A LOCKING SYSTEM TO GUARANTEE AEROELASTIC STABILITY OF A WING MOVABLE SURFACE

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Abstract

When dealing with Civil Tiltorotors, safety assumes a crucial role in the design of the entire machine. The Leonardo Helicopter Next Generation Civil Tiltrotor is featured with a wing movable surface (called Morphing Wing) whose actuation and aeroelastic stability is ensured by means of two hydraulically independent actuators controlled by the same computer. Nevertheless, to comply with Civil Aviation rules, a passive mechanical system has been developed to backup the hydraulic actuators in case of their failure: the Locking Mechanism. Made of a spring-based component and a levers system, the Locking Mechanism is a passive reversible system that is engaged and disengaged by the moving surface actuators. It is able to provide a tunable preload in order to ensure the desired connection stiffness of the moving surface, moreover its levers system provides advantageous forces throughout its movement. A numerical analysis performed through Matlab and Amesim verified the Locking Mechanism capability to satisfy design requirements and has allowed to identify the mechanism performances, highlighting its tunability hence the wide usage spectrum.

1. NOTATION

Symbols

t	Time, s
β	Bellcrank orientation angle, deg

Acronyms

FCC	Flight Control Computer
LHD	Leonardo Helicopters Division
LM	Locking Mechanism
MW	Morphing Wing
NGCTR	Next Generation Civil Tiltrotor

2. INTRODUCTION

Hovering performance and lifting capability of tiltrotor aircrafts are strongly affected by the aerodynamic interaction between wing and rotors. In helicopter flight mode, the presence of the wing under the rotor modifies the rotor wake and thus is responsible for the loss of around 10% of the rotor thrust [1].

New tiltrotors projects aim to reduce wing-rotor interaction in order to increase performance, increase available payload and reduce fuel consumption. In this regard, Leonardo Helicopters is developing a Next Generation Civil Tiltrotor (NGCTR) equipped with a Morphing Wing such that, when the aircraft is in helicopter mode, the wing surface exposed to the rotor wash is minimized, thus reducing thrust wastage. NGCTR Morphing Wing (patent EP3674202B1 filed by Leonardo [2]) is a movable surface that operates in two discrete states:

- *Deployed* at a maximum angle of deflection when the tiltrotor flies in helicopter mode at low forward speeds.
- *Stored* in horizontal position when the tiltrotor flies in airplane mode at high forward speeds.

2.1. NGCTR Morphing Wing system

In normal operation, the surface position is controlled by means of two hydraulic servo-actuators, connected to two independent hydraulic systems. The actuators move the surface and provide the desired connection stiffness when the surface is stored. This is aligned with what usually typically employed for non-critical flight surfaces, however the two actuators are controlled by the same Flight Control Computer: in case of failure of the FCC, the Morphing Wing actuation function would be lost.

If there was no back-up system of the actuators, in the airplane mode condition at high forward speeds, the low stiffness of the connection of the movable surface to the fixed wing could lead to controllability issues and eventually flutter. Then, a minimum value for connection stiffness shall be ensured in all nominal and failure conditions.

Civil Aviation rules state that aeroelastic stability of the Morphing Wing must be guaranteed within the entire flight envelope both in nominal and in all failure conditions not demonstrated to be extremely improbable (FAR AC 25.629 and Appendix K). Therefore, in the event of FCC failure or in the event of single or double hydraulic failure, a backup system of the hydraulic actuators is needed to keep the Morphing Wing in horizontal position and to guarantee the stiffness for aeroelastic stability.

2.2. Locking system design requirements

The backup system design requirements are related to the minimum preload on the Morphing Wing upstop, which results in the connection stiffness that ensures aeroelastic stability in case of actuators failure. Considering an increment of 10% as a margin, the minimum preload that the device has to apply on the upstop is estimated in 75% of the actuator stall load.

At the same time, the force required for the disengagement of the locking device must be lower than the actuator stall load: in normal operative conditions, at low flight speeds the actuators have to be able to overcome the LM resistance and deflect the Morphing Wing. An additional design constraint is the tight space available on the Morphing Wing frames, as noticeable in Figure 1.

Moreover, it is aimed to be a redundancy of the hydraulic actuators: it follows that it has to be independent of the hydraulic system. Being simplicity and reliability also a desired feature, the ideal solution is a mechanical passive system that does not require external inputs.

