# On the Dynamic Release of the Semi Aeroelastic Wing-Tip Hinge Device



Andrea Castrichini
Airbus



Thomas Wilson
Airbus

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A. Castrichini[1], T. Wilson[2]
Airbus Operations Ltd., Filton, BS99 7AR, United Kingdom

J.E. Cooper[3]
University of Bristol, Bristol, BS8 1TH, United Kingdom

**A recent consideration in aircraft design is the use of folding wing-tips with the aim of enabling higher aspect ratio aircraft with less induced drag, but also meeting airport gate limitations. This study investigates the effect of exploiting folding wing-tips in-flight, as a device to reduce aircraft loads. A nonlinear hinge device is employed to allow a clean wing configuration during the cruise flight while enabling the wing-tip deflection only for larger load cases. It was found that significant reductions in the dynamic loads were possible.**

## Nomenclature

*Symbols*

| | | |
|---|---|---|
| $b_j$ | = | Gust spanwise shape function |
| $b_l$ | = | Aerodynamic lag-pole |
| $D$ | = | Damping matrix |
| $H$ | = | Gust gradient |
| $F_{Aero}$ | = | Aerodynamic forces vector |
| $k$ | = | Reduced frequency |
| $K$ | = | Stiffness matrix |
| $K_\theta$ | = | Torsional spring stiffness |
| $L_g$ | = | Gust length |
| $M$ | = | Mass matrix, Mach |
| $M_{Hinge}$ | = | Hinge moment |
| $q_{dyn}$ | = | Dynamic pressure |
| $Q_O$ | = | Generalized aerodynamic force matrices |
| $Q_e$ | = | External forces |
| $Q_{iO}$ | = | Coefficient matrices of RFA |
| $R_l$ | = | Aerodynamic states vector |
| $u$ | = | Nodal displacement |
| $V$ | = | True air speed |
| $w_j$ | = | Gust vector |
| $w_g$ | = | Gust velocity |
| $w_{g0}$ | = | Peak of the gust velocity |
| $w_{ref}$ | = | Reference gust velocity |
| $x_0$ | = | Gust origin position |
| $x_j$ | = | $j^{th}$ panel's control node position |
| $\gamma_j$ | = | $j^{th}$ panel's dihedral angle |
| $\delta_{tj}$ | = | Kronecker Delta |
| $\delta_x$ | = | Aerodynamic control surfaces vector |
| $\theta$ | = | Wing-tip folding angle |
| $\xi_h$ | = | Modal coordinate |
| $\Phi$ | = | Modal base |

*Superscript*

| | | |
|---|---|---|
| $\dot{}$ | = | Differentiation with respect to time |
| $\tilde{}$ | = | Fourier transform |
| $\bar{}$ | = | Generalized variable |

## I. Introduction

Much effort has been made to design aircraft to optimize fuel consumption through reduction of aerodynamic drag. A sizable contribution to the overall drag is lift-induced drag, which could be reduced by increasing the wing span, but such a design solution has well defined limits imposed by the maximum aircraft dimensions allowed at airports and also the increase in bending moments along the wing. A possible solution to the first issue is the use of folding wings that can be employed on the ground similar to the retractable wings used on aircraft-carrier-borne aircraft. An example of this approach relevant to civil applications is the latest version of the B-777, which will have a folding wing capability to be activated during taxing to and from the gates. The inclusion of such a design feature raises the question as to whether such a folding device could also be used to enable load reduction on the aircraft during the flight.

