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CAMBER-MORPHING AIRFOILS TO REDUCE GUST SUSCEPTIBILITY

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Abstract: The paper presents the design and optimization of a morphing airfoil, able to change its shape harmonically in a passive way, with the aim of alleviating the loads developed by sinusoidal gust. The study is purely two-dimensional and performed exclusively in the frequency domain, so considering a linear behavior of the aerodynamics. The K ussner and Schwartz frequency domain model is applied to describe the unsteady aerodynamics. An airfoil with the Fishbone architecture has been chosen, as structural system. Such design allows the insertion of pressure chambers in the spine region in order to adaptively modify the chordwise bending stiffness of the structure and to adapt its performances to the frequency of the gust.

Keywords: Morphing; Adaptive structures; Gust; passive and semi-active control

1 INTRODUCTION

Morphing capabilities of aerodynamic surfaces are currently the object of several researches, since they allow to achieve multiple functions in both fixed wing and rotary wing aircrafts [1]. Morphing wings or rotor blades may lead to improvements in performances, maneuverability, aerodynamic and aeroelastic stability, vibration and noise reduction, thanks to the possibility of changing the shape of an aerodynamic surface in a smooth fashion, by means of smart technologies in materials, adaptive structural topologies, new sensors and actuators.

In particular it could be interesting to change the camber or curvature of an airfoil because it has a significant impact on the forces it could generate. Fluid dynamic systems often take advantage of this fact by employing structures with variable camber. Researchers have long pursued continuous changes to airfoil camber as an alternative due to the potential for significantly reduced drag. However, often many very good and potentially simple aerodynamic concept clashes with practical implementation issues related to increases in weight and complexity of implementing the actuation system.

For this reason in this work we want to concentrate on passive or slowly adaptive systems because we expect those systems to be simpler to build bringing improvements in the performance. For instance, the passive approach was the driver of the *chiral sail* concept presented in the paper [2]. In that case the aerodynamic loads developed when a symmetric airfoil was immersed in flow with a positive angle of attack was sufficient to aeroelastically increase the curvature, obtaining in turns a larger lift coefficient slope with respect to the angle of attack.

Here the objective will be to design the chord stiffness distribution of a morphing airfoil in order to minimize the gust response, i.e. translational and rotational response of the airfoil.

2 WORK DESCRIPTION

The Küssner and Schwarz theory will be used to compute the gust response [3]. A generic sinusoidal gust (Figure 1), supposed not to change while approaching the airfoil (frozen gust hypothesis) can be described, in a reference frame centered in the beginning of the gust itself, as

$$v_g(\xi) = w_g e^{j\frac{2\pi}{l}\xi} \tag{1}$$

where l is the wavelength of the gust and w_g its amplitude.

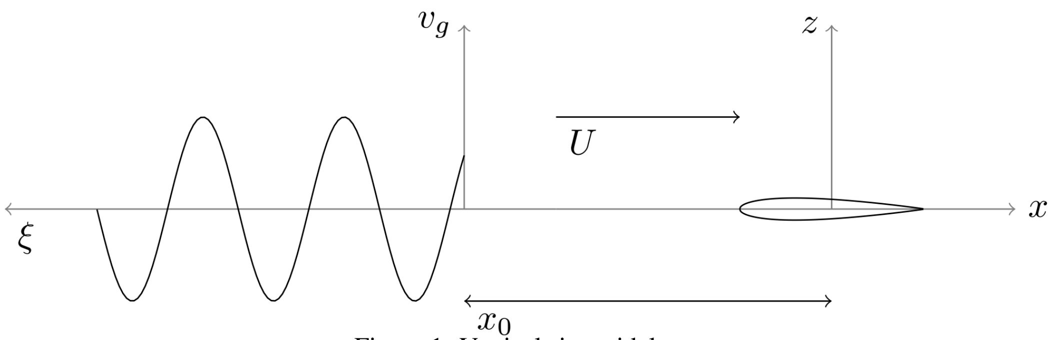

Figure 1: Vertical sinusoidal gust

It is then necessary to refer the gust speed to the airfoil's reference frame, centered in its middle point. From figure 1 it is possible to see that

$$t = \frac{x + \xi + x_0}{U} \qquad \rightarrow \qquad \xi = Ut - x - x_0 \tag{2}$$

Supposing the gust to be periodic, it is possible to state that $x_0 = 0$, then, substituting the obtained change of variables in the gust velocity definition it is possible to get to

$$v_g(x,t) = w_g e^{j\frac{2\pi U}{l}(t - x/U)} = w_g e^{-j\omega\frac{x}{U}} e^{j\omega t} = w_g e^{j\varphi(x)} e^{j\omega t} \tag{3}$$

