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8th February 2024

Re: Review of the thesis titled, "Structured control laws for flexible wing concepts" written by Ing. Filip Svoboda for the purpose of Doctor of Philosophy (PhD)

Dear Sirs/Madams,

I am writing this review report in response to your kind request for reviewing the dissertation thesis submitted by Ing. Filip Svoboda for the purpose of PhD degree in the field of study, "Control Engineering and Technology" at FEL, CTU.

The thesis developed several structured control laws for flexible wing structures. Firstly, a structured decentralized control laws are designed for flexible systems in one-dimension. Secondly the control law was extended for the application in multi-dimensional system with inherent coupled subsystems. Thirdly, a procedure for the synthesis of novel decentralized controller for active damping of an aeroelastic morphing wing has been shown. The third contribution is of particular interest from the industrial practice/application point of view.

The Chapters 2, 3 and 4 are organised in a logical manner and succeeds to provide the complex matter both in its theoretical background and in relevant aerospace test cases. However, the thesis lacks the Conclusion section and comments on the Recommendations for Future Works. I understand the candidate followed "Paper Format" as the structure of the paper, but at the moment it appears that author's three journal publications are simply "listed" in the thesis and left on reader's discretion to understand. As of now it appears that the compilation of the thesis was rushed. It would be good to know the author's point of view on the future direction of this research work. Please note this is not a comment on the technical & scientific content/contribution of the thesis, rather than how the thesis is organised.

Relevance of the contributions from the thesis

The thesis topic is highly relevant to the current research needs in the scientific control and aerospace community. With the current global push for the Green Aviation the future aircraft are likely to become even lighter and highly flexible and future technologies such as morphing wing structures is a strong candidate for the inclusion in the future wing technologies. The implementation of complex flight controllers for commercial aircraft is always seen in a

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conservative way. In contrast the work from this reviewed thesis calculates the stabilizing feedback gains for the agents which then makes the analysis of the overall system easier in terms of stability margin and damping performance.

Fulfilment of the main objectives

The three objectives listed in the Introduction sections listed below have been fulfilled.

1. Develop easily scalable design algorithms for decentralized control laws focused on active damping of mechanical flexible structures (Chapter 2 of the thesis).
2. Expand the developed algorithms to aeroelastic problems, namely to active control approaches for flutter resistance augmentation Chapter 3 and 4 of the thesis).
3. Demonstrate applicability of the developed methods for emerging morphing wing concepts (Chapter 4 of the thesis).

Below are the Chapter-by-Chapter comments and questions that would require further clarifications during the viva/presentation.

Chapter 1 - Introduction

The entire section of the chapter is written without a single reference. There are few important sentences that requires appropriate referencing, some of them are listed below:

- A minimum required flutter margin is usually 15% above design dive speed VD
- On page 4 – The paragraph "In 2017…." Reference is essential.

Here the candidate introduced the experimental wind tunnel model. It is not clear how this experimental model was used in the later stages of the research work. Was it only used to validate the FEM model of the wing which as used in Chapter 4? Some clarification here will be useful.

Chapter 2 - Low-complexity decentralized active damping of one-dimensional structures

This chapter works as the foundation of the candidate's research work. In this section the candidate formalises a simple full state feedback control for each node associated with the one-dimensional flexible structure. Further the candidate presented two control strategies for calculating the gain feedback gains of the system, i) Damping ratio, ii) Maximum Stability Margin.

In figure 2.2 in the thesis, the y-axis of the figure, what is δ? Is it the same as d_{damp} in Eq. 2.29? If so, there is a typo and a symbol unexplained. Few comments on δ is missing. If the δ is big, then the stability margin is bigger? I would like some explanation on why the δ starts to roll-off from the damping ratio ζ >0.7 (referring to Fig. 2.2)

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The illustration of the control strategies with an example is useful and related comparisons with well-established controllers such as LQR and $\mathcal{H}_\infty$ controllers. The authors depict the time domain and frequency domain responses of 24th node for demonstrating the effectiveness of the control strategies. In Fig 2.9 candidate presents the Bode plots of the controllers as a comparison to several damping ration with open-loop (undamped) system. What is the response for the Phase plots, I only see the magnitude plots in Fig 2.9?

