SIMULATION OF FLEXIBLE MECHANISMS IN A ROTATING BLADE FOR SMART-BLADE APPLICATIONS

A. Paternoster, R. Loendersloot, A. de Boer, R. Akkerman

Structural Dynamics and Acoustics,
Faculty of Engineering Technology,
University of Twente,
P.O. BOX 217
7500AE Enschede
The Netherlands

ABSTRACT

The active Gurney flap technology is investigated to improve the performance of rotorblades by allowing helicopter blades to further control the lift unbalance that rises at high speed and by damping vibration loads on the rotor hub. This technology needs validation by wind tunnel testing of a scaled model blade under rotational loading. An optimised geometry of a flexible actuation system has been designed to provide motion for the deployment of the Gurney flap for a Mach-scale model blade [1]. This paper presents the refinement of the flexible actuation system to allow deployment of the Gurney flap and simulation strategies to model the mechanism under loads due to the blade motion and the aerodynamic forces acting on the Gurney flap . The physics domains are addressed separately to be simulated with specific software packages. A co-simulation process permits the simulation of the Gurney flap motion under LMS Virtual.Lab Motion multi-body dynamic software [2] and the simulation of the flexible mechanism under Comsol Multiphysics Finite Element Model software [3]. This simulation scheme successfully models the mechanism under harmonic loads. For faster actuation input, the co-simulation is replaced by a one-way coupling which models the deployment mechanism under loads due to the rotation of the blade, the motion of the Gurney flap and the aerodynamics. The outcome of both simulations shows that the flexible deployment system is suitable for the actuation of the Gurney flap in the two actuation cases presented. The simulation scheme can be applied to simulate similar systems that are under constraints from a large variety of physical domains.

1. INTRODUCTION

Adaptive blades can significantly increase the performances of current rotorcraft systems. The efficiency and the maximum speed of a rotorcraft in motion depends on the lift provided by the retreating blade which is reduced by the helicopter forward speed. The Green Rotorcraft project (part of Clean Sky Joint Technology Initiative) is investigating an active Gurney flap to improve current rotorblades [4, 5]. Building a suitable actuation mechanism is complex due to the large mechanical and integration constraints present in a rotating rotorblade. This process involves the development of a one-eighth Mach-scaled model blade to investigate the performance of an active Gurney flap system in a wind tunnel environment.

To meet these challenges the research on flexible designs integrated within a rotorblade led to the development of a piezoelectric mechanism. This mechanism converts electrical signals into a complex motion that permits the deployment and folding of a Gurney flap at the trailing edge of the rotorblade profile [1]. To verify the proper operation of this system, more complex simulations need to be realised. This paper first summarises the Gurney flap technology and the current status of the research done at Twente University in the scope of Clean Sky JTI [4]. Then, simulation strategies for a multi-physics environment are presented along with results in the case of harmonic actuation and fast deployment.

2. BACKGROUND

2.1. The active Gurney flap concept

The Gurney flap is a small flap placed at the trailing edge, of which the length is typically 2% of the profile chord length [6, 7]. It improves the lift of a profile over a wide range of angles of attacks [8]. Furthermore, the Gurney flap provides both a better static and dynamic stall behaviour [9]. When a helicopter is in forward motion, the pitch angle of the rotorblade between the retreating and the advancing side is adjusted in order to balance the lift difference that rises from the airspeed mismatch as shown in Figure 1.

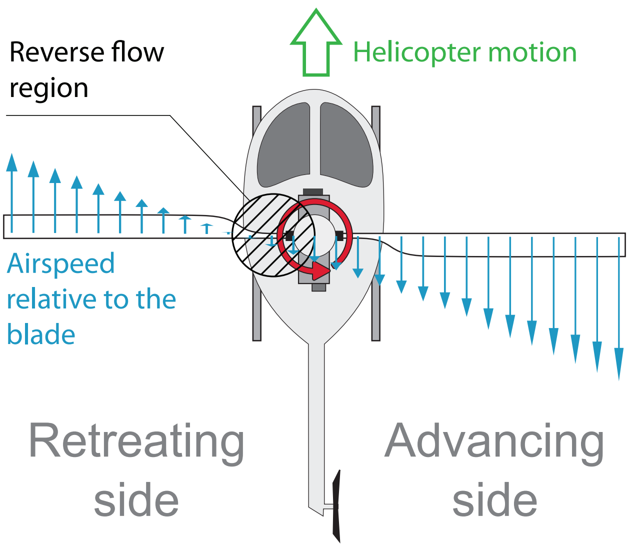


Figure 1: Unbalance of the airspeed around a helicopter in forward motion.