This is the gust velocity, but for Küssner and Schwarz theory it in necessary to know the upwash speed on the airfoil, that is in this case $v(x,t) = -v_g(x,t)$. Knowing the expression of the upwash coefficients, it is possible to compute the distribution of difference of pressure coefficients ΔC_p on the airfoil, using the Küssner and Schwarz result

$$\Delta C_p(\theta, t) = \Big(4a_0 \tan\frac{\theta}{2} + 8\sum_{n=1}^{\infty} a_n \sin n\theta\Big) e^{j\omega t} \tag{4}$$

with

$$a_0 = C(k)(P_0 + P_1) - P_1 \tag{5}$$

$$a_n = P_n + \frac{jk}{2}(P_{n-1} - P_{n+1}) \tag{6}$$

being $C(k) \in \mathbb{C}$ the *Theodorsen function*, defined [4] as:

$$C(k) = \frac{K_1(jk)}{K_1(jk) + K_0(jk)} = F(k) + jG(k) \tag{7}$$

which is expressed in terms of the modified Bessel functions of the second kind $K_n(jk)$. The lift and quarter-chord aerodynamic moment values are computable with appropriate integrations.

The morphing of the airfoil can be represented as the displacement of the airfoil mean line oscillating harmonically at the frequency ω. In this work a superimposition of a sequence of cubic polynomials has been used to obtain a generic representation of the mean line deformation. So, the generic vertical displacement z function of the chord-wise coordinate x ($x \in [-b, b]$, dimensionless results are obtained by imposing $b = 1$) and the time t can be expressed as

$$z(x,t) = \begin{cases} \mathcal{P}_0(x)e^{j\omega t} & \text{if } x < x_{F_1} \\ (\mathcal{P}_0(x) + \mathcal{P}_1(x))e^{j\omega t} & \text{if } x_{F_1} \leq x < x_{F_2} \\ (\mathcal{P}_0(x) + \mathcal{P}_1(x) + \mathcal{P}_2(x))e^{j\omega t} & \text{if } x_{F_2} \leq x < x_{F_3} \\ \dots \end{cases} \tag{8}$$

with each $\mathcal{P}_k(x) = A_k\big(\frac{x-x_{F_k}}{b}\big)^3 + B_k\big(\frac{x-x_{F_k}}{b}\big)^2 + C_k\big(\frac{x-x_{F_k}}{b}\big) + D_k$, with $x_{F_0} = 0$, representing a cubic polynomial with the following fitting conditions for $k \geq 1$

$$\mathcal{P}_k(x_{F_k}) = 0 \tag{9}$$

$$\frac{\mathrm{d}\mathcal{P}_k(x_{F_k})}{\mathrm{d}x} = 0 \tag{10}$$

$$\frac{\mathrm{d}^2\mathcal{P}_k(x_{F_k})}{\mathrm{d}x^2} = 0. \tag{11}$$

It is possible to compute the upwash coefficients associated with this movement and then the related aerodynamic forces through the Küssner and Schwarz result.

The oscillating movement of the airfoil mean line must be obtained actively through the deformation of the airfoil structure. Of course the structure must be designed to be be adequately compliant, as done for instance in Ref. [2].

It is possible to write its equation of motion in weak form by means of the *principle of virtual works*

$$\int_{-b}^{b} \delta z''^T EJ(x) z'' \,\mathrm{d}x = -\int_{-b}^{b} \delta z^T m(x)\ddot{z} \,\mathrm{d}x + \int_{-b}^{b} \delta z^T F_{\text{aero}}(x) \,\mathrm{d}x + \int_{-b}^{b} \delta z^T F_{\text{act}}(x) \,\mathrm{d}x \tag{12}$$

where $2b$ is the chord, EJ is the bending stiffness, m is the distributed mass, and $F_{\text{aero}}(x) = \frac{1}{2}\rho U^2 \Delta C_p(x,t)$ is the distributed aerodynamic load developed along the airfoil. The solution z can be approximated using the Ritz-Galerkin approach, by means of hermitian finite elements shape functions. This allows the computation of mass and stiffness matrices to be used for the subsequent computation of the elasto-mechanic power required. The structural and the aerodynamic models are interfaced using the shape function used to develop the structural model in order to obtain a consistent set of equation.

