Robust Control Synthesis for Gust Load Alleviation of Large Aeroelastic Wind Turbine Models

Bing Feng Ng*, Rafael Palacios, J. Michael R. Graham, Eric C. Kerrigan

***Abstract*—This paper introduces a methodology for the design of gust load control systems directly from large aeroelastic models. Firstly, a state-space representation of the vortex particle unsteady aerodynamics suitable for control synthesis is implemented. Secondly, through the use of robust controllers, large reductions in loadings are demonstrated. Thirdly, controllers synthesized from models of coarse spatial discretisation that are an order of magnitude smaller in size than converged models, are shown to be capable of rejecting disturbances on the fully converged models. Their performances are also comparable to expensive higher order controllers developed from full models.**

***Index Terms*—Gust load alleviation, vortex panel, discretization, robust control.**

I. INTRODUCTION

As the size of wind turbines increase to allow for larger energy capture, they are subject to greater risks of fatigue failure and extreme loading events. Most wind turbines today are equipped with pitch control for speed regulation, which can also be used for load alleviation [1]. However, these responses are slow and limited by the inertia of the blades [2]. Innovative blade designs with active aeroelastic control techniques developed for aeronautics applications [3] could therefore be a solution to maintaining steady loading on the blades, thereby reducing vibrations and rapidly fluctuating loads [4].

This paper will model the effect of actively controlled flaps using the unsteady vortex particle method represented in state-space form [5]. We will focus on using this model for load alleviation through LQG, $\mathcal{H}_\infty$ and PD controllers, with comparisons made to their performance and energy expenditure. Given that the vortex method requires dense spatial discretisation for convergence, the challenge is in synthesising controllers from these increasingly-large computational models. This paper will explore the possibility of developing controllers from vortex models of coarse spatial discretisations. Not only does this retain physical degrees of freedom, it allows direct control synthesis to be performed concurrently in the design process, thus avoiding the need for additional computational effort in computing reduced order models. As demonstrated by [6], this method may be an improvement over large-scale model reduction techniques, and controllers synthesised from low order models avoid numerical issues present in model reduction of large-scale systems.

B.F. Ng, R. Palacios and J.M.R. Graham is with the Department of Aeronautics, Imperial College London, SW7 2AZ, United Kingdom.

E.C. Kerrigan is with the Department of Electrical and Electronic Engineering and Department of Aeronautics, Imperial College London, SW7 2AZ, United Kingdom.

* PhD student (email: b.ng10@imperial.ac.uk)

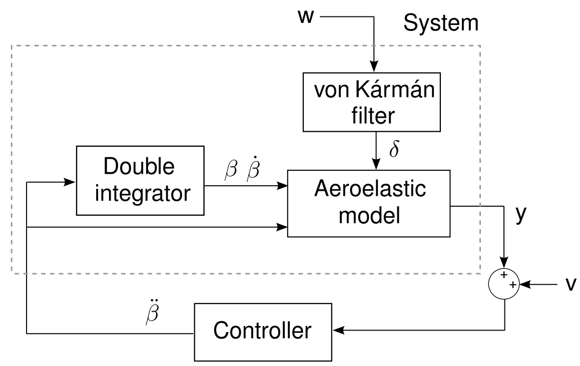

Fig. 1. Closed-loop block diagram.

II. MODELLING

The aeroelastic model has been developed and the reader is referred to [7; 8] for the full derivation. A simplified closed-loop block diagram of the aeroelastic model is illustrated in Figure 1. Performance is measured based on the percentage reduction in Root-Mean-Square (rms) of lift coefficient output (C_L) between open and closed-loops. Another measurement is the control energy expenditure chosen as $E = \frac{1}{T}\int_0^T \mid \ddot{\beta} \mid^2 dt$. This measure is selected as the flap angular acceleration, which is proportional to the torque $\tau = I_\beta \ddot{\beta}$, is in turn related to work done.

III. NUMERICAL RESULTS

A. Load reduction using controllers from converged models

LQG and $\mathcal{H}_\infty$ controllers were synthesised from the converged vortex aeroelastic model (50 panels per chord and 5 wake chords). For the same turbulence input, the achieved reductions in rms(C_L) were 82% and 79%, respectively. The time series comparing open-loop to closed-loop responses of $\mathcal{H}_\infty$ is shown in Figure 2.

