AEROELASTIC BEHAVIOUR OF HINGED WING TIPS

Thomas Wilson & Alvaro Azabal
Airbus Operations Ltd, United Kingdom

Andrea Castrichini & Jonathan Cooper
University of Bristol, United Kingdom

Rafic Ajaj
University of Southampton, United Kingdom

Martin Herring
Airbus Group Innovations, United Kingdom

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Abstract: The primary purpose of a hinged wing tip on an airliner aircraft is to allow an aerodynamically efficient high aspect ratio wing to enter an airport gate of standard dimensions. There exists a potential opportunity to allow a wing tip to move in flight to alleviate the loads and achieve a lower wing weight. This paper will provide a summary of the latest studies investigating the Aeroelastic behaviour (loads and flutter) of hinged wing tips.

1. INTRODUCTION

Folding wings have long been a reality in naval aviation to allow fixed wing aircraft to be stored in confined spaces on aircraft carriers. The concept of applying the same technology to large civil aircraft is not new, and now Boeing is developing the B777X aircraft that will include a wing span extension of the order of 7m with the objective of achieving a performance improvement via a reduction in drag, but will be able to access the standard 65m gate thanks to a folding mechanism. More specifically the drag reduction is achieved because the largest contributor of drag (approximately 40%) for a typical airliner configuration is induced drag, which is proportional to the reciprocal of the wing span squared. However, the wing weight increase for such an aircraft can be expected due to the longer wing, the folding mechanism, and above all the reinforcement of the existing wing to resist the higher loads from the greater span. The overall relationship between wing span and weight is subject to the particularities of the aircraft configuration, but a cubic relationship is sometimes considered as a first order approximation.

It has been recognised that the hinge associated with folding a wing tip on the ground could in principle also be used in flight for the purpose of load alleviation, thus enabling a wing span increase and drag improvement with a much lower increase in loads and weight, consequently further improving the performance (i.e. fuel burn) of the aircraft. In order to realise this opportunity the potential range of aeroelastic behaviour of hinged wing tips needs to be properly understood. This paper builds on the work presented at the 4th Aircraft Structural Design Conference in 2014 [1], presenting results from the latest flutter and loads studies.

Figure 1 provides a pictorial explanation of the context and opportunity of folding wing tips for load alleviation. The illustrations include an example of a high aspect ratio wing concept from Boeing, the fixed gate infrastructure at London Heathrow airport, the Boeing B777X with ground folding wing tips, the North American XB-70 Valkyrie with in-flight folding wing tips (this precedent was actually for lateral control and stability rather than load alleviation), the typical wing aerodynamic loading distribution for a ‘clean’ wing and with ailerons deployed for load alleviation (thus moving the centre of lift inboard), and typical wing tip bend angles for entry into the gate (approximately 90^{o}) and for load alleviation (approximately 30^{o}).

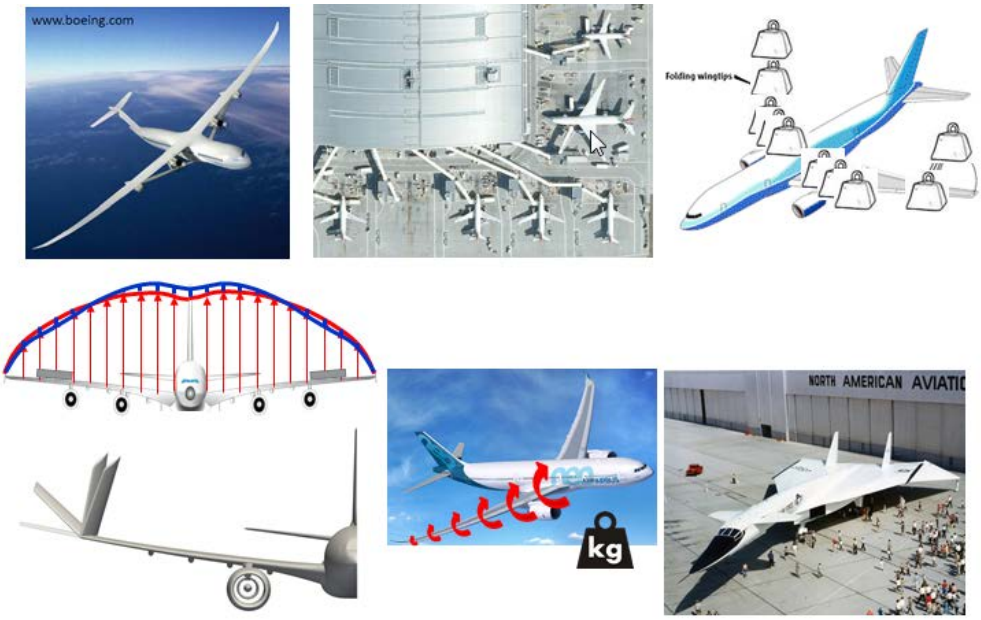

Figure 1: Pictorial explanation of the context and opportunity of folding wing tips for load alleviation.

Figure 2 shows a first order guestimate of the relationship between aircraft drag and wing span increase for a wing where the tip folds only on the ground, and for a wing which benefits from a folding wing tip for load alleviation – the ideal case is plotted whereby the folding wing tip completely mitigates the weight increase from the extra span.

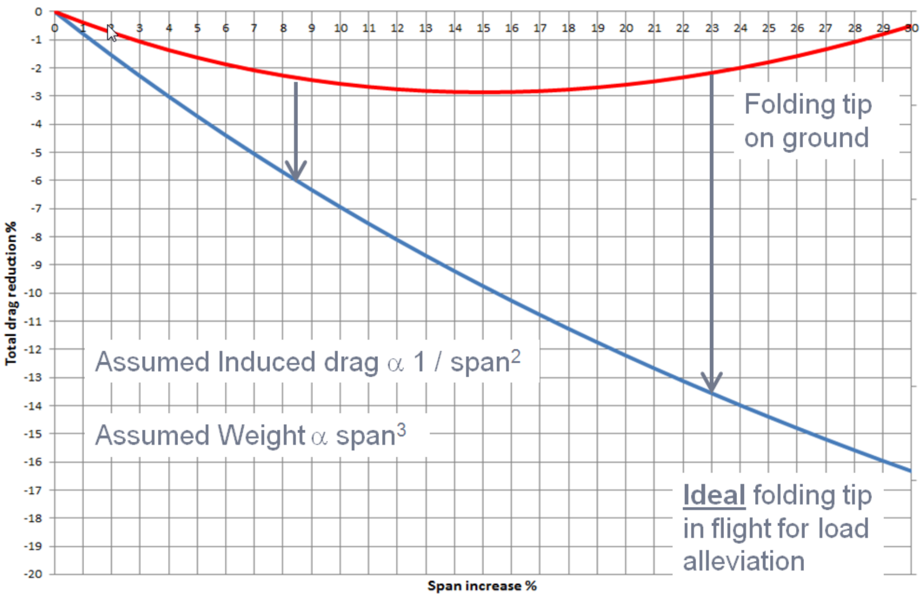

Figure 2: First order guestimate of the relationship between aircraft drag and wing span, with and without folding wing tip for load alleviation

2. OVERVIEW OF PREVIOUS WORK

Interest in folding wing tips for loads alleviation in recent years has yielded a number of papers that all indicated that some level of load alleviation is possible thanks to a 'flared hinge', but with the possibility that the loads alleviation benefit might have to be traded against the necessity to mitigate flutter within the extended flight envelope (i.e. up to 115% of the dive speed) [1 to 4].

