Aerospace Science and Technology 55 (2016) 439–448

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Morphing elastically lofted transition for active camber control surfaces

Benjamin K.S. Woods [a,*,1], Laura Parsons [b,2], Alexander B. Coles [b,2], James H.S. Fincham [b,3], Michael I. Friswell [b,4]

[a] *University of Bristol, Bristol, BS8 1TR, UK*
[b] *Swansea University, Swansea, SA2 8PP, UK*

ARTICLE INFO

Article history:
Received 2 December 2015
Accepted 23 June 2016
Available online 29 June 2016

ABSTRACT

This paper introduces a compliant morphing flap transition that seeks to address a long-standing source of noise and drag in the design of aircraft wings – the gap present at the spanwise ends of the control surfaces. These gaps create large discontinuities in the flow and allow for pressure leakage from the lower to upper wing surface, generating significant amounts of vorticity, noise, and drag. The concept introduced here seals this gap with a smooth, three-dimensional morphing transition section that elastically lofts between the rigid wing and moving control surface in a passive and continuous manner. Previous transition concepts are first discussed, followed by establishment of an initial desired transition shape. Computational fluid dynamics analysis of the desired transition shape indicates both an increase in lift and a decrease in drag. The morphing, elastically lofted transition concept proposed here will then be introduced. In this concept, the complex three-dimensional shape change required is created with a novel structural architecture that combines material and geometric compliance with geometric bend-twist coupling. The concept design and operating principles will be introduced, relevant geometric parameters will be derived, and an initial prototype demonstrator capable of large deflections and smooth transition surfaces will be shown.

1. Introduction

The gaps present at the ends of aerodynamic control surfaces such as flaps and ailerons are known to be significant sources of noise and drag [1,2], and researchers have long sought to build structures capable of bridging these gaps. However, success to date has been elusive as the changes in geometry required are quite significant, the aerodynamic load levels are substantial, and the deformations are fully three-dimensional, making mechanical solutions difficult. Fig. 1 shows the wing of an Airbus A380 with multiple control surfaces deflected, and the significant size of the resulting gaps can be seen. The relevance of this problem is increasing as multiple segment control surfaces become more common (creating additional gaps), and as control surfaces are increasingly used not just as control effectors for occasional maneuvers but also to actively and continuously manage the lift distribution of a wing. The impact of these gaps on the drag and noise of the aircraft can be significant. In an industry that is facing increasing pressure to improve operating efficiency throughout the full range of flight conditions and to reduce noise generated, particularly on take-off and landing, a device which can help address both problems and which has potential to be retrofit into existing aircraft is particularly attractive.

2. Background

Work by various industrial and academic research groups has suggested a number of different approaches to sealing these gaps. In 1984, Kunz proposed a mechanical approach with an auxiliary flap perpendicular to the main flap and connected to it with a sliding interface, as seen in Fig. 2a [4]. It is not known if this device was ever built, but it would seem to require a significant amount of mechanical complexity. Later, in 1998, Diller and Miller of Northrop Grumman proposed a combined mechanical/compliant transition for the spanwise ends of rigid flaps and as a covering for the chordwise gap at the start of the flap [5]. Shown schematically

---

* Corresponding author.
E-mail addresses: ben.k.s.woods@bristol.ac.uk (B.K.S. Woods), laurapar@ymail.com (L. Parsons), alexandercoles@hotmail.co.uk (A.B. Coles), james@fincham.me.uk (J.H.S. Fincham), m.i.friswell@swansea.ac.uk (M.I. Friswell).

[1] Lecturer in Composite Structures, Dept. of Aerospace Engineering.
[2] Undergraduate Researcher, College of Engineering.
[3] Research Officer, College of Engineering.
[4] Professor of Aerospace Structures, College of Engineering.

http://dx.doi.org/10.1016/j.ast.2016.06.017
1270-9638/© 2016 Elsevier Masson SAS. All rights reserved.