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[1] Loads and Aeroelastics Engineer

[2] Head of Technical Capability for Aircraft Loads Flight Physics

[3] Airbus Royal Academy of Engineering Sir George White Chair in Aerospace Engineering

Recent works [1-5] have been aimed at studying the benefits of using a flexible wing-fold device for load alleviation and considering how it would be implemented on civil jet aircraft. The main idea consists of introducing a hinge in order to allow the wing tips to rotate, and it is known that the orientation of the hinge line relative to the airflow is a key parameter to enable successful load alleviation. When the hinge line is rotated outboard of the streamline, folding the wing-tip up introduces a decrease in the local angle-of-attack [1] and such an effect provides a means to reduce the loads acting on the wing, leading to the possibility of achieving a wing-tip extension with limited or even minimal impact on wing weight. Previous works have demonstrated that a free hinge is necessary in order to maximise the loads alleviation performance [1]. However, zero hinge stiffness leads the wingtip to be deflected during straight and level cruise flight due to the static trim loads, and furthermore, to a continuous oscillating motion due to unsteady aerodynamic loads. Such deflections and continuous motions are undesirable as they will be detrimental to the aerodynamic performance, trim behaviour, and may generate undesired structural vibrations and rigid-body motion. Ideally, the wing-tip should not deflect during cruise, but only operate once a significant gust is encountered. With a linear hinge device there is a conflict between having no spring stiffness for good gust loads alleviation and a high spring stiffness to counteract static trim deflections and continuous oscillations. Initial solutions to this problem investigated piecewise linear and negative stiffness devices [2,3].

In this paper, an investigation is made into the use of a nonlinear hinge device in order to keep the folding wing tip in a clean configuration during the trim cruise flight and releasing it only when needed. Such a concept is called Semi Aeroelastic Hinge (SAH). During the cruise, the wing-tip is kept in place by using a dedicated blocking mechanism. When a triggering event is detected, the wing-tip is actively released and the tip device acts then as a passive loads alleviation system, purely driven by the aerodynamic and inertial forces. After the loads event is finished, an actuator is then engaged to bring back the wing-tip to the initial clean configuration.

The resulting dynamic wing-tip release response, affecting the loads alleviation performance, is the focus of such research activity. Numerical simulations using representative commercial aircraft models are used to show how such nonlinear device effects the performance of the folding wing-tip concept.

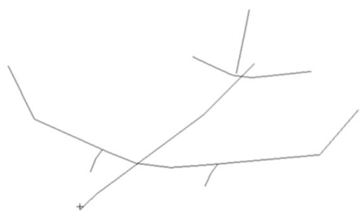
## II. Aeroelastic Model

### A. Structural Modelling

A nonlinear reduced order model is defined to model the hinge linear and nonlinear hinge mechanisms.

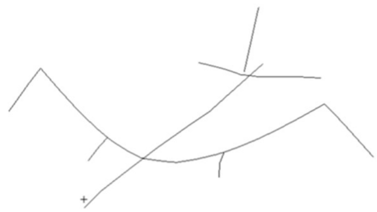
The idea is to use the set of flexible modes obtained when a very low hinge spring stiffness is defined along the hinge line; a zero stiffness value was avoided to prevent numerical singularities during the modal analysis. This approach led the first two flexible modes to be local symmetric and anti-symmetric pseudo-rigid wing-tips deflection as shown in Fig. 1(a, b). Such modal shapes are by definition orthogonal with the remaining flexible modes that involve a combination of wing-tips and main airframe deformations, Fig. 5(c, d), therefore they could be used to describe independent wing-tip rotations. The overall span reduction due to the wing-tips deflection was not considered.

Linear and nonlinear hinge devices, such as springs, dampers or actuators, can be modelled by applying external moments on the hinge nodes along the hinge axis in order to simulate the related restoring moments on the wing-tips and main airframe, as shown in Fig. 2. The hinge moments could be defined as linear or nonlinear functions of the wing-tip folding angle and, once projected onto the structural modes, defined as a set of generalized forces that could excite mainly the local wing-tip modes and so drive the wing-tips motion.