Figure 3 defines the hinge flare angle as that between the longitudinal axis of the aircraft and the hinge rotation axis. As a consequence of the flare angle as the wing tip bends up there is a line-of-flight nose-down change in geometric angle of attack. Therefore upwards tip motion is associated with an incremental aerodynamic download, giving rise to both a mechanism for load alleviation, and ensuring static stability. The relationship between bend angle and geometric angle of attack has been previously defined [1], and for a typical airliner wing with a hinge axis perpendicular to the wing quarter chord axis a 1^{o} upwards bend of the wing tip will result in approximately a 0.5^{o} nose-down geometric angle of attack change. Figure 3 also shows the typical position of the tip for entry into a restricted airport gate (i.e. tip bend angle approximately 90^{o} and also a likely bend angle in a gust or manoeuvre limit load condition which in this case has been estimated as 30^{o}).

Figure 3: Definition of hinge flare angle (right) and typical wing tip positions at gate and under limit load conditions (left)

A folding wing tip for load alleviation with a flared hinge can be considered to be a general case of the 'Aeroelastic Wing Tip' concept shown in figure 4 [5, also studied by 6 to 8]. In this concept the aerodynamic centre of the wing tip sits behind the rotational joint between the wing and wing tip, thus ensuring that as load increases on the tip it immediately offloads itself. The Aeroelastic Wing Tip could be considered as having a flare angle parallel to the wing quarter chord axis, however this angle does not permit the wing tip to be used to reduce the span on the ground.

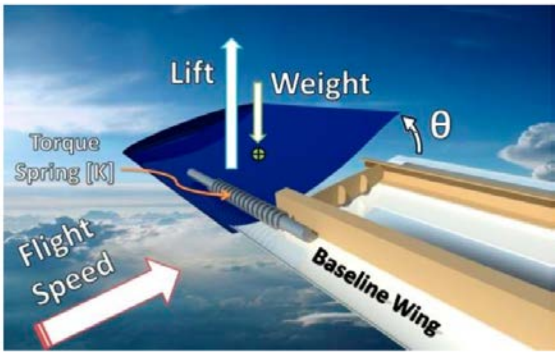

Figure 4: Aeroelastic Wing Tip concept

In the process of working on the folding wing tips for load alleviation topic a number of historical precedents (further to the XB-70) have been discovered, as illustrated in figure 5. The Rey R.1 aircraft first flew in 1949, and was reportedly flown at Le Bourget in 1951 where a 60% reduction in wing stresses resulting from gust loads was reported thanks to the hinged wings. In figure 5 it can be clearly seen that the hinge axes were flared relative to the longitude axis of the aircraft. The concept behind the R.1 was patented in 1938. Much later, in 1999, McDonnell Douglas (now Boeing) was granted a patent which recognised the symbiosis between using a hinge for folding a wing tip on the ground also in flight for load alleviation. This was followed by Boeing paper in 2004 [9] which drew an analogy between the flared hinge and aeroelastic tailoring (where control of the coupling between wing bending and geometric angle of attack is also sought to promote passive load alleviation). Patents from Airbus UK (in 2007) and Aurora Flight Sciences (in 2009) also envisaged the use of flared hinges for load alleviation. However the first known use of a hinged wing for load alleviation is actually from 1923 and the successful flight of the C.3 autogyro designed by Juan de la Cierva. In order to compensate for dissymmetry of lift between the forward and rearward going blades de la Cierva introduced an articulated rotor head that allowed the blades to flap. Variations of this rotor head design feature in all modern helicopters. Moreover many helicopters feature a hinge flap axis that is angled – or ‘flared’ – to achieve a coupling between blade flapping and pitching. Helicopter engineers refer to this angle as the ‘δ3’.

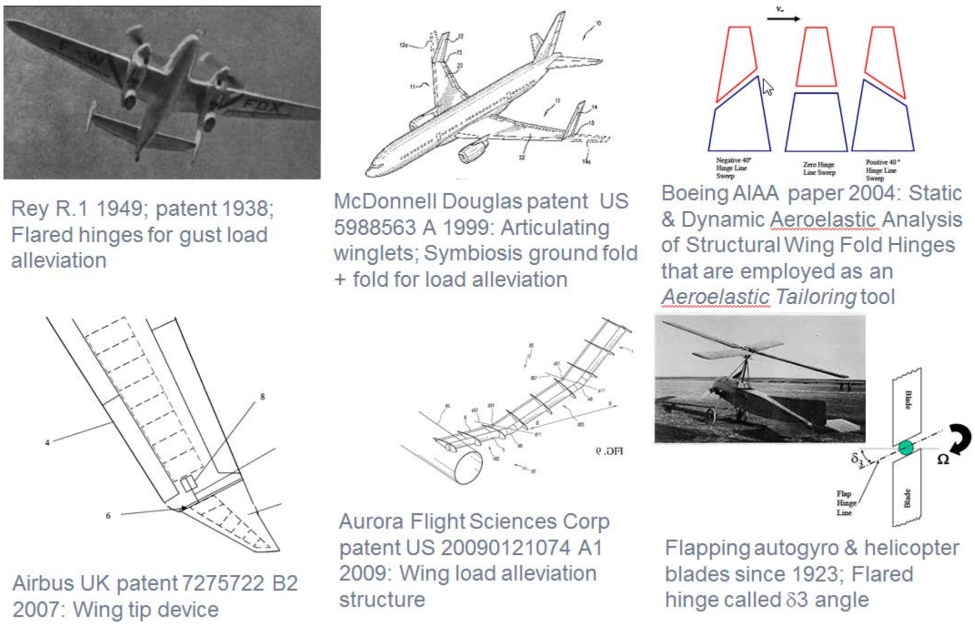

Figure 5: An historical overview of folding wing tips for load alleviation

In figure 6 previously unpublished Airbus results are shown for a simplified calculation, based on strip theory, of a 2.5g manoeuvre for a typical long range aircraft with a flared, zero stiffness hinge at 80% span. Thanks to the hinge it can be seen that the sectional lift on the wing tip has collapsed to close to zero due to the upwards bend about the hinge and downward line-of-flight rotation. However inboard of the hinge the sectional lift has actually risen because as the wing tip is offloaded the wing inboard of the hinge bends less, and because it is swept there is a net nose-up increase in line of flight twist. In terms of wing root bending moment it can be seen that if the response of the flexible wing, and also the aircraft re-trim, is not accounted for then a reduction of 30% is predicted. However if the response is accounted for then this falls to 18%.

It should be obvious therefore that the aeroelasic (in)efficiency of the wing tip is limiting the load alleviation potential. Finally is should be noted that in this example the tip bends by 26° about the hinge.

