Bat-inspired integrally actuated membrane wings with leading-edge sensing

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Abstract

This paper presents a numerical investigation on the closed-loop performance of a two-dimensional actuated membrane wing with fixed supports. The proposed concept mimics aerodynamic sensing and actuation mechanisms found in bat wings to achieve robust outdoor flight: firstly, variable membrane tension, which is obtained in bats through skeleton articulation, is introduced through a dielectric-elastomer construction; secondly, leading-edge airflow sensing is achieved with bioinspired hair-like sensors. Numerical results from a coupled aero-electromechanical model show that this configuration can allow for the tracking of prescribed lift coefficient signals in the presence of disturbances from atmospheric gusts. In particular, disturbance measurements through the hair sensor (a feedforward control strategy) are seen to provide substantial advantage with respect to a reactive (feedback) control strategy determining a reduction of the oscillations of the lift coefficient.

1. Introduction

Bats and some other natural fliers are equipped with membrane wings that, thanks to their compliance, provide passive shape adaptation to the changes in the pressure gradients (Galvao et al 2006). In several experimental and numerical investigations, wing adaptation has been found to delay stall, and increase lift and longitudinal stability (Albertani et al 2007, Song et al 2008, Stanford et al 2008, Gordnier 2009, Rojratsirikul et al 2010, Arbos-Torrent et al 2013, Tregidgo et al 2013, Buoso and Palacios 2016). However, their application in small, man-made air vehicles is limited due to their sensitivity to flow disturbances. This could be overcome with suitable sensing and actuation strategies. Bats, for example, use the skeleton to stretch the membrane of their wings and obtain high aerodynamic performance and agility (Cheney et al 2014, 2015). Sterbing-D’Angelo et al (2011) and (2016) also showed that bats’ flight performance is significantly influenced by the presence of distributed innervated hairs, concentrated over bony fingers but generally distributed over dorsal and ventral membrane wing surfaces. These are thought to work as local flow sensors, providing stimuli for the regulation of the membrane shape based on the instantaneous flow conditions. Other experimental works have observed the presence of hair-like sensors in other insects and fliers, relating their presence to the necessity of extracting information about the flying environment (Pflüger and Tautz 1982, Ai et al 2010).

It is generally acknowledged that the two key factors enabling the extraordinarily high performance of natural fliers are the real-time modification of the shape of the compliant wing and arrays of distributed sensors. The first of these can be mimicked in an artificial wing by using dielectric elastomers (DEs) as membrane materials. DEs are soft polymers that are sandwiched between two compliant electrodes. When voltage is applied, they generate a compressive force in the thickness direction, causing a corresponding polymer expansion in the target area (Pelrine et al 2000). This concept, which is compatible with both fixed and flapping wings, couples the advantages of the shape adaptation of membrane wings with embedded actuation without moving components. The wing, therefore, benefits from active membrane deformation, as obtained from bony fingers in bats, without the need and additional complexity of articulation mechanisms. For the distributed sensing, we propose flow measurements via hair-like sensors. The concept has been investigated by Dickinson (2010), Dickinson et al (2012) and Phillips et al (2015), who considered both isolated and patch-arranged sensors reproducing the topology of natural fliers.
A few experimental studies have also investigated the feasibility of fixed membrane wings with embedded actuation. Hays et al. (2013) showed large lift control capability due to camber shape change under static voltage loads. Curet et al. (2014) showed further control enhancements when the sinusoidal voltage excitation exploited the resonant frequencies of the coupled system. On the numerical side, Hays et al. (2013) used a numerical model for the membrane structure to post-process the experimental results and estimate membrane stresses and thickness but, to date, only Buoso and Palacios (2015) and Buoso and Palacios (2016) have developed an electro-aeromechanical model coupling high-fidelity descriptions of both fluid and structural domains. The predictive capabilities of these models allow the investigation of strategies for real-time control of the aeroelastic response of DE membrane wings using the measured instantaneous lift coefficient, as demonstrated in a previous work from the authors for a two-dimensional case (Buoso and Palacios 2017). However, some results have also shown that the upper frequency limit of the disturbances that can be efficiently compensated with a feedback-only approach is not high enough for outdoor conditions. The two main factors leading to this limitation are the feedback-only control strategy and the intrinsic time-delay of the actuated system (Williams et al. 2009, Kerstens et al. 2011). This will be assessed here by means of a numerical investigation on the dynamics of an actuated wing coupled with a feedforward control system with pressure sensing at the leading edge. Section 2 describes the wing concept, and section 3 the aeroservoelastic framework and the methods for the investigation of the closed-loop wing performance. Numerical results on the tracking performance of the wing with and without atmospheric gusts are shown in section 4, and discussed in section 5.