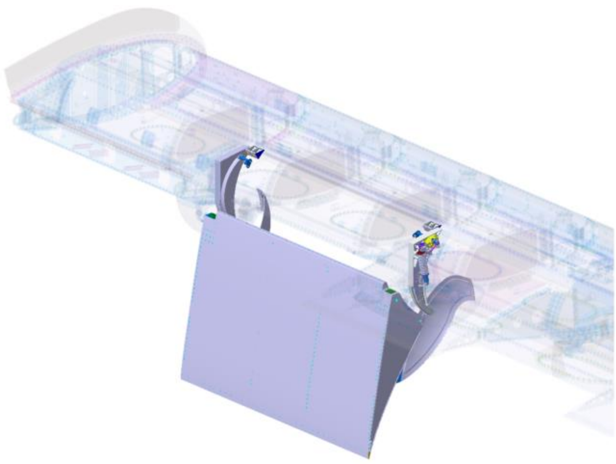

Figure 1. NGCTR Morphing Wing deflected Position

2.3. State of the art

In order to identify the desired solution, the state of the art has been deeply investigated, but it resulted that none of the solutions is able to guarantee the aeroelastic stability of the Morphing Wing. Exploring the literature, the designs that can be found just partially solve the aero-elastic stability problems.

Bell Helicopter Textron patented and developed a system [3] to provide and measure a desired preload between two moving parts (Figure *2*). In particular, that system is used between a fuselage and a nacelle in a tiltrotor application. When a tiltrotor is used in Airplane mode, the Nacelles are rotated horizontally. To provide aero-elastic stiffness to the connection, the conversion actuator used to rotate the nacelles pushes the Striker on the Cradle. The preload applied to the connection is read from a set of strain gauges in-stalled on the Striker: the higher the Striker deformation, the higher the preload. Thanks to the strain gauges, the preload value can be finely controlled depending on the application need, and failures can be easily detected. Even if it is an on-demand tunable configuration, this solution is deemed very complex, space consuming and heavy. To provide the preload it is used an external actuator, which failure will cause the complete preload loss. Ideal is to have a purely passive mechanical mean able to give a preload, characterized by high reliability and low weight.

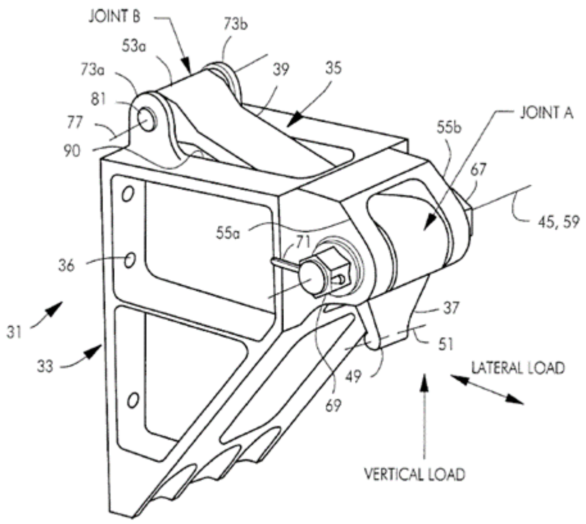

Figure 2. US6220545B1 Patent

Figure *3* shows a mechanism developed and patented by Bell Textron Inc. [4] to fold blades in a pitch-lock position or prevent blade folding in a fold-lock position. The design is based on linkages connected to rotating elements which allow blades to be moved in two different configurations: they can be set in folded position with locked pitch or in extended position with folding locked. The movement from one configuration to another is performed by means of an actuator, while the locking is ensured by spring-like elements.

Even if the described mechanism can combine movement and locking in one assembly, the locking is not redundant, and does not solve safety issues in NGCTR application. Most of all, this device is not able to provide a sufficiently high preload, since it was not designed with the aim of ensuring any aeroelastic stability.

The need of developing an innovative concept able to enclose within himself unique peculiarities is mandatory for the present application.