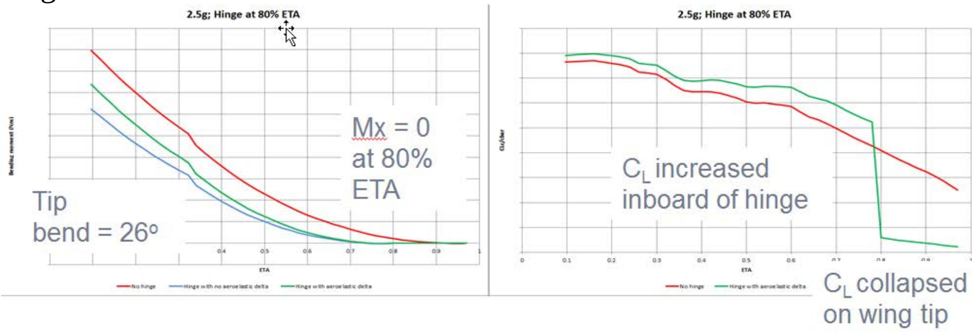

Figure 6: 2.5g manoeuvre at M86 & 36000ft for a typical long range aircraft with a flared, zero stiffness hinge at 80% span

The University of Bristol results [1] shown in figures 7 and 8 demonstrate the effect of wing tip mass and hinge stiffness on wing root bending moment due to a gust, and also on flutter. It can be seen that the heavier the wing tip the smaller the gust load alleviation of a folding tip, but also the lower the flutter speed. Moreover the lower the hinge stiffness the greater the gust load alleviation, but again the lower the flutter speed (unless the wing tip is very light). This is why it was noted above that the previous work suggested that the load alleviation potential of a folding tip might have to be traded against the necessity to mitigate flutter.

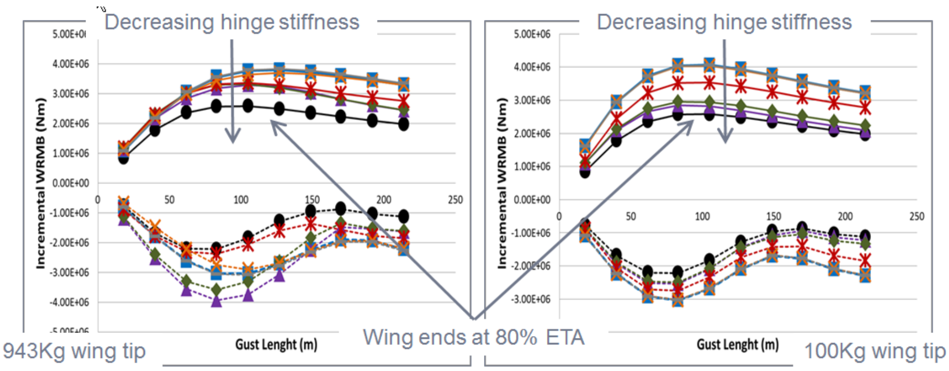

Figure 7: Incremental wing root bending moment versus gust length for a long range aircraft with a flared hinge at 80% span; Variations in hinge stiffness and two wing tip masses are shown

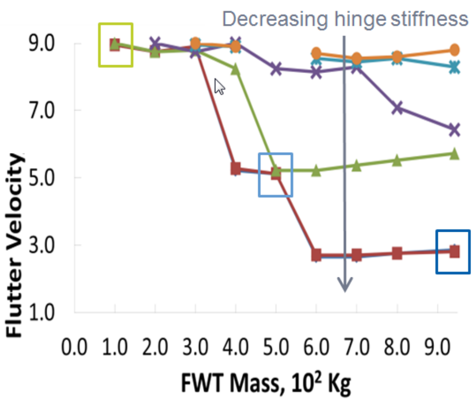

Figure 8: Flutter speed for a long range aircraft with a flared hinge at 80% span; Variations in hinge stiffness and wing tip mass are shown

3. ZERO STIFFNESS HINGES

Following on from the previous work a number of key questions were posed:

- ⇨ Do the findings found for long range aircraft also apply to short range aircraft (given the wing tip should be lighter and should be aeroelastically more efficient), in particular achieving maximum load alleviation with a zero stiffness hinge?
- ⇨ Is it possible to achieve a sufficiently high flutter speed without compromising load alleviation for a realistic wing tip mass?
- ⇨ And could a zero stiffness hinge be possible? Ignoring *for now* the need for some kind of active or passive non-linear behaviour in order to maintain a planar wing shape for efficient 1g flight.
- ⇨ And why is a zero stiffness hinge so effective for load alleviation?

The first three questions are addressed in the next sections where an analysis of a short range aircraft with a zero stiffness hinge is presented. In this section the focus is on the effectiveness of a zero stiffness hinge – or to extend the definition, an ideal hinge with no spring stiffness, damping or friction retarding the rotational motion. The attraction of such a hinge in the context of aircraft loads is quite simply that an ideal hinge does **not** transmit bending moment. However the contribution of a wing tip to the bending moment in the inner part of the wing is not just due to the tip bending moment, but also the tip shear load (which becomes increasingly important towards the wing root due to the moment arm), and of course a hinge will transmit shear load (and torque too, but this is much less important). Figure 9 shows the free body diagram of an idealised hinged wing tip on an aircraft performing a 2.5g manoeuvre. The equations developed from this diagram demonstrate that the shear force at the hinge depends on the relative position of the spanwise centres of lift and gravity, respectively. If the CoL and CG are coincident then the shear force transmitted across the hinge will, like the bending moment, be zero. Moreover the analysis suggests that the wing root bending moment can be minimised by moving the CG inboard of the CoL in order to change the sign of the shear force.

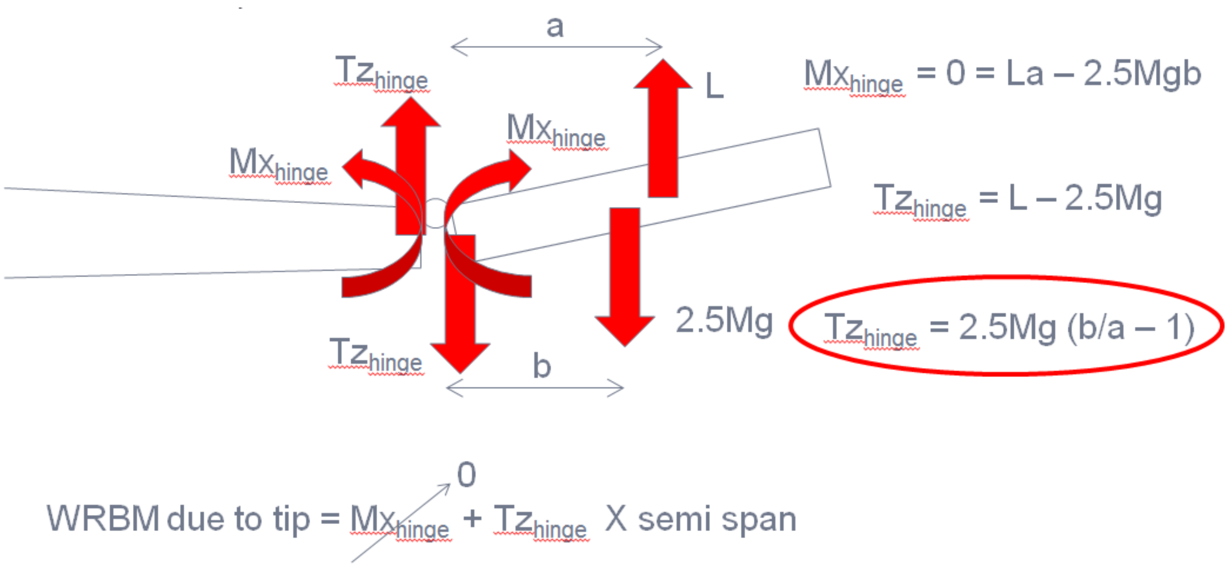

Figure 9: Free body diagram of an idealised hinged wing tip on an aircraft performing a 2.5g manoeuvre

It should be emphasised that the analysis in figure 9 is highly simplified, but it does provide a first order explanation of how a zero stiffness hinge can help reduce bending moment from the hinge to the wing root. Moreover the above analysis is for a steady loading scenario. For a gust encounter unsteady terms will be introduced, notably aerodynamic damping and rotational inertia. The results presented in the next sections give some indication of the role these unsteady terms can play.

