Design, analysis and experimental validation of a morphing UAV wing

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ABSTRACT

The design of wings with morphing capabilities is known to give aerodynamic benefits. These aero-dynamic benefits come from both the use of hinge-less surfaces and the greater adaptability to flight conditions. This paper describes the structural design of a twisting wing to be used for an unmanned air vehicle (UAV) and presents finite element analysis and experiment results. This is part of a research project carried out at the University of Southampton in which one of the goals is to compare different novel wing designs and technologies to determine which one of them gives the best performance. The twisting capability provides roll control without hinged surfaces hence providing aerodynamic improvement. The wing is manufactured using polystyrene foam and is cut out of block of this material using a hot wire machine. In order to link this foam structure to a main spar, ABS plastic inserts were manufactured using a 3D printer. The mechanisms used to actuate the wing are also made from this material. A full scale UAV wing has been manufactured and tested in order to compare with FEA results.

1.0 INTRODUCTION

Classic roll control flaps create severe discontinuities in the flow which increase in great measure the drag generated. This makes the use in cruise conditions of these surfaces inefficient and they are only used for discrete events such as roll manoeuvre or take-off and landing. Morphing capabilities provide a means by which the total lift of the wing can be changed in-flight without a high drag penalty. That is the reason why these technologies are currently being introduced into UAV design (see, for instance, Ref. 1) to enhance performance. This enhanced performance is a requirement since UAV missions are getting more sophisticated and not only in the military field [2] but also in civil fields[3].

Many different technologies are currently under investigation. In Ref. 4 the authors describe a range of means by which morphing capabilities can be achieved. These authors split morphing technologies up into two main groups: plan-form changes and wing compliance. The first group of methods entail large morphing motions such as area changes or sweep changes whereas compliance methods usually involve small changes such as camber changes or other small aerofoil changes. The technology studied in this paper falls into this last category.

Large morphing motions can produce significant aerodynamic improvements. For instance, a large aspect ratio is desirable for subsonic flight as it reduces induced drag. However, as the flight speed approaches sound speed, large aspect rations produce huge shock drag. Therefore, aspect ratio morphing can produce significant performance improvements. Compliance methods produce smaller shape changes. These small changes can nevertheless bring with them substantial performance improvement. Small changes in leading edge shape can vary completely the leading edge suction peak profile, therefore changing the entire aerofoil behaviour.

Paper No. 3723. Manuscript received 12 May 2011, revised version received 28 June 2011, accepted 4 July 2011.
This paper is based on a presentation given at the 2010 RAeS 2nd Aircraft Structural Design Conference, London, UK.

https://doi.org/10.1017/S0001924000006503 Published online by Cambridge University Press

There are several technologies that can be used to achieve small changes. A compliant aerofoil approach (Ref. 5, see also Ref. 6) achieved these changes by introducing forces and torque at different locations within the structure. This structure consisted of a set of struts linked together and was designed so its final shape is as desired. Other compliant structures use bi-stable structures. These are usually made up of asymmetric composite lay-ups (see Refs 7 and 8). Their main attraction is that, since both positions are stable, there is only an energy requirement during the snap between positions.

The approach in this work uses forces applied to both root and tip cross-section actuators to deform the whole wing. To facilitate this process an open cross-section is used as described in Section 2. Open cross-section wings are also used in Ref. 9. The wing final shape is optimised by varying its internal shape following the procedure followed in Refs 10 and 11. Twist and camber changes are achieved as a result of the forces applied to the structure. Since it is possible to improve the induced drag of a wing by varying the aerodynamic twist (Refs 12 and 13) the optimisation process tries to do so by varying the wing geometric parameters.

2.0 WING DESIGN AND FEA MODELLING

Since from Refs 12 and 13 we know that any plan-form wing can achieve minimum induced drag by designing the wing with a specific aerodynamic twist which is function of the aspect ratio and the lift coefficient (equivalent to designing the wing with a specific lift distribution along the span), the choice made in this work was that of a straight wing without taper for its obvious simplicity in manufacturing. To help the wing to twist, an open cross-section is used. A schematic of the wing can be seen in Fig. 1. In this figure elements from the actuating system have been removed but the simplicity of the whole wing is still noticeable. One of the hinges that are attached to the lower surface along the wing span can be seen as well as one of the sliders. The slider is made from two pieces that can slide over each other (see Fig. 2). These elements are the ones that actuate the wing making it twist. The two parts are pulled/pushed accordingly so relative displacement between them is achieved which, in turn, generates the warping of the wing. In the design shown in Fig. 1 the wall thickness is fairly uniform. Thickness distribution, however, can be optimised so, when deformed, the wing can achieve better aerodynamic performance as explained later. Part of the design is, therefore, left to the optimisation process.

