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## Passively actuated spoiler for gust load alleviation

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### Abstract

This paper summarises a conceptual study regarding a passively actuated spoiler for gust load alleviation. The design of such system is intended to limit the use of computers, sensors and actuators to operate the device. The study mainly relies on using Theodorsen's unsteady flow theory for a typical airfoil section. To cope with the limitations of this type of model for spoiler aerodynamic, corrections are brought from unsteady high fidelity flow simulations by means of transfer functions. The outcome is a 2D aeroelastic model with three degrees of freedom. It describes the spoiler contribution to the overall aeroelastic behaviour of the airfoil in the event of a gust encounter. Results show that the spoiler can help to reduce loads passively, but requires to be retracted with an active system to work properly.

### 1. INTRODUCTION

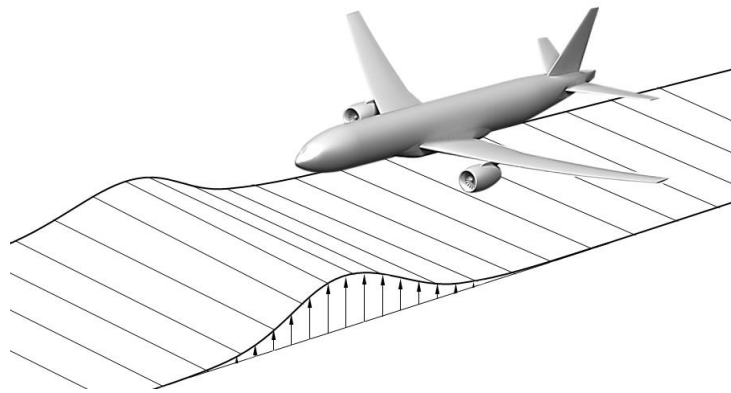
Load alleviation has been a field of research which has received increased attention over the past decade. This is thanks to the development of light-weight highly flexible wings for modern airliners, long endurance drones, and wind turbines. It has been identified as an efficient way to reduce structural fatigue and to improve aircraft handling as well as passenger safety and comfort. Gust loads mainly come from atmospheric conditions [1] and can be represented as in Figure 1. The idea of load alleviation is not new and such systems have been in operation since the 1970s [2]. Lockheed engineers applied this technology on the C5 Galaxy to reduce fatigue load cycles on the wing structure as they had been underestimated during the design phase [3]. Therefore, load alleviation was used to save weight, as extra airframe reinforcement would have been needed otherwise. At about the same time, Lockheed also implemented a similar system on its civil airliner, the L1011 Tristar, and nowadays, such features are common on civil aircraft [2]. Current load alleviation strategies mainly rely on the use of ailerons and spoilers. The latter are normally used as airbrakes and for roll control, but aren't necessarily tailored for load alleviation. Several research papers have been focusing on improving control surfaces integration onto aircraft wings [4]–[6], yet they generally dismiss the use of spoilers for load control. Also, mostly active mechanisms are investigated in these studies. The advantage of a passive load alleviation system is to be a “fail-safe” alternative to active ones that can be more complex and less reliable.

Many ideas of dedicated passive load alleviation devices are available in the literature. They usually involve using non-linear materials or springs to deflect a control surface or to morph its shape in a passive manner. The non-linear behaviour is needed to maintain an optimal aerodynamic shape at 1g level flight

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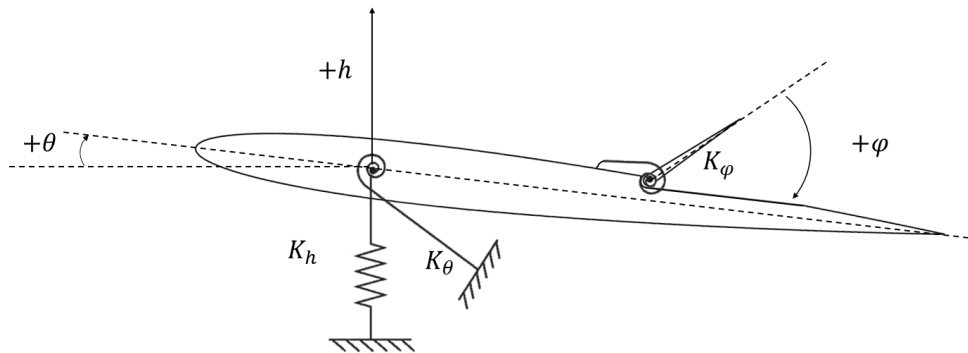
while allowing sufficient deflection in case of a gust encounter. Another requirement is that the system needs to respond fast enough with limited latency to avoid any adverse effect such as an increase of the loads. As examples of passive load alleviation concepts, we can cite the rotating wing tip [7], the folding wing tip [8], the underwing control surface [9], the very flexible winglet [10] and the bi-stable shape morphing airfoil [11]. Some of the ideas mentioned above could be applied to spoilers as well. However, the aeroelastic and unsteady aerodynamic behaviour of a wing equipped with deflected spoilers is not well documented. Most researches rely on medium or high fidelity simulations [12], [13], usually too expensive for design optimisation. Therefore, to realise any conceptual study of a passively actuated spoiler, a lighter model needs to be developed. The following sections of this paper describe the development of a model based on Theodorsen's theory for unsteady flow [14]. Results of the conceptual study and future work are presented at the end.