2. Wing model

The numerical investigation will consider a 2D prestretched membrane (VHB4905 DE polymer) with carbon grease electrodes mounted on a rigid frame. No effects from spanwise tension are considered, which implies a sufficiently large aspect ratio (Rojratsirikul et al. 2010, Arbos-Torrent et al. 2013). Also, infinitely rigid supports with negligible aerodynamic effects are considered, in order to focus on the membrane dynamics. The reference configuration for the wing, schematically represented in figure 1(a), is its flat and undeformed condition with no actuation voltage \( V = 0 \), and in absence of incoming flow \( V_{\infty} = 0 \).

In the non-actuated condition, when immersed in a fluid flow with \( V_{\infty} \neq 0 \) and angle of incidence \( \alpha \), the membrane compliance determines wing cambering as shown in figure 1(b). A typical contour plot of the vorticity of the flow around the membrane is shown in figure 1(c). Under aerodynamic forces, the membrane presents a static aeroelastic equilibrium configuration for low angles of attack, while at higher values of \( \alpha \), before the disturbance excites the inertial effect from the membrane. In flow control applications, there is already some evidence that such controllers can result in some benefits at low frequencies, but also amplify disturbances at higher frequencies (Williams et al. 2009, Kerstens et al. 2011).
It is characterised by dynamic oscillations due to the interaction with the separated flow (Buoso and Palacios 2015). When the wing is actuated (figure 1(d)) the voltage determines a relaxation of the membrane pretension, causing an increase in camber and a reduction of the natural frequencies of the aeroelastic system. The structural deformation has an effect on the fluid itself, as shown in figure 1(e). The effectiveness of the actuation depends on the stress that can be generated by the applied voltage, which, under the assumption of an ideal parallel-plate capacitor, is proportional to \( \epsilon \left( \frac{V}{h} \right)^2 \), where \( \epsilon \) is the dielectric constant of the polymer, \( V \) is the applied voltage, and \( h \) the membrane thickness, which that also defines the distance between the electrodes (Pelrine et al 2000).

In our investigation, a single hair sensor at the leading edge is considered, but the methodology could easily be extended to patches of them, as shown by Dickinson (2010), Dickinson et al (2012) and Phillips et al (2015). In fact, the same model could be used when considering the average signal from a patch of hairsensors. Bat wing hairs scale with the size of the animal, but wing hair characteristic geometry is on the order of 10 microns in diameter and 100 to 1000 microns in length (Crowley and Hall 1994). At the air speed of this simulation, this leads to hair Reynolds numbers based on diameter on the order of 1. Although not a creeping flow environment, the flow over the hair sensor will remain attached, and is assumed to have negligible influence on the downstream laminar flow.

