2020 2nd IEEE International Conference on Gridding and Polytope Based Modelling and Control (GPMC) | 978-1-7281-8219-3/20/$31.00 ©2020 IEEE | DOI: 10.1109/GPMC50267.2020.9333823

Aerodynamic and LPV Modeling of a Distributed Propulsion Morphing Wing Aircraft

Béla Takarics*†, Réka Dóra Mocsányi*, Bálint Vanek*, Dávid Sziroczák‡, Dániel Rohács‡
*Systems and Control Lab
Institute for Computer Science and Control
Kende u. 13-17. 1111 Budapest, Hungary
Email: {takarics, mocsanyi, vanek}@sztaki.hu
‡Department of Aeronautics, Naval Architecture
and Railway Vehicles
Budapest University of Technology and Economics
Stoczek street 6. 1111 Budapest, Hungary
Email: {dsziroczak,drohacs}@vrht.bme.hu
†Department of Control for Transportation and Vehicle Systems
Budapest University of Technology and Economics
Stoczek street 2. 1111 Budapest, Hungary

Abstract—**Hybrid-electric, unconventional aircraft solutions can possibly be the solutions for the ambitious emission reduction targets set by regulators, based on society's demands. One such disruptive solution is a morphing wing cargo UAV, with distributed propulsion. This paper investigates the aerodynamics, flight dynamics and control of a scaled down technology demonstrator UAV, built to validate the feasibility of the morphing wing concept. Several types of analyses are run to gain knowledge on the performance, stability and control properties of the aircraft. The flight mechanical effects of the distributed propulsion system are taken into account based on the integral momentum theorem. The increased flow speed behind propellers increases the local lift forces. Therefore, the distributed propulsion can be used to control the roll, pitch and yaw motion of the morphing wing aircraft. The nonlinear 6 degrees of freedom, distributed propulsion aircraft model is constructed utilizing the stability and control derivatives obtained from the aerodynamic analysis. Grid and Tensor Product (TP) type linear parameter-varying (LPV) models of the morphing wing aircraft are generated via Jacobian linearization and TP model transformation. The LPV models capture the parameter varying dynamics arising from the airspeed, morphing wing and payload weight variations. Gain scheduled lateral and longitudinal baseline controllers are synthesized using the grid-based LPV model of the aircraft.**

I. INTRODUCTION

There are significant changes affecting the world of aviation these days. As with many other fields of life today, society's desire for greener, more efficient and immediate, on demand transportation solutions are presenting challenges in the industry and act as a non-classical market pull force. Due to societal pressure regulators and stakeholders have defined ambitious future targets, for example emission reductions in the order of 90% and 75%, in terms of NO_X and CO_2 respectively.

Based on today's understanding of technology levels, and technology forecast, this radical improvement can't be achieved using incremental development alone. Aviation is required to begin its third development "S" cycle, and needs novel, disruptive technological solutions and out-of-the-box thinking to achieve the radical targets. Electric and hybrid-electric powered aviation can be an answer, as seeing the trends in other forms of transportation, electric propulsion has the potential to achieve the target when implemented correctly.

The author's previous article [1] investigated the opportunities and challenges associated with electric and hybrid-electric propulsion systems. The key challenges identified were the low specific energy of energy storage systems, the related operational aspects of such system (safety, crashworthiness, life, etc.) and the lack of historical data and experience to use in design and operation. Taking these into account, the conclusion is that for the successful development of electric or hybrid electric aircraft, the following cases need to be considered:

- Accept limited range and speed (25-50%) compared to conventionally powered aircraft.
- Develop energy storage solutions with significantly higher energy density, in the order of $1kWh/kg$
- Develop unconventional structures and operational methods.

The aircraft presented in this paper reflects to the last bullet point, the unconventional solutions. In the IDEA-E project [2] a market need of a small UAV hybrid-electric cargo aircraft with $150kg$ payload capacity, $100km$ range and $90min$ endurance was defined and conceptual and preliminary design was performed on the UAV. During the design, it became clear, that such solution could be made feasible using very low, 0.2 airframe structural mass fraction, and as such would require unconventional structural solutions. One such solution was the development of the fabric covered morphing wing concept.