**Figure 1.** Illustration of a vertical gust hitting an aircraft in flight.

## 2. DEVELOPEMENT OF THE AEROELASTIC MODEL INCLUDING SPOILER

The unsteady model developed by Theodorsen provides the base for aeroelasticity and is ideal to quickly solve aeroelastic problems such as flutter and gust response. His original model had three degrees of freedom; one for the airfoil pitch  $\theta$ , one for the plunge  $h$  and one for the aileron deflection  $\beta$ . In the model used for this study, the spoiler is added and the aileron is not considered. On Figure 2. shows an overview of the coupled aeroelastic system:



**Figure 2.** Overview of the aeroelastic model with three degrees of freedom.

The coupled system can be represented in the following matrix form (Eq 1.). It is solved with Matlab/Simulink which allows non-linear multidomain computations. Since we are dealing with linear aerodynamic, the forces from the airflow can be decomposed into a sum of terms that can be computed individually. In addition to the aerodynamic effects from the airfoil pitch and plunge, we are also accounting for the spoiler deflection  $\varphi$  and gust inputs  $w$ .

$$\begin{bmatrix} m & -S_\theta & -S_\varphi \\ -S_\theta & I_\theta & I_s - S_\varphi X_{s,a} \\ -S_\varphi & I_s - S_\varphi X_{s,a} & I_\varphi \end{bmatrix} \begin{Bmatrix} \ddot{h} \\ \ddot{\theta} \\ \ddot{\varphi} \end{Bmatrix} + \begin{bmatrix} K_h & 0 & 0 \\ 0 & K_\theta & 0 \\ 0 & 0 & K_\varphi \end{bmatrix} \begin{Bmatrix} h \\ \theta \\ \varphi \end{Bmatrix} = \begin{Bmatrix} L_\theta^a + L_h^a + L_w^a + L_\varphi^a \\ M_\theta^a + M_h^a + M_w^a + M_\varphi^a \\ M_\theta^s + M_h^s + M_w^s + M_\varphi^s \end{Bmatrix} \quad (1)$$

$m$ ,  $I_\theta$  and  $I_\varphi$  are respectively the total mass of the airfoil (including the spoiler), the inertia of the airfoil around the elastic axis and the inertia of the spoiler around the spoiler hinge. Similarly  $K_h$ ,  $K_\theta$  and  $K_\varphi$  are the structural stiffness term for the airfoil in plunge and pitch, and for the spoiler rotation.  $m$  is obtained as followed:

$$m = m_a + m_s \quad (2)$$

$I_\theta$  and  $I_\varphi$  are obtained from the airfoil and spoiler inertia around their respective center of gravity  $I_a$  and  $I_s$  by the mean of the parallel axis theorem.  $X_a$  is the distance between the airfoil center of gravity and the airfoil elastic axis,  $X_{s,s}$  is the distance between the spoiler center of gravity, and the hinge location. Finally,  $X_{s,a}$  is the distance between the spoiler center of gravity and the airfoil elastic axis.