Since the external shape of the structure is critical for aerodynamic performance, a good finite element analysis (FEA) modelling of the structure is desirable. A good model will not only help to have a good control of the deformed surface but will also allow prediction of the forces necessary to actuate the structure. Abaqus is the FEA tool used here for this purpose. The geometry is imported into Abaqus from the computer aided design (CAD) tool SolidWorks. Once the geometries are imported the rest of the features needed to perform structural analysis have to be defined. These features are as important as the geometry itself, and include boundary conditions, loads and mesh. The solution of the FEA is very sensitive to the mesh type.

In this work reduced integrated brick elements have been used to model the whole structure. This type of element is computationally less efficient than shell elements. However, since the thickness of the walls was set as a function to be optimised it could happen that the thickness became big enough to make shell theory not applicable for the analysis. These reduced integrated elements are also susceptible to 'hourglass' behaviour which is an excessive deformation that can propagate over large regions of the structure[†]. Therefore, especial care has to be taken when modelling the structure (especially walls) with this type of element. For walls, for instance, at least four elements through the thickness are required to capture bending of the wall and avoid the presence of 'hourglass' regions. This increases the number of elements compared to both shell elements and fully integrated brick elements. Unfortunately, fully integrated elements are not suitable for compressible materials as is the case here. A snapshot of the Abaqus mesh model can be seen in Fig. 3. It can be seen in this image that there are four elements through the thickness throughout the foam walls.

3.0 MANUFACTURING AND TEST

A demonstration wing was manufactured with a span of 1m and chord length of 350mm. Since this wing is for deformation tests only, the trailing edge is substituted by sliders specifically designed to readily control displacement. The final assembly can be seen in the photograph of Fig. 4.

The sliders are made of ABS plastic using a 3D printer. This material has low friction coefficient so both parts of the mechanism slide easily. The wing surfaces are cut out of a polystyrene block of foam with a hot wire machine. The process, although simple in concept, presents several manufacturing issues. The first of the issues is that as the wire melts the foam it removes part of it. This removed material has to be taken into account when designing the thicknesses. The second of the issues is that, when the material is removed, the part of the foam block remaining above 'sits' on the part left below. This foam displacement also has to be taken into account when designing the pieces although part of this effect can be corrected by choosing a suitable piece orientation in respect to the foam block and the areas to be cut first. The last issue is that, after cutting, a slightly stiffer layer of foam covers the surface hence creating certain non-homogeneity. This layer is formed when the melted foam hardens. This last issue only affects the foam properties and it is not severe.

In order to validate the model some experiments were performed with the manufactured wing model. Two different examples of the experiments carried out are presented next. In Fig. 5(a) one of the

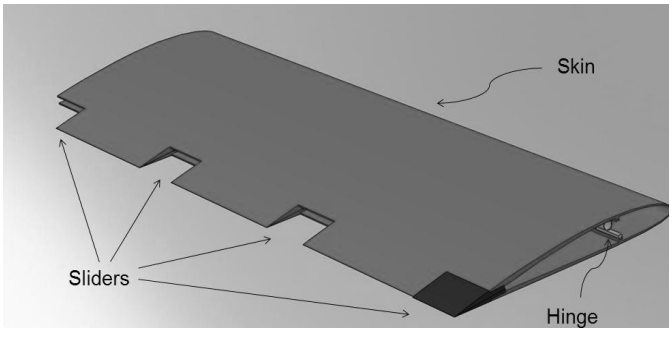


Figure 1. Schema of the wing with one actuator.