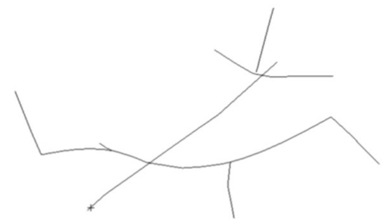


(a) 1st Mode *4.17E-3 Hz*

(b) 2nd Mode *4.18E-3 Hz*



(c) 3rd Mode *2.22E0 Hz*



(b) 4th Mode *2.54E0 Hz*

**Figure 1. Typical Modes of an Aircraft with the Folding Wing-Tips**

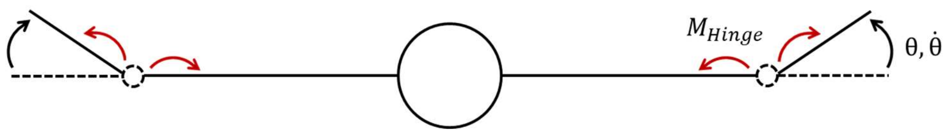



**Figure 2. Applied Hinge Moments**

The nonlinear dynamics equations of the system are described as

$$\bar{M}\ddot{\xi} + \bar{D}\dot{\xi} + \bar{K}\xi = \bar{Q}_e + \bar{F}_{Aero} + \bar{M}_{Hinge} \tag{1}$$

where $\bar{M}$, $\bar{D}$, $\bar{K}$ are the generalised mass, damping and stiffness matrices, $\bar{Q}_e$ collects the non-aerodynamic external generalised forces (i.e. gravity) while $\bar{F}_{Aero}$ are the generalised aeroelastic forces and $\bar{M}_{Hinge}$ are the generalised moments due to the nonlinear hinge device.

The aeroelastic problem is formulated by considering as unknown the structural physical displacements $u$ expressed on a modal basis as

$$u(x,t) = \sum_{n=1}^{N_{Modes}} \Phi(x)\,\xi(t) \tag{2}$$

where $\Phi$ is the modal matrix and $\xi$ the modal displacements. This kind of formulation introduces a significant approximation since only a limited number of structural modes are used. Only a number of modes equal to the structural degrees of freedom prevents any loss in accuracy in the passage from the physical displacement base to a modal base.

The idea is to simulate a mechanism that allows the wing-tip to rotate only when the aerodynamic forces are higher than some predefined threshold value. Such device was modelled by applying, to the wing-tips and main airframe, the restoring moments due to a piecewise linear spring whose stiffness was varied according to the loads experienced by the aircraft such that

$$M_{Hinge} = -K_\theta \theta$$
$$\begin{cases} K_\theta = 1.E^{12} Nm/rad & if \quad 0 < t < t_{release} \\ K_\theta = 1.E^{0} Nm/rad & if \quad t \geq t_{release} \end{cases} \tag{3}$$

## B. Aerodynamic Modelling

Unsteady aerodynamic effects are modelled using the Doublet Lattice Method [6,7] (DLM). Quasi-steady aerodynamic corrections are also introduced to account for wing twist and aerodynamic profiles camber.

Such aerodynamic method is based upon linear unsteady potential flow theory and the assumptions of inviscid, irrotational, compressible and attached flow, subject to small angle of attack or side slip. As a consequence, nonlinear aerodynamic effects were not accounted for. Also nonlinear geometric structural and aerodynamic effects are not included.

Such an approximation is in general acceptable when applied to conventional aircraft structures subject to small deformations. Despite the presence of the hinge, the wing-tip deflections resulted to be limited; therefore, linear structural and aerodynamic models can be still considered acceptable for a preliminary investigation of the effect of the folding wing-tip on aircraft loads and dynamic response. Moreover, other works based on high fidelity simulation [8] and experimental measurements [4], have highlighted similar trends as the ones identified by using linear methods [1].

In unsteady aeroelastic problems, the relationship between the motion of the structure and the consequent aerodynamic response is usually described through the use of the Generalised Aerodynamic Forces (GAF) matrices which take as input the generalised structural displacements or atmospheric turbulence and provide as output the generalised aerodynamic forces. The dynamic system has to take into account the mutual interaction of the fluid and the structure; the aerodynamic forces deform the structure, the deformation of the structure introduces a change in the aerodynamic boundary conditions and so changes the aerodynamic forces, and so on.