The morphing mechanism is conceptualised as a lightweight solution that is capable of supporting the air loads, can be adjusted to account for the varying mass of the cargo UAV and can be used as efficient flaps and ailerons. In order to validate the feasibility of such mechanism, in 2019 a technology demonstrator UAV was designed and built at the department [3]. The UAV in addition to validating the morphing concept can be fitted with a regular wing, in which case it can be used alongside other departmental UAS, such as the micro-gasturbine test UAV [4], for research and educational purposes. The cargo UAV concept, along with the technology demonstrator is shown in Figure 1.

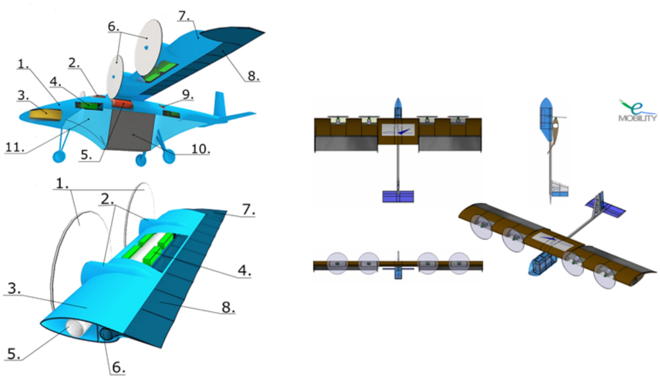

Fig. 1. Cargo UAV (left) and technology demonstrator UAV (right) models

The key parameters of the UAV are the following:

- MTOM: $2kg$
- Wingspan: $1.4m$
- Wing area: $0.28 - 0.31m^2$
- Speed range: $32 - 80km/h$

The developed aircraft conceptual design methodology is adequate to evaluate the main characteristics of the aircraft, such as high-level aerodynamic coefficients estimation, propulsion performance prediction, basic stability estimation, mass breakdown, packaging and so on. However in order to further develop the concept, more detailed investigation regarding aerodynamics, flight mechanics, dynamics and control are required, the results of which are presented in this paper.

The first contribution of the paper is the aerodynamic modeling and analysis of the morphing wing aircraft using XFLR-5 software [5]. In addition to the performance analyses, the assessment of the longitudinal, as well as the lateral stability of the aircraft is concluded. As a first approach to take the distributed propulsion system of the aircraft into account, the flow around the wing is adjusted according to the integral momentum theorem [6]. The flow acceleration caused by the propellers has a positive influence on the lift generated by the wing, therefore enhancing the aircraft's flight performance. The aerodynamic analysis and the distributed propulsion modeling of the morphing wing aircraft is presented in Section II. upon which the nonlinear 6 degrees of freedom (DoF) model can be created.

A common way of control synthesis for aircraft is utilizing gain scheduling and the linear parameter-varying (LPV) framework [7], [8]. There are three main representations for LPV systems. These are the grid-based LPV models [9], linear fractional transformation (LFT) [10] and polytopic [11]–[15] models. All these LPV representations have their advantages and disadvantages, therefore, they complement each other. The present paper focuses on grid and polytopic based LPV models and the goal is to develop such LPV models of the morphing wing aircraft, (Section III.). The polytopic model is derived via Tensor Product (TP) model transformation. TP model transformation is an efficient numerical method capable of transforming LPV models into TP type polytopic models. The main underlying principle behind the TP model transformation is the higher order singular value decomposition (HOSVD) [12]. The grid based LPV model serves as a basis for the baseline control design. Lateral and longitudinal, gain scheduled baseline controllers are derived for the morphing wing aircraft based on the considerations of [16], shown in Section IV which is then followed by the Conclusions.

II. Aerodynamic analysis

The dynamic model of the aircraft requires the aerodynamic, stability and control coefficients of the vehicle. For this an open-source aerodynamic analysis tool, XFLR-5 was used [5]. The program first requires the geometry and load distribution of the aircraft, based on which the different analyses can be run. After constructing the models, performance analysis of the aircraft can be executed to determine general aerodynamic properties and information on its static stability in steady flow. Performance analysis requires the plane surface to be separated to panels, since it is carried out using the vortex lattice method, which is a potential based panel method. According to [17], the basic concept of panel methods is that a large number of elementary quadrilateral panels with one or more types of singularities attached to them are placed on the actual or mean surface of the geometry in question. A functional variation across the panel can be specified to determine the singularities, for which the actual value is set by the corresponding strength parameters. The parameters can be calculated by solving the fitting boundary condition equations. The vortex lattice method (VLM), first formulated in the 1930's, is similar to the standard panel methods introduced above. Considerable differences listed in [18] are that VLM's formulations ignore the thickness of surfaces using calculations based on combinations of thin lifting surfaces, boundary conditions are applied on a mean surface and singularities are not distributed over the entire surface. It is basically a simple method with a purely numerical approach and the advantage of computational efficiency. After achieving statically stable models, dynamic stability and control analyses are carried out in order to gain the stability and control derivatives of the vehicle. The obtained coefficients - aerodynamic, stability and control - are then utilized in the dynamic nonlinear 6 DoF model created in Matlab/Simulink.