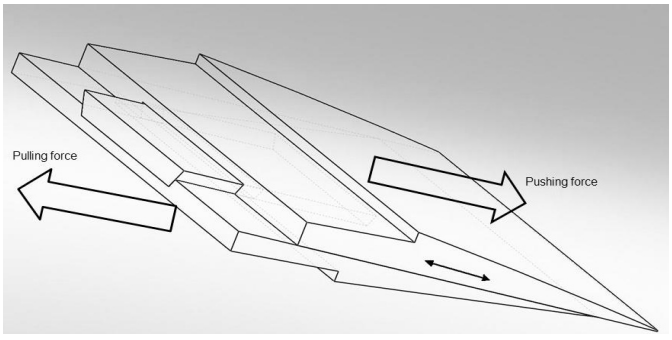


Figure 2. Slider schema.

[†] For further reference see Abaqus theory manual.

https://doi.org/10.1017/S0001924000006503 Published online by Cambridge University Press

load cases can be seen along with its FEA model. In this case ten millimetres relative displacement at the tip cross-section slider were imposed constraining the displacement at the root cross-section and leaving the remaining sliders free. The photo shows good agreement between both the FEA model and the demonstration wing. The slight differences are attributable to camera distortion as well as to the inaccuracies in adjusting both images. The force predicted by Abaqus in order to perform the required ten millimetres displacement was 24N. Measurements on the demonstrating wing were, on average, 27N. This small difference was expected because of the friction of the moving parts of the slider. The same thing happens with Fig. 5(b). In this case displacements on both tip and root cross-sections sliders were imposed. Five millimetres were imposed at the root slider such that it increased the camber at the root and another five millimetres were imposed at the tip such that it reduced camber. As said before, the agreement between the deformed demonstration wing and the FEA model is remarkable. Also there is a good match between the forces predicted and the actual forces needed to perform the required displacement. In this case the predicted force was 18N and the actual force was 17N. In this case the actual force is lower than the predicted one by 1N. This can be considered among the tolerance of the predictions as well as the balance used. Moreover, in this case, as there is antisymmetric displacement, the displacement of the inner sliders is much lower than in the previous case and, therefore, there are fewer extra forces to overcome. These results are summarised in Table 1 and it can be seen how friction forces play an important role in the 10mm case.

4.0 AERODYNAMIC CONSIDERATIONS AND OPTIMISATION

Thus far only mechanical considerations of the wing have been presented. However, the wing is intended to be mounted on a high performance UAV. An aerodynamic simulation of the straight morphing wing without any twist was performed in both the 'relaxed' state and the deformed state at a fixed angle of attack. The method used to predict the aerodynamic coefficients is a full potential code (called FP) in conjunction with a viscous method

Table 1
Results from the test wing structure

	Numerical Model Force (N)	Experiment (N)	δ,%
5mm case	18	17	–5·5
10mm case	24	27	12·5

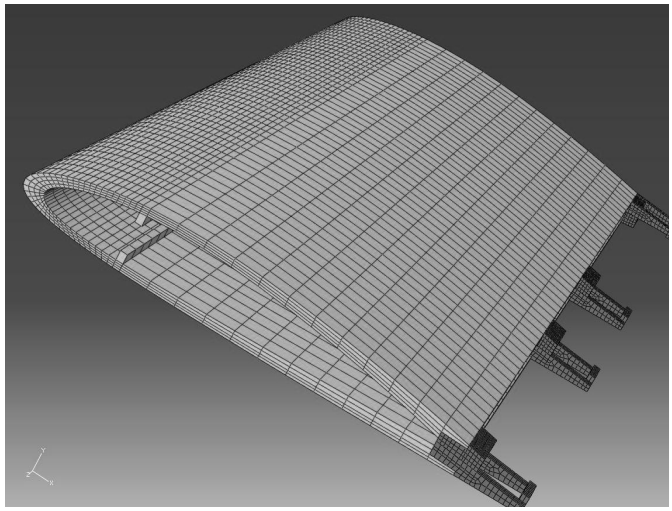


Figure 3. Finite element mesh.