The lift difference limits the helicopter maximum speed because the pitch of the blade can only compensate the lift difference until the profile stall angle of attack is reached. The active Gurney flap aims at enhancing the lift on the retreating side of the helicopter to allow larger angle of attacks and therefore a faster and more efficient helicopter. As a consequence, the Gurney flap needs to be deployed quickly when the blade enters the retreating side. Appropriate performance is achieved when the Gurney flap is deployed within 10 degrees of sweeping angle.

Vibratory loads caused by the blade dynamics also limit the efficiency of the rotor, generate discomfort for passengers and noise which should be reduced while flying over densely populated areas. The Gurney flap can also actively damp adverse vibrations on the rotor by harmonic actuation at 1/rev, 2/rev and 4/rev [7, 10].

2.2. Mach-scale model blade for wind tunnel testing

The validation of the Gurney flap active system performance is an important milestone in the Clean Sky JTI program. Besides the fixed-wing wind tunnel test, a rotating blade test within a wind tunnel environment is scheduled to verify the correct behaviour of the Gurney flap for various flight scenarios. This requires the development of an actuation system for a Mach-scaled model blade. This system must answer the specific constraints linked to the scaling of the model blade as shown in Table 1.

Table 1: Comparison of the dimensions and the requirements for the full scale blade and the Mach-scaled model blade.

Property	Full scale	Model blade
Profile reference	Naca 0012	Naca 0012
Blade length	8.15 m	1 m
Rotation speed	26.26 rad/s	210 rad/s
Tip speed	214 m/s	214 m/s
Deployment within	7 ms	1 ms
Max g-acceleration	573 g	4500 g

2.3. Flexible deployment actuation mechanism

To meet the mechanical constraints, a mechanical system that comprises of piezoelectric patch actuators and bending beams has been designed and optimised [1]. The result is a Z-shape system that amplifies the strains generated by piezoelectric elements into significant horizontal motion close to the trailing edge. Refinement of this design leads to a reverse deployment system that comprises of two actuators to provide a rotational motion of 90 degree as shown in Figure 2.

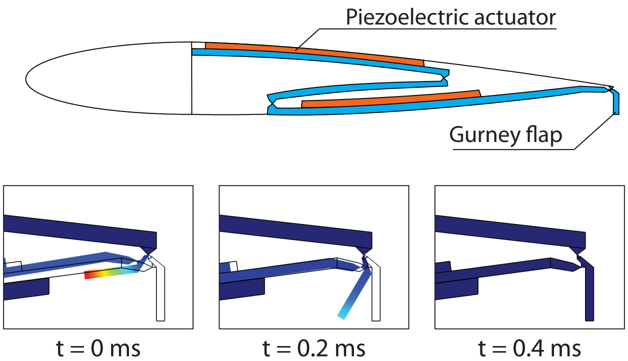


Figure 2: Sketch of the refined Z-shape deployment system and detail of the folding motion of the Gurney flap.

3. SIMULATION OF A GURNEY FLAP MECHANISM

3.1. Defining and simplifying a multi-physics model

Many physical domains need to be simulated to faithfully simulate a deployment cycle of the Gurney flap mechanism. Modelling a piezoelectric component requires an electrical domain and a mechanical domain. The structure on which the piezoelectric component is bonded to is part of the mechanical domain as well as the rotorblade in rotation. Finally, there is the aerodynamic domain, which models the interaction of the flow on the Gurney flap and on the rotorblade. The complexity of this problem is summarized in Figure 3.

Although many components are in the mechanical domain, it needs to be broken down to efficiently solve the piezoelectric coupling, the flexible elements of the deployment mechanism and the dynamics of a rotorblade. From the problem shown in Figure 3 simplifications were made to reduce the coupling between components. The following assumptions are made:

- the airflow forces are not applied on the rotorblade,
- the airflow forces are quasi-static on the Gurney flap,
- the voltage is imposed on the piezoelectric component,
- the piezoelectric mechanism has a limited influence on the rotorblade behaviour,
- the blade behaves as a rigid body.