In order to model this morphing wing properties of the aircraft accurately, several versions representing different wing chord length settings and payloads are required. To achieve a sufficient range of models, discrete points are chosen, at which performance, stability and control analyses are executed. In this case 3 chord settings and 3 payload weights are chosen resulting in a sum of 9 discrete models. The middle chord length is at 220 mm from which the length can be modified by 30% in each direction. The airfoils used for the morphing wing aircraft are presented in Figure 2. As for the payload carried by the vehicle, the weight ranges from 0 kg to the maximum load of 1.5 kg. Additional payload was included to investigate the effect of the aicraft's weight on each version of the wing. The parameter values applied in the nine separate models are presented in Table I.

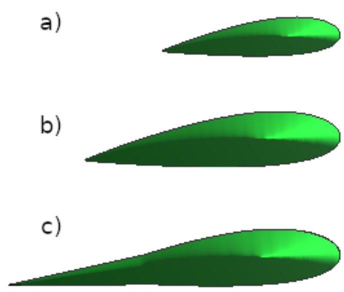

Fig. 2. Morphing airfoil

TABLE I. PARAMETER VARIANCE FOR THE DISCRETE MODELS

Varying parameters	**Discrete parameter values**		
	lower boundary	mean	upper boundary
Chord $\bar{c}$	(a) 154 mm	(b) 220 mm	(c) 286 mm
Payload $m_{payload}$	0 kg	0.75 kg	1.5 kg

With each version of the aircraft, the properties of interest are calculated with the airspeed fixed at 22 m/s during the performance analyses. These simulations were run at different angles of attack ranging from $-5°$ to $5°$. The results for the 3 unloaded model model are shown in Figure 3 and 4. The trim angle of attack is between $-0.0437°$ and $0.0001°$ and the corresponding lift coefficients are positive. The slopes of the $C_m - \alpha$ curves are negative, indicating the longitudinal stability of each aircraft.

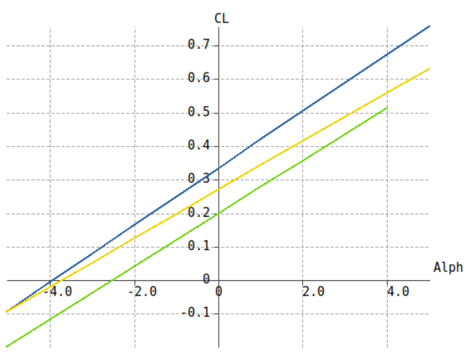

Fig. 3. C_L vs α graph

The assessment of lateral stability is achieved by the inspection of the dynamic modes of the aircraft. In Figure 5. the pole migration of an example version of morphing wing aircraft can be observed, while the properties of the dynamic modes of the same version are detailed in Table II. It can be seen from the pole migration diagram that each dynamic mode, both longitudinal and lateral, are stable with the exception of the spiral mode at lower airspeed. Table II. shows that the damping of the spiral mode is a negative number indicating its instability.

Additionally, since this vehicle generates thrust using a distributed electric propulsion system, the effect of these