4. SHORT RANGE AIRCRAFT LOADS AND FLUTTER STUDY: MODELLING

The study introduced in this section is for an aircraft *very loosely* based on the Airbus A320 family, with wing tip extensions to bring the total span from around 36m to roughly 45m. It has been assumed that the wing tips are hinged to allow entry into an approximately 36m wide airport gate. And the objective of the study is to compare the loads and flutter behaviour when the hinge is fixed versus free in flight.

Three mathematical models were built in Nastran, A, B and C. Model A comprised of the following elements:

- ⇨ Structural model: Full wing FEM reduced to an equivalent 'EIGJ' beam model, with engine pylons modelled as springs and a rigid fuselage and tail. The 'free' hinge was modelled with a RJOINT element active in 5 degrees of freedom. Pictured in figure 10.
- ⇨ Mass model: Lumped masses, with two aircraft mass cases: M1 = ~50T and M2 = ~90T. The mass model included a high local mass to represent the hinge and associated systems (e.g. locks, actuator, local reinforcement, and so on). Two tip masses were considered: Heavy = 100%, and light = 67% which is approximately meant to accommodate the fact this if the wing tip can fully offload then it may well be structurally sized by a failure case (i.e. tip movement impeded) where a factor of safety of 1.0 is applied instead of the nominal 1.5 ultimate factor.
- ⇨ Aerodynamic model: Doublet lattice model (DLM), without any corrections to force or moment gradients, nor any inclusion of aerodynamic terms at zero angle of attack. The DLM is also pictured in figure 10.
- ⇨ Loads cases: Vc/0ft, Vc/Mc and Vd/Md.
- ⇨ Flutter case: Mach 0.81.

The following Nastran solutions were used to perform the calculations:

- ⇨ Nastran SOL144 to simulate 2.5g manoeuvres.
- ⇨ Nastran SOL146 to simulate incremental tuned discrete gusts (with gradients from 30 to 350ft), added to the 1g component from Nastran SOL144. Note that the transient from the actuation of the wing tip has not been modelled – i.e. the wing tip is assumed to be already fully free to move before the gust makes contact with the aircraft.
- ⇨ Nastran SOL145 to perform the flutter calculations.
- ⇨ For SOL145 and SOL146 the modes were truncated at 10Hz due to concerns about the quality of the structural model.

In addition to model A, the following additional models were also prepared:

- ⇨ Model B: As model A, but with updated wing tip (including hinge) masses, approximately 2.5 times heavier.
- ⇨ Model C: As model B, but 3D FEM without reduction to EIGJ beam, plus more detailed pylon modelling and a flexible fuselage and tail. Thanks to improved confidence in the quality of the model the modal truncation was increased to 25Hz.

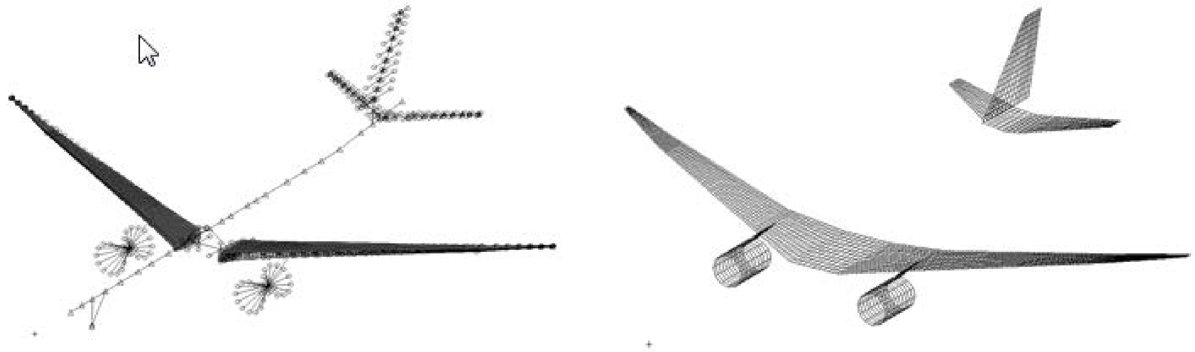

Figure 10: Finite element model (model A, before reduction to EIGJ beam) and doublet lattice model

5. SHORT RANGE AIRCRAFT STUDY: MODEL A RESULTS

Figure 11 shows the tuned discrete gust and 2.5g manoeuvre shear, moment and torque wing loads at Vc/Mc for mass case M2 for the fixed and free hinge. At the free hinge the bending moment and the shear load are very close to zero. At the wing root the bending moment has been reduced by approximately 13% for the gust and approximately 17% for the manoeuvre. Figure 12 shows the gust bending moment distribution as a ratio of the loads for the free hinge to the loads for the fixed hinge. Although the bending moment at the hinge is effectively zero (noting a small amount of 'noise' from the model), in reality some other case will structurally size the wing tip, the hinge and the adjacent part of the wing, such as the failure case noted in section 4. Thus the load alleviation benefits are likely to be capped in the mid and outer parts of the wing.