$$I_\theta = m_a X_a^2 + m_s X_{s,a}^2 + I_a + I_s \quad (3)$$

$$I_\varphi = m_s X_{s,s}^2 + I_s \quad (4)$$

$S_\theta$  and  $S_\varphi$  are the coupling terms that relate the different states between them:

$$S_\theta = m_a X_a + m_s X_{s,a} \quad (5)$$

$$S_\varphi = m_s X_{s,s} \quad (6)$$

The lift and moment values related to the airfoil pitch and plunge can be evaluated directly from the Theodorsen's model. Each set of forces and moments can be split into a quasi-steady and an added mass part. The quasi steady part is multiplied by the Jones's approximation [15] of the Theodorsen function  $C(k)$  to account for phase shift and change in response amplitude as respect of the reduced frequency  $k$ . Lift is computed at the quarter chord of the airfoil, while the moment is evaluated around the elastic axis:

$$L_\theta^a = \rho b^2 (v\pi\dot{\theta} - \pi b a \ddot{\theta}) + 2\pi\rho v b C(k) \left( v\theta + b \left( \frac{1}{2} - a \right) \dot{\theta} \right) \quad (7)$$

$$L_h^a = \rho b^2 (\pi \dot{h}) + 2\pi\rho v b C(k) \dot{h} \quad (8)$$

$$M_\theta^a = -\rho b^2 \left( \pi \left( \frac{1}{2} - a \right) v b \dot{\theta} + \pi b^2 \left( \frac{1}{8} - a^2 \right) \ddot{\theta} \right) + 2\pi\rho v b^2 \left( a + \frac{1}{2} \right) C(k) \left( v\theta + b \left( \frac{1}{2} - a \right) \dot{\theta} \right) \quad (9)$$

$$M_h^a = -\rho b^2(-a\pi b\dot{h}) + 2\pi\rho vb^2\left(a + \frac{1}{2}\right)C(k)\dot{h} \quad (10)$$

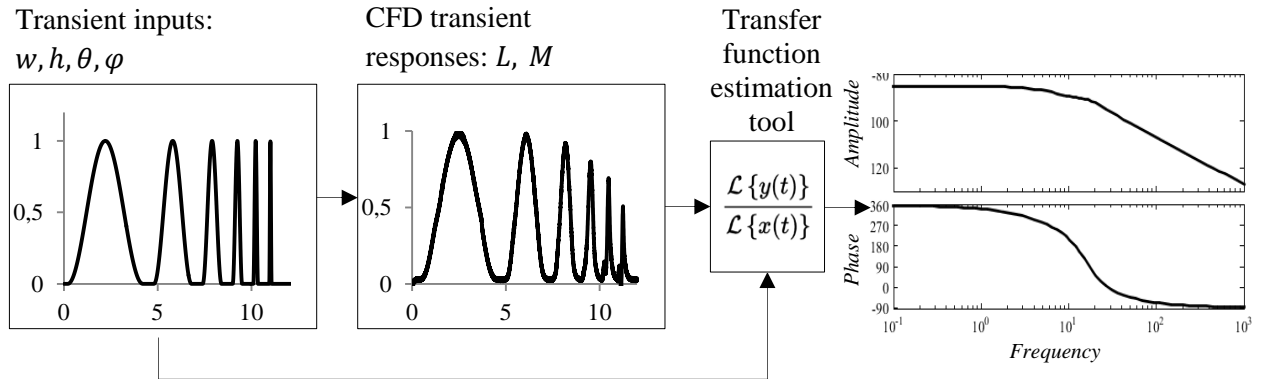
Regarding the forces induced on the airfoil by a gust encounter, Kussner is used instead of Theodorsen because it can evaluate the lift as the airfoil penetrates into a “1-cos” gust  $w$ . The two formulations (Eq 11-12.) that are used for the lift and the moment are taken from [16].  $a$  is the distance between the elastic axis and the center of pressure located at the airfoil quarter-chord.

$$L_w^a = 2\pi\rho vb\left(0.565\left(\frac{v}{b}\right)\dot{w} + 0.13\left(\frac{v}{b}\right)^2 w\right) \quad (11)$$

$$M_w^a = L_w^a a \quad (12)$$

$$\ddot{w} + 1.13\left(\frac{v}{b}\right)\dot{w} + 0.13\left(\frac{v}{b}\right)^2 w = v_w \quad (13)$$