In the final section of Examples, the authors picked a damping ratio of 0.6 for comparison case, why is that? In Fig. 2.9 the authors did not show a response for $\zeta = 0.3, 0.5, 0.7\ and\ 0.9$.

Quoting authors conclusive statement, "Comparison with LQ controller and H∞ designs shows that the presented approach achieves similar results yet with much lower computational and actuator complexity." What is the basis of this statement? Did the author/candidate perform any computational studies on this? The feedback gain K can be calculated off-line using LQR and using the author's presented way. My question is, why one as a practitioner of flight control systems would use the proposed methods by the authors than LQR? In fact, from Fig. 2.14, for the given tunning parameters LQR produces slightly better damping. If I am wrong to say this, I would like to know why during the viva.

Chapter 3 - Decentralized control for large scale systems with inherently coupled subsystems

This chapter is an extension of the author's work presented in Chapter 3. Here the author presented a scalable control design methodology for Large Scale Systems (LSS). The candidate presented a design methodology for designing controllers for LSS with coupled subsystem dynamics are taken into consideration. The dimension of the design problem is kept constant with growing number of agents by using the single-agent dynamics and their interaction topology instead of relying on the entire system model.

The state-feedback gain is solved by formulating the problem as a linear matrix inequality problem. This is referred as Algorithm 1 in the chapter.

The numerical example in section 3.5 for understanding the controllers is really helpful here. The comparison of the proposed decentralized controller with the more conventional controllers such as LQR and $\mathcal{H}_\infty$ controllers is useful.
Some open questions for the numerical example case:

For structures with 10 nodes and 100 nodes, what was the target frequency that was being damped?

I see from Fig. 3.1; the low frequency of the system's response is significantly modified by the controller LMI agent. This is a problem if applied to aerospace structures, like wing because the issues like aeroservoelastic becomes significant where the rigid body dynamics starts to

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interact with flexible modes. Any comments on this? If I got it wrong, I would like some explanations during the viva. If my understanding is correct, I think this controller is nice as a theoretical study but will have very little practical application for flexible wing.

Any comments on how the phase plots look like for the open loop systems and the closed loop systems shown in the Example section?

Chapter 4 - Decentralized active damping control for aeroelastic morphing wing

This chapter presents the theoretical work developed in Chapter 2 and 3 applied to a aeroelastic morphing wing. The preliminaries section of this chapter is standard aeroelastic modelling techniques/procedures for flexible wings.

In the controller design/synthesis section, the candidate/authors follow similar procedures as discussed in Chapter 3 of this thesis. The only significant exception being that for efficient solving of the Corollary 1, a relaxed LMI condition is introduced.

The simulation section is again helpful to assess the applicability of the proposed controller.

A block-diagram for the inclusion of S_{ab}^{HB} would have been helpful here to understand the implementation of this so-called pre-filter to minimize the effects of DC gain caused by the state-feedback.

In the simulation sections the usefulness of the newly synthesised controller is demonstrated for gust disturbance, robustness and flutter speed (flutter alleviation). In the Bode plots, what are the responses for phase? I understand the calculated gains are simple state-feedback, however some comments on it would be useful.

This chapter is very useful for practicing flight control engineers.

Some open questions for comments/discussions during the viva/presentation to assess the candidate's understanding of the practical application

1. The idea of morphing wing has been there for over decades as evident from the literature survey, what factors have limited the use of morphing wing structures in industrial scale?

2. From the implementation point of view, how practical is it to have many distributed controllers and their effectiveness when there is fault in the system?

3. What are the certification implications/constraints for these types of controllers for aerospace systems in commercial transport aviation?

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General comments on the thesis

This thesis represents a creative scientific contribution by providing novel controller synthesising techniques for decentralized controllers for large flexible structures, such as a flexible morphing wing. A logical sequence of extensions is presented throughout the thesis in a convincing way. Illustrative aerospace test problems highlight the methods and their potential in application generally well. The candidate has certainly extended the knowledge in this area of research. Further candidate's understanding will be assessed during the viva/presentation.

The author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving a Ph.D. degree.

Yours faithfully

Dr. Mushfiqul Alam BEng MSc PhD MRAeS CEng AFHEA