The same modal formulation is used to describe the unsteady aerodynamic forces which are therefore strongly dependent on the number of modes that are used in the dynamic analysis. In the frequency domain, the unsteady aerodynamic forces are defined as [7]

$$\tilde{F}_{Aero} = q_{dyn}[Q_{hh}(M,k)\tilde{\xi}_h + Q_{hx}(M)\tilde{\delta}_x + Q_{hj}(M,k)\widetilde{w}_j] \tag{4}$$

where $Q_{hh}$ ($\mathrm{N_{Modes}} \,\mathrm{X}\, \mathrm{N_{Modes}}$), $Q_{hx}$ ($\mathrm{N_{Modes}} \,\mathrm{X}\, \mathrm{N_{ControlSurf}}$), $Q_{hj}$ ($\mathrm{N_{Modes}} \,\mathrm{X}\, \mathrm{N_{Panels}}$), are respectively the generalized aerodynamic forces matrices related to the Fourier Transform of the generalized coordinates $\tilde{\xi}_h$, control surfaces vector $\tilde{\delta}_x$ and gust shape $\widetilde{w}_j$ and $q_{dyn}$ $\left(q_{dyn} = \frac{1}{2}\rho V^2\right)$ is the dynamic pressure.

The gust vector defines the downwash on a generic aerodynamic panel *j* due to the gust such that

$$w_j = b_j(y)\cos\gamma_j \frac{w_{g0}}{2V}\left(1 - \cos\left(\frac{2\pi V}{L_g}\left(t - \frac{x_0 - x_j}{V}\right)\right)\right)\delta_{t_j} \tag{5}$$

where, $L_g$ is the gust length (twice the gust gradient *H*), $V$ is the true air speed, $\delta_{t_j}$ is a Kronecker Delta which is equal to 1 only in the time window when the gust crosses the $j^{th}$ panel $\left(\frac{x_0 - x_j}{V} \leq t_j \leq \frac{x_0 - x_j}{V} + \frac{V}{L_g}\right)$, $b_j$ is a shape function defining the gust spanwise shape and $w_{g0}$ the peak gust velocity, the latter defined (in m) as [9]

$$w_{g0} = w_{ref}\left(\frac{H}{106.17}\right)^{\frac{1}{6}} \tag{6}$$

For computational efficiency the AIC, and therefore the GAF, matrices are generated for a limited set of reduced frequencies $\left(k = \frac{\omega c}{2V}\right)$ and Mach numbers; the remaining intermediate values are evaluated through interpolation schemes [7].

Due to the nonlinearity of the equation of motion, the aerodynamic forces are recast in a time domain formulation using the Rational Fraction Approximation (RFA) method proposed by Roger [10] as

$$F_{Aero} = q_{dyn} \Bigg\{ \left[ Q_{hh0}\xi_h + \frac{c}{2V} Q_{hh1}\dot{\xi}_h + \left(\frac{c}{2V}\right)^2 Q_{hh2}\ddot{\xi}_h \right] + [Q_{hx0}\delta_x] \tag{7}$$

$$+ \left[ Q_{hj0}w_j + \frac{c}{2V} Q_{hj1}\dot{w}_j + \left(\frac{c}{2V}\right)^2 Q_{hj2}\ddot{w}_j \right] + \sum_{l=1}^{N_{Poles}} R_l \Bigg\}$$

where $R_l$ is the generic aerodynamic state vector related to the generic lag-pole $b_l = \frac{k_{max}}{l}$. These extra states allow the modelling of the unsteady response of the aerodynamics by taking into account of the delay of the aerodynamic forces with respect to the structural deformations. These aerodynamic states were evaluated through the set of dynamic equations

$$\dot{R}_l = -b_l \frac{2V}{c} IR_l + Q_{hh2+l}\dot{\xi}_h + Q_{hj2+l}\dot{w}_j \qquad l = 1, \dots, N_{Poles} \tag{8}$$

which are solved together with the equations of motion (1).