Nomenclature

C_d	drag coefficient	y	spanwise distance along transition
C_l	lift coefficient	α	skew angle of corrugations
c_t	chordwise length of morphing portion of rib	β	bend-twist coupling ratio
h	half-amplitude of control surface displacement	ΔC_l	change in lift coefficient
l	spanwise length of morphing portion of transition	θ	rotation angle of trailing edge tip of transition/rib
w	trailing edge displacement		

Fig. 1. Airbus A380 wing with multiple control surfaces deflected showing the large gaps created [3].

in Fig. 2b, their approach covered the gap between flap and wing with compliant silicone elastomer skins which were mechanically reinforced with a large number of embedded rods. These rods were intended to slide into and out of holes in the silicone rubber to allow for the change in length required of the transition, as seen in Fig. 2c. The use of so many sliding interfaces passing through the elastomeric material, which would have a high coefficient of friction and which would be susceptible to wear, is problematic and the concept does not seem to have been adopted. Caton et al. of The Boeing Company patented a surprisingly similar concept in 2002 [6], which uses the same approach of reinforcing rods sliding inside of an elastomer skin as shown in Fig. 2d. The primary difference between their approach and that of Diller and Miller is use of two shorter reinforcing rods instead of a single longer one. This change requires the inclusion of an additional component to cover the joint (which requires even more sliding interfaces), and the design is still likely to suffer from significant tribological issues. In 2013 a second concept from Boeing, shown in Fig. 2e, was patented which creates a smooth outer transition surface by covering a series of rigid, mechanical elements in an elastomeric skin [7]. A number of rigid rib segments are mounted to spanwise rods, which slide into and out of the rigid portion of the wing to create the changing length required of the transition section. Of particular note in this design is the use of rotating tips at the trailing edge extents of each rib. This additional mechanical degree of freedom allows the angle of the trailing edge to rotate to follow the smooth shaped desired. This approach requires, however, that the skin is not attached to the rigid rib sections for a significant chordwise length, which raises concerns about out-of-plane deflection under aerodynamic loading. The rotating tips further increase the number of mechanical joints, adding weight and exacerbating concerns about maintainability.

In 2012, a group from NASA Langley research center patented a compliance based approach to flap transitions [8]. Shown in Fig. 2f, this concept consisted of a wedge of elastomer bridging the spanwise gap between flap and wing and is significantly simpler than previous approaches. Various configurations were proposed, including solid elastomer, elastomer skins with hollow center, and elastomer skins over foam core. This concept was one of several noise reduction measured tested in a recent wind tunnel campaign by NASA [9], and was shown to reduce measured noise emissions from a deflected flap by 3 dB or more over a wide frequency range, while also improving the lift to drag ratio of the flap (by an unspecified amount). It appears however, that the device tested was a non-straining elastomeric mockup of the desired shape. This is likely due to the difficulty that was experienced with designing a working version of this transition [10], wherein the very high strain requirements of ∼500% led to unacceptably high force requirements and difficulties designing appropriate fixtures. Attempts to reduce these forces by using the hollowed out configuration led to extensive wrinkling of the transition surface.

Successful transonic wind tunnel testing of a related concept as part of the DARPA smart wing program is overviewed by Kudva [11]. This concept didn't employ transition sections *per se*, at least not in the passive sense being discussed here, but created a similar effect from a series of active camber morphing segments along the span which each had two actuation points. These two degrees of freedom allowed each segment to control the amount of camber and the twist angle of the trailing edge independently. As a result, the camber deflections could be smoothly built up along the span with minimized gaps in between segments. Another compliance based approach was introduced by Pankonien and Inman as a further development of a smart material based active camber concept [12]. This morphing transition concept used an elastomeric skin over 3D printed elastomer honeycomb sub-skin to bridge the gap between different active camber modules along the span of a wing. Low speed wind tunnel testing showed the basic efficacy of the approach, although performance under full-scale aerodynamic loading and energy requirements are unknown. Work by da Rocha-Schmidt and Baier investigated an alternative approach based on shear deformation of a reinforced elastomer skin [13]. The reinforcement in this case consists of a woven metal wire mesh, which is able to deform easily in shear without directly straining the wire filaments. This shear deformable skin is placed over a shear deformable cellular core to create a sandwich structure. Work on this recent concept so far has focused on finite element analysis (FEA) and coupon testing of the skin materials.

One of the more promising concepts shown to date is a morphing transition under development by FlexSys Inc., shown in Fig. 2g. This concept has been designed to work in concert with a compliant active camber concept known as FlexFoil^{TM} that has been under development for some time [14]. The transition has recently completed flight testing on a modified Gulfstream III jet aircraft [15], but little is known about the operating principle or performance as these authors were unable to find any academic publications or even patents. What can be seen though from the picture in Fig. 2g is that while the device does indeed span the gap between control surface and rigid wing, it consists of an alternating series of segments which do and don't allow trailing edge rotation, so the net effect is a number of small but discrete steps. The authors suspect that the design is made from a series of thin, spaced rib sections made with the same compliant camber morphing geometry as the control surface that are then covered in an elastomeric