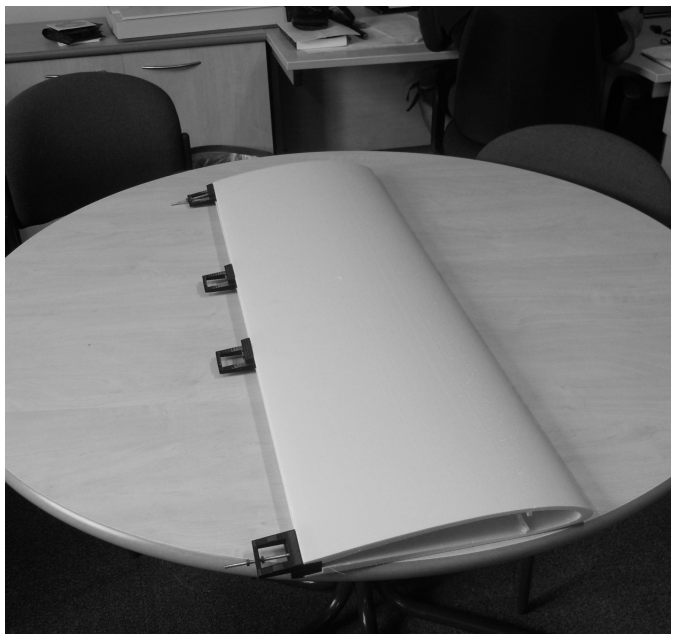
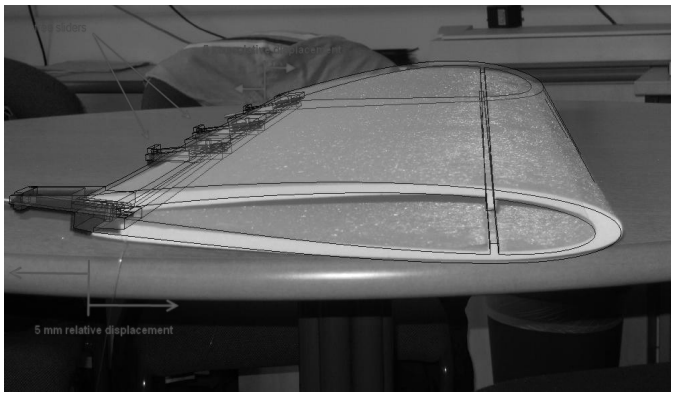


Figure 4. Demonstration wing assembly.



(a) 10 mm relative tip displacement case



(b) 5mm relative displacement at tip (decambering) and 5mm relative displacement at the root (increasing camber)

Figure 5. Photos of the deformed model with the FEA deformed model superimposed.

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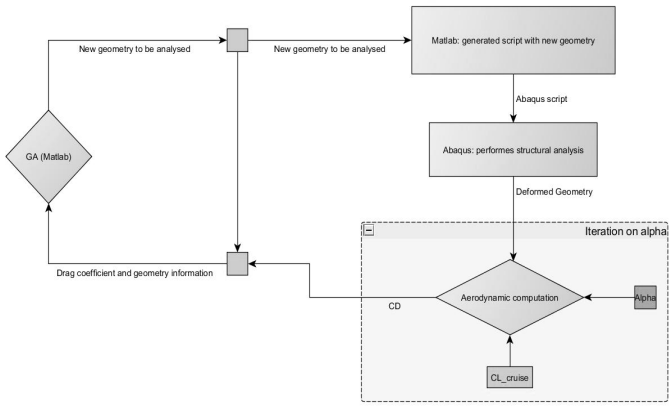


Figure 6. Optimisation Flow diagram.

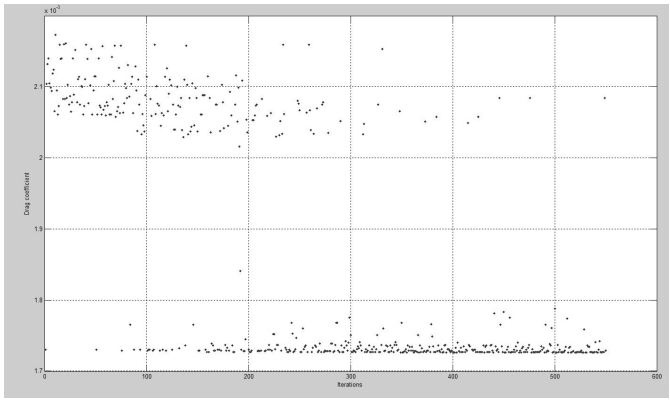


Figure 7. Evolution of the drag coeffcient with the number of iterations.

called VGK. FP is a full potential method that computes the exact solution to the inviscid compressible three dimensional potential flow by a finite difference scheme. After the inviscid solution is computed the VGK method computes an approximation of the components of the drag coefficient due to viscosity. Although the method is not very accurate it does provide a reasonable solution, especially at low speeds[†]. For this wing, twisting in such a way that the camber decreases towards the tip, it was found that the lift coefficient was decreased by 58% and the centre of pressure of the semi-wing was moved by 20% inboard spanwise. These results show that the concept is very efficient for roll control as the roll moment is heavily increased (induced drag was found to decrease by 50% whereas flaps increase drag when deflected).