3. Methods

This section briefly describes the numerical approach adopted to characterize the dynamic response of the aeroelastic system described above, in both its high-fidelity and reduced-order implementations, and to design the controller that enables outdoor flight. For details on spatial and temporal discretisations, numerical schemes and convergence criteria, the reader is referred to references (Buoso and Palacios 2015, 2016, Buoso and Palacios 2017), wherein the implementation of the proposed high-fidelity numerical model has also been verified against relevant data available in the literature. By ‘high-fidelity’ we denote the solution of the system dynamics by standard methods, e.g. finite volumes and finite elements, which discretise and solve the fluid and structural dynamics equations in the physical domain. In contrast, by the term ‘reduced-order model’ we refer to a system description obtained using methods which allow its representation with a much reduced number of degrees of freedom.

3.1. High-fidelity electromechanical model

The fluid solver is based on the direct integration of the Navier–Stokes equations as implemented in STAR-CCM+ (CD-Adapco 2013). No turbulence models or sub-grid schemes are needed due to the low Reynolds number of the problem (\( Re = 2500 \)), which is at the lower end of the flow regimes for practical membrane wing applications. At this low speed, the flow remains laminar and two-dimensional, thus reducing the computational effort for its analysis. However, these conditions are still representative of fluid-membrane coupled behaviour, and in particular of membrane vibrations typical of the operative conditions of such wings. The dielectric membrane is described using a geometric non-linear formulation coupled with a hyperelastic material and implemented in Abaqus (Dassault System 2013). Electrostatic stresses acting on the wing when actuated are treated via the definition of an electrostatic stress tensor (Buoso and Palacios 2014). Both solvers are coupled with an implicit time stepping scheme, using the integrated Co-Simulation Engine (Dassault System 2013, CD-Adapco 2013).

The hair-like sensors are not directly modelled, as they are assumed to be sufficiently small not to affect the dynamics of the membrane. The mapping function between the sensor deformation and the pressure field at the leading edge is, therefore, obtained through calibration that depends on the structure of the hair-like sensor and the flow conditions. These assumptions are supported by the investigations in references (Dickinson 2010, Dickinson et al 2012, Phillips et al 2015).

3.2. Model reduction

As mentioned above, the cost of the high-fidelity, fully-coupled model is prohibitively large in the context of control system design. Therefore, we have also developed a methodology for the reduced-order description of the coupled electro-aeromechanical system (Buoso and Palacios 2017). The system reduction is achieved by projecting the full description onto a basis formed by structural eigenmodes and fluid proper orthogonal decomposition modes obtained for a pre-selected training signal. The final aeroelastic reduced-order model (ROM) is a SISO (single input/single output) system, with voltage and lift coefficient as time-dependent input and output, respectively. Such a low-order linear model can provide estimates of the instantaneous pressure at any point of the wing and is thus quite suitable for the preliminary study of a control strategy, allowing the investigation of the number and location of system outputs required.

3.3. Control system design

The specification for the controller is to track a prescribed lift in the presence of atmospheric disturbances. This will be achieved with an architecture based on a state feedback linear-quadratic-Gaussian (LQG) design. To improve the performance of the controller, we add a feedforward component proportional to the pressure measurement at the leading edge which is also used as input for the LQG state estimator. This allows the use of a single sensor for both feedback and feedforward contributions. A more
detailed description of the full control architecture can be found in the appendix, and a detailed analysis on the design approach in Buoso and Palacios (2017).

As a note, throughout the manuscript we often use the term performance or root mean square (RMS) to refer to the RMS values of the difference between the instantaneous lift coefficient and the reference one. This metric accounts for deviations in both the tracking of the mean lift coefficient and the amplitude of the oscillations. Good performance of the controller implies small RMS values. In fact, since the baseline flow conditions do not show lift unsteadiness, the aim of this control exercise is the stabilization of the lift coefficient in case of atmospheric gusts, to provide suitable working conditions for possible payloads.