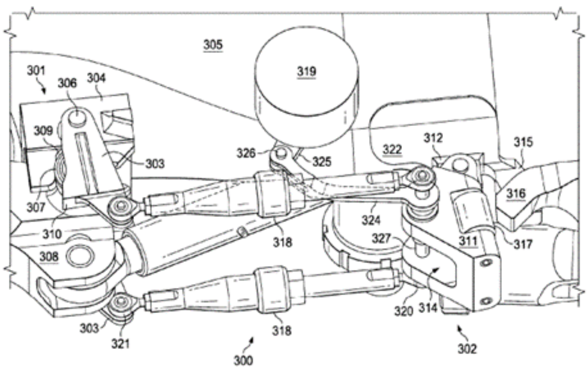

Figure 3. US 11,511,848 B2 Patent

3. LOCKING MECHANISM DESCRIPTION

3.1. General

The solution chosen by Leonardo Helicopters as a backup of the hydraulic actuators of the Morphing wing is a fully passive mechanical locking device, also called Locking Mechanism. LHD has filed a patent application regarding the present solution.

Figure 1 shows the NGCTR Morphing Wing at maximum deflection angle, installed on the fixed wing: two Locking Mechanism are mounted on the two frames at the lateral endings of the Morphing Wing. Figure 4 shows a detail of the Locking Mechanism within the Morphing Wing frames in deployed state.

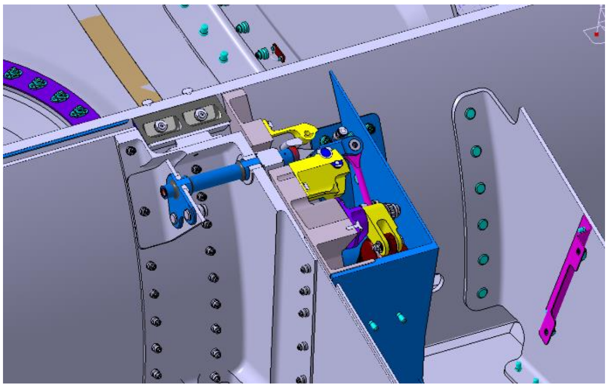

Figure 4. Locking Mechanism – Wing View

The preloading capability is function of a pre-compressed spring. The spring force is transmitted through a system of levers to a *rolling pin* (the blue pin in Figure 4), which is integral with the movable surface shown in Figure 5.

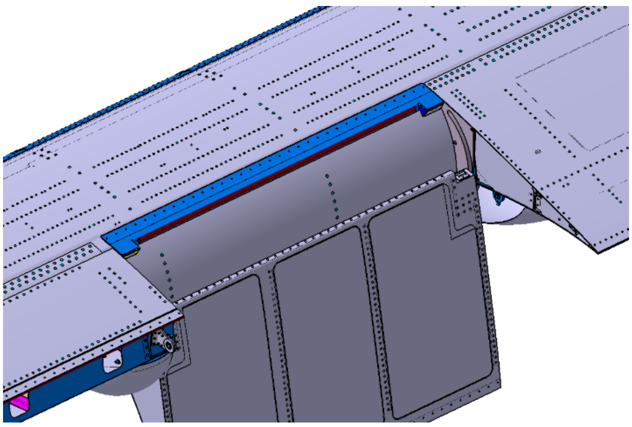

Figure 5. Morphing Wing - Detail

The rolling pin creates the physical connection between the movable surface and the fixed wing. When the hydraulic actuators are triggered and the Morphing Wing is moving, the rolling pin moves along a curved track on the Morphing Wing frame.

When the Morphing Wing is horizontal (stored configuration), the rolling pin is *locked* in the lever system of the Locking Mechanism. To deploy the Morphing Wing, the actuators have to provide to the rolling pin (integral to the Morphing Wing) sufficient force to push the levers and further compress the Locking Mechanism spring: then, the LM is disengaged and the rolling pin is free to move along its track. A sliding pin keeps the LM in disengaged position blocking the spring expansion.

When the Morphing Wing is deflected (deployed configuration), the rolling pin is *unlocked* from the lever system, which means free to move along its track according to the actuators input. Therefore, during the upward movement of the Morphing Wing, the LM does not oppose any significant resistance (a part from the force required to remove the sliding pin).

When the Morphing wing reaches the horizontal position, the Locking Mechanism is mechanically triggered: during the motion, the sliding pin is extracted and the spring can expand.

4. NUMERICAL ANALYSIS OF PERFORMANCES

4.1. Preliminary design and analyses

The Locking Mechanism design was performed through Catia V5. A Matlab model of the system was developed to support the preliminary design phases in order to verify the fulfilment of constraints and to optimize the solution.

