WIND TURBINE LOAD PERFORMANCE USING ITERATIVE LEARNING CONTROL

Owen Tutty*, Mark Blackwell*, Eric Rogers**, & Richard Sandberg*
*Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK
**Faculty of Physical and Applied Science, University of Southampton, Southampton SO17 1BJ, UK

Summary A non-linear model of flow past a blade section with trailing edge actuation is used to investigate the ability of iterative learning control (ILC) to control fluctuations in the lift. It is found that a two-term ILC can successfully attenuate the loads. The control reduces the fatigue load by two orders of magnitude and the peak load by at at least an order of magnitude over a wide range of operating conditions. Performance is maintained even in extreme cases where the peak lift doubles over that found with uniform flow.

INTRODUCTION

Wind turbines blades are subjected to fluctuating aerodynamic forces, with both deterministic components (e.g. from stator-rotor interaction and yaw misalignment) and stochastic components, arising from the variable nature of the wind. Both types of disturbance create loads that require management. This work is on damping fluctuations in the lift on an aerofoil using circulation control, as a model of a section of a blade equipped with a smart rotor. Smart rotors are currently an active topic of research [1]. The aim is to improve performance and load control by integrating smart devices (e.g. trailing edge flaps, microtabs) into rotor blades, predominately to reduce fatigue loads but also to regulate power, and attenuate ultimate/extreme loads, particularly those that threaten the structural integrity of the turbine.

Wind turbines operate in the atmospheric boundary layer where there is a non-uniform mean velocity profile, and a regular variation in wind speed past the blade throughout a cycle, even in reasonably steady, non-gusting, conditions. This gives an oscillatory component to the flow past the blades. Also, a turbine may be downstream of others, which can also add an oscillatory component to the flow. This work investigates the use of iterative learning control (ILC) to address this problem. The problem considered is particularly suited to algorithms from the repetitive and ILC area. In repetitive control, the reference signal to be tracked is periodic and algorithms under this class take advantage of this, using information from previously executed periods to update the control signal. However, in the current application, non-periodic effects can have a significant impact and hence the focus is on the related area of iterative learning control [2]. To date there has been almost no work reported on the application of such control laws to flow control problems.

PROBLEM FORMULATION AND MODELLING

Two-dimensional flow past an NREL S825 aerofoil is used as a model of a section of a smart rotor with distributed actuation on the blade. Normally the angle of attack will not be high enough to provoke separation, and the pressure distribution on the surface of the blade and the lift can be calculated by assuming the flow is inviscid, with a panel method used to satisfy the boundary conditions on the surface of the body. Disturbances are introduced into the flow in the form of a set of discrete vortices, which are convected past the aerofoil. The interaction between the discrete vortices and the body produces a nonlinear system of equations. A second order Runge-Kutta method is used to move the vortices.

Trailing edge devices used for lift control act by modifying the flow near the trailing edge (TE), generating vorticity, and thereby altering the circulation on the body and hence the lift. This can be modeled in the current framework by allowing a jump in the tangential velocity at the TE rather than applying the Kutta condition. That is, by using $u = v_b - v_a$ as the control input, where v_a and v_b are the tangential velocities just above the upper and lower surfaces of the aerofoil just upstream of the TE. The lift as the output of the system. This provides a relatively simple (compared to a full CFD simulation) but realistic model of the flow and in which the jump in the tangential velocity at the TE is used as actuation, and the aim is to damp the fluctuations in the lift (L) due to the unsteady nature of the free stream and the influence of the vortices. The lift on the aerofoil with a uniform velocity (L_r) is used as a reference value, with the error defined as $E = L - L_r$, the aim being to significantly reduce if not minimise E.

Results are presented in non-dimensional form using the mean free stream velocity V_∞ and the chord (length) of the aerofoil H as reference values, with a reference time of H/V_∞.

RESULTS

Consider first periodic flow with free stream velocity $V_0 = 1 + A\sin(2\pi t/T)$ and no vortices. Suppose that a period operates over N_c steps where $N_c = T/\Delta t$, and Δt is the time step. Label the cycles as j, $j = 0, 1, \ldots$, and the step within a cycle as k_c, $k_c = 0, 1, \ldots, N_c - 1$, so that $k = jN_c + k_c$. Consider a phase-lead ILC of the form

$$u_j^{k_c} = u_{j-1}^{k_c} + \mu E_{j-1}^{k_c} \tag{1}$$

where $E_{j-1}^{k_c}$ is the error at time step $k = (j-1)N_c + k_c$. With a gain of $\mu = 10$, this ILC was found to damp out the oscillation in the lift for a wide range of values of A and T.

a) Corresponding author. E-mail: ort@soton.ac.uk.