B. Controller synthesis with spatially coarse vortex aeroelastic model

Given that LQG and $\mathcal{H}_\infty$ controllers are at least the same size as the model, control synthesis using high order converged vortex aeroelastic models are computationally expensive. Hence, the number of panels per chord was reduced for control synthesis, and the resulting controller is placed in closed-loop with the converged vortex aeroelastic model.

As shown in Figure 3, an $\mathcal{H}_\infty$ controller developed using just 2 panels per chord was able to achieve good performance when applied in closed-loop with the converged model with

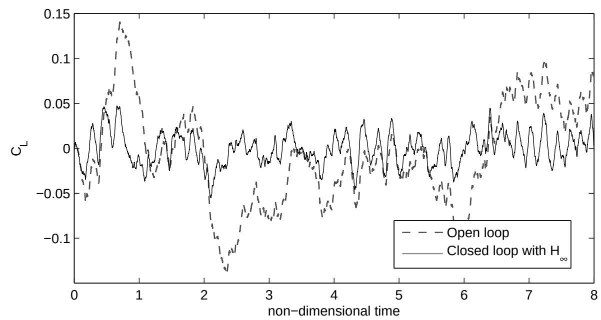

Fig. 2. Closed-loop with $\mathcal{H}_\infty$ controller.

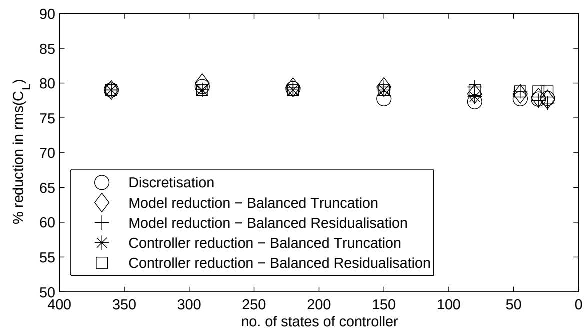

Fig. 3. Comparison of performance using $\mathcal{H}_\infty$ controllers of decreasing sizes synthesized from spatial discretisation and different model reduction techniques.

50 panels per chord. Comparisons with model reduction and controller reduction [9] are also shown on the same plot.

C. Proportional-Derivative (PD) controller

Using a PD controller, we were able to find an optimal set of gains that achieved 77% reduction in loading which is similar compared to LQG and $\mathcal{H}_\infty$. Comparing the control energy expenditure between the three control methods (with tuning to obtain similar performances), we observe that PD controllers expend 70% more control energy. Comparing the time series of the closed loops using $\mathcal{H}_\infty$ and PD controllers, we see that PD commands a larger flap deflection velocity, as shown in Figure 4.

IV. CONCLUSION

Active aeroelastic control offers huge potential in load alleviation for large wind turbines. For this, we first need robust hardware with high reliability and minimum maintenance requirements, and second, robust control tools that minimize the cost of actuation across a range of operating conditions. We have shown that 80% reduction in rms(C_L) can be achieved using LQG, $\mathcal{H}_\infty$ and PD controllers, but PD controllers can expend 70% more control energy. We also demonstrated a procedure to obtain controllers from large aeroelastic models through relaxation of spatial discretisations. This method enables physical degrees of freedom to be retained and allows direct control synthesis in a concurrent design process without additional computation effort in implementing model

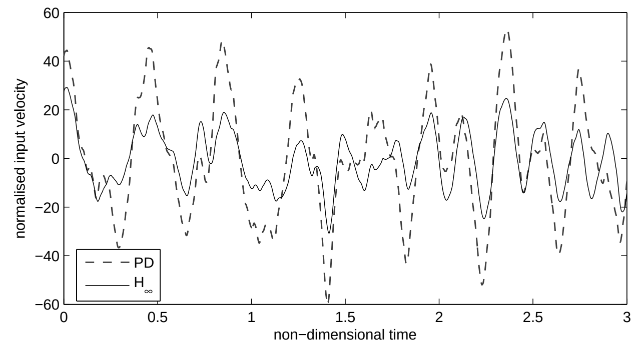

Fig. 4. Comparing control input (flap deflection) velocity for $\mathcal{H}_\infty$ and PD controllers.

reductions. Work is currently in place to adapt a non-linear aeroservoelastic tool to control of large wind turbine rotors using Imperial College's framework for the Simulation of High Aspect Ratio Planes (SHARP).

ACKNOWLEDGMENT

The first author would like to thank the Singapore National Research Foundation for its financial support.

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