Among the requirements mentioned in chapter 2.2, the main functional requirement of the Locking Mechanism is the capability to provide a preload on the Morphing Wing upstop: by providing a preload, the fixed wing and the movable surface are forced to stay in contact, thus obtaining a certain connection stiffness. The value of the necessary preload estimated by aeroelastic calculations was used as design input.

Since reliability is of key importance, a passive mechanical system was preferred with respect to active means such as pneumatic actuators, electrical actuators or complex mechanical devices such as geared mechanisms or ballscrews. Spring-like design appeared to be the best choice from the beginning, since it allows to adequately tune the necessary preload and to keep the entire design simple.

Another fundamental requirement for the system is its reversibility: the system shall provide a preload in Morphing Wing stored condition but shall also be able to be disengaged when preload is not of interest (during Morphing Wing deflection). Reversibility was obtained with a relatively simple mechanical system of linkages.

- In deployed configuration the system gradually moves toward a condition of series of rotating levers leading to a decreasing of the resistant force due to angle change.
- In stored configuration the system can exert on the rolling pin the maximum available force thanks to a sequence of rotating levers that amplify the input load due to angle change.

Figure *6* is a clear explanation of what just described. When the morphing wing is horizontal, the system is in preloading configuration: the spring works at about 55% of its total stroke. The spring force is amplified by the levers resulting in a higher effective force on the rolling pin (about 80% of stall load). Both the spring and the levers can be tuned in order to reach the desired requirement on the force exchanged with the rolling pin.

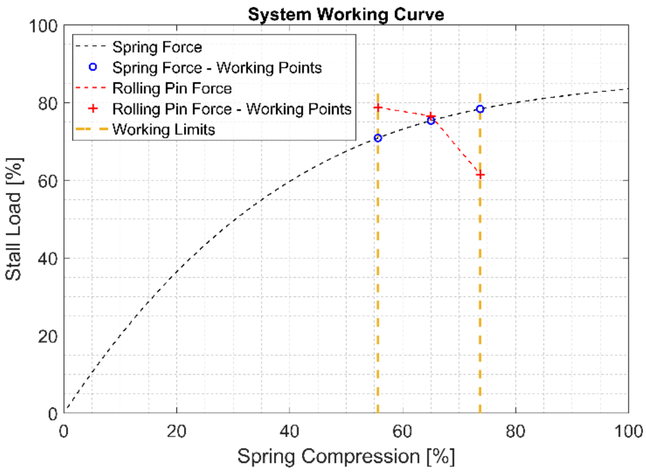

Figure 6. Locking Mechanism Working Curve (see Appendix A)

When the Morphing Wing moves toward the deployed configuration, the system shall move from the preloading configuration to the unlocked rolling pin configuration. Since the Morphing Wing is moving against the system, the higher is the Locking Mechanism resisting force, the higher is the wasted power to move the Morphing Wing. Thanks to an accurate levers design, the system is able to take down its given force while moving from stored condition to deployed condition, decreasing it by almost 20%, even if the spring is more compressed: in this configuration the spring stroke reaches almost 75% of the total spring stroke, while the spring force increases by 10%.

The change of configuration from Deployed to Stored state and vice versa exploits only the hydraulic actuators embedded in the tiltrotor hydraulic system, leading the LM to be a fully passive system. Being the system fully mechanical, high reliability is ensured.

The characteristic curve shown in Figure *6* is the most suitable one for the present design: this allows to exploit a spring element whose force rate is quite low, within a range which is almost linear.

Depending on the Spring-like component and levers the working stroke can be adjusted in order to meet the design requirements. Figure *7* shows different spring elements configurations which allow to meet the load requirements while keeping the same stroke. This shows the very high system configurability, making the system suitable for each purpose. In the same manner, the load extremes can be kept fixed while changing the necessary stroke.

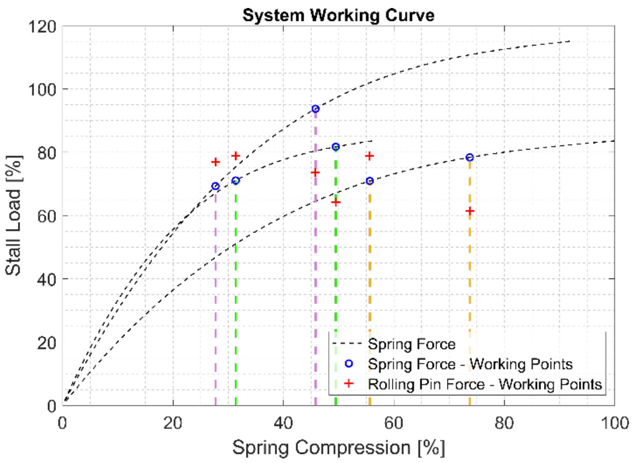

Figure 7. Locking Mechanism Working Curve Sensitivity Analysis (see Appendix A)

Once the conceptual design is known, a detailed designed is carried out through CATIA, identifying all the necessary components.