The design of the controller starts with the computation of its feedback-only component, using the reduced-order model. The integral gain, \( K_i \), and the integral weight, \( Q_i \), for the LQG cost function are the main parameters determining the tracking performance of this system, having been selected through a parametric investigation (Buoso and Palacios 2017). The main requirement for the design is to achieve the fastest possible response in tracking a step signal in \( C_l \) without destabilising the whole aeroelastic system. Since the design is based on the linearised description from the reduced-order model, it will inevitably neglect non-linear effects introduced by large actuation voltages and high frequencies. For this reason, it is required to test the controller in the high-fidelity model to assess the stability of the closed-loop aeroelastic system.

The architecture of the controller is finally augmented with a feedforward component that is proportional to the flow disturbance as measured from the leading edge hair-sensor. This solution gives the control system awareness of the incoming gust disturbance before it actually excites the inertial response of the wing. Membrane instantaneous tension can thus be modified from the prediction of the future wing dynamics rather than the actual dynamic itself. This aspect corresponds to an instantaneous reflex of the bat nervous system to the excitation of innervated hair sensors. In our artificial wing, this reflex-type response is complemented by the action of the feedback scheme, which, returning to the bat paradigm, parallels the voluntary modification of the wing based on the intended flight trajectory. For the artificial wing, due to the actuation delay in the aeroelastic system, the efficient implementation of the feedforward control component requires additional delay between sensor input and actuation. This is obtained from the contribution of two components. The first corresponds to delay from actuation to the corresponding lift variation. A previous experimental work for similar flow conditions has observed a delay of the order of \( 1t^* \) to \( 4t^* \) for low frequencies of actuation (Tregidgo et al 2013), with \( t^* = tV_\infty/c \) being the non-dimensional time. This is expected to be similar to that of the condition of our numerical investigation. The second component defines the delay of the lift response with respect to the evolution of the pressure at the leading edge, \( P_e \). The delay from sensing to actuation is thus obtained as the difference of the two. After its calculation from the response in the closed-loop system for the reduced-order model, the selected value was tested in the high-fidelity model. As before, the controller has to be tested in the full model to evaluate the effect on non-linearities which are not included in the model. This might lead to the need to adjust the selected value after its variation in the high-fidelity model, thus requiring a small number of simulations in the high-fidelity model.

3.4. Outdoor flight conditions

We consider a flow with Reynolds number \( Re = 2500 \), free-stream velocity \( V_\infty = 1.445 \text{ m s}^{-1} \) and constant reference angle of attack \( \alpha_0 = 4^\circ \). The aerodynamics of the membrane supports is neglected. Flow disturbances are simulated through a sinusoidal variation of the angle of attack at inlet over the reference value of the form \( \alpha = \alpha_0 - \delta \alpha [1 - \cos(2\pi St_\alpha)] \), with \( \delta \alpha \) and \( St_\alpha \) being the amplitude and reduced frequency of the evolution. The flow disturbance then convects through the domain, and hits the wing, determining a variation of the lift coefficient. Following our previous work, we have identified two gust cases, with reduced frequencies of \( St_\alpha = 0.02 \) and 0.04 respectively, which can be useful for understanding the wing behaviour. The slower one (\( St_\alpha = 0.02 \)) has been calculated to be the upper effectiveness limit of the feedback-only controller, while the faster one, well above this limit, will be used to judge the performance improvement from the feedforward architecture (Buoso and Palacios 2017).

4. Results

4.1. Reference configuration

The membrane has initial thickness ratio \( h/c_0 = 0.167\% \), and prestretch \( \lambda_p = 1.02 \), defined as the ratio between the deformed, \( c \), and reference, \( c_0 \), membrane chord. The reference case, obtained for a steady inlet angle of attack, \( \alpha_0 = 4^\circ \), and no actuation, is characterised by a maximum amplitude \( y^* = y/c = 0.02 \) at \( x/c = 0.43 \), with \( y \) and \( x \) being the membrane point vertical displacement and chord-wise position respectively. The lift coefficient in that case is \( C_{l0} = 0.47 \). Results will be presented in terms of the non-dimensional time \( t^* \) and Strouhal number, \( St = f c/V_\infty \), with \( f \) being the frequency of the signal considered.