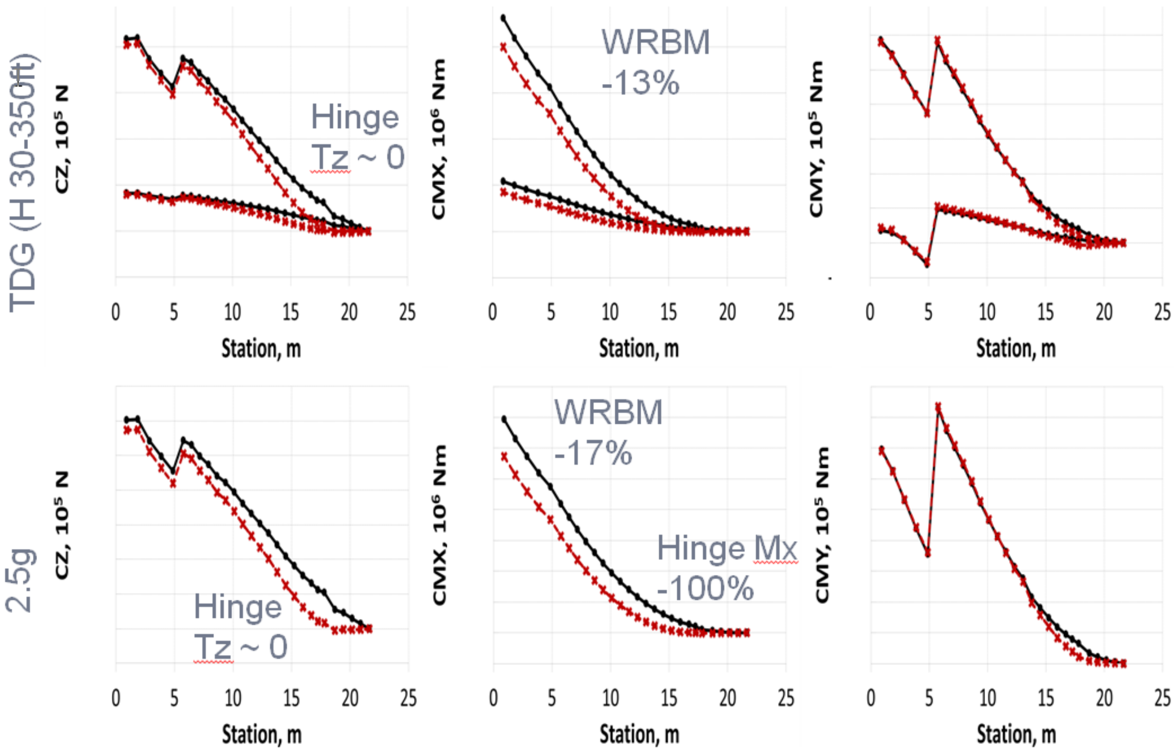

Figure 11: Tuned discrete up / down gusts (top) and 2.5g manoeuvre (bottom) shear, moment and torque (left to right) wing loads at Vc/Mc for mass case M2; Black = fixed hinge, red = free hinge

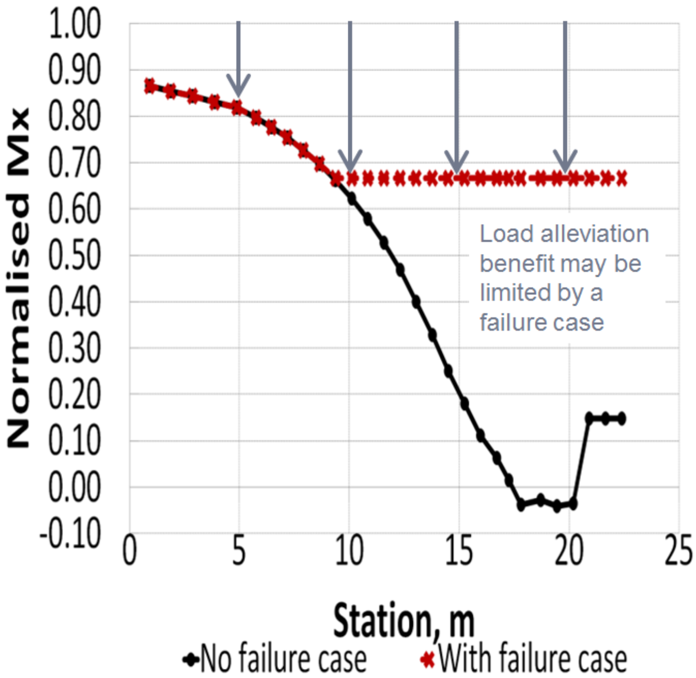

Figure 12: Tuned discrete up gust bending moment distribution at Vc/Mc for mass case M2; Ratio of loads for the free hinge to the loads for the fixed hinge, with and without failure case

Table 1 shows the normalised wing root bending moment (WRBM) gust and manoeuvre results from the loads 'mini loop'. The range in WRBM reduction for the gust is from -8 to -13%, with -13% for the envelope. And for manoeuvre the range is -15 to -19%, with -16% for the envelope. This level of load alleviation delta compares well to existing load alleviation systems which are typically based on ailerons & spoilers. Note that load alleviating hinged wing tips are not an alternative to existing load alleviation systems but can be used in combination, although it will be necessary to avoid double failure of both systems. A spot check on a rigid model showed a WRBM reduction of -25%, thus illustrating the aeroelasic (in)efficiency effect noted in section 2. Finally it is estimated that the level of load alleviation demonstrated could lead to a weight saving opportunity in the order of hundreds of kilograms per aircraft.

Mass	Altitiude	Mach	Gust WRBM			Manoeuvre WRBM		
			Fixed Hinge	Free Hinge	Δ%	Fixed Hinge	Free Hinge	Δ%
M1	0	0.51	0.68	0.59	-12.2	0.52	0.42	-18.6
M2	0	0.51	1.00	0.87	-12.6	0.95	0.78	-17.9
M1	25000	0.82	0.61	0.53	-12.7	0.54	0.44	-18.3
M2	25000	0.82	0.93	0.80	-13.3	0.99	0.82	-17.5
M1	25000	0.89	0.45	0.41	-8.3	0.54	0.45	-16.5
M2	25000	0.89	0.76	0.67	-12.8	1.00	0.84	-15.8
Envelope			1.00	0.87	-12.6	1.00	0.84	-15.8

Table 1: Normalised wing root bending moment results from the loads 'mini loop'

Figure 13 shows the flutter results for the fixed and heavy tip / hinge versus the light and free tip / hinge for the M1 mass case. For the fixed hinge the flutter speed is well below the 1.15Vd airworthiness requirement, which is a mark of the insufficient quality of the structural model rather than a specific risk with the aircraft configuration being analysed. Compared to the fixed hinge the free hinge has a flutter speed which is 50% higher. On the damping plot for the free hinge the flapping mode can be seen to be increasing in damping rapidly as a function of airspeed. This large amount of aerodynamic damping is of course stabilising. On the frequency plot for the free hinge the flapping mode can be seen to be increasing from zero linearly with speed, crossing the first wing bending mode but not strongly coupling with it. Reference [1] provided an analytical explanation for this linear trend, and it is repeated here.

$$f_n \approx \frac{1}{2\pi}\sqrt{\frac{K_{aero}\left(1-\xi_n{}^2\right)}{I_{\theta wt}}} = \frac{V}{2\pi}\sqrt{\frac{\frac{1}{2}\rho s_{wt} c_{wt} Cm_\theta \sin\Lambda\left(1-\xi_n{}^2\right)}{I_{\theta wt}}}$$

In the next sections it will become clear how controlling the *gradient* of the flapping mode frequency as a function of airspeed is a crucial tool for delaying the coalescence with the first wing bending mode and thus stabilising flutter. Moreover the two key levers for achieving this are the flare angle Λ and the second moment of inertia of the flapping wing tip $I_{\theta\omega t}$.