4.2. Siemens Amesim model

A Siemens Amesim model was implemented to simulate the functioning of the final design of the Locking Mechanism. The objective of the analysis was to validate the Matlab calculations and verify the capability of the device to meet design constraints and operational requirements.

This Amesim model simulates its operation from horizontal to deflected Morphing Wing and vice versa. The forces exchanged by the mechanism and the rolling pin can be computed in the two operative conditions.

The schematization of the locking mechanism was carried out progressively by studying one component at a time and, then, including it into the global sketch. In the global sketch, one simplifying assumption was introduced: the three-dimensional Locking Mechanism was simplified with an equivalent bi-dimensional model. To make this system equivalent to the original one, a rotation of the reference frame was applied.

To create the Amesim model, the libraries exploited were signal and control, 1D Mechanical and 2D Mechanical. The Amesim sketch of the locking mechanism is reported in Figure 8.

Figure *9* shows the Amesim preview of the bi-dimensional Locking Mechanism. The orange shapes in Figure *9* represent the actual shapes of the rolling pin and of the bodies that it contacts: this allows to simulate also the sliding of the components and the related friction force.

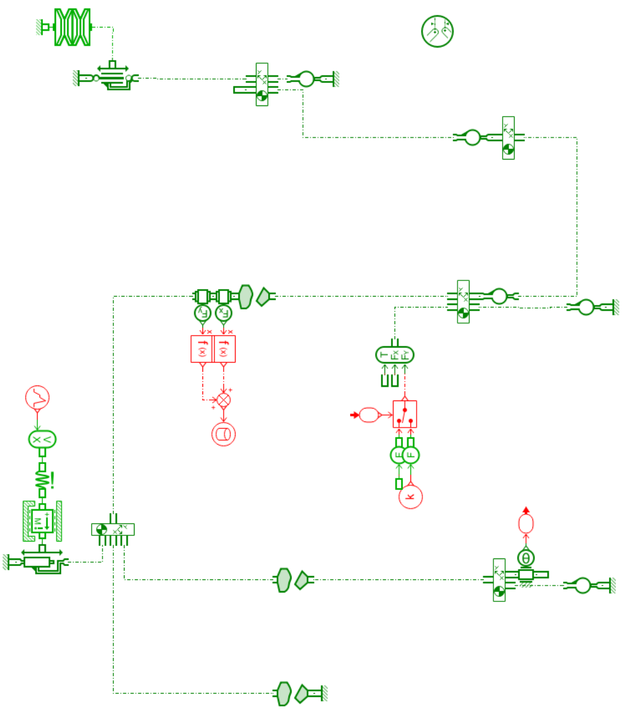

Figure 8. Amesim sketch of the Locking Mechanism

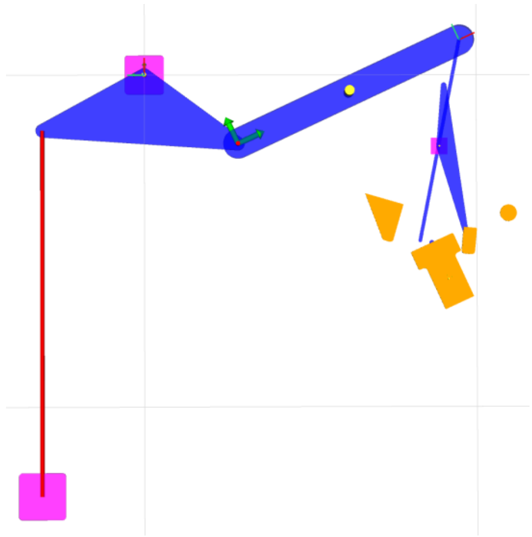

Figure 9 Amesim preview of the Locking Mechanism

As a consequence of the 2D simplification, the sliding pin that blocks the spring expansion could not be implemented in the 2D model. The adopted solution relies on a support model that assess the magnitude of the reaction that the blocking pin would apply to counteract the force of the spring. The support model is depicted in Figure *10*. The force obtained thanks to the support model is then imposed in the global model.