## III. Numerical Results

A single aisle aircraft linear structural model is used for the analyses. The wing-tip extensions are connected to the main wing structure in a similar way as in previous work [1]. The total span is increased by roughly 25%. A single flight point was considered at 25000 ft of altitude and a Mach number of M=0.82.

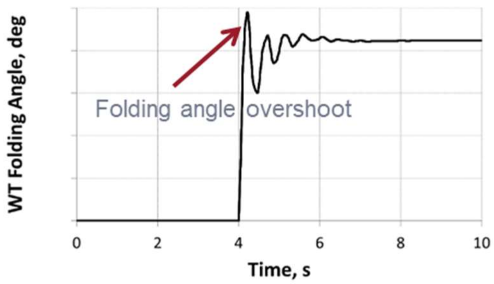
A family of 10 "1-cosine" gusts between 18m and 214m of length has been considered following the EASA Regulations [9].

### A. The folding wing-tip release

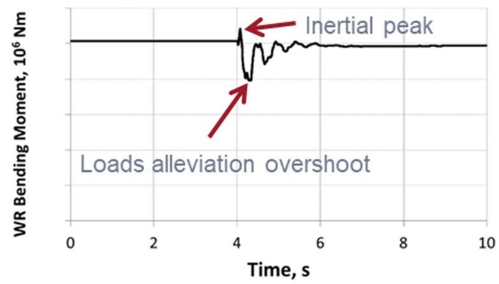
This section reports the effect of the folding wing-tip release for an aircraft trimmed at 1g flight level. Figure 3 shows the aircraft response in terms of folding angle, wing root bending moment and pitch angle. As soon as the SAH is released, the wing-tip swings upward and then stabilises to a new steady deflected configuration. Figure 3(b) shows the impact on the wing root benign moment. As soon as the wing-tip is released, a sudden increment of the loads, with respect to the previous steady value, occurs. This effect is due to the folding device producing inertial upwards shear forces at the hinge when it slows down approaching the maximum folding angle. Due to the unsteady effects, the aerodynamic forces build up with some delay with respect to the wing-tip motion, this allows an overshoot of the wing-tip folding angle leading to an overshoot of the loads alleviation performance with respect to the deflected steady configuration.

An interesting effect between the folding wing-tip and the aircraft flight mechanics can be observed. Due to the wing sweep angle the folding wing-tips are placed aft the aircraft centre of gravity. This means that when the upward folding wing-tip deflection generates a local negative incremental lift, this reflects in a positive pitching moment contribution. As result, the aircraft tends to increase the overall pitch angle, as shown in Fig. 3(c), and to gain altitude. The increment of the pitch angle reflects also in an increment of the 1g loads experience by the aircraft that tend to balance out the loads alleviation introduced by the folding wing-tip as reported in Fig. 3(b) showing similar steady loads before and after the release.

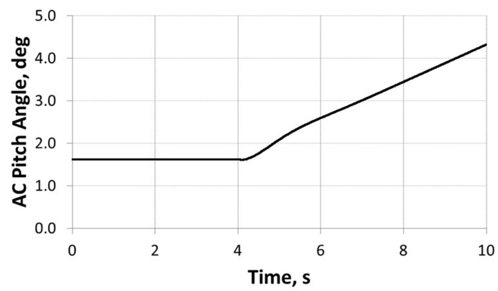
For this reason, it is envisaged to vary also the elevator in order to trim again the aircraft when the SAH is employed, thus limiting the angle of attack increment. The results for this second case are reported in Fig. 4 showing a significant reduction of the steady loads after the release as well as a lower folding wing tip angle and aircraft pitch angle.