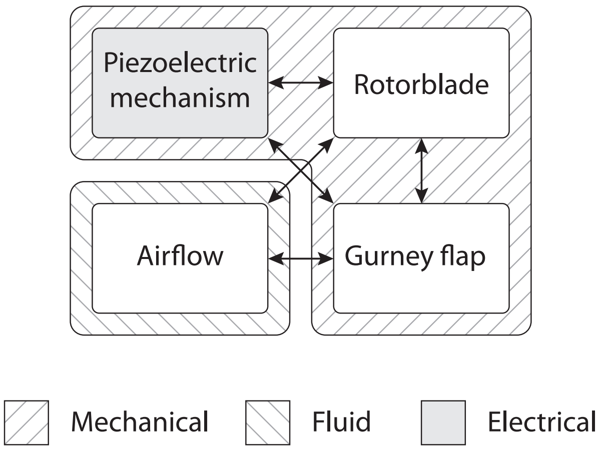


Figure 3: Distribution of physics domains across the components to simulate.

These assumptions lead to a reduction of the complexity of the problem as shown in Figure 4. The physical domains are distributed across 3 simulation environments. The multi-body simulation that comprises the rotorblade in rotation with the Gurney flap is performed with LMS Virtual.Lab Motion software [2]. The piezoelectric mechanism is modelled through Comsol Multiphysics within the piezoelectric physics environment [3]. The CFD simulations are performed with Comsol Multiphysics within the turbulent flow environment. These softwares were chosen for their capabilities to interface with Matlab: Comsol 4.2 can be executed as part of a Matlab script and Virtual.Lab Motion models can be exported as Simulink models where Virtual.Lab Motion solver can process them.

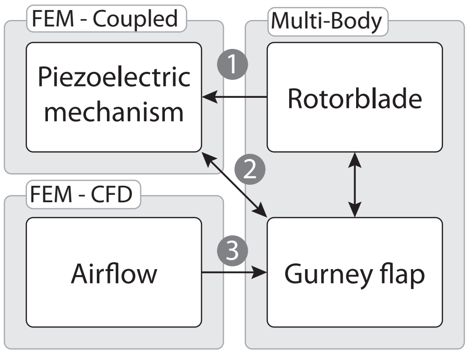


Figure 4: Model investigated. The connections between the softwares are ① one-way coupling, ② co-simulation and ③ data lookup table.

As shown in Figure 4, the connections between the simulations are kept to a minimum. The blade being hardly influenced by the motion of the mechanism a one-way coupling is set-up. The acceleration of the blade at the position of the mechanism is used to provide inertia forces in the mechanism during rotation (Figure 4 ①). A co-simulation process provides exchange of force and displacement data between the Gurney flap and the piezoelectric mechanism (Figure 4 ②). The force the airflow applies on the Gurney flap is taken into account with a data table comprising pressure data from a large set of CFD simulations under various conditions (Figure 4 ③).

3.2. Models considered

3.2.1. Piezoelectric FEM simulation

The mechanism is modelled in Comsol Multiphysics as a two-dimensional structure using plain strain assumption. A contact model is added to take the contact between the structure and the skin of the rotorblade profile into account. Finally the motion of the end part that drives the deployment of the Gurney flap is constrained to follow the kinematic relations set up in the multi-body dynamics model.

3.2.2. Rotorblade and Gurney flap multi-body simulation

The rotorblade is modelled as a rigid body. The hub of the rotorblade is modelled based on the blade definition for the full scale version of the blade. The rotorblade is trimmed to maintain zero pitch.

3.3. Coupling FEM analysis to Multi-body-Dynamics

Performing simulations of rotating elements within a multi-body dynamics software while keeping the simulation of flexible elements for a Finite Element Method, allows to maximise the efficiency of both solvers. Coupling these two solvers means exchanging force and displacement data. This is performed through a modified ping pong scheme. In a ping pong scheme the simulation is cut into timesteps at which data is passed from one solver to another [11, 12] as shown in Figure 5. The flexible piezoelectric mechanism simulation outputs displacements to the Gurney flap in the multi-body simulation that are applied as translations. The multi-body dynamics software calculates the reaction forces that are a sum of the forces due to the inertia, the imposed translations and aerodynamic pressure. This data is sent back to the FEM model of the piezoelectric mechanism with the acceleration of the blade due to its motion.