The training voltage signal, for the identification of the reduced-order description, is of the form \( V = V_0 \sin(2\pi St_\alpha t^*) \), where \( V_0 = 250 \text{ V} \) and the non-dimensional actuation frequency \( St_\alpha = f c/V_\infty \) varies linearly from 0 to 0.4, in a time window of \( T^* = 90 \). The amplitude \( V_0 \) has been limited to linear membrane response, since the reduced-order methodology is...
based on linear assumptions. The frequency content $f_i$ of the training signal has been selected to include the first two resonant frequencies of the coupled aeroelastic system and the range of gust frequencies expected during outdoor flight (Buoso and Palacios 2017).

### 4.2. Controller design

In this study, the controller is required to track a step variation of $C_l$ reaching a steady state within $t^* = 40$ with a constant inlet angle of attack, $\alpha_0 = 4^\circ$. The integral tracking coefficients, $K_i$, giving satisfactory performance in the reduced-order model were included in the range $0.1 - 1.2 \times 10^8 \text{ V}^2 \text{ s}^{-1}$. Figure 2 shows the time-evolution of the lift coefficient in the reduced-order model when tracking a step signal of $1.05 C_{l0}$ and varying the LQG tracking gains, $K_i$. As expected, large values of $K_i$ lead to a fast response, but can also determine undesirable oscillations around the tracking value. Additionally, as demonstrated in our previous work, the increase in $K_i$ reduces the effectiveness of the controller in the rejection of gusts (Buoso and Palacios 2017). The compromise between these two aspects led to the selection of a value of $K_i = 0.35 \times 10^8 \text{ V}^2 \text{ s}^{-1}$.

Figure 2 compares the performance of the feedback-only architecture in both the full and the reduced-order models when tracking of step responses of $1.02 C_{l0}$ and $1.05 C_{l0}$. The comparison shows a good agreement between the two models, particularly for the settling time, which, however, deteriorates when moving to larger step amplitudes, due to the greater impact of non-linearities.

As mentioned in section 3.3, an important aspect for the design of the controller is the characterisation of the total delay in the system. Figure 3 plots the phase delay of the response in the reduced-order model to a harmonic voltage input of varying frequencies; it shows an approximately constant phase difference, $\varphi = 320^\circ$, between the maximum peak of $P_t$ and $C_l$. Considering a gust reduced frequency of $St = 0.04$, and subtracting the actuation delay, the corresponding time delay to be used in the feedforward loop is approximately $\tau = 8t^*$. After a parametric investigation on the high-fidelity model using $\tau = 8t^*$ as starting value, omitted here for conciseness, the delay has been identified to be near $\tau = 7.2t^*$, which is very close to that calculated from the reduced-order model. The selection of the feedforward gain, $K_f$, can only be done in the full model when simulating the encounter of gusts, wherefore it will be described in the next section.

### 4.3. Gust rejection

After the assessment of the wing performance in the tracking problem in absence of disturbances, the controller is now used to track a $1.05 C_{l0}$ step in the lift in the presence of disturbances, for both feedback-only and feedforward architectures. All simulations are carried out in the high-fidelity model, which is assumed to provide an accurate representation of the wing dynamics. The amplitudes of the oscillations of the angle of attack are $\delta_\alpha = 0.4$ and $0.05$ for the cases $St_g = 0.02$ and $0.04$ respectively. These amplitudes lead to similar amplitudes of oscillations of the lift coefficient.

Figures 4 and 5 show the lift evolution and the controller effort for two different gusts. For both gusts, the plots compare the open-loop tracking of a $1.05 C_{l0}$ step with the feedback-only response. For the open-loop case, the actuation voltage has been calculated using the internal model controller (IMC) for reference input tracking. The resulting voltage value is $200 \text{ V}$. For the gust with $St_g = 0.02$ the controller action allows for the drastic reduction of the oscillations in the lift coefficient, lowering the RMS value from 8.79 of the open-loop case to 2.39. However, as expected, for the faster gust the controller tracks the prescribed lift (in an average sense), but amplifies the oscillations, as compared to the open-loop case, leading to an increase of the RMS of about 10% (from 2.62 to 2.94 for the open and closed-loop cases, respectively).