High performance, however, requires good aerodynamic performance throughout the flight and not only in turns. This requires the design to be optimised and since this is a morphing wing it should give optimum aerodynamic performance at any given flight condition. This complex optimisation process has not been performed at this stage of the project. A good starting point, however, is to optimise the wing for cruise conditions. Although the outcome will not be the best possible morphing wing it will, however, perform better than conventional wings since it will not have hinged surfaces nor skin seams. The process followed is that sketched in Fig. 6. As can be seen in the figure a genetic algorithm (GA) is in charge of varying the parameters involved in the optimisation process. These parameters are geometric (a set of parameters that define the thicknesses of the internal walls) and the gap displacement of the tip. This last parameter is an indicator of the degree of deformation which can also be translated into an energy requirement indicator. These geometric parameters are conveniently translated into a script that can be executed with Abaqus. This script holds the geometric changes to be performed by Abaqus as well as other commands to regenerate the model mesh or redefine point sets.

Once the structural analysis is performed, the deformed geometry is fed to the aerodynamic module for coefficient computation. This module was designed in such a way that the angle of attack is a given parameter. Since this wing is to be used on a UAV with given weight, the lift coefficient in cruise is fixed (a cruise lift coefficient of 0·244 for a target UAV of 10kg flying at 24ms^{-1}). Therefore, an iteration on angle of attack has to be performed (this is sketched in the dashed right bottom box of Fig. 6). When this process is finished the drag coefficient along with the geometry analysed are fed back to the GA (the member of the population (geometry) is assigned a value (drag coefficient)).

The Genetic Algorithm used is the Matlab inbuilt one. It uses an heuristic crossover function with a crossover fraction of 0·8 (default) and a Gaussian mutation scheme. For this search problem a population of fifty 'individuals' are analysed for ten generations. This means a total of 550 analyses, see Fig. 7. Due to the large number of iterations the viscous computations are not considered in this study. Although viscid drag is an important part of the total drag of the wing the methodology employed is still useful for qualitative analysis. It can be seen that after 300 iterations the drag coefficient is stabilised to a value of $CD = 0{:}00172$. From this figure it can also be seen that the number of samples with higher drag coefficient decreases with the number of iterations which is consistent with GA theory. Some comments can be made about the optimum thickness distribution shown in Fig. 8. The first effect to notice is that the lower surface is kept thin. This allows this surface to bend so camber can be reduced as seen in Fig. 8(b). The profile at the tip tends to become symmetric when deformed, so lift is reduced at this part of the wing similarly to what happens for an elliptic planform wing. Another consequence of the final geometry is that the leading edge keeps its shape since the foam there is kept thick. This means that, given the geometric variables available, there is no deformation that could improve the flow around the leading edge at this flight