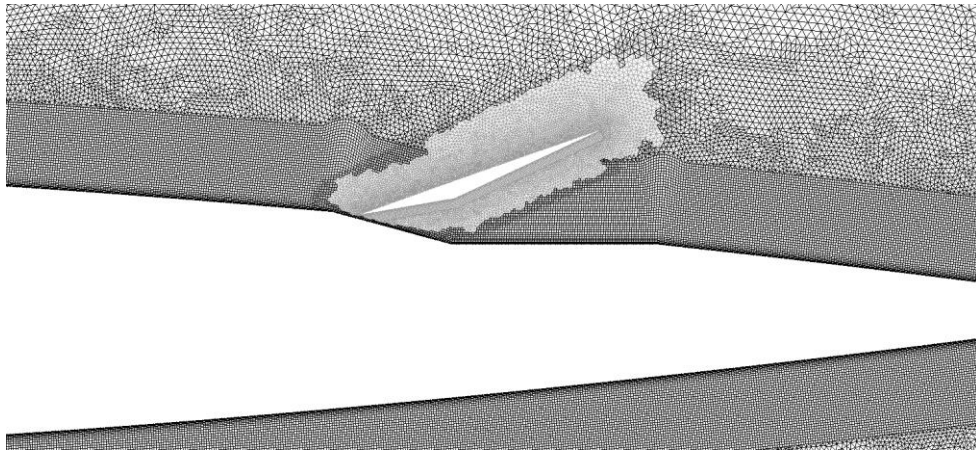
For the responses that involve the spoiler, limited work has been found on this topic. Literature that was devoted to the spoiler usually focused on wind tunnel experiments and computationally expensive computational fluid dynamics (CFD) simulations [12], [13], [17]. Therefore no low fidelity model was found that describes the unsteady aerodynamic behaviour of a spoiler. The approach chosen here is to generate transfer functions which can be used to approximate  $L_\varphi^a$ ,  $M_\varphi^a$ ,  $M_\varphi^s$ ,  $M_w^s$ ,  $M_h^s$  and  $M_\theta^s$ :



**Figure 3.** Transfer function evaluation process. Several CFD analysis can be necessary.

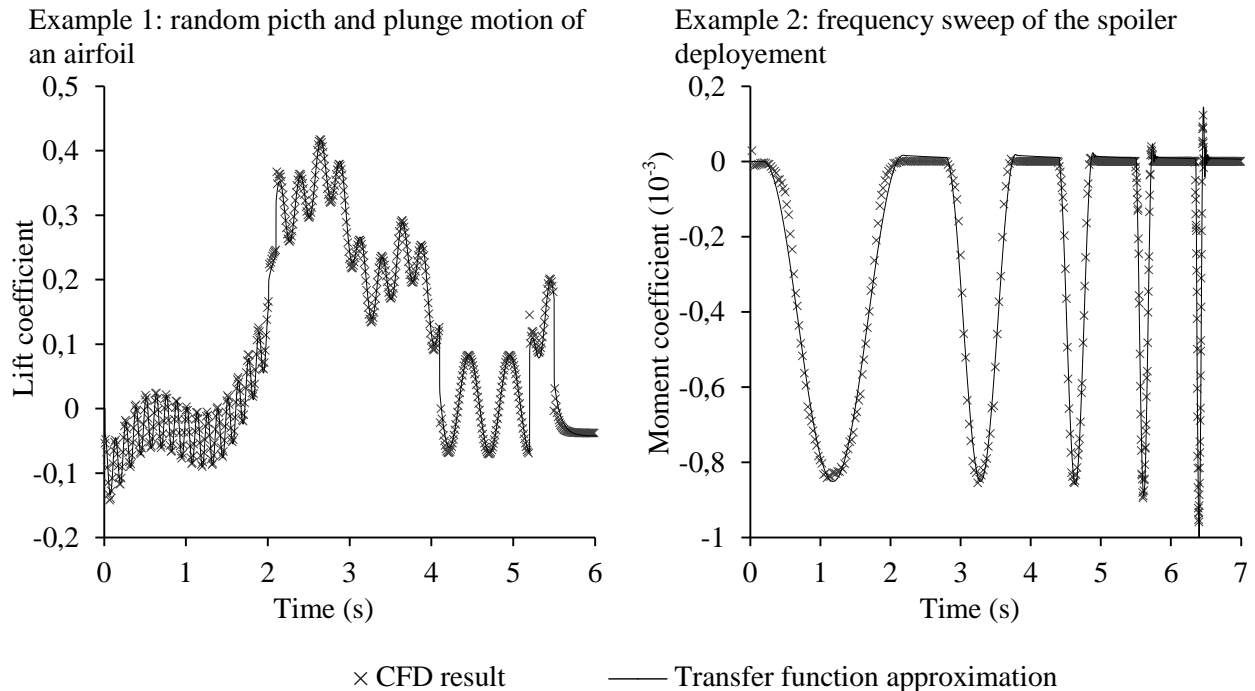
Four simulations are required to generate the six different transfer functions, as  $L_\varphi^a$ ,  $M_\varphi^a$ ,  $M_\varphi^s$  can be evaluated in the same run. It is important to note that new transfer functions would need to be evaluated in case of any important change related to spoiler location or geometry. However, the effect of the spoiler deflection  $\varphi$  is assumed to vary linearly for small angles. A frequency sweep is performed to account for a realistic range of reduced frequency  $k$ . In the present work, the reduced frequency range of the different inputs varies from 0.209, which is highly unsteady, to 0.026 which is quasi-steady. The flow speed is  $30 \text{ m}\cdot\text{s}^{-1}$  and the chord is 1 m. The spoiler hinge is located at 65% of the chord and its length is 10 cm.

