distributions, pitch moment coefficient, etc.) and FishBAC deflections can be extracted. Figure 5 shows a diagram of the FSI's convergence routine

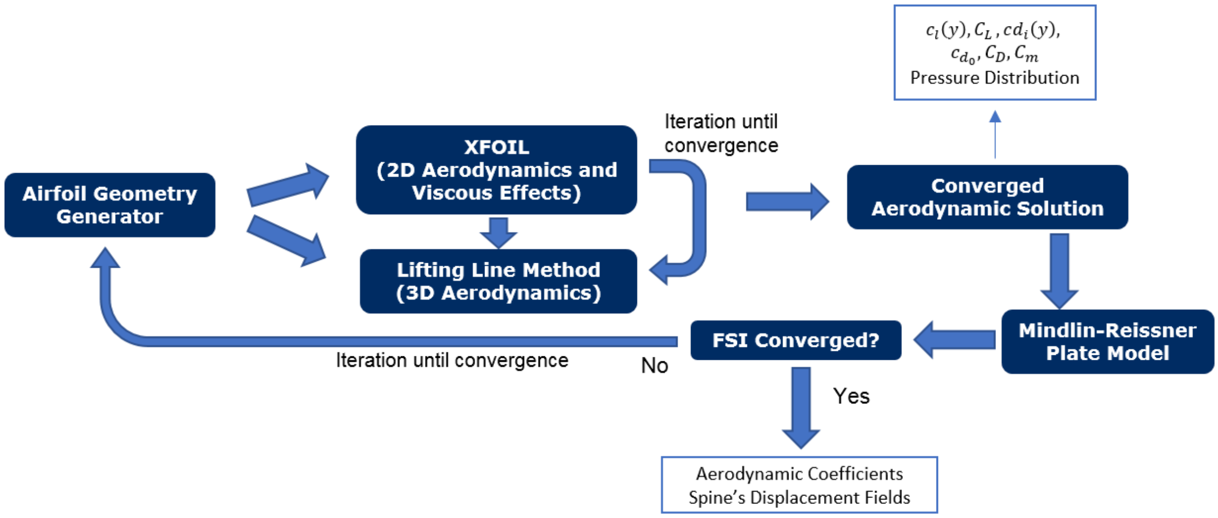

Figure 5: Fluid-Structure Interaction (FSI) algorithm

5 SPANWISE AERODYNAMIC CONTROL: PRELIMINARY RESULTS

A composite FishBAC wind tunnel model is used for dimensions and geometry purposes. This model uses a NACA 23012 airfoil geometry, with a chord length of 270 mm and a span of 1000 mm. Assuming that this wind tunnel model represents half-span of a full wing, a symmetric boundary condition is applied to the root of the wing in the aerodynamic solver. Therefore, the full wingspan on this study corresponds to 2000 mm, and both aerodynamic and structural solutions are symmetric about the half-span location of y = 0 mm.

Since the composite FishBAC wind tunnel model is actuated at two independent locations along the span, it is possible to induce gradual changes in camber along the span. This ability to control spanwise aerodynamic forces could potentially be exploited for induced drag reduction and control purposes. To estimate these variations in lift coefficient along the span, an angle of attack sweep is performed at 30 m/s, using the three-dimensional FSI routine. Two different load cases are considered: a single actuation input —where torque input is applied at the outboard actuation point— and a symmetric differential input, which occurs when torque inputs of equal magnitudes but opposite directions. Lift coefficients are plotted at two different angles of attach, where the aerodynamic solution is fully converged. For both actuation load cases, the two angles of attack selected are 0º and 10º. Furthermore, a symmetric aerodynamic boundary condition is placed at the root of the FishBAC wing, hence the FishBAC model represents a half-wing model.

Figure 6 show the lift coefficient along the span, for a single actuation input. Results show a maximum $\Delta c_{l,\text{single}}$ = 0.487 and $\Delta c_{l,\text{single}}$ = 1.255, for the 0º and 10º angle of attack, respectively. Furthermore, Figure 7 shows the spanwise lift distribution for differential actuation load cases —i.e. when actuation inputs of equal magnitude but opposite directions are applied. In this differential actuation load case, a maximum $\Delta c_{l,\text{diff}}$ = 0.3671 and $\Delta c_{l,\text{diff}}$ = 1.004 are achieved, across half of the span. Also, it is observed that a negative lift coefficient of $\Delta c_{l,\text{diff}} \approx$ - 0.16 at the root and a positive $\Delta c_{l,\text{diff}} \approx$ 0.21 at the tip.