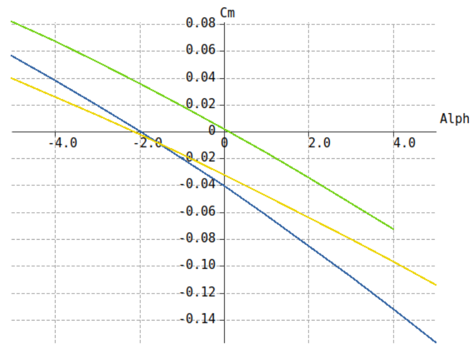

Fig. 4. C_m vs α graph

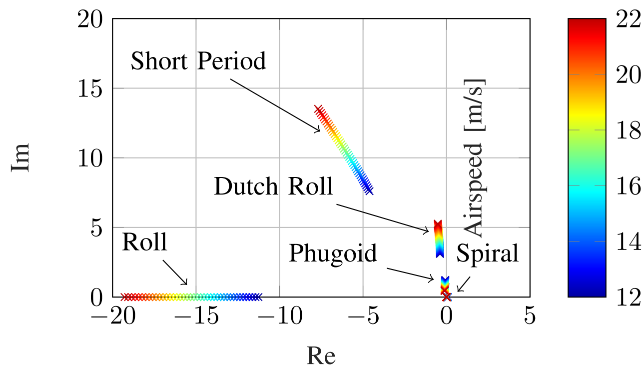

Fig. 5. Dynamic modes of the aircraft at $V = 20\ m/s$, $c = 220\ mm$, without payload

devices on the aerodynamics of the wing requires further attention. Previous studies have shown that a larger flow speed increased by the propulsion system, especially by a distributed propulsion system, results in a significant benefit to the lift coefficient [19]–[21]. To take the effect of the propellers into account, the lift coefficient distribution on the wing obtained via the XFLR-5 performance analysis was modified to match the increased flow speed generated by the propellers. To generate a distribution that contains this impact, the wing area is separated into 5 surfaces. As seen of Figure 6. the separate areas are the ones behind the 4 propellers and the fifth is the sum of the remaining surface of the wing. The dynamic pressures at the 5 surface can be different from each other, which will then directly effect the local lift force. The integral momentum theorem is used to compute the flow speed behind each of the propellers individually. According to this theorem, there is a sudden increase in the speed and pressure at the surface of the propeller [6]. Data on the required

TABLE II. DYNAMIC MODE PROPERTIES AT $V = 20\ m/s$, $\bar{c} = 220\ mm$ WITHOUT PAYLOAD

Mode	**Damping**	**Frequency** $[rad/s]$	**Time constant** $[s]$
Phugoid mode	0.188	0.576	9.23
Short period mode	0.496	14.2	0.142
Roll subsidence mode	1	17.6	0.0568
Dutch roll mode	0.1	4.83	2.06
Spiral mode	-1	0.0188	-53.2

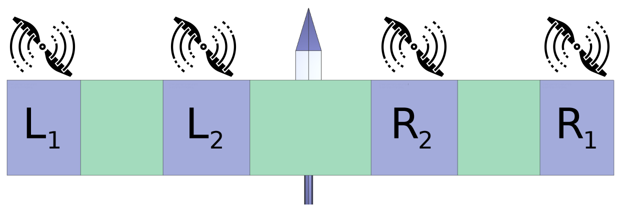

Fig. 6. Distribution of the wing surface

thrust presented in Figure 7. is needed to calculate the speed increment.

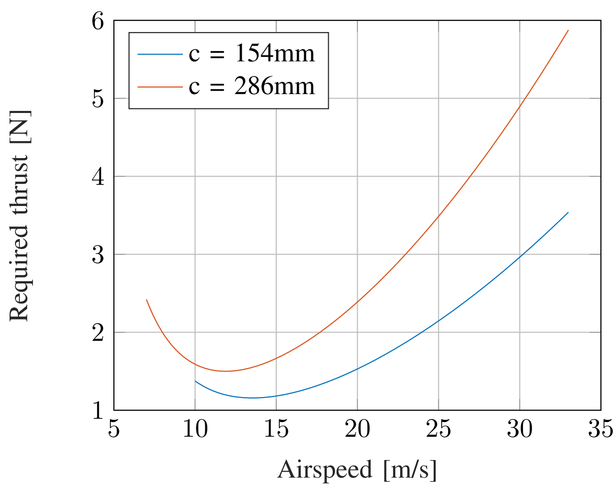

Fig. 7. Required thrust for the whole aircraft at 2 different chord setting [22]

The thrust force T can be calculated as

$$T = \rho R^2 \pi (V + v) v_3, \tag{1}$$

where ρ is the air density, V is the velocity of the flow, v is the speed increment directly after the propeller and v_3 is the speed increment of the flow where the pressure decreases to its initial value. As shown in [6], the distant induced velocity v_3 is twice in magnitude compared to the local induced velocity v. Using this fact, the thrust force becomes

$$T = 2\rho R^2 \pi (V \cdot v + v^2). \tag{2}$$

After rearranging the quadratic equation to its standard form, it becomes

$$v^2 + V \cdot v - \frac{T}{2\rho R^2 \pi} = 0. \tag{3}$$

The speed increment behind the propeller can therefore be directly obtained and can be used to calculate the local dynamic pressures behind each propeller. With such approach, the local lift forces can be computed. This modeling method allows the propellers to operate separately, which enables differences in the magnitude of thrust generated by each of them. As a result, a higher thrust force on one side of the wing causes a yawing and rolling motion of the aircraft. At the same time the increased lift on the corresponding area of the wing generates a momentum around the longitudinal axis, enhancing the motion caused be the larger thrust force. Additionally, using such a model allows for safe operation in case of a motor failure as well.