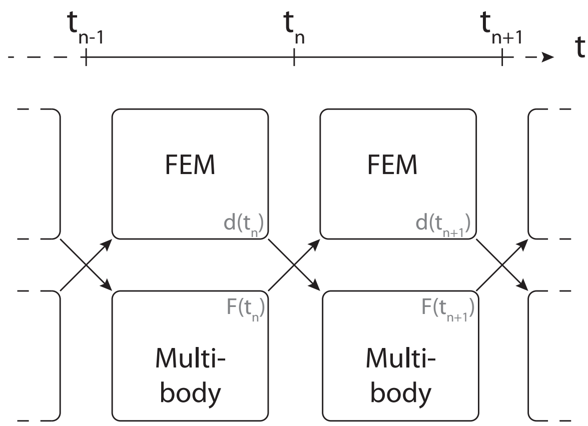


Figure 5: Ping pong scheme for co-simulation. The last computed values of the force and the displacement are exchanged at the time-step.

Investigation of the scheme is done through mass-spring systems. Early analyses show that a very small time-step is required to keep both solvers stable. In order to increase the time-step, the scheme is modified to provide more data to the multi-body simulation. This time the FEM analysis communicates data corresponding to the entire time-step. The multi-body simulation is run for the same time-step taking the complete time data of the displacement into account. The force obtained from the multi-body simulation for that time-step is extrapolated for the following time-step before sending it to the FEM analysis as shown in Figure 6. This modified scheme provides better stability for the same time-step size.

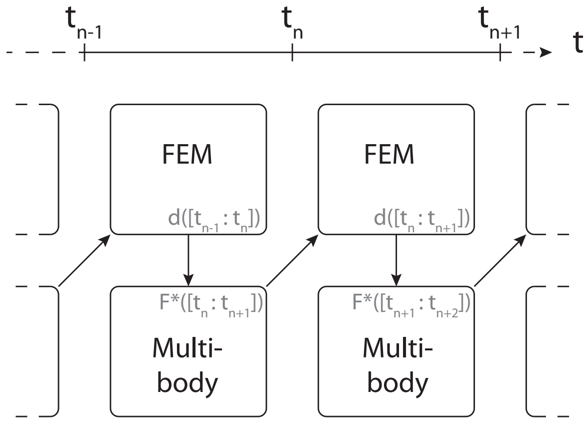


Figure 6: Modified ping pong scheme for co-simulation. The FEM sends the displacement of the full time-step while the multi-body simulation sends the force extrapolated for the next time-step.

The extrapolation function has a great influence on the outcome of the simulation, especially when the driving voltage is not smooth. The displacements calculated by the co-simulation scheme can vary significantly depending on the extrapolation function chosen as shown in Figure 7.

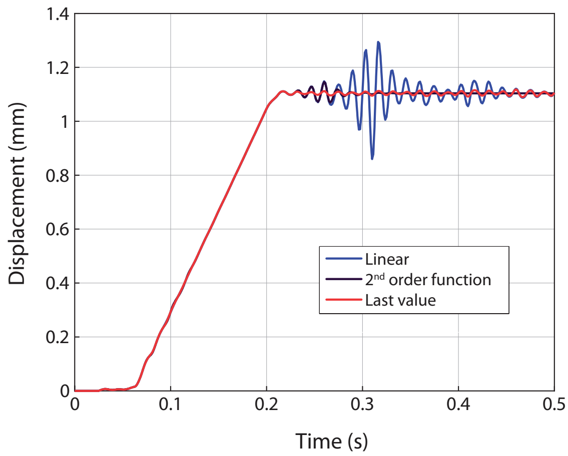


Figure 7: Displacement calculated on a simplified system using 3 different extrapolation functions to predict the force applied in the FEM when a square profile is used as voltage input.

A linear extrapolation tends to overestimate the loads which excites the structure further more. Choosing the value at the end of the time-step removes dynamic effects from the system. In this example, the second order polynomial provides the best results and is chosen for this model. The co-simulation process is therefore limited to situations where the loads are smooth and where the system has a response close to the extrapolation function.