(a) Folding wing-tip angle

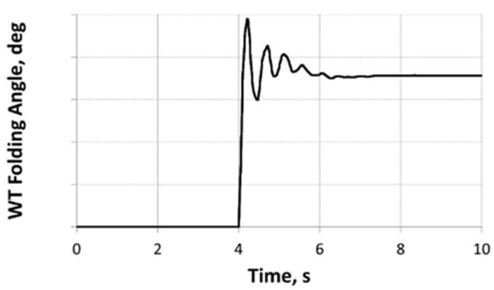



(b) Wing root bending moment

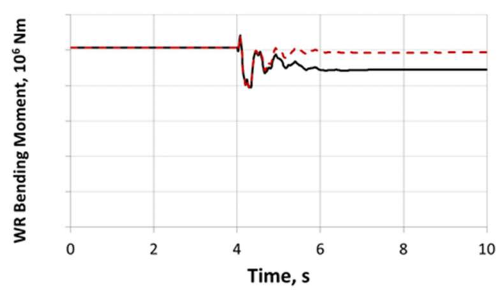



(c) Aircraft pitch angle

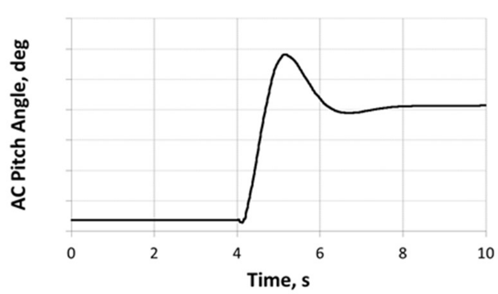
**Figure 3. Folding wing-Tip Release Without Re-Trim**




(a) Folding wing-tip angle




(b) Wing root bending moment




(c) Aircraft pitch angle

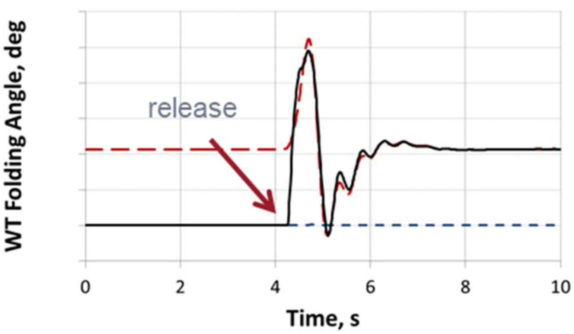
**Figure 4. Folding wing-Tip Release With Re-Trim**
**(dashed red: not re-trimmed)**

## B. On the folding wing-tip release during a gust

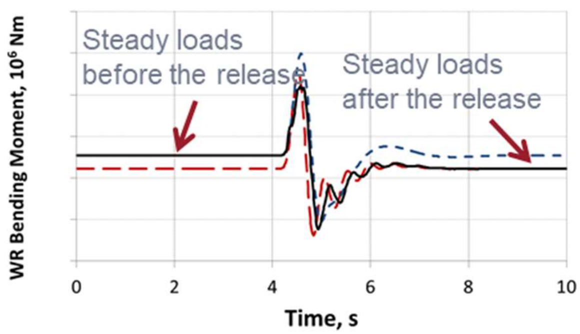
An investigation is now made on the interaction between the folding wing-tip dynamic release and the external gust loads.

As regard the release strategy, it is assumed the variation of the angle of attack induced by the gust is measured at the aircraft nose, when such a variation is higher than 1 degree with respect to the cruise value, the wing-tip is then unblocked. An additional delta time can be considered to account for the delay between the gust detection and the actual release.