III. LPV Model of the Aircraft

The LPV framework is well suited to capture the parameter dependent dynamics of the aircraft. In the case of the morphing wing aircraft, in addition to the airspeed, the wing morphing and payload weight have significant effect on the dynamics. The aim is to derive an LPV model that capture all these effects. The formal definition of the LPV model [7], [8] is given as

$$\begin{aligned} \dot{x} &= A(\rho(t))x + B(\rho(t))u \\ y &= C(\rho(t))x + D(\rho(t))u \end{aligned} \tag{4}$$

where $A : \mathcal{P} \to \mathbb{R}^x$, $B : \mathcal{P} \to \mathbb{R}^x$, $C : \mathcal{P} \to \mathbb{R}^x$, $C : \mathcal{P} \to \mathbb{R}^x$ are continuous matrix function. $x : \mathbb{R} \to \mathbb{R}$ denotes the state vector, $u : \mathbb{R} \to \mathbb{R}$ the input vector, $y : \mathbb{R} \to \mathbb{R}$ denotes the output vector and $\rho : \mathbb{R} \to \mathcal{P}$ is a time varying scheduling signal, where $\mathcal{P}$ is a compact subset of $\mathbb{R}^\rho$.

A. Grid-based LPV model

The grid-based LPV model consists of linear time-invariant (LTI) models $(A_k, B_k, C_k, D_k) = (A(\rho_k), B(\rho_k), C(\rho_k), D(\rho_k))$. These LTI models are obtained by evaluating the LPV model over a finite grid of the scheduling parameter values $\rho_{k1}^{N_{grid}} = \mathcal{P}_{grid} \in \mathcal{P}$. The grid-based LPV model is derived from the nonlinear aircraft model via Jacobian linearization. For this the scheduling parameter is defined first in the following way

$$\rho(t) = \begin{bmatrix} V(t) \\ \bar{c}(t) \\ m_{payload}(t) \end{bmatrix} \tag{5}$$

The first step of Jacobian linearization is trimming the aircraft. This is done for straight and level flight condition at the range of airspeed $V = [12.5, 22]\ m/s$, chord $\bar{c} = [154, 286]\ mm$ and payload $m_{payload} = [0, 1.5]\ kg$ at 39, 3 and 3 equidistant points, respectively. The next step is to obtain the LTI model sets over these scheduling grid to form the grid-based LPV model. The pole migration of the LPV model of the morphing wing aircraft is shown as the function of the airspeed with $\bar{c} = 220\,mm$ and $m_{payload} = 0\,kg$ in Figure 5.

B. TP type polytopic LPV model

The TP type polytopic LPV model is obtained from the grid based LPV model via TP model transformation [12]. The highest singular values in each dimension of the scheduling parameter after the HOSVD are

$$\sigma_V = \begin{bmatrix} 6447.3 \\ 455.6 \\ 28.6 \\ 2.62 \\ 0.25 \end{bmatrix}, \quad \sigma_{\bar{c}} = \begin{bmatrix} 6437.7 \\ 485.9 \\ 310.6 \end{bmatrix}, \quad \sigma_{m_{payload}} = \begin{bmatrix} 6417.6 \\ 706.5 \\ 302.4 \end{bmatrix}$$

It can be noted that the singular values of σ_V become rather small beyond the third singular value. Since the TP model transformation can set a trade-off between accuracy and complexity [12], keeping the first 3 singular values in this dimension is expected to result in a TP type LPV model with low complexity but sufficient accuracy. Such huge decrease in the singular values cannot be observed in the morphing chord and payload dimension which means that the number of vertices of the polytopic model can not be reduced in these dimension without a significant loss of accuracy. The weighting functions of the TP type LPV model with a tight convex hull are shown in Figure 8. As a result, the grid

