latest developments in this fascinating field rather than reading yet another treatment of basic plasma physics.

Dr David MacTaggart
Lecturer in Applied Mathematics
University of Glasgow

Morphing Wing Technologies: Large Commercial Aircraft and Civil Helicopters

Edited by A. Concilio *et al.*

Elsevier Butterworth-Heinemann,
The Boulevard, Langford Lane, Kidlington,
Oxford OX5 1GB, UK. 2017. lv; 911 pp.
Illustrated. £160. ISBN 978-0-08- 100964-2.

This book presents a general introduction and comprehensive review of state-of-the-art Morphing Wing Technology (MWT) at sub-system and aircraft level. It is well structured, well written and edited with rich literature in the subject. It provides useful knowledge and a wide scope of MWT through case studies from completed research programmes. After so much research effort and achievement in this field over a couple of decades, it is indeed the right time to produce such a book on this particular subject. Although the book is produced in the form of a compilation of technical reports and papers, some of the figures need more editing effort for satisfactory quality. Like the review of a journal paper, the comments of a negative aspect do not imply negative feedback on the book.

Section 1 of the 'Introduction' (chapter 1) presents an excellent introduction to the background and current scenario of MWT. It provides a variety of projects and examples to support the review. As mentioned, 'morphing' is a word that may overlap and relate to a few other terms such as 'adaptive', 'smart' and 'intelligent', hence it needs to be clearly defined first. For the sake of argument, morphing is a result of the geometric change of a physical body by either active or adaptive means. An adaptive structure as shown in figure 4 may be classified as a system that achieves pre-determined or purposely designed morphing. A Shape Memory Alloy (SMA)-based structural system that deforms to a re-defined shape in response to a temperature change is a typical example. In this case, the morphing is very limited in terms of its spatial and temporal response. This is different from active morphing systems that rely on sensor signal feedback and an active control system to achieve more powerful, 'real-time' actuation. Based on the review, a sketch of MWT development through time and Technology Readiness Level (TRL) may be drawn to summarise the review.

Chapter 2 presents a top-level industrial vision on MWT. Since the aim of employing MWT is to improve the aerodynamic performance of an aircraft, a range of quantified figures is expected. An increase in aerodynamic efficiency of between 30% and 40% for spanwise morphing of 40–60% is quoted. It would be ideal to see a similar vision or expectation on the improvement in aerodynamic efficiency for chordwise morphing (variable camber) compared with a fixed wing having conventional slat and flaps in terms of take-off and landing performance.

Chapter 3 presents a further review on MWT development, in particular the aerodynamic performance of aircraft with a variable-camber wing. It is interesting to see a mixture of theoretical, Computational Fluid Dynamic (CFD) simulation with quantified aerodynamic performance and applications to aircraft. It is also interesting to see a short review of rotor blade performance, although little data are available on the effect of a flexible blade or variable camber.

Section 2 ('Requirements and Performance') of chapter 4 presents a review of a span morphing concept and its effect on aircraft performance. In the first section of the 'Introduction', it would be better to present a sketch of span morphing concepts such as variable swept and folding angles and span extension. As mentioned in the second section, two effects associated with span morphing may be more critical than the usual chordwise morphing from the loading and structural point of view. However, it is worth pointing out that, unlike chordwise morphing, span morphing is normally achieved by a hinge mechanism rather than a flexible skin and may incur a large weight penalty. Figure 2 only shows a wingbox section, which does not illustrate the spanwise feature of the design and the Three-Dimensional (3D) deformation in relation to figure 12.

Chapter 5 presents the CFD modelling method and the effect of a morphing wing shape on aerodynamics based on a case study of regional aircraft. The content on wing shape optimisation is useful, although it is focused on chordwise morphing. The results shown in figure 26 are interesting. It would be more interesting and useful to comment on its potential application to aircraft. For example, would the optimised shape (Actuated or Activated Trailing Edge Device ATED Opt CL 0.52) be more beneficial in the take-off case, and the other one in cruise and only applicable to the outer wing beyond the flap region? Chapter 6 presents a review on the expected performance of the adapting morphing leading edge (LE) and trailing edge (TE) based on a medium-fidelity CFD tool. It is comprehensive, including aerodynamic analysis, weight-saving estimation, a couple of examples of state-of-the-art morphing devices and comments on TRL.

In section 3 on 'Skins', further study and proposed concepts on morphing skins are presented, despite their lower TLR than mechanical actuation devices in this field. Therefore, a critical review is expected. Chapter 7 presents a review on one type of foam to produce morphing skin deformation with a particular focus on the material properties in response to temperature. The mechanical property requirement for a particular type or other concept of morphing skin structure should be made clearer in the 'Introduction'. For example, would a low tension/compression modulus but high shear modulus be preferred for the semi-sandwich morphing skin as shown in figure 26? What is the limit of potential application in terms of the scale and loading of a wing skin (maybe applicable to a small and light loading wing)? Chapter 8 presents a review of a skin panel with a lattice structure (rather than material) in a type of periodic cell configuration. I suppose that the main feature is its directional stiffness, i.e. large structural flexibility in one or two degrees of freedom (DoF) and high stiffness in others. For morphing skin applications, the design objective in the topology or optimisation process should be made clearer. For example, the optimal cell shape may be dominated by specified directional stiffness subject to deformation constraints in the other directions. It would be better to show an example or case study, or at least a figure of such a skin panel design.