The gust case with frequency $St_g = 0.04$ is now used for the investigation of the effect of different feedforward gains in the response of the controlled wing. Figure 6 shows the lift response for various feedforward gains, $K_f$, with no delay, $\tau = 0$, and with the identified delay of $7.2t^*$ (section 4.2). The cases shown span the range of values which do not cause a destabilisation of the system. The minimum values of RMS are achieved, for both values of delay, for $K_f = 1.5 \times 10^5 \text{ V}^2 \text{ Pa}^{-1}$ (2.27 and 2.40 for $\tau = 0$ and $\tau = 7.2t^*$ respectively). However, the case with delay shows lower values of RMS for longer gusts which have fully propagated in the domain and exhibit the dominant frequency component of the forcing input disturbance. RMS values calculated for longer simulations (150 $t^*$) were 2.06 and 1.80 with $\tau = 0$ and $\tau = 7.2t^*$ respectively. The feedforward parameters thus selected are $K_f = 1.5 \times 10^5 \text{ V}^2 \text{ Pa}^{-1}$ and $\tau = 7.2t^*$.

The dynamics of the wing in the case of the gust with $St_g = 0.04$ is investigated for a longer period of time to allow the evaluation of the performance of the final control architectures after the gust has convected in the domain and transients in the fluid domain, due to the initialization of the oscillating gust, have disappeared. Figure 7 shows the lift and voltage time histories for the open-loop, feedback-only and feedforward cases as function of the non-dimensional time $t^*$. The RMS value for the lift coefficient of the open-loop case is 2.35, while for the closed-loop cases the RMS values are 2.62 and 1.80 for the feedback-only and feedforward cases, respectively. Figure 7(c) shows the contour plots of the instantaneous structural displacements of the membrane (from the equilibrium configuration), as function of non-dimensional time and their chord-wise position, for the open-loop and the two controlled cases. Comparing the two actuated cases in figure 7(c), it is observed that the feedforward component does not suppress the structural oscillations,
Figure 2. Step responses with LQG servo controller: (a) effect of variation of integral gains ($K_i$ in $10^8 V^2 s^{-1}$) on ROM, (b) comparison of controller with gain $K_i = 0.35 \times 10^8 V^2 s^{-1}$ in reduced-order and high-fidelity models for two different $C_l$ step amplitudes, 1.02 $C_{l0}$ and 1.05 $C_{l0}$.

Figure 3. Phase plots of lift coefficient and leading edge pressure from the reduced-order model as function of the actuation frequency input.

Figure 4. Closed-loop step response (1.05 $C_{l0}$) in presence of a gust for open-loop and feedback-only schemes ($K_f = 0$) in the high-fidelity model. Gust parameters: $\delta\alpha = 0.4^\circ$, $St_\alpha = 0.02$. (a) $C_l$ time evolution. (b) Voltage input.
which are in fact larger than in the open-loop case. These oscillations are actually advantageous, since the controlled wing shape changes are the mechanism to drive lift changes. However, the structural oscillations in the feedforward case are reduced by as much as 30%, as compared to the pure feedback case.

With the aim of testing the performance of the controller for the upper limit of natural frequencies, which was found to be near $St_\alpha = 0.1$ for outdoor applications (Tregidgo et al 2013), we have considered a disturbance with $St_\alpha = 0.08$ and $\delta \alpha = 0.05^\circ$ (figure 8). The new value of the phase delay from $C_l$ and $P_e$ for the new $St_\alpha$ (figure 3) leads to the selection of the new feedforward delay of $\tau = 3.8t^*$. RMS values for this gust are 1.80, 3.16 and 2.25 for the open-loop, feedback-only and feedforward cases, respectively. The time evolution of the lift coefficient in the case with feedforward component shows some high frequency oscillations from $t^* = 80$, which derive from the sensor measurements, and would require the design of a suitable filter.