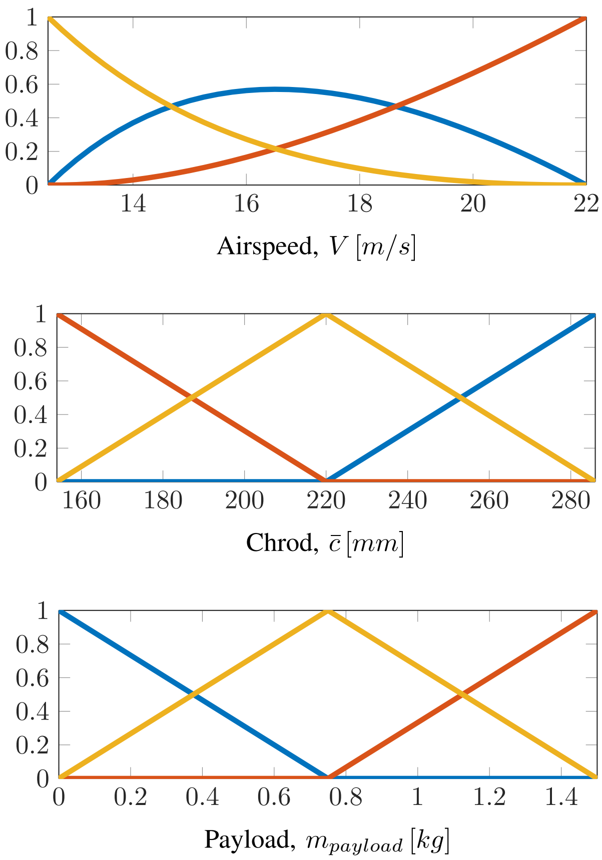

Fig. 8. Tight convex hull weighting functions of the TP model

based LPV model of the aircraft consisting of $39 \times 3 \times 3$ LTI models was transformed to a TP type convex polytopic LPV model with $3 \times 3 \times 3$ vertex systems. Such polytopic model can significantly reduce the computational cost of the control synthesis that is usually related with grid-based LPV models at the expense of more conservative results.

IV. Gain Scheduled Baseline Control Design

A. *Baseline control design*

The goal of this section is to present the main considerations and results of the baseline controller design. The inner loops of the baseline controller are developed for the decoupled lateral and longitudinal dynamics of the aircraft. The aircraft dynamics change significantly with respect to the airspeed, airfoil morphing and payload. Therefore, it is advantageous to apply gain scheduled controller design techniques using the grid based LPV model of the aircraft presented in the previous section. Gain scheduled controllers can efficiently account for such changes ir the model dynamics. The scheduling parameters for the controller are the same as for the LPV model of Section III.

1) Roll mode controller: The main approach of the control design follows the considerations presented in [16]. The controller structure is shown in Figure 9.

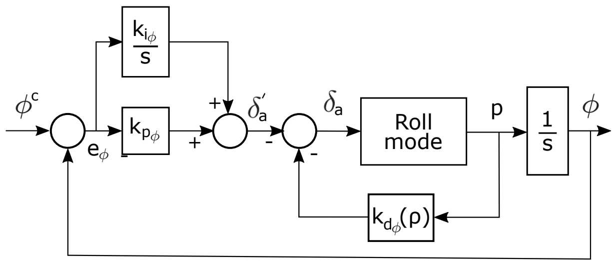

Fig. 9. Roll attitude control

The lateral controller is a PID type controller. It is assumed that the maximal roll angle command satisfies $|\phi_{cmd_{max}}| \leq 50°$ and the maximal aileron deflection satisfies $|\delta_{ail_{max}}| \leq 25°$. The damping factor of the roll mode is set as $\zeta_\phi = 0.9$. Such control design specifications lead to a gain scheduled derivative gain $K_{d_\phi}(\rho)$ to provide constant damping factor over the flight envelope. The parameter variation of the roll rate damping gain with 50% wing morphing and 50% payload is shown in Figure 11. Root locus plots help determine the values for $K_{p_\phi} = -0.5$ and $K_{p_\phi} = -0.1$. The closed loop roll mode properties have infinite gain margins and higher 150° phase margins that provide a high level of robustness. The bandwidth of the roll mode is not significantly altered by the controller and remains within $8-20\,rad/s$. The bandwidth of the closed loop mode can be increased by increasing K_{p_ϕ} if required.