CFD simulations are solved with ANSYS Fluent R17.1, using an overset grid. The mesh is comprised of nearly 500.000 triangular and rectangular elements. As shown in Figure 4, they are distributed between the global mesh around the airfoil, and a local mesh that moves along the spoiler. Overset grids have the advantage to be much quicker to generate from one iteration to another compared to regular mesh deformation technics.



**Figure 4.** Mesh around the spoiler at the rear of a NACA0010 symmetrical airfoil. The cells which are redundant between the two mesh layers are suppressed.

The spoiler and airfoil motions, as well as gust inputs, are prescribed using Fluent user define functions (UDF). Since the flow is separated behind the spoiler when deployed, a  $k-\omega$  turbulent model is used as well. For the simulations which don't require the spoiler to deflect, a regular "monolithic" mesh is used with an inviscid solver. A more classical mesh deformation is therefore used to account for the displacements of the whole airfoil. The time step can vary from 0.001s to 0.05s based on the complexity of the simulation.



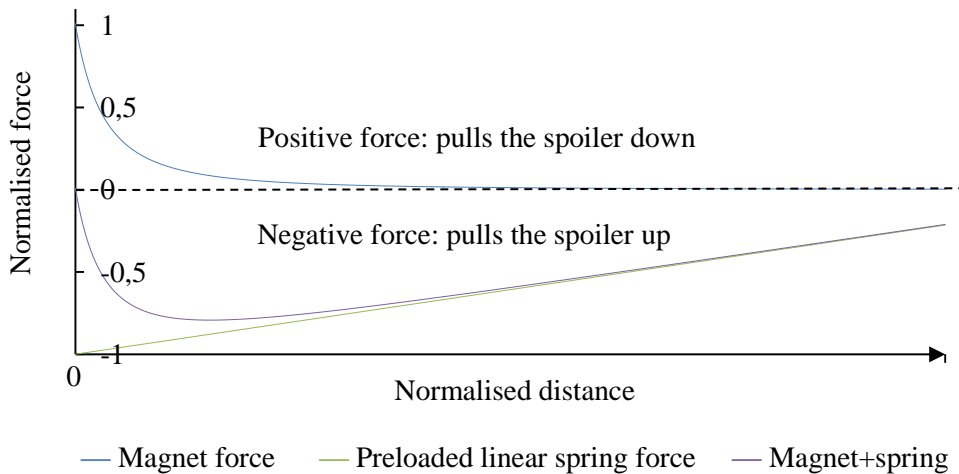
**Figure 5.** Comparison between CFD results and their approximations with transfer functions.

In example 1 of Figure 5, the lift coefficient resulting from the random pitch and plunge motion of an airfoil is approximated using two transfer functions. Although Theodorsen's model is used for such purpose in the coupled aeroelastic system, the comparison shows good agreement and demonstrates the

validity of the methodology described above. In example 2 of Figure 5, a spoiler is deployed at various speeds with an amplitude of 2.5 degrees. The moment coefficient at the spoiler hinge is recorded and the results show that a transfer function can approximate it well. The procedure was repeated successfully for  $L_{\phi}^a$ ,  $M_{\phi}^a$ ,  $M_w^s$  and  $M_h^s$ . It is noted that the implementation of the spoiler slightly modifies the airfoil aerodynamic characteristics. Small disturbances in lift and moment therefore appear even when the spoiler is retracted, however they are removed from the results for more clarity. Therefore only the incremental moment due to the spoiler deflection is shown on Figure 5.