5. Discussion

Results presented in the previous section have shown that the hair-membrane integral actuation concept can compensate for the oscillations of the lift coefficient due to atmospheric gusts. Numerical and experimental investigations in the literature have demonstrated that in an open-loop case, membrane compliance can partially compensate for flow disturbances reducing lift coefficient oscillations, as compared to a rigid case. However, without active control of the membrane deformation, oscillations can still be too large.
Therefore, a control architecture is needed to enhance wing performance, and to track prescribed signals. The selection of an aggressive strategy with large tracking gains can result in large oscillations of the lift when considering the feedback-only performance in the full model. Performance consistently improves when tracking smaller changes in the $C_L$ as the controller is based on linear assumptions. Despite this effect, the prescribed lift coefficient settles to the desired value in a similar time to that predicted in the ROM, showing good performance signal tracking in absence of disturbance.

Figure 7. Closed-loop step response in tracking a step $1.05 C_L$ in presence of a gust in the high-fidelity model. Comparison of open-loop and closed-loop with and without feedforward. Gust parameters: $\delta \alpha = 0.05^\circ$, $St_\alpha = 0.04$. (a) $C_L$ time evolution. (b) Voltage input. (c) Structural displacements along the membrane from equilibrium configuration.

Figure 8. Tracking performance with $1.05 C_L$ step in presence of gust in the high-fidelity model. Gust parameters: $\delta \alpha = 0.05^\circ$, $St_\alpha = 0.08$. Feedforward action with $K_f = 1.5 \times 10^3 V^2 Pa^{-1}$ and $\tau = 3.8 t^*$. 
When considering the wing dynamics in presence of gusts, the controllers designed were able to track the mean lift, but their overall performance was dependent on the frequency of the incoming disturbance. The analysis has, in fact, highlighted that there is a limited bandwidth of effectiveness of the control system which, even though enlarged by the implementation of a feedforward component, is related to the physical system limitations. This is corroborated by previous experimental and numerical investigations in the literature. For the lowest frequency considered, $St_a = 0.02$ (figure 4), a feedback-only control approach achieves significant reduction of the oscillations, as compared to the open-loop case (RMS values reduced of a factor of 3.7). At higher frequencies of the disturbance ($St_a = 0.04$ in our investigation), the feedback-only scheme, while still tracking the required mean reference signal, amplifies the lift oscillations, as compared to the open-loop case (RMS value is increased by about 11% with the feedforward-only architecture). This happens because the period of the signal of the disturbance approaches the actuation time-delay of the wing. Therefore, because of the delay, lift reductions cannot be immediately compensated and, in the case of the periodic disturbances considered, the effect of actuation coincides additively with the peaks in the lift due to the gust. This results in an amplification of the oscillations, which negatively impacts wing performance. It is thereby clear that the deformation of the wing based on a feedback-only architecture is only sufficient with very short–actuation time delays, which might explain why bats possess the sensory architecture to provide a potential feed-forward response.