These results highlight the FishBAC's ability to control spanwise aerodynamic loads, not just by having the ability to reduce lift coefficient along the span, but also by generating negative lift forces at certain sections of the wing. Lastly, there is a location in the wing where zero lift is generated, which can be shifted depending on the actuation input.

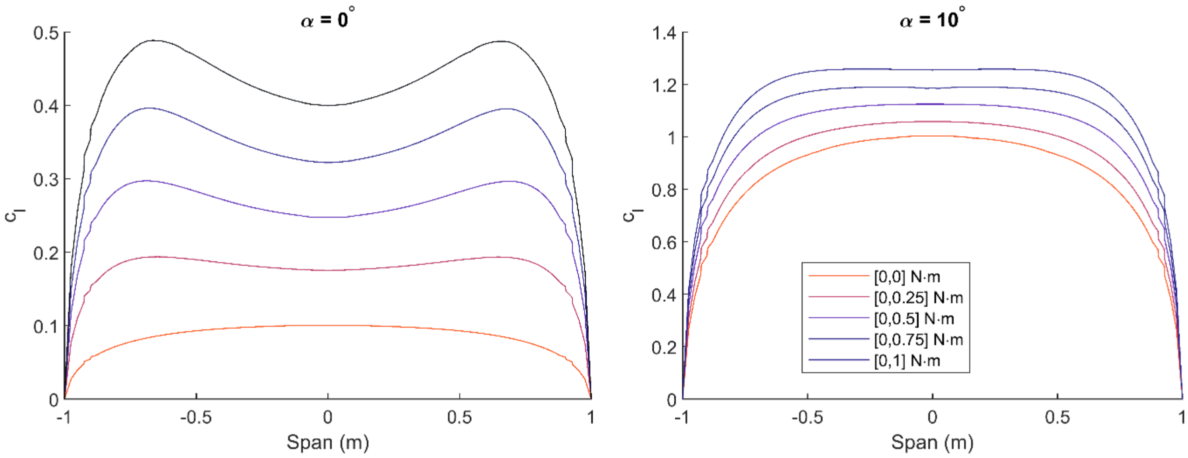

Figure 6: Spanwise lift coefficient distribution for a single actuation input load case. at two fixed angles of attack. The freestream flow was fixed at 30 m/s, and Reynolds number of 540000

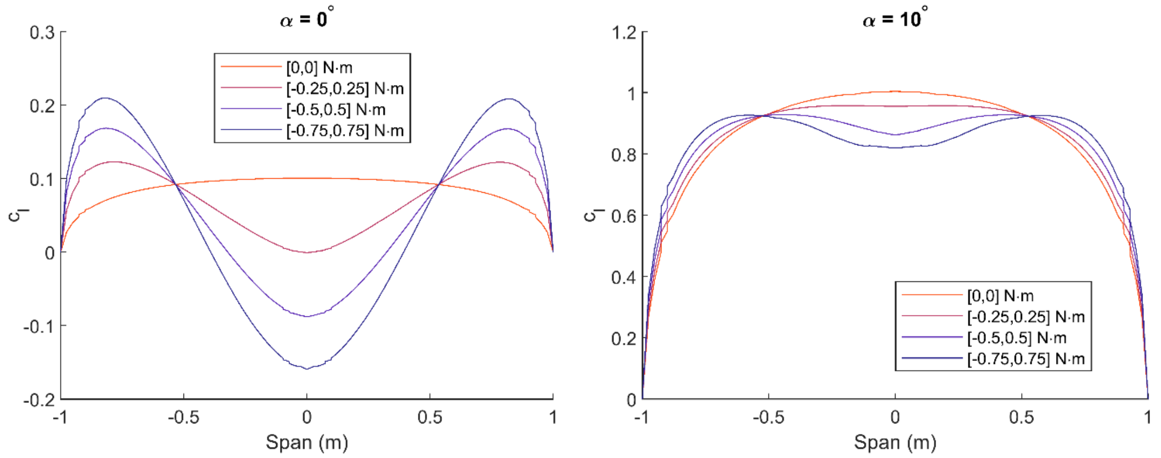

Figure 7: spanwise lift coefficient distribution for asymmetric differential actuation (i.e. equal magnitude but opposite direction) at two fixed angles of attack. The freestream flow was fixed at 30 m/s, and Reynolds number of 540000