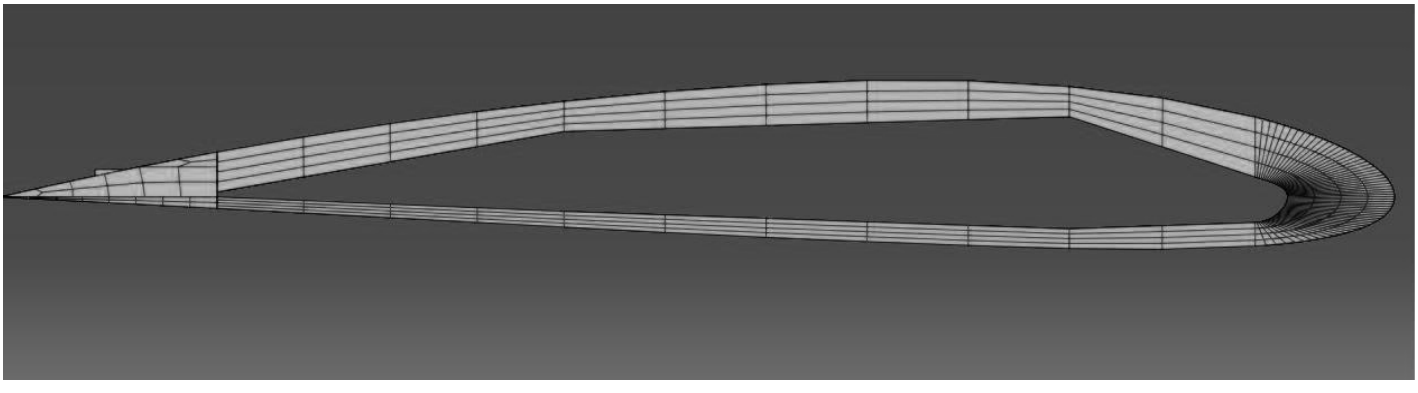


Figure 8(a). undeformed optimised thickness distribution.

[†] For more information about FP see http://www.esdu.com/cgi-bin/ps.pl?sess=unlicensed_1110706110109lnl&t=doc&p=di_02013a.

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condition. One last observation of the results is that the total displacement at the tip remained constant for the last 200 iterations (four generations). This suggests that the total amount of twist reached an optimum and the lift distribution was tuned for this thickness distribution.

5.0 CONCLUSIONS AND FUTURE WORK

The design and manufacture of a demonstration morphing UAV wing capable of twist has been carried out. Experiments and FEA simulations suggest that trailing edge sliders can be used for controlling twist morphing. Aerodynamic analysis showed that the system is more effective and efficient than a conventional flap system.

An optimisation was performed to increase performance at cruise speed. The optimisation process showed that a reduction of up to 16% in induced drag can be made for the cruise configuration compared to a wing without twist, which shows the potential of the technique.

One of the drawbacks of the optimised shape is a thin lower surface as aerodynamic loads will tend to deform this surface.

More work has to be done for further development of the slider concept. This work will entail the design and mounting of an internal actuating system in order for the wing to be complete. This will allow, along with an aerodynamic trailing edge, wind tunnel tests to compare with the aerodynamic computations. Also, the deformed shape has to be optimised so that the wing can be optimal at different flight conditions during cruise and other flight segments. Another direct consequence of the optimised shape is that aerodynamic loads need to be introduced in the optimisation process to take account of pressure load generated deformation.

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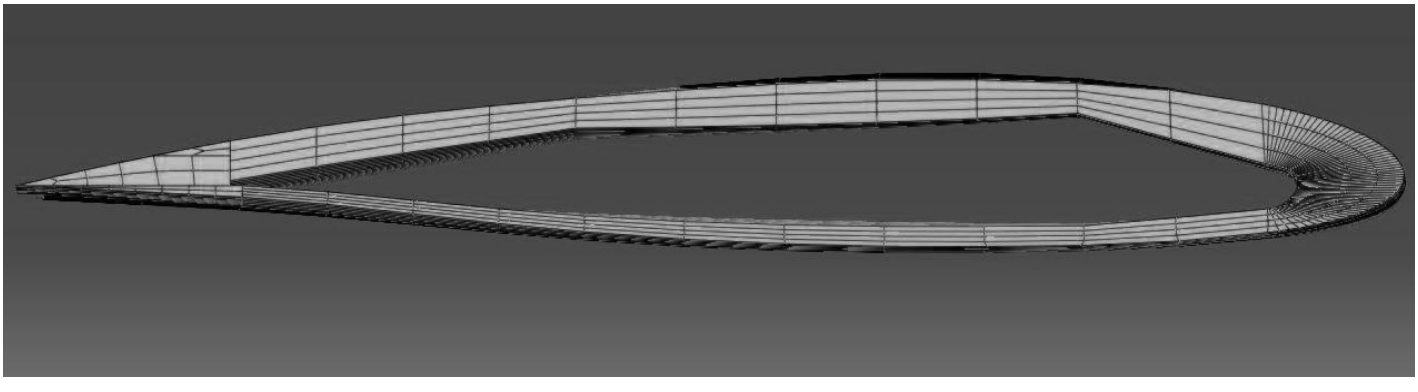


Figure 8(b). deformed optimised thickness distribution.

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