3.4. CFD - lookup table

A quasi-static 2D turbulent CFD model is set up to estimate the force acting on the Gurney flap over the large combination of conditions for the rotor-blade and the Gurney flap. The variables taken into account are:

- the velocity of the airflow far from the blade,
- the angle of attack of the profile,
- the deployment angle of the Gurney flap.

The force increases with larger angles of attack, deployment angles and airflow speeds as shown in Figure 8. This force is implemented in the multi-body simulation as an external force and is calculated as a function of the three parameters mentioned earlier by an external function for each time-step of the Virtual.Lab Motion solver.

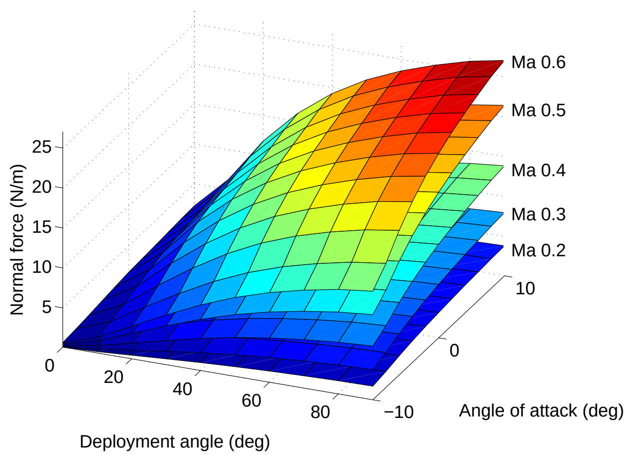


Figure 8: Force acting on the Gurney flap for various airflow speeds as a function of the angle of attack of the profile and the deployment angle of the Gurney flap.

4. RESULTS AND DISCUSSION

4.1. Forced deployment with no blade rotation

The co-simulation process was sufficient to correctly simulate harmonic deployment of the Gurney flap at low frequencies (210 rad/s – 1/rev) for a fixed blade. Separating the force applied by the flow reveals that the airflow is the main force acting on the piezoelectric mechanism as shown in Figure 9.

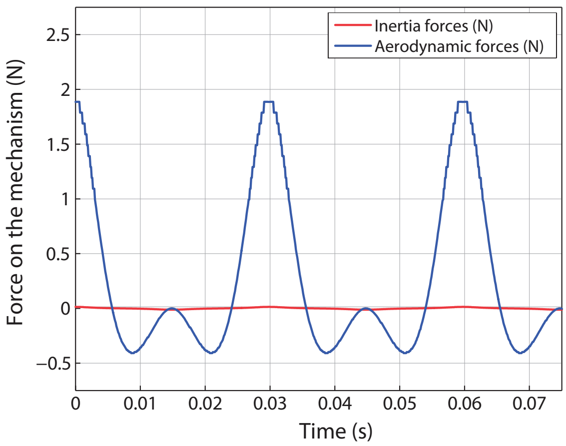


Figure 9: Force acting on the mechanism when deploying the flap at 210 rad/s (1/rev).

Unfortunately, the co-simulation process was unable to provide insight for deployment speeds in the range of the requirements for the fast Gurney flap deployment. This is due to the instability of the co-simulation during faster operation. Decreasing the time-step may solve that issue but requires extra computation time and power that was unavailable. Further improvements can be formulated to refine the co-simulation scheme.

A simplified analytical expression of the system can be chosen as an extrapolation function to better reflect the dynamics of the system and therefore increase the stability of the simulations. For systems with a short response time, it might be of interest to modify the co-simulation process by solving the same time-step multiple times until the error between the two solvers for one parameter is below a defined threshold.

4.2. Blade simulation under rotation.

To simulate faster and step actuation profiles, the co-simulation is replaced by a one way coupling as shown in Figure 10.