Chapter 9 presents a review of a skin panel made of corrugated laminate (also applied to metallic panels). Examples of such panel configurations can be found in light-weight aircraft (fin and rudder), civil engineering and even domestic applications. Those examples should be presented for a review of the background and concept. This will guide audiences' attention to focus on the modification details of the 'top-hat' shape stiffener and the core between the blades of a T-shape stiffener to reduce the bending stiffness in one direction for morphing wing applications.

Section 4 on 'Systems Design' in chapter 10 presents a review on active metal structures (mechanical systems). The design approach and analysis method based on the working principle of kinematic chains are useful, although limited to a classical multi bar-hinge (finger-like) mechanism. The efficiency of such a mechanical system should be a concern and discussed. The method should work for a mechanism with actuation force/torque applied at the root of the mechanism, but it is unclear whether it would work for multi-actuation force/torque distributed along the chord. The actuator device with a mass of 0.64kg for an output torque of 54Nm in table 2 seems far too efficient compared with the 2.6kg motor with torque of 2.11Nm in table 1. The examples of an SMA arc shape actuator to produce torque and cell bending by pulling is interesting. Although the design and quantified evaluation are very useful, it would be more beneficial to assess

SMA application limits constrained by the blocking force and slow time response.

Chapter 11 presents a review of various sensing technology to monitor the structure deformation. A critical view on the traditional technology may be necessary. The sensors presented are normally employed for strain measurements of structures. For morphing wing applications, however, the objective of monitoring the structural deformation (if necessary) is to achieve the pre-designed aerodynamic shape rather than health monitoring. An external monitoring technology may be simpler and more effective. Chapter 12 presents a piece of research work to study the influence of varying the upper surface curvature of an aerofoil on the aerodynamic efficiency. The study is comprehensive and presented with very detailed data. However, few results on the drag reduction, which is the ultimate aim to shift the laminar to turbulence transition point backwards, are presented (and should be discussed in subsection 5 or quoted in the 'Conclusions').

Section 5 on 'Numerical Simulation' in chapter 13 presents finite element (FE) modelling of a wing integrated with a morphing winglet (WL), LE and TE. The FE modelling and analysis are a kind of usual practice. For the LE morphing, the boundary condition setting and detailed skin stress in the critical region are interesting but not presented in detail. For the multi-hinge morphing TE shown in figure 4 (supposing the same mechanism for the WL morphing as shown in Fig. 5), it should be made clearer whether the actuator was modelled as a rigid bar with a specified actuator elongation for the effect of the actuation, and whether the aerodynamic loading was taken into account. Chapter 14 presents an aeroelastic analysis of a morphing wing using the extra-mode method. The theoretical basis of this method is expressed in adequate detail. A morphing wing case study is presented too. However, a view and discussion are expected on the aeroelastic stability difference of a wing with a morphing device versus a conventional rigid device, apart from the aerodynamics and reduced mode frequency. In addition to the non-linear stiffness from the hinge and actuator (aero-servo-elastic system), any other factor should be considered as an innovative solution beyond the conventional aeroelastic analysis method. If the shape change was modelled as a time-dependent function, was flutter analysis in the time domain necessary and what is the impact of the rate of change on the flutter result?

Chapter 15 presents the stress analysis of a morphing system. The design, numerical modelling and detailed stress analysis method for a morphing wing – in particular, the hinge and lugs – remain the same as for a rigid control surface of a fixed wing. It would be beneficial to point out any different or special technique, or whether none is required in the analysis of a finger-like actuation mechanism.

In section 6 on 'Morphing Wing Systems' in chapters 16–18, detailed design, modelling and experiment of a morphing LE and TE wing are, presented although the concept and morphing mechanism are limited to a classical multi-hinge arc for LE and a finger-like mechanism for TE morphing. Actually, more than one morphing mechanism were developed in the previous EU project SADE (Smart High Lift Devices for Next Generation Wings) but not mentioned. Regarding the working principle of the architecture for a morphing LE, an optimal mechanism should be designed to ensure that the skin is in bending rather than membrane tension and compression when achieving the designed morphing shape. The same principle should be applied to TE, which should be less critical for a sliding TE design. For the presented example, it is unclear whether the TE is closed and whether the skin was fixed to the finger-like segment.