The developed model can been used to perform stiffness optimization using the structural design variables of the airfoil to improve the aerodynamic behaviour when subject to a gust. Several objective functions can be chosen depending on the specific application. Considering an application to morphing rotor blades, it is possible to choose to keep the section lift perturbation minimal in the face of the velocity perturbation produced by the gust (*i.e.* the induced velocity). while limiting as much as possible the changes in the blade pitching moment. This turns the

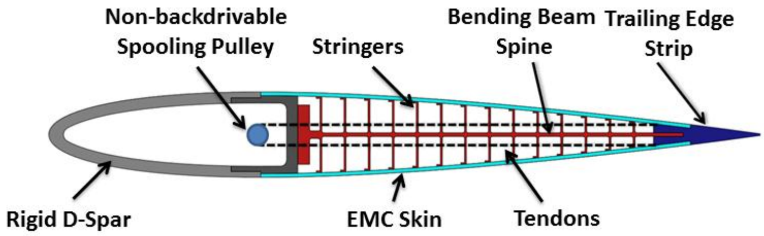

Figure 2: Fish bone morphing camber concept from [5].

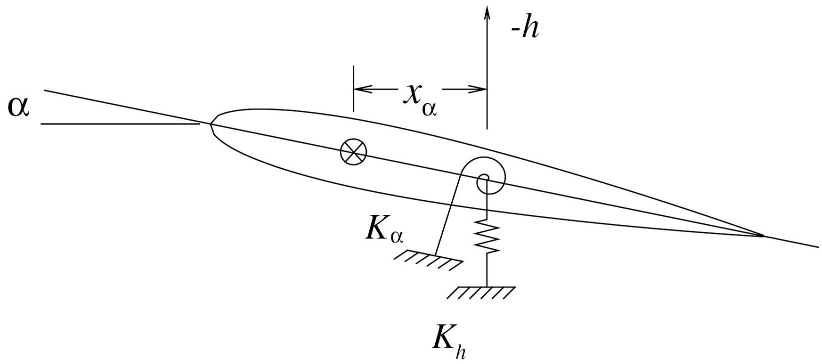

Figure 3: Aeroelastic typical section.

problem into a non-linear constrained single-objective optimization

$$\begin{aligned} \text{Minimize} \quad & J(\mathbf{p}) = |C_M(\mathbf{p})|^2 \\ \text{Subject to} \quad & f(\mathbf{p}) = |C_L(\mathbf{p})|^2 = 0, \\ & p_i \in [\text{LB}, \text{UB}] \text{ for } i = 1, \ldots, n_{\text{var}}, \end{aligned}$$

with $\mathbf{p}$ the parameter vector composed by the coefficients of all the polynomials of the piecewise cubic mean line (eq. (8)).

3 OBJECTIVE AND RESULTS

The paper presents the application of the optimization procedure presented here to a specific airfoil structure topology. In this case the Fish Bone design presented in [5] and shown in figure 2. The concept combines four primary features to create a large authority, compliance based, camber morphing scheme. However for this specific application the antagonistic tendon used to actively control the camber will not be considered. Instead, several pneumatic pipes will be inserted in the different bays of the trailing edge and the pressure within those bays will be used to control the stiffness chordwise. The behaviour of the morphing airfoil will be investigated considering it coupled with a typical section aeroelastic model, as the one shown in figure 3, where the bending and torsional stiffness values are computed starting from the structural characteristics of the morphing section.

4 PRELIMINARY OPTIMIZATIONS WITHOUT THE PRESSURE CHAMBERS

In the initial phase the optimization process optimize the following variables:

- the thickness of the frontal part of the D-spar at the trailing edge;

Parameter	Value	Unit
Total mass per unit length	3.62	kg/m
Shear centre horizontal position	-0.5553 b	mm
Torsional stiffness per unit length	1863.5	Nm^2/m
Spanwise bending stiffness	1198.8	Nm^2/m

Table 1: Structural characteristic of the reference rigid airfoil.