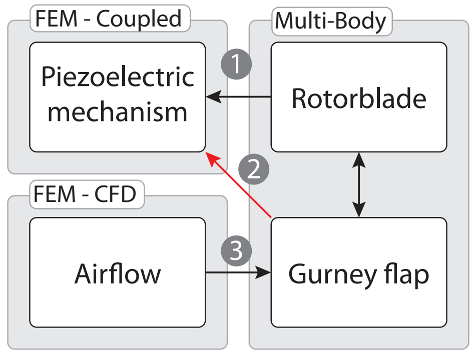
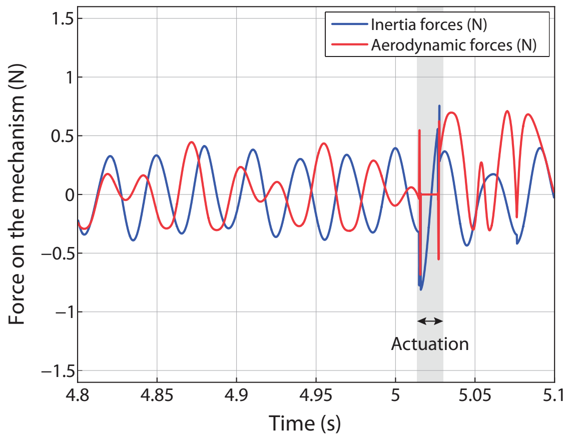


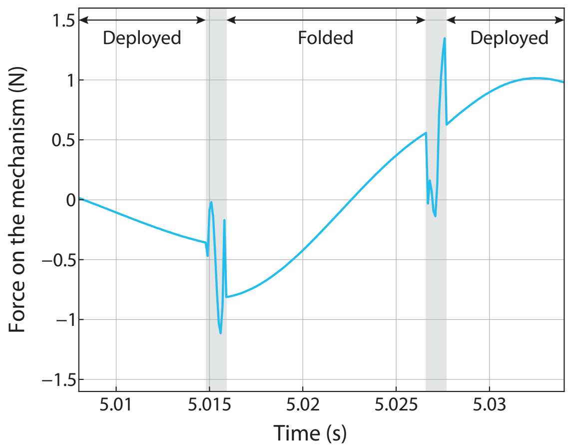
Figure 10: Model investigated. The connections between the softwares are ① one-way coupling, ② co-simulation replaced by one-way coupling and ③ data lookup table.

The multi-body simulation and the FEM are therefore independent. First the multi-body simulation is performed with the airflow force acting on the Gurney flap. The blade is accelerated until the operational rotation speed of 2000 rpm is reached. Then, the Gurney flap is actuated by a position driver with follows the following profile: the flap is first folded within 1 ms before being deployed after half a blade revolution within the required 1 ms. Data concerning the reaction forces and the acceleration of the blade due to its rotation is stored.

This data is then used in the FEM analysis to take into account the effect of the vertical and longitudinal acceleration due to the rotation of the blade and the lead/lag motion. A voltage profile is applied to the piezoelectric components following the same square profile applied in the multi-body simulation. In the multi-body simulation, contrary to the harmonic deployment case, the forces on the mechanism due to the dynamics of the blade and the forces due to the airflow have the same order of magnitude as shown in Figure 11 (a). Combination of the two force gives the force the mechanism need to deliver for a 1 ms deployment as shown in Figure 11 (b).



(a)



(b)

Figure 11: (a) Oscillations of aerodynamic and inertia forces on the mechanism over multiple rotations of the helicopter blade. (b) Force on the mechanism during the folding and deployment phase of the Gurney flap.

This data is then included in the FEM analysis of the piezoelectric mechanism along with the loads due to the blade rotation. The resulting transient analysis shows that the piezoelectric mechanism is capable of switching the deployed and folded position within the required deployment duration as shown in Figure 12. However as damping is not implemented inside the FEM analysis significant vibrations are present in the folded position and once the flap is deployed again. In the final mechanism, control will be applied on the piezoelectric actuator to ensure correct positioning and avoid the excitation of the deployment system.

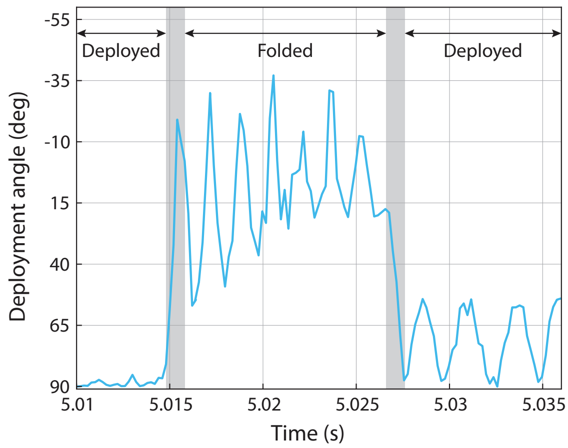


Figure 12: Deployment angles computed by the FEM analysis.