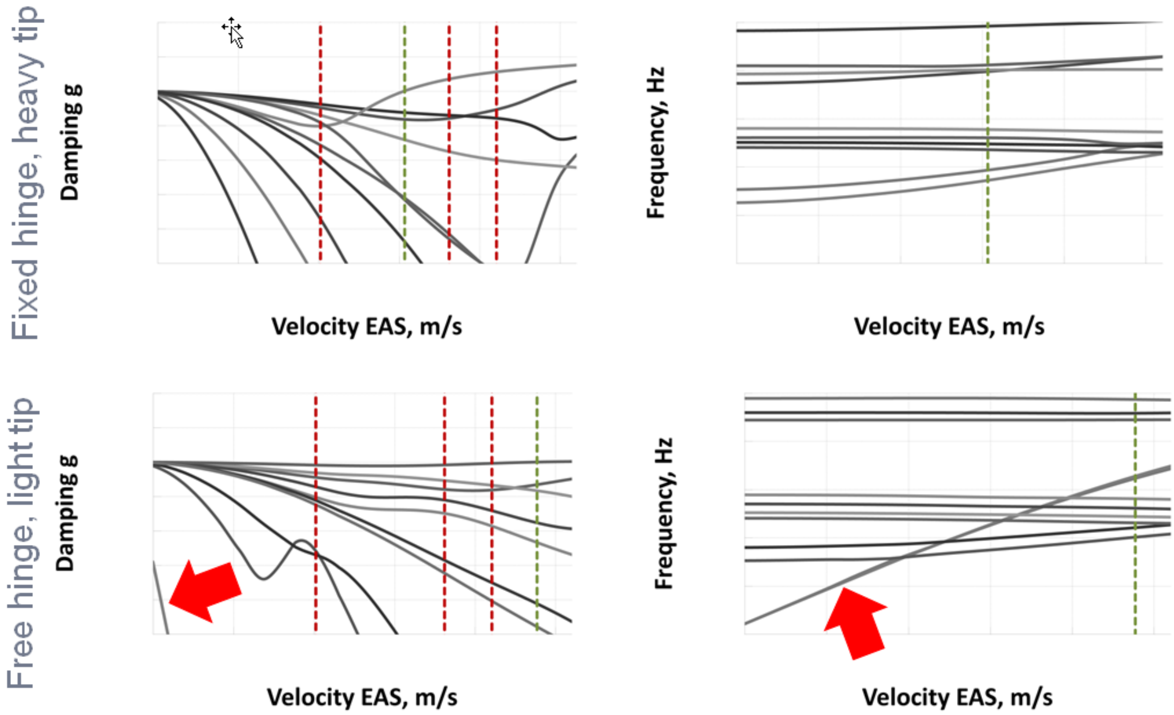

Figure 13: Flutter results for the fixed and heavy tip / hinge versus the light and free tip / hinge for the M1 mass case

6. SHORT RANGE AIRCRAFT STUDY: MODEL B RESULTS

In figure 14 a comparison is made between the flutter results for model B versus model A for the fixed and free hinge. For the fixed hinge the flutter behaviour is deteriorated by the heavier wing tip (mass approximately 2.5 greater), and the flutter speed is even further from 1.15Vd. Again the insufficient quality of the structural model is noted. For the free hinge there is now a strong flutter coupling, which touches the zero damping line, as a result of the flapping mode coupling with the first wing bending mode. This flutter mechanism is considered to be the key aeroelastic risk associated with a free hinge.

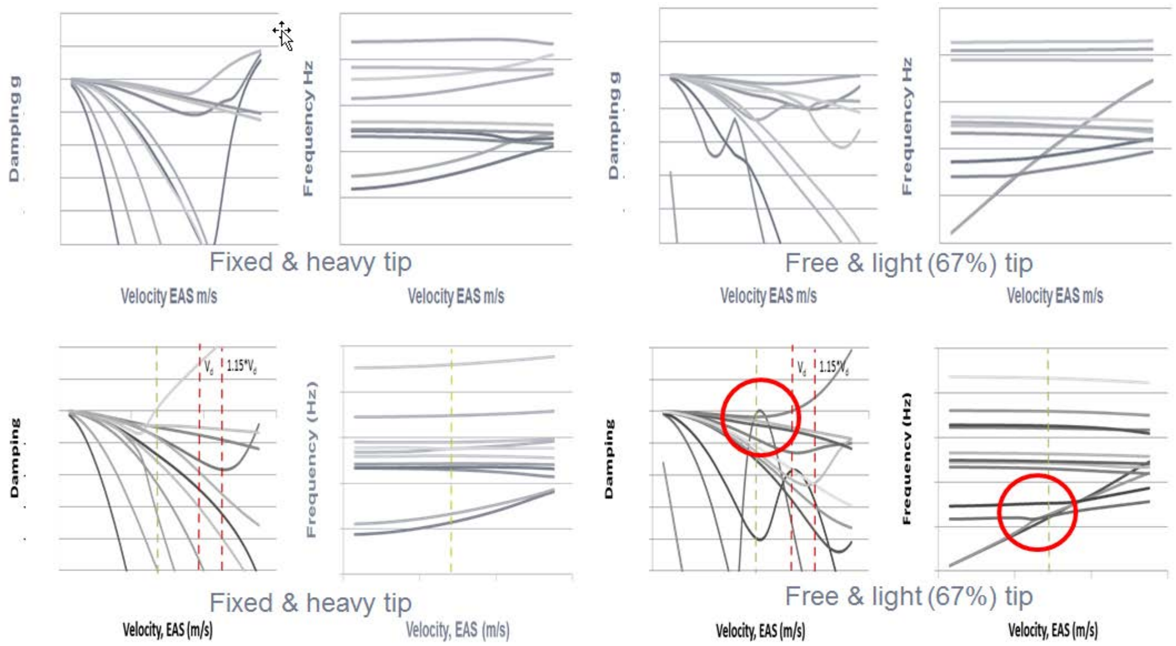

Figure 14: Flutter results for the fixed and heavy tip / hinge and the light and free tip / hinge for the M2 mass case for model A (top) versus model B (bottom)

Figure 15 shows the effect of adding 50Kg masses to the tips of the wing tips. The masses increase the second moment of inertia of the wing tip thus decreasing the flapping frequency versus airspeed gradient and delaying the coalescence with the first wing bending mode, which leads to the tip flapping / wing bending coupling mechanism being strongly stabilised.

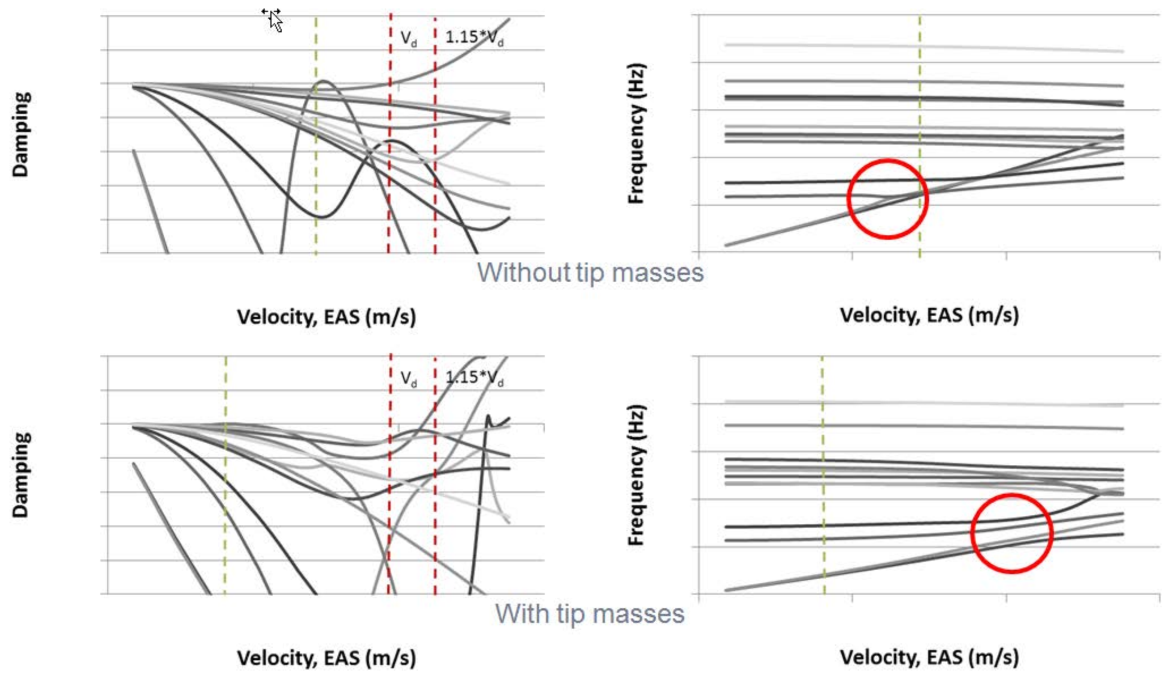

Figure 15: Flutter results for the light and free tip / hinge for the M2 mass case for no tip masses (top) versus with 50Kg tip masses (bottom)