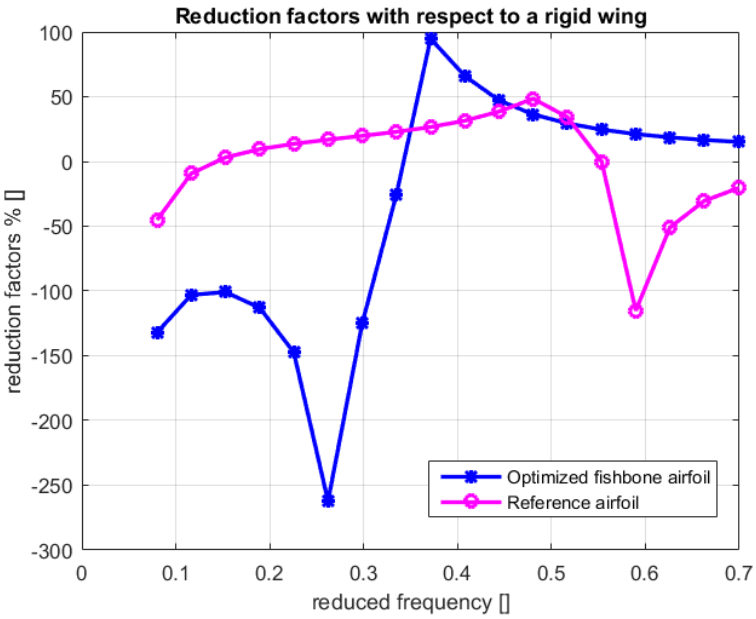

Figure 4: Reduction of the lift developed by the gust on the flexible airfoils (baseline rigid and morphing) with respect to the lift developed by a fixed airfoil at different reduced frequencies.

- the thickness of the vertical part of the the D-spar;
- the length of the spine;
- the thickness of the spine;
- the position and weight of a bobweight.

To quantify the improvements obtained using the morphing airfoil all results are compared with those obtained by a using a reference non-morphing airfoil composed by a D-spar plus a classical trailing edge solution with a homogeneous material. For the reference airfoil, it has been considered a NACA 0012 with a chord of $2b = 400$ mm made using PLA, since the future plans consider the possibility to test the concept in a wind tunnel using airfoil built using a 3D printing technique. The resulting structural characteristic of this rigid airfoil are given in the table 1.

As figure of merit for the optimization it has chose to minimize the weighted sum of the maximum lift developed for the effect of the gust at several assigned reduced frequencies. For those initial optimizations a set of 10 evenly distributed reduced frequencies between 0.1 and 1.0 have been considered.

In figure 8 it is shown the reduction factor of the maximum lift obtained by the airfoil when compared to the same lift obtained by a rigid fixed airfoil.

It is possible to see that a low reduced frequency the morphing airfoil leads to an amplification of the additional lift produced by the gust, while at higher frequency it is possible to reach a

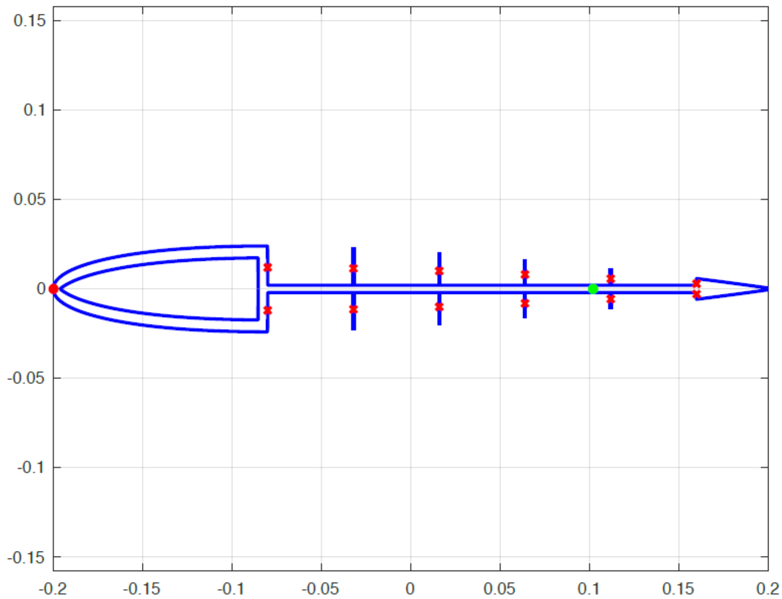

Figure 5: Fishbone morphing airfoil with 5 pressure chambers.

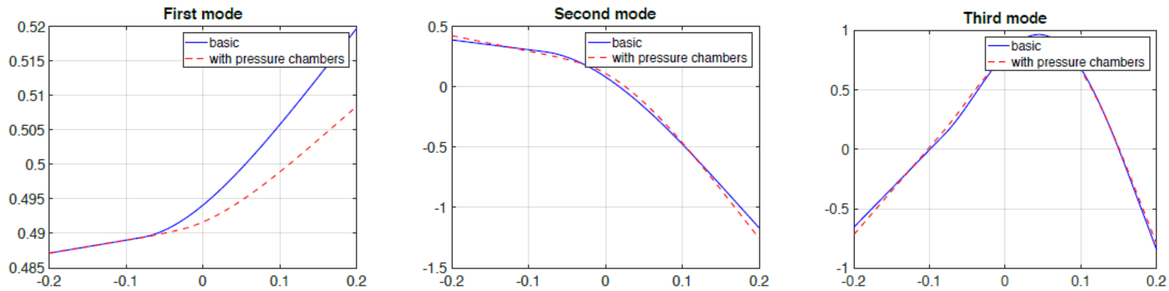

Figure 6: Modification of the mode shapes of the morphing airfoil with only the first inflated chamber.

peak reduction of 100%, much higher than the one obtained by the reference rigid airfoil.