2) Short period mode controller: The longitudinal inner loop of the baseline controller is also designed based on [16]. Figure 10. depicts the structure of the longitudinal baseline controller.

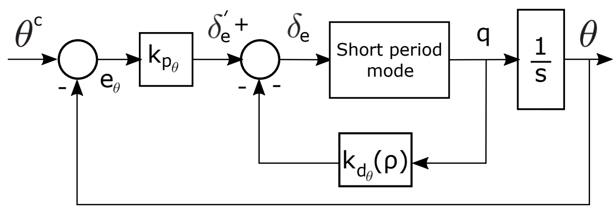

Fig. 10. Pitch attitude control

The longitudinal baseline controller is a PD controller. The main considerations for deriving the longitudinal controller are the following: the maximal pitch angle command satisfies $|\theta_{cmd_{max}}| \leq 30°$; the maximal elevator deflection satisfies $|\delta_{elev_{max}}| \leq 25°$; the damping factor of the short period mode is set as $\zeta_\theta = 0.9$. The constant damping factor of the closed loop short period mode is ensured by the gain scheduled derivative gain $K_{d_\theta}(\rho)$. The proportional gain $K_{p_\theta} = -0.833$ is constant and regulates the pitch attitude. It has to be pointed out that because there is no integral term available in the short period mode controller, the DC gain is significantly smaller than 1. This drawback is however usually addressed by the outer loop controllers that are not investigated in the current paper. The phase and gain margins of the closed loop short period mode is infinite. Figure 11. shows the parameter variation of the short period damping gain for 50% wing morphing and 50% payload. The bandwidth of the closed loop short period mode is not significantly altered by the controller

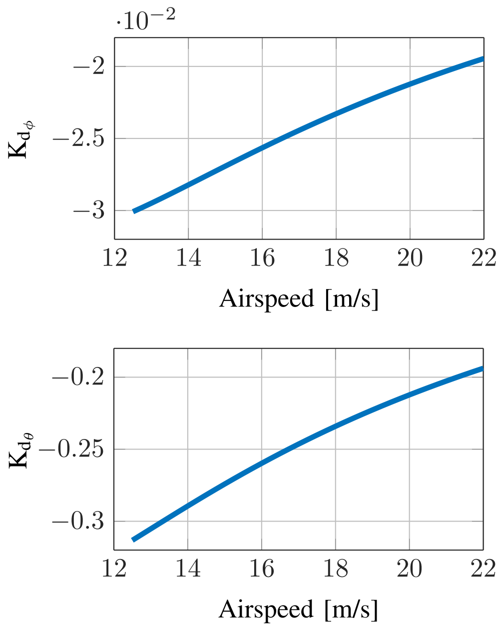

Fig. 11. Parameter variation of $K_{d_\phi}(\rho)$ and $K_{d_\theta}(\rho)$

and remains within $10 - 25\,rad/s$. The damping factor is however increased from $\zeta_{\theta_{OpenLoop}} \in [0.3 \quad 0.5]$ to $\zeta_\theta = 0.9$.

V. Conclusion

A 6 DoF nonlinear, distributed propulsion model of the morphing wing aircraft was constructed. The aerodynamic stability and control derivatives were obtained from the XFLR-5 software. The effect of the distributed propulsion system was taken into account using the the integral momentum theorem. A grid based LPV model was obtained by Jacobian linearization. The scheduling parameter vector includes the airspeed, morphing wing chord and the payload mass. TP type polytopic model of the morphing wing aircraft is obtained from the grid based model via TP model transformation. A significant drop in the number of the vertex in the airspeed dimension was achieved. Finally, a gain scheduled inner loops of the baseline controllers were developed based on the grid based LPV model of the aircraft. The closed loop lateral and longitudinal dynamics of the aircraft have sufficiently high bandwidth and the lightly damped short period mode has increased damping to reduce oscillatory motion. Future steps of the research include investigating fault detection algorithms for the distributed propulsion system, optimal propulsion bending and advanced Kalman-filter development.

Acknowledgment

Innovációs és Technológiai Minisztérium

Supported by the ÚNKP-20-4 New National Excellence Program of the Ministry for Innovation and Technology.

This paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences.

The research reported in this paper and carried out at the Budapest University of Technology and Economics was supported by the ”TKP2020, Institutional Excellence Program” of the National Research Development and Innovation Office in the field of Artificial Intelligence (BME IE-MI-FM TKP2020).