Consider now flow with an oscillatory free stream with $A = 0.1$ and $T = 0.25$, and with vortices introduced into the flow upstream of the aerofoil. The vortices generate a significant disturbance in the lift in addition to that from the oscillation in the free stream velocity, as shown for a typical case in Figure 1. The ILC controller (1) applied to this flow suppresses the oscillatory part of the fluctuation but not the disturbances created by the vortices. However, a classic controller of the form

$$u^k = u^{k-1} + \mu E^{k-1} \qquad (2)$$

(P-type ILC in this context) with $\mu = 20$ largely suppresses the part of the fluctuation due to the vortices but leaves a residual, almost periodic fluctuation in the lift.

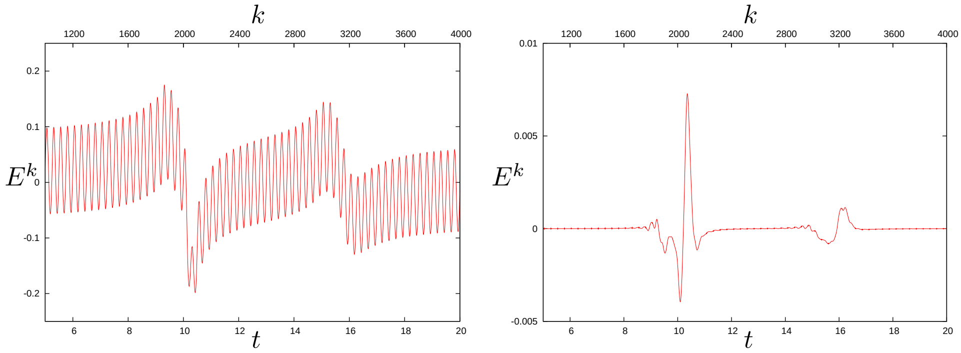

Figure 1. The error E^k for oscillatory flow past the aerofoil with two vortices with no control (left) and for flow with two vortices and the controller (3) with $\mu_0 = 10$ and $\mu_1 = 20$. .

This residual oscillation can be largely suppressed by applying a controller incorporating both P and phase-lead ILC, also referred to as two-term ILC. Specifically,

$$\hat{u}_j^{k_c} = u_{j-1}^{k_c} + \mu_0 E_{j-1}^{k_c}, \qquad \bar{u}^k \ = \ \bar{u}^{k-1} + \mu_1 E^{k-1}, \quad \text{and} \quad u_j^{k_c} \ = \ \hat{u}_j^{k_c} + \bar{u}^k \qquad (3)$$

The error for this controller with $\mu_0 = 10$ and $\mu_1 = 20$ is shown in Figure 1. The oscillatory component of the fluctuation has been almost completely eliminated, while the disturbance from the vortices has been heavily damped. Increasing the values of the gains above these values did not significantly affect the performance of the controller.

Two measures have been used to estimate the degree of damping, a 2-norm with $\mathcal{L}_2 = [\int_{T_0}^{T_1} \int (L(t) - L_r)^2 dt/(T_1 - T_0)]^{\frac{1}{2}}$ and a ∞-norm with $\mathcal{L}_\infty = \max_k \mid L^k - L_r \mid$. In general terms, $\mathcal{L}_2$ can be thought of as measuring the fatigue load, and $\mathcal{L}_\infty$ the peak load on the blade. For the case presented here, there was a reduction of two orders of magnitude in both measures when applying the two-term ILC. A large number of calculations have been performed using the two-term ILC with a wide range of periods and amplitudes of oscillation, numbers, strengths and initial spacing of vortices, and angles of attack (up to $10°$) of the aerofoil. In all cases there was a reduction of two orders of magnitude in the $\mathcal{L}_2$ measure of the disturbances. There was at least one order of magnitude in the $\mathcal{L}_\infty$ measure, even for extreme cases in which the vortices were strong enough to double the peak value of lift on the aerofoil.

CONCLUSIONS

A simple but realistic CFD model has been applied to the problem of oscillatory flow past an aerofoil with vortical disturbances in the flow, interacting non-linearly with the aerofoil, and with trailing edge vorticity/circulation generation for actuation, as a model of a section of a smart wing turbine rotor blade. This model has then been used for a detailed initial investigation into the application of simple structure ILC, with control laws designed by consideration of the system output, rather than, as is common, from a state-space representation.

Two different measures were used to assess the ability of the method to damp the disturbances, a 2-norm (fatigue load) and an ∞-norm (extreme/peak load). In general, the control successfully damped the fluctuations in the lift, with the 2-norm two orders of magnitude lower than for the corresponding case with no control, while the ∞-norm was at least one order of magnitude lower. Performance was maintained in extreme cases. The control laws in this paper have simple hardware implementations whereas model based methods often require state estimation.

Current work involves the use of local measure measurements (surface pressure values) as input for the control algorithm and more detailed modelling of the trialing edge actuation.

References

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