Finally, the combination of the feedforward component with the previous feedback architecture considerably extends the range of frequencies on which the controller can efficiently track a signal in presence of disturbances. The idea is that availability of the information on the incoming disturbance before it influences the dynamics of the wing can be used to enhance flight stability. However, the advantage is marginal for an instantaneous response to sensor measurement (figure 6) due to the large delays in the response of the system. Determining the optimal delay for the actuation signal from the sensor measurement was found to be crucial to obtaining satisfactory performance, with a reduction of the amplitude of the oscillations as compared to the open-loop case. In practical applications, this strategy will require the real-time identification of the dominant frequency content of the signal, as with the real-time extremum seeking algorithm. This would be feasible because of the large delay between the measurements and the actuation, which would allow a real-time analysis of the spectra of the sensor measurement. It would be interesting to see how membrane actuation stimuli are generated in bats, to understand if voluntary (feedback) and reflex (feedforward) components are decoupled, and if, for the reflex response, it is possible to identify a similar delay to that of the feedforward controller. Additionally, the quantification of the delay of the involuntary reflex response and the contribution of the non-voluntary and voluntary actions in the membrane deformation could provide a deep insight into the dynamics involved in the problem of the control of wings at low Reynolds numbers. In the cases investigated in this work, as seen from figure 7, the best performance is obtained after the initial transient since the delay in the feedforward is tuned for the particular frequency of the periodic signal. In fact, for the case shown in figure 7, the feedforward concept allows a reduction of the RMS value of 50% and 28%, respectively, as compared to the feedback-only and open-loop cases. Also, when moving to large frequencies (figure 8) the feedforward component mitigates the amplification of the disturbance determined by the feedback-only approach, and tracks the required mean value of the lift, but it does not reduce the lift oscillations as compared to the open loop case, thus leading to an increase of the RMS of 18%. However, the feedforward architecture makes it possible to reduce the RMS value by nearly 35%, as compared to the feedback-only case.

6. Conclusions

This paper has investigated the closed-loop performance of a morphing wing concept that takes inspiration from bat-wings—and, in particular, from their ability of actively modifying shape based on the flight dynamics and on the sensing of local flow information. In our case, the wing is made of dielectric elastomers (DEs), coupling the advantages of passive shape adaptation from membrane compliance with active control of the structural deformation by the application of a voltage. The control system is based on pressure information obtained from hair-like sensors at the leading edge.

A feedback-only controller, based on a reduced-order description of the full aeroelastic system, has been designed for robust signal tracking. Additionally, a feedforward scheme based on measurements of the pressure at the leading-edge is included in the controller architecture. Thanks to this feature, present in many biological fliers, an actuation proportional to the pressure measurement at the leading edge can be introduced in the model before the disturbance causes the membrane to vibrate. In this exploratory investigation, we have only considered the lift component; for full dynamics control, the evaluation of drag and pitching moment would also need to be considered. Numerical results show that the closed-loop system dynamics benefits from the feedforward component—, which, when combined with feedback, enables much better tracking of the prescribed lift coefficient. The delay of the feedforward has been found to depend on the dynamic content of the disturbance. However, the results have shown that a closed-loop controller is effective in tracking the prescribed
lift response in terms of mean value, and can compensate for its variation from the effect of gusts when augmented with a feedforward scheme.

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Appendix

The detailed architecture of the closed-loop system is shown in figure A1. Following the standard notation in control theory, the block diagram is presented in terms of the Laplace transform of the system processes and variables. We denote with \( s \) the complex variable of the Laplace domain, with \( \Sigma \) the summation block and \( e^{-\tau s} \) the representation of the Laplace domain of the delay of the signal (Skogestad and Postlehwaite 2005).

The controller integral action, \( U_I(s) \), is proportional to the integral error, \( E(s)/s \), between the instantaneous value of the lift coefficient from the low-order description of the system introduced in section 3.2. The voltage applied to the plant, \( U(s) \), and the error between the measurements from the sensor on the wing, \( E_{sys}(s) \), and the corresponding predicted value from the ROM are inputs to the LQG controller.

The magnitude of the zeros of the transfer function of the open-loop plant can give a preliminary indication of the limitation of the closed-loop performance. In particular, the upper frequency limit of the effectiveness of a pure feedback controller can be approximated by \( zm/4\pi \), where \( zm \) is the magnitude of the smallest zero of the transfer function (Skogestad and Postlehwaite 2005, Kerstens et al 2011).

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