This work was supported by Hungarian National EFOP-3.6.1-16- 2016-00014 project titled “Investigation and development of the disruptive technologies for e-mobility and their integration into the engineering education” (IDEA-E).

References

[1] D. Sziroczák, I. Jankovics, I. Gál, and D. Rohács, “Conceptual design of small aircraft with hybrid-electric propulsion systems,” *Energy*, vol. 204, p. 117937, 2020.

[2] I. Gál, D. Rohács, and J. Rohács, “Developing the unmanned unconventional cargo airplanes with hybrid propulsion system,” in *31st Congress of the International Council of Aeronautical Sciences (ICAS)*, 2018.

[3] D. Sziroczák, “Case study on development and building of a cargo hybrid UAV demonstartion model,” in *ISEAS & ISSA 2019 Conference*, 2019.

[4] K. Beneda and B. Sipula, “Design of an ultra-high bypass ratio fan stage for a research turbojet engine,” *Acta Avionica*, vol. 21, 2019.

[5] A. Deperrois, “Xflr-5, open source vlm software,” 2019.

[6] T. Gausz, “Szárnyprofil, szárny és légcsavar vizsgálata,” *Repülőgépek és Hajók Tanszék kiadványa*, 1995.

[7] J. S. Shamma, *Analysis and design of gain scheduled control systems*. PhD thesis, Massachusetts Institute of Technology, Cambridge, 1988.

[8] G. Becker, *Quadratic stability and performance of linear parameter dependent systems*. PhD thesis, University of California, Berkeley, 1993.

[9] F. Wu, *Control of Linear Parameter Varying Systems*. PhD thesis, Univ. California, Berkeley, 1995.

[10] A. Packard, “Gain scheduling via linear fractional transformations,” *Systems & Control Letters*, vol. 22, pp. 79–92, Feb. 1994.

[11] P. Apkarian, P. Gahinet, and G. Becker, “Self-scheduled h∞ control of linear parameter-varying systems: a design example,” *Automatica*, vol. 31, pp. 1251–1261, Sept. 1995.

[12] P. Baranyi, Y. Yam, and P. Varlaki, *Tensor Product Model Transformation in Polytopic Model-Based Control*. CRC Press, 2013.

[13] L. Kovács and G. Eigner, “Tensor product model transformation-based parallel distributed control of tumor growth,” *Acta Polytechnica Hungarica*, vol. 15, Mar. 2018.

[14] V. C. da Silva Campos, L. M. S. Vianna, and M. F. Braga, “A tensor product model transformation approach to the discretization of uncertain linear systems,” *Acta Polytechnica Hungarica*, vol. 15, Mar. 2018.

[15] Y. Kan, Z. He, and J. Zhao, “Tensor product model-based control design with relaxed stability conditions for perching maneuvers,” *Acta Polytechnica Hungarica*, vol. 15, Mar. 2018.

[16] R. W. Beard and T. W. McLain, *Small unmanned aircraft: theory and practice*. Princeton University Press, 2012.

[17] K. Towell, “Aerodynamics for engineers – sixth edition j. j. bertin and r. m. cummings pearson education limited, edinburgh gate, harlow, essex, CM20 2je, UK. 2013. 832pp. illustrated. £64.99. ISBN 978-0-273-79327-4.,” *The Aeronautical Journal*, vol. 118, pp. 455–456, Apr. 2014.

[18] R. M. Cummings, W. H. Mason, S. A. Morton, and D. R. McDaniel, *Applied Computational Aerodynamics*. Cambridge University Press, Apr. 2015.

[19] K. A. Deere, S. Viken, M. Carter, J. K. Viken, M. Wiese, and N. Farr, “Computational analysis of powered lift augmentation for the LEAPTech distributed electric propulsion wing,” 2017.

[20] K. A. Deere, J. K. Viken, S. Viken, M. B. Carter, M. Wiese, and N. Farr, “Computational analysis of a wing designed for the x-57 distributed electric propulsion aircraft,” in *35th AIAA Applied Aerodynamics Conference*, American Institute of Aeronautics and Astronautics, June 2017.

[21] M. Selig, “Modeling propeller aerodynamics and slipstream effects on small UAVs in realtime,” in *AIAA Atmospheric Flight Mechanics Conference*, American Institute of Aeronautics and Astronautics, Aug. 2010.

[22] B. Horvay, “Aerodinamika, repülésmechanika, súlypont,” 2019.