The influence of the hinge flare angle is shown in figure 16. Three angles have been investigated, where the middle angle of approximately 25^o represents the hinge axis being orientated perpendicular to the wing quarter chord axis. Reducing the flare angle by 10^o reduces the flapping frequency gradient leading to the flapping / wing bending coupling mechanism being effectively removed (and stabilising other flutter mechanisms too). Increasing the flare angle by 10^o is extremely destabilising. In addition it is observed that the change of damping of the flapping mode with airspeed is increased as the flare angle is decreased. Lastly it was found, but not shown here, that these changes in flare angle change the WRBM by not more than 1% (the trend is less flare angle, more bending moment).

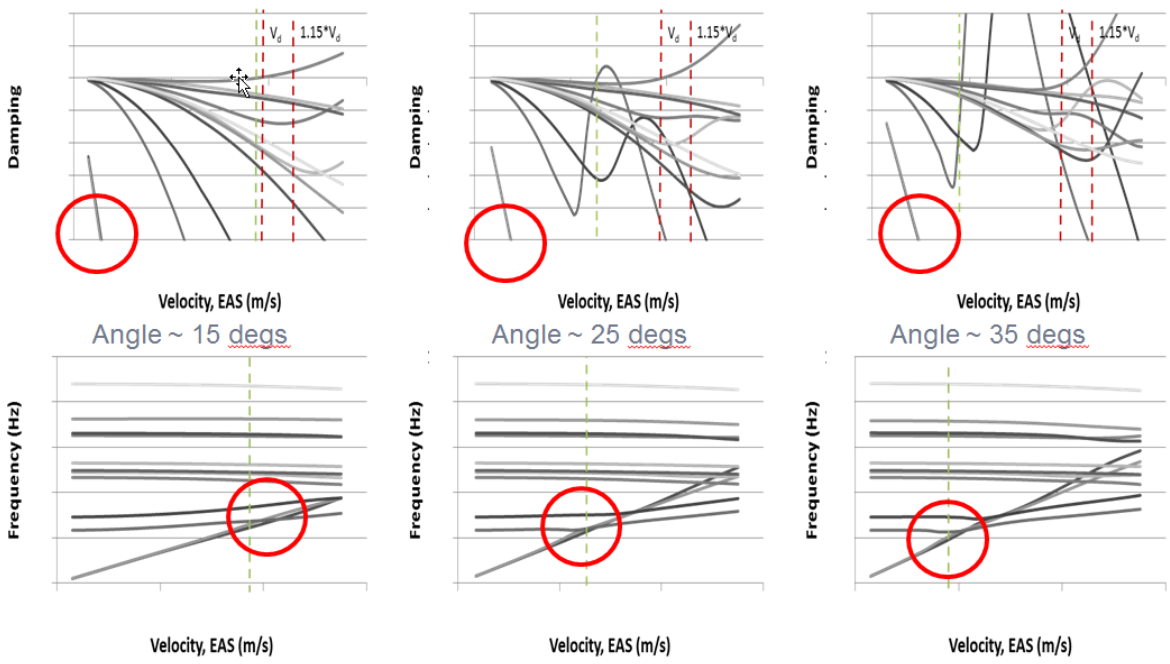

Figure 16: Flutter results for the light and free tip / hinge for the M2 mass case for hinge flare angles of 15^o, 25^o and 35^o

7. SHORT RANGE AIRCRAFT STUDY: MODEL C RESULTS

In figure 17 a comparison is made between the flutter results for model C versus model B for the fixed and free hinge. For the fixed hinge the flutter behaviour is significantly improved with no flutter below 1.15Vd. This is a measure of the improved quality of the structural model, especially the wing and pylons, plus the influence of the flexible fuselage and tail. However for the free hinge the flapping / wing bending coupling mechanism is unstable well below Vd. The cause of this is not any change in the wing tip properties (they are unchanged, and the flapping gradient has changed very little), but the fact that in model C the wing bending stiffness is significantly lower which reduces the first wing bending mode frequency thus shifting the coalescence with the flapping mode to a lower airspeed.

The influence of the hinge flare angle is shown in figure 18 and the trend is the same as for model B: 10^o less flare angle removes the flutter from below 1.15Vd, whereas 10^o more flare angle is extremely destabilising.

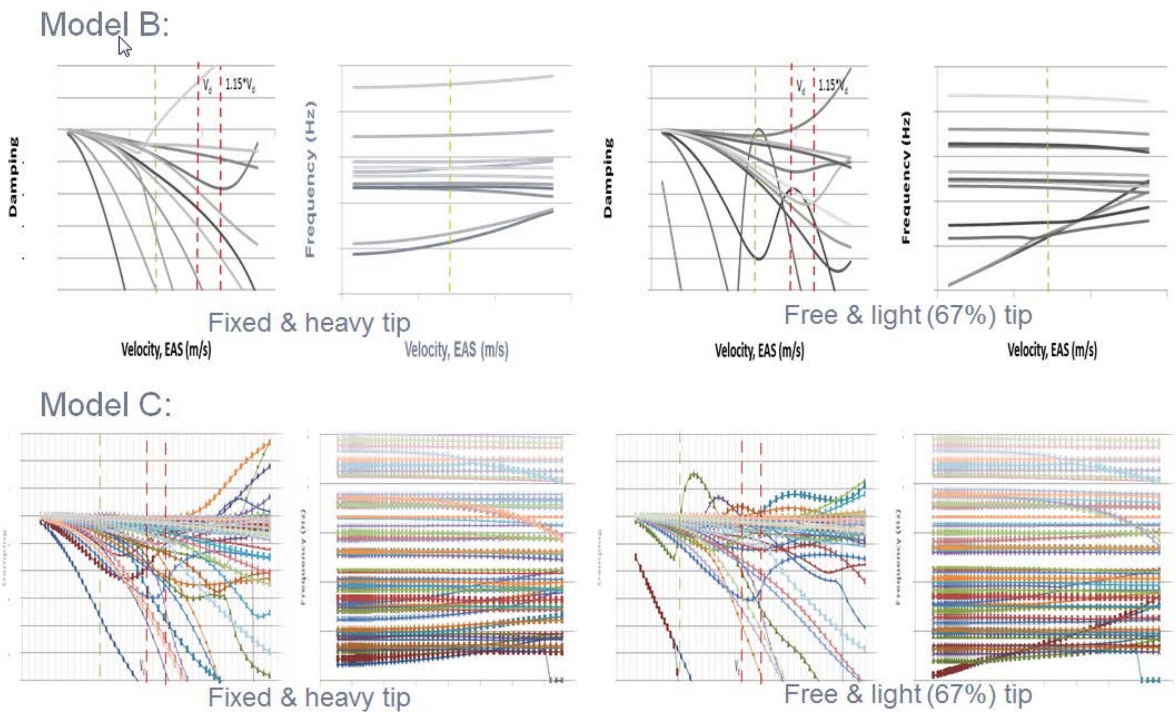

Figure 17: Flutter results for the fixed and heavy tip / hinge and the light and free tip / hinge for the M2 mass case for model B (top) versus model C (bottom)