### 3. RESULTS

Once the aeroelastic system is built, different simulations have been performed within Simulink to evaluate the effectiveness of the spoiler for load alleviation. A model without a spoiler is used as a reference. For a fully passive load alleviation system to work, a non-linear behaviour needs to be introduced to maintain an optimal aerodynamic shape at 1g level flight while allowing sufficient deflection in case of a gust encounter. In the present work, the passive spoiler relies on the use of linear springs and magnets, which here serve the purpose of the non-linear element. Indeed, the attraction force between two magnets can be approximated by Coulomb's law and varies with the inverse of the distance squared. Therefore it provides the equivalent behaviour of a highly non-linear spring. The main advantage of this combination is to allow a quick deployment of the spoiler to mitigate the loads efficiently with little delay and no control logic involved. The combined stiffness is shown on Figure 6:

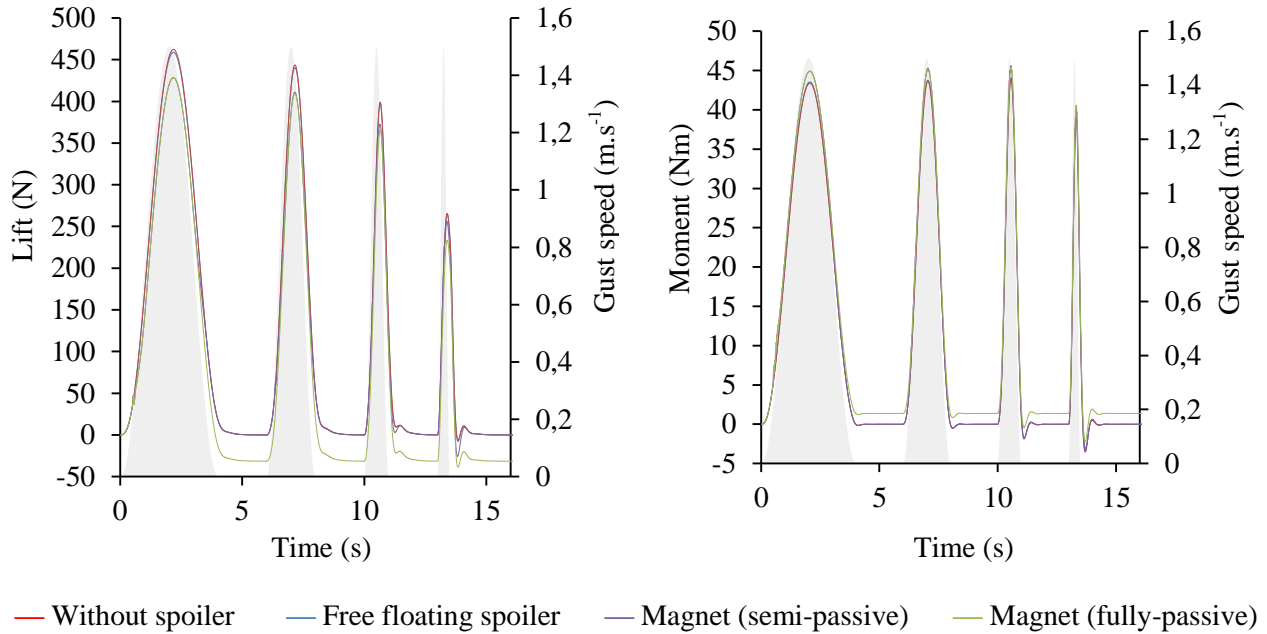


**Figure 6.** Force/displacement curve of the magnet and the spring.

The pre-loaded linear spring is here to help the spoiler deflection, by counteracting aerodynamic forces that will build up on it when deflected. The strong attraction force from the magnets prevents the spoiler to open if there is no gust. However if a gust hits the airfoil, the pressure forces on the top of the spoiler will slightly move the two magnets apart (one is attached on the airfoil, the other to the spoiler), therefore causing their attraction to drop non-linearly. To show the necessity of such mechanism, a free floating spoiler is also experimented.