In section 7 on 'Full Scale Realisation, Safety and Reliability' in chapter 19, a detailed design for manufacture is presented for the finger-like morphing architecture (section 2). From figures 6, 7 and 8, it looks like a piece of skin mounted to each 'dead box' DB section is rigid while a flexible silicon panel connected between two adjacent skins covers at the hinge position allows for elastic deformation. Although the membrane tension of the skin cover can be minimised, a non-smooth morphing shape should be a concern and hence discussed in the review. Attention was finally focused on a continuous skin design in section 3.2, where a 'double-C' type stringer was proposed. To clarify the arrangement of the stringers, the X–Y–Z co-ordinate system should be marked in figures 24, 25, 26, 27, 28, 29 and 30 and be consistent with figure 26. Presumably, the straight stringers between the double-C linkage were orientated spanwise to maintain skin flexibility chordwise. However, it is unclear how to prevent stretching the skin cover, which is mounted on the stringers. If it were in pure bending, the 'double-C' design will not be a good option. A critical review should be conducted.

In chapter 20, detailed assembly techniques for morphing LE, TE, actuators and wingbox structures are presented. Since the morphing LE mechanism (architecture) is neither described nor presented in section 6.2, it is unclear whether the presented actuator installation applies to any or a particular type of LE mechanism.

Chapter 21 is focused on a review of morphing device/system safety and reliability for certification. Section 2.1 states that the function of a drop nose is to maintain laminar flow for reduced drag and also higher lift in take-off and landing. A quantified aerodynamic benefit gain should be quoted. What consequence of losing the aerodynamic gain would there be from the flight safety point of view? The safety and reliability evaluation is at top level, rather than a breakdown to details of components such as linkages and bolts in comparison with the conventional slat mechanism; For example, each segment of a multi-finger morphing TE mechanism is similar to a single piece of conventional aileron. Would the mechanical failure probability of a five-bay multi-finger morphing TE be at least five times greater than that of an aileron? Chapter 22 presents an experimental approach and techniques applied to a morphing TE structure, presenting no obvious differences from tests on a conventional structure. A stiffness comparison between the multi-finger morphing TE and a conventional control surface should be presented for a clearer and useful view on the topic. I suspect that the stiffness (and frequencies) would be lower than for the conventional component due to the skin and rib discontinuity. Chapter 23 presents wind-tunnel testing of a morphing fin and wing TE to measure the static and dynamic aeroelastic behaviour and gust response of a subscale aircraft model based on previous EU projects. Adequate details of the experiment set-up and results are presented, although it is difficult to assess the morphing effectiveness without comparison with a conventional design as reference. In addition, it is unclear whether the sub-scale model is dynamically similar to the full-scale wing in the gust response and flutter wind-tunnel test.

Section 8 on ‘Smart Helicopters’ in chapter 24 presents the MWT applied to a rotor blade. In the ‘Introduction’, the necessity of employing MWT for rotor blades is clear. However, the features and challenges that are different from fixed-wing MWT should be briefly described. Those may include smaller chord and morphing amplitude requirements, but higher actuation frequency (with a typical range) and inertia force acting on the device. Those points would set the basis and context to review the MWT for rotor blade. As presented in sections 2.2 and 3.1, the active device review focuses on piezo-based actuators. However, it lacks a review on the feasibility, TRL and key challenge (actuation amplitude and power?) of piezo-actuated morphing rotor blades after so many years of effort. For example, what is the practical scale of rotor blades to employ morphing TE controlled by piezo-actuators? When employing SMA for the variable camber blade reviewed in section 2.4, would the maximum SMA actuation frequency (3Hz?) meet the minimum rotation speed demand (5rev/s?) of a typical rotor blade? Table 5 presents some quantified requirements for individual blade control (IBC) vibration and noise that may be achieved by using piezo-actuators.

Chapter 25 presents a review of aerodynamic analysis of morphing blades with a focus on CFD simulations. Presumably, a rigid blade model is assumed for the analysis. In the parametric study cases (table 6), the results in figure 32 show a significant effect of Trailing-Edge Deformations (TEDs) on C_L when >10°, but no result for the TED effect is reviewed. It is interesting and should be noted that the blade Aspect Ratio (APR) has a significant influence on the LE and tip vortex, and hence C_L. It would be more interesting to see the influence of the optimised blade shown in figure 39 on C_L versus the result in figure 32 for a straight blade. Chapter 26 presents an alternative low-power IPS using piezo-actuator/exciters embedded in the wing LE. Detailed numerical and experimental work is presented. However, the IPS design may not be suitable for a morphing LE, since the resulting large deformation is far beyond the ultimate strain of the piezo-material layer embedded in the LE laminate. If it were a morphing LE, ice would be detached by very small morphing of the LE shape (millimetre scale) since the adhesion of ice is so weak (shear strength <0.03MPa) according to figure 5. Finally, chapter 27 presents a review of various devices employed for helicopter vibration reduction. A detailed description and high-quality figures are presented, but bear little relationship to morphing technology.

Shijun Guo, CEng
FRAeS