5. CONCLUSION AND FUTURE WORK

Adaptive blade technologies can significantly increase helicopter performances by tuning a blade characteristics to the surrounding aerodynamic conditions. The Gurney flap concept provides a mean to change these characteristics and the Z-shape actuation system provides the required force and displacement to deploy it according to quasi-static simulations. This paper explores simulation processes to model a set of physical domains to get realistic insights on the Gurney flap performances under two main types of loading. The harmonic deployment for vibration and noise control can be simulated with the proposed co-simulation scheme. In the case of a fast deployment in the retreating side of the helicopter, the co-simulation is not stable enough to simulate the motion of the Gurney flap. The alternative method presented decouples the multi-body simulation that provides the reaction loads from the FEM analysis which calculates the displacements. Therefore, the simulations are run separately and provide a detailed analysis of the loads the flap is subjected to and demonstrates that the Z-shape mechanism can switch from one configuration to another within the required 1 ms.

This paper proves the relevance of flexible piezoelectric mechanism for the deployment of the Gurney flap which comply with the mechanical constraints of a Mach-scale helicopter model blade. Future work include the manufacturing of a prototype and its testing fixed in a wind-tunnel.

The simulation processes presented in this paper can be applied to similar situations where many tools are required to model complex physical domains.

6. ACKNOWLEDGEMENTS

LMS is gratefully acknowledged for its participation in this study and especially Yves Lemmens for his contribution and expertise on modelling using LMS Virtual.Lab Motion.

This project is funded by the Clean Sky Joint Technology Initiative (grant number [CSJU-GAM-GRC-2008-001]9) - GRC1 Innovative Rotor Blades, which is part of the European Union's 7th Framework Program (FP7/2007-2013).

7. REFERENCES

[1] A. Paternoster, R. Loendersloot, A. Boer de, and R. Akkerman. Geometric optimisation of a gurney flap hinge-less deployment system for a helicopter model blade. In *Proceedings of the 37th European Rotorcraft Forum*, November 2011.

[2] LMS. LMS Virtual.Lab Motion simulation software. *http://www.lmsintl.com*, 2012.

[3] COMSOL. COMSOL Multiphysics Engineering Simulation Software. *http://www.comsol.com*, 2012.

[4] CleanSky. Clean Sky Joint Technology Initiative. *http://www.cleansky.eu*, 2012.

[5] W. Maybury and Et al. GRC1.1 Technology Review Document. Technical report, CS JU/ITD GRC/RP/1.1/31005, 2010.

[6] J.J. Wang, Y.C. Li, and K-S. Choi. Gurney flap-Lift enhancement, mechanisms and applications. *Progress in Aerospace Sciences*, 44(1):22–47, January 2008.

[7] K. Yee, W. Joo, and D-H. Lee. Aerodynamic Performance Analysis of a Gurney Flap for Rotorcraft Application. *Journal of Aircraft*, 44(3):1003–1014, May 2007.

[8] M.D. Maughmer and G. Bramesfeld. Experimental Investigation of Gurney Flaps. *Journal of Aircraft*, 45(6):2062–2067, November 2008.

[9] M.R. Thiel and G.A. Lesieutre. New Actuation Methods for Miniature Trailing-Edge Effectors for Rotorcraft. *AIAA Proceedings*, (May), 2009.

[10] Y.H. Yu, B. Gmelin, and W. Splettstoesser. Reduction of helicopter blade-vortex interaction noise by active rotor control technology. *Progress in Aerospace*, 33(97):647–687, 1997.

[11] M. Trčka, J.L.M. Hensen, and M. Wetter. Co-simulation for performance prediction of integrated building and HVAC systems âĂŞ An analysis of solution characteristics using a two-body system. *Simulation Modelling Practice and Theory*, 18(7):957–970, August 2010.

[12] J.L.M. Hensen. A Comparison of Coupled and Decoupled Solutions for Temperature and Air Flow in a Building. *ASHRAE Transactions*, (105):962–969, 1999.