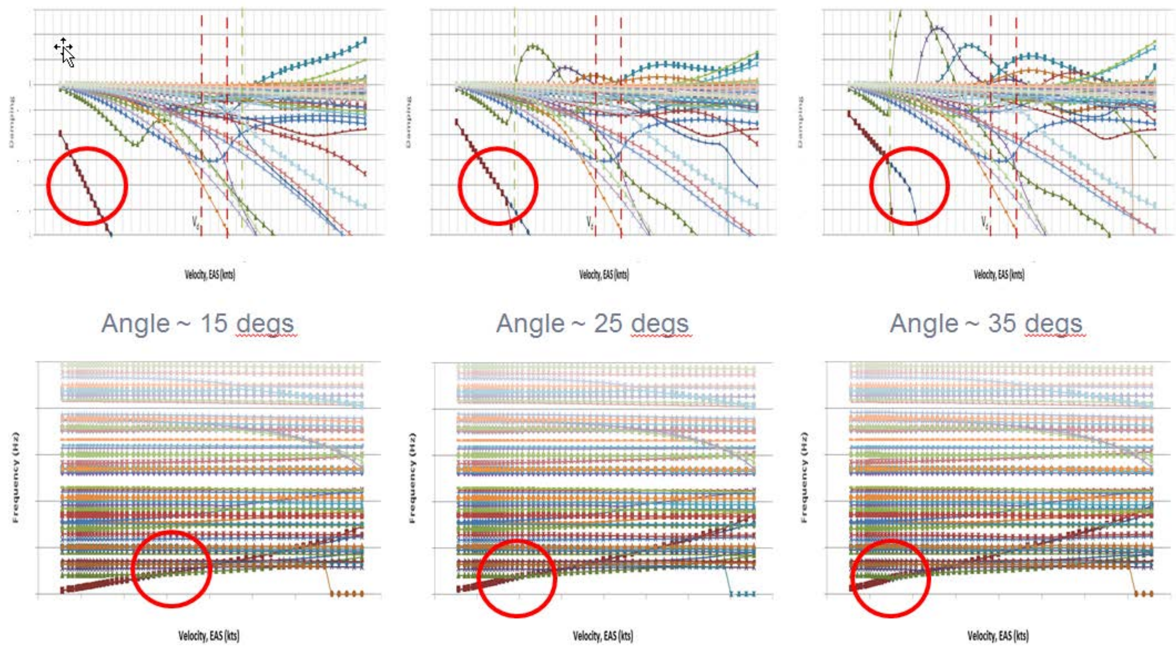

Figure 18: Flutter results for the light and free tip / hinge for the M2 mass case for hinge flare angles of 15°, 25° and 35°

Figure 19 shows the effect of moving the hinge approximately one metre inboard. Two effects are observed; Firstly that the change of damping of the flapping mode with airspeed is increased – in simple terms it is understood that as the size of the flapping tip increases, the amount of aerodynamic damping should also increase. The other effect is that the frequency gradient of the flapping mode decreases, thus delaying the coalescence with the first wing bending mode. In principle the greater size of the flapping wing tip should increase the aerodynamic stiffness and thus the frequency gradient. However this relationship is linear, whereas the second moment of inertia increases as a cubic relationship with the size of the tip, and this dominates as per the equation in section 5 to reduce the flapping mode gradient. These two observed effects, the damping and frequency gradient, combine to have a strongly stabilising effect on the flutter mechanisms.

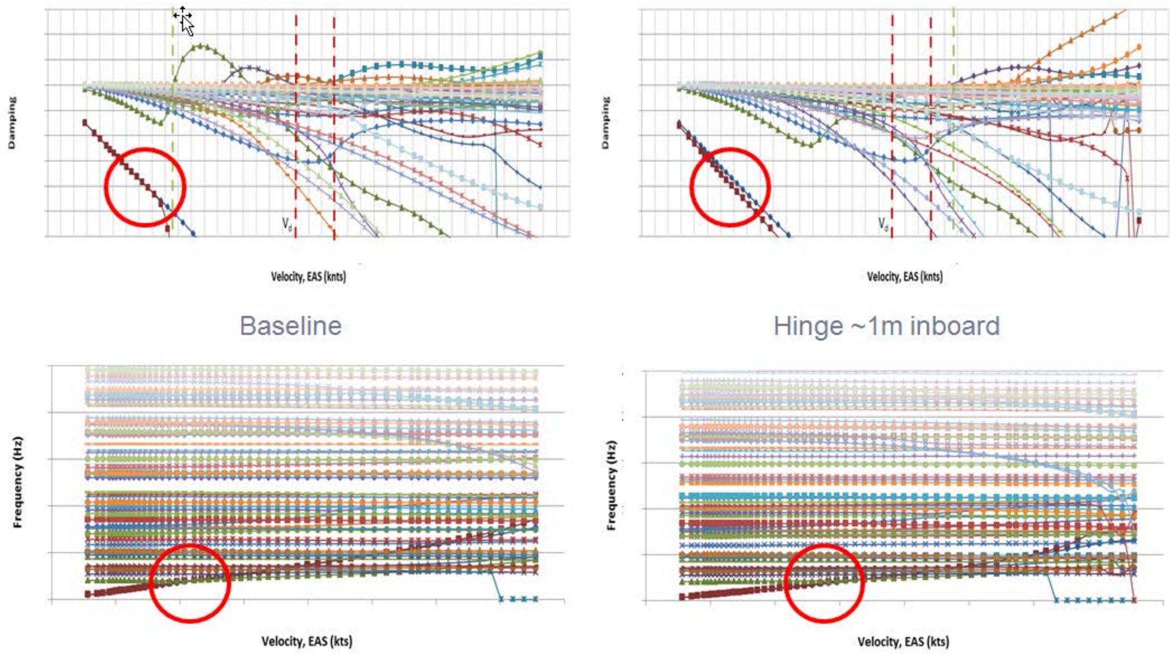

Figure 19: Flutter results for the light and free tip / hinge for the M2 mass case for baseline hinge position (left) and the hinge moved approximately 1m inboard (right)

8. CONCLUSIONS AND NEXT STEPS

The short range aircraft study has shown that a flared hinge with a zero stiffness or 'free' hinge leads to a significant gust and manoeuvre loads alleviation benefit, which may enable a potentially substantial weight saving opportunity. The introduction of the free hinge can cause flutter, but it has been shown that flutter can be stabilised via tip masses, the choice of hinge location and hinge flare angle – with the latter having a minimal impact on wing root bending moment. More generally it is clear that gaining a deep understanding of the aeroelastic behaviour of hinged wing tips is crucial in order to exploit the load alleviation potential.

Going forward more studies are required, including loads analysis with model C and further improvements to the structural and aerodynamic parts of the model, plus considering continuous turbulence and low speed cases. Furthermore a discussion needs to be had on whether a practical system could be realisable which embodies the required non-linear behaviour to permit free hinge movement for load alleviation but maintains a planar wing shape for efficient 1g flight. Finally the collaboration between Airbus and the universities will continue, including supporting a wind tunnel demonstration at the University of Bristol.

9. ACKNOWLEDGEMENTS

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