Figure 5 shows the typical response of the aircraft when the folding wing-tip is released during a gust event. A comparison is done between the SAH, an aircraft with a fixed hinge and an aircraft with a pure floating hinge [1]. The plots show that, for the aircraft with the SAH, the initial wing root benign moment is the same as the one with the fixed hinge. When released, the folding wing-tip allows to alleviate the peak dynamic gust loads as well as the 1g loads contribution; the loads then stabilise at a lower steady level as for the aircraft with a pure floating hinge. The same observations are valid for the folding angle.



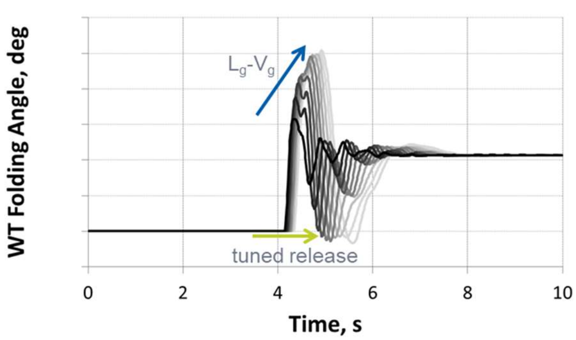

(a) Folding wing-tip angle



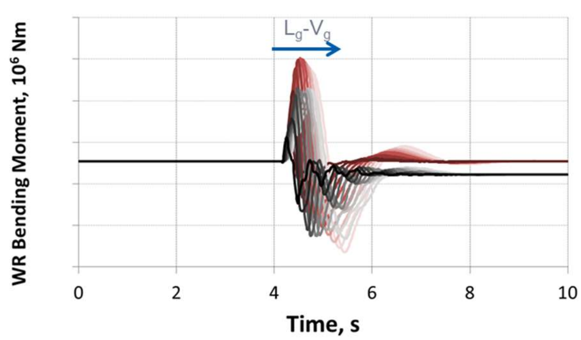

(b) Wing root bending moment

**Figure 5. Folding Wing-Tip Release and Gust Loads Combination**
**(solid back: SAH; dashed dot red: floating hinge; dashed blue: fixed hinge)**

Figure 6 reports the folding angle and the wing root bending moment time histories for a family of gusts. As shown in Fig. 6(a) each gust triggers the release at a different time. As regard the loads, the SAH shows a sensible reduction both of the dynamic gust and 1g steady loads for all the different gust lengths.




(a) Folding wing-tip angle

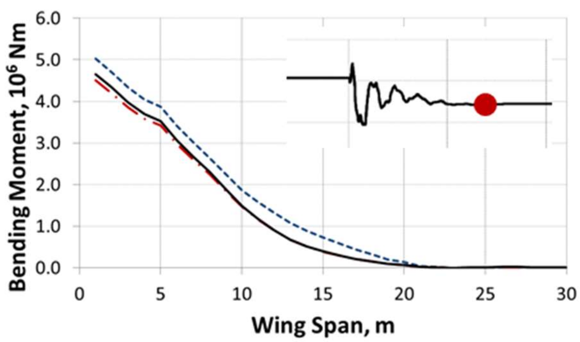



(b) Wing root bending moment

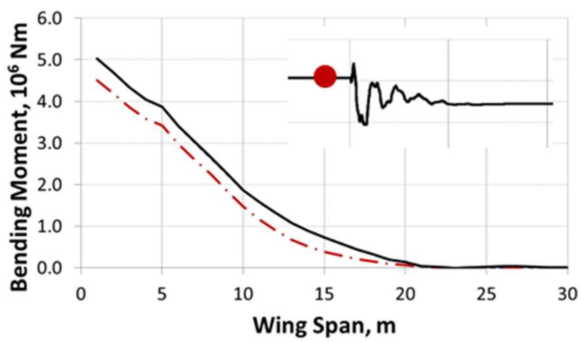
**Figure 6. Folding Wing-Tip Release and Gust Loads Combination –**
**(solid black: SAH; solid red: fixed hinge)**