6 CONCLUSIONS

This paper introduces a preliminary study on the FishBAC's ability to control *spanwise* aerodynamic loads. The study is performed using a loosely coupled fluid-structure interaction (FSI) routine developed specifically for the FishBAC. The structural solver is based on a previously validated Mindlin-Reissner plate model (structural solver) and a viscous-corrected 2D panel method and lifting line theory, as aerodynamic solver. The geometry used in this study resembles a composite NACA 23012 FishBAC wind tunnel model with two actuation points per half-span. By varying the actuation inputs, the amount of camber can be gradually changed along the span —which can be exploited for spanwise lift control. A maximum lift coefficient spanwise variation of $\Delta c_{l,\text{single}} = 1.225$ and $\Delta c_{l,diff} = 1.004$ were achieved, for the single and differential actuation load cases, respectively. Furthermore, it was observed that the FishBAC can generate positive and negative lift, simultaneously, at different spanwise locations along the wing.

Future work includes validation of these spanwise aerodynamic variations using a CFD/FEM-based FSI routine, as well as experimental validation by 3D wind tunnel test of a composite FishBAC cantilever wind tunnel model.

ACKNOWLEDGEMENTS

This work was supported by the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training in Advanced Composites for Innovation and Science [grant number EP/L016028/1].

Furthermore, this project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 723491.

Andres E. Rivero would like to acknowledge the University of Bristol's Alumni and Friends association for partially covering conference travel expenses through an Alumni Travel Grant.

REFERENCES

[1] Greff E. The development and design integration of a variable camber wing for long/medium range aircraft. Aeronaut J 1990;94:301–12.

[2] Woods BKS, Friswell MI. Preliminary Investigaion of a Fishbone Active Camber Concept. ASME Conf. Smart Mater. Adapt. Struct. Intell. Syst., 2012. doi:10.1017/CBO9781107415324.004.

[3] Rivero AE, Weaver PM, Cooper JE, Woods BK. Progress on the Design , Analysis and Experimental Testing of a Composite Fish Bone Active Camber Morphing Wing. ICAST 2017 28th Int. Conf. Adapt. Struct. Technol., Cracow, Poland: 2017, p. 1–11.

[4] Rivero AE, Fournier S, Weaver PM, Cooper JE, Woods BKS. Manufacturing and characterisation of a composite FishBAC morphing wind tunnel model. ICAST 2018 29th Int. Conf. Adapt. Struct. Technol., Seoul, Republic of Korea: 2018, p. 1–14.

[5] Rivero AE, Weaver PM, Cooper JE, Woods BK. Parametric structural modelling of fish bone active camber morphing aerofoils. J Intell Mater Syst Struct 2018:1045389X1875818. doi:10.1177/1045389X18758182.

[6] Rivero AE, Weaver P, Woods BK. Structural Modelling of Compliance-Based Morphing Structures under Transverse Shear Loading. AIAA SciTech 2019 Forum, San Diego, CA: American Institute of Aeronautics and Astronautics; 2019. doi:10.2514/6.2019-0229.

[7] Tang AY, Amin N. Some Numerical Approaches to Solve Fluid Structure Interaction Problems in Blood Flow. Abstr Appl Anal 2014;2014:1–8. doi:10.1155/2014/549189.

[8] Woods BKS, Dayyani I, Friswell MI. Fluid/Structure-Interaction Analysis of the Fish-Bone-Active-Camber Morphing Concept. J Aircr 2014;52:307–19. doi:10.2514/1.c032725.

[9] Şugar Gabor O, Koreanschi A, Botez RM. A new non-linear vortex lattice method: Applications to wing aerodynamic optimizations. Chinese J Aeronaut 2016;29:1178–95. doi:10.1016/j.cja.2016.08.001.

[10] Anderson JD, Corda S, Van Wie DM. Numerical lifting line theory applied to drooped leading-edge wings below and above stall. J Aircr 1980;17:898–904. doi:10.2514/3.44690.

[11] Drela M. XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils. In: Mueller T, editor. Lect. Notes Eng. 54th ed., Berlin, Heidelberg: Springer; 1989, p. 1–12. doi:10.1007/978-3-642-84010-4_1.