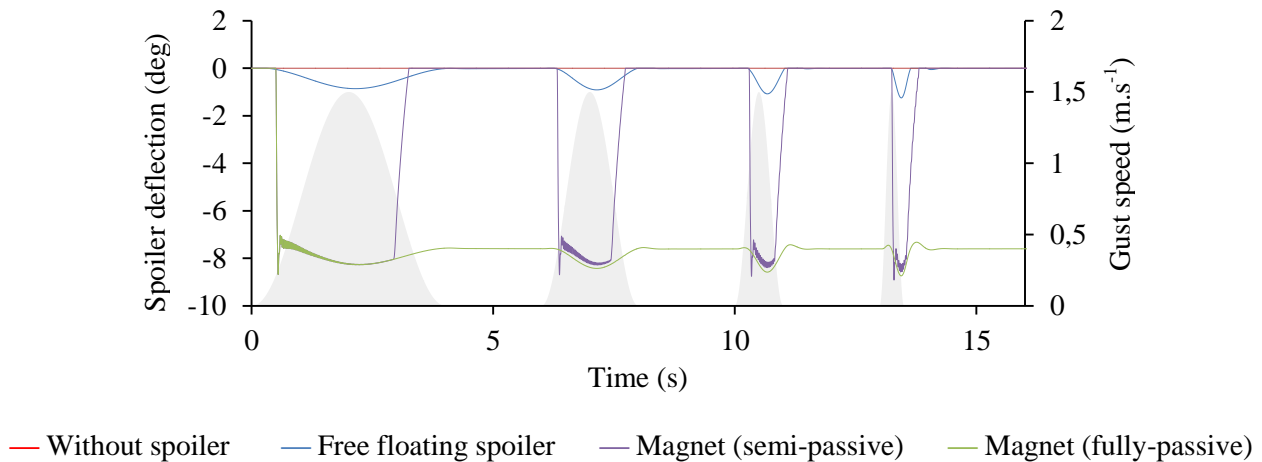
Results shown on Figure 7 and Figure 8 indicate that the spoiler never fully retracts after a gust encounter, reducing the lift during steady flight and possibly affecting the lift/drag ratio of the airfoil. The solution here could be a semi-passive system, which would still relies on a fully passive strategy for the deployment, but would require an actuator to completely close the spoiler again once the gust is over. For

this solution, it is necessary to evaluate when the spoiler needs to be retracted. In the present work, the spoiler will start to be pulled down when the gust load rate is negative. With this system, up to 9% of the lift from the gust is reduced, however because the spoiler is located at the rear of the airfoil, an additional moment around the elastic axis is added up to 4%.



**Figure 7.** Lift and moment after four gust inputs. Gust profiles are shown in grey. The airfoil angle of attack is set to 0 deg.

Figure 8 highlights the effect of the actuator on the spoiler motion. If no actuator is used, the spoiler will stay deflected. On the other hand, if no spring is installed to help the spoiler to deflect, only a small deployment angle is reached, with limited effect on the lift (about 1% load reduction).



**Figure 8.** Spoiler deflection after four gust inputs.

While requiring an actuator, a semi-passive system would also conserve the other capabilities of the spoiler for brake and roll, and would render this device truly multipurpose. The feasibility of having



magnets on a real aircraft wing also needs to be assessed; however other solutions such as bi-stable laminates could be used for the same purpose.

#### 4. CONCLUSION AND FUTURE WORK

In this paper, an innovative solution for a passively actuated spoiler for loads alleviation is presented. This device relies on the use of linear pre-loaded springs and magnets. The main advantage of this combination is to allow a quick deployment of the spoiler to mitigate the loads efficiently with little delay and no control logic involved. A conceptual study is realised, and relies on the theory developed by Theodorsen for unsteady flow. Within Matlab/Simulink, a model that features a two dimensional airfoil is equipped with a spoiler and is subjected to gust disturbances. This airfoil can also pitch and plunge. The aerodynamic behaviour of the spoiler is determined using transfer functions from high fidelity CFD simulations. Results based on the developed model show that in order to function properly, the spoiler needs to be retracted actively. Nonetheless, the present system can react to gust loads passively and achieve up to 9% load reduction.

Future work will include the derivation of the spoiler design parameters such as its length or position, to limit the number of CFD simulations to evaluate the transfer functions. This is necessary in order to perform optimisation with multiple design parameters. CFD computations of the detached flow behind the spoiler could also gain in accuracy by using a more elaborated turbulence model or large eddy simulations. The effect of higher deflection angles will also be evaluated as well as drag changes due to dynamic spoiler deployment. The current aeroelastic model could be used to develop and optimise active control as well. Ultimately, the extension of the current method to a full 3D models is envisioned to account for passive or active spoiler load alleviation early on in the aircraft design process.

#### ACKNOWLEDGMENTS

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