The results reported in Fig. 4(b) show that the release of the folding wing-tip introduces transient dynamic loads with peaks that can be higher than clean configuration 1g level loads, but also leading to an overshoot of the loads alleviation performance. Therefore, it is of interest to investigate how such dynamic effects couple with the gust loads. Figure 7 shows the effect of different wing-tip time release on the aircraft span wise bending moment distribution, the reported loads are the envelope from a family of ten “1-cosine” gusts. Four different scenarios are envisaged:

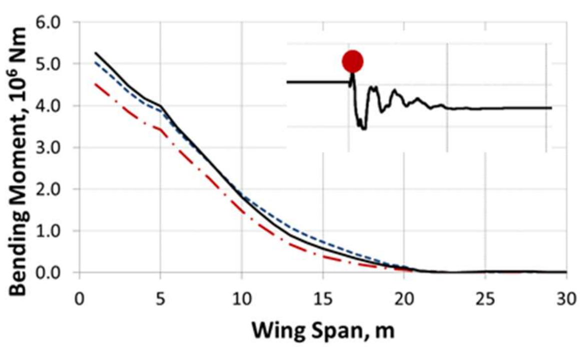
- Scenario 1: the wing-tip is released with enough advance with respect to the gust. A steady floating wing-tip status is already achieved at the moment the gust loads starts to build-up. In this case the analyses show that the SAH leads to very similar loads of the one of an aircraft with a pure floating hinge
- Scenario 2: the wing tip is released after the gust is already passed. As expected, the aircraft experiences the same envelope loads of the fixed hinge case.
- Scenario 3: this is the worst case since the peak gust loads combine with the peak inertial loads introduced by the release leading to a worsening of the loads even with respect to the fixed hinge case.
- Scenario 4: the loads alleviation overshoot is in phase with the gust peak loads. As result, an improvement of the loads alleviation performance against the pure floating hinge is observed.



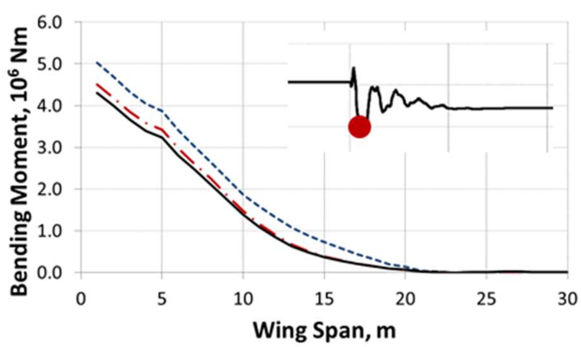

(a) scenario 1




(b) scenario 2




(c) scenario 3




(d) scenario 4

**Figure 7. Release Delay Effect on the Loads**
**(solid back: SAH; dashed dot red: floating hinge; dashed blue: fixed hinge)**

## IV. Conclusions

A preliminary investigation on the use of nonlinear folding wing-tips as a loads alleviation device was performed using a numerical aeroelastic model of a typical commercial jet aircraft. A wing-tip device was connected to the wing with a hinge, and the effects of the SAH hinge device on “1-cosine” gusts and 1g loads were investigated.

The nonlinear hinge device was employed in order to only implement the device in extreme loading levels via a piecewise linear stiffness replicating the effect of a blocking/release mechanism. The results have highlighted that the loads alleviation capabilities were strongly affected by the timing between the hinge release and the loads event.

An early folding wing-tip release is envisaged in order to allow the same loads alleviation performance of a pure floating hinge aircraft. An improvement or a worsening of the loads alleviation effects were observed by varying the hinge release delay.

Further investigations are needed in order to better understand the effect to the phasing between the release and the gust loads in order to optimize the release strategy. However, the loads alleviation performance are promising and show that through the proper design of the wing-tip device it is possible to increase the wing aspect ratio with little, if any, increase in the internal loads experienced by the aircraft, leading to better aerodynamic efficiency and/or reduced structural weight on existing platforms.

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