5 OPTIMIZATIONS OF THE AIRFOIL WITH PRESSURE CHAMBERS

In this second optimization it is considered to add 5 pressure chambers on the top and the bottom of the spine, as shown in figure 5. By inflating the chambers on both sides of the spine it is possible to modify the stiffness of the airfoil along the chard, because the inflated chambers act as additional springs that are inserted in the airfoil.

Figure 6 shows the modification of the airfoil mode shapes obtained by inflating the fist chamber with 5 bars, while Figure 7 shows the effect on the modal forms when all five chambers are inflated with the same pressure.

It is possible to see that the shape modification is significant while the frequency change is very small, almost negligible.

This shape change could be exploited to adapt the capabilities of the morphing airfoil. For instance it is possible to modify the pressure level in the different chambers in order to move the performance peak to different values of reduced frequency.

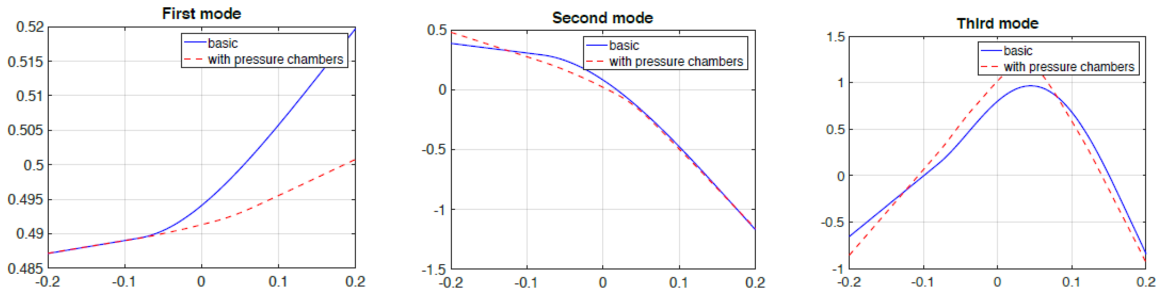

Figure 7: Modification of the mode shapes of the morphing airfoil with 5 inflated chambers.

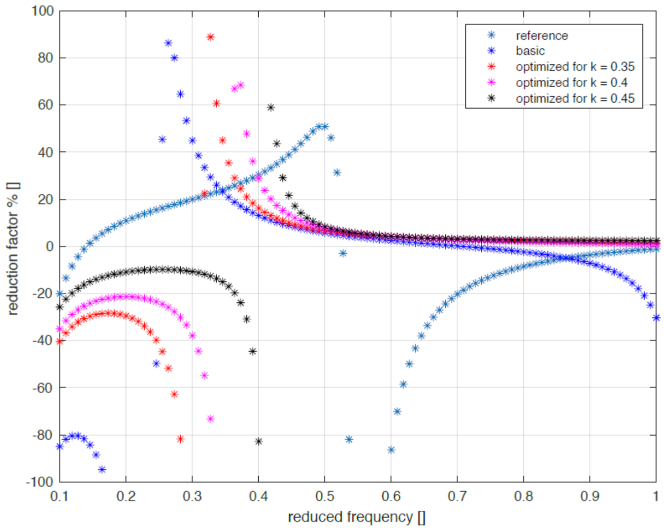

Figure 8: Reduction of the lift developed by the gust on the flexible airfoils (baseline rigid and morphing) by chainging the pressure in the different chambers.

In figure are shown the results obtained by starting with the structural characteristics of the morphing airfoil defined at the end of the previous section and modifying only the pressure in the different chambers.

It is clear how the peck can be moved in and effective way with the pressure changes.

6 CONCLUSIONS

The paper showed that it is in principle possible to develop a morphing airfoil that can improve the gust susceptibility in a passive by optimizing the structural characteristics of the airfoil along the chord and by exploiting the capability of a system of pressure driven chambers that modify the stiffness distribution of the airfoil along the chord.

The adaptivity of the response to the reduced frequency of the gust make this system well suited for the situation where periodic gust conditions are met such as those of the rotorcraft aerodynamic surfaces.

What shown here is only a first attempt. Further investigation will include consideration related to the detailed design of such system. A future wind tunnel test campaign is foreseen to prove the capabilities presented here.

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