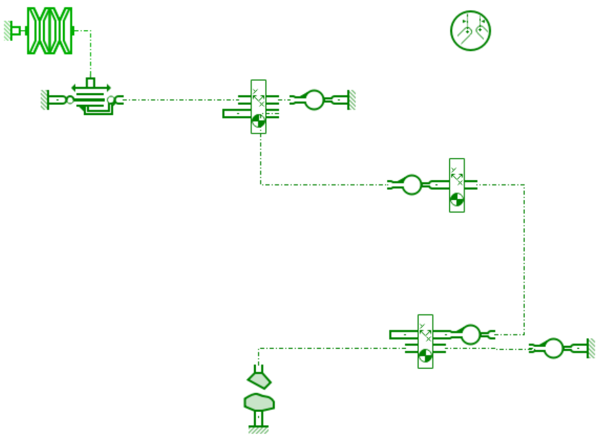

Figure 10. Amesim sketch of the support model

4.3. Siemens Amesim results

This Amesim model simulates its operation from horizontal to deflected Morphing Wing and the opposite movement.

Figure 11 displays the trend over time of the spring force superimposed on the force applied to the rolling pin (roller force) in the direction of its translation: this force component corresponds to the force provided by the actuator to the roller. The force values were normalized with respect to the actuator stall load.

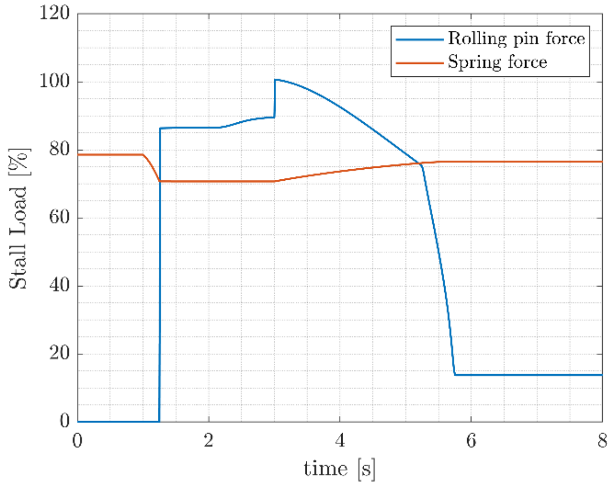

Figure 11. Spring force and roller force trend

The system is initially in equilibrium in deployed configuration. In this condition the rolling pin is unlocked, so it is free to move according to the actuators input: the force that it exchanges with the mechanism is null.

At the time instant t≈1s, the Locking Mechanism locking pin is removed and the spring expands until when the trigger contacts the rolling pin. The condition from t≈1.3s and t=3s corresponds to the horizontal Morphing Wing when the rolling pin is locked inside the Locking Mechanism: the value of the “roller force” in this time interval is the preload that the Locking Mechanism provides to the Morphing Wing upstop. Amesim evaluates that the preload is around 86% of the actuator stall load, so the the minimum requirement (75% actuator stall load) is satisfied.

From t=3s the Amesim model simulates the Locking Mechanism operation during the Morphing Wing deployment. To disengage the device, at t=3 s the rolling pin applies to the levers an additional force provided by the Morphing Wing actuators and activates the lever system. The peak value of roller force recorded at t=3s is the force that the roller must be able to apply to the trigger to unlock the system. It can be noted that the release of the Locking Mechanism requires the 100% of the actuator capacity. The fact that there is no margin in actuator force isn’t a concern considering that the actuator stall load estimation is very conservative. Moreover, this is mainly due to the dynamics where the rolling pin starts moving instantaneously, with a defined velocity. Notice that the peak lasts for few milliseconds.

From t≈3.1s to t≈5.5s the rolling pin pushes the lever system and compress the spring. The spring force increases but the roller force decreases: the rotation of the lever system modifies the relative angles between the levers, so the roller has to counteract just a component of the spring force and then the force needed by the roller to continue its movement and unlock the mechanism is reduced.

From t≈5.8s the only resistance the rolling encounters is the friction on the Locking Mechanism surface.

Appendix A and Figure 12 provides nine frames of the Amesim simulation of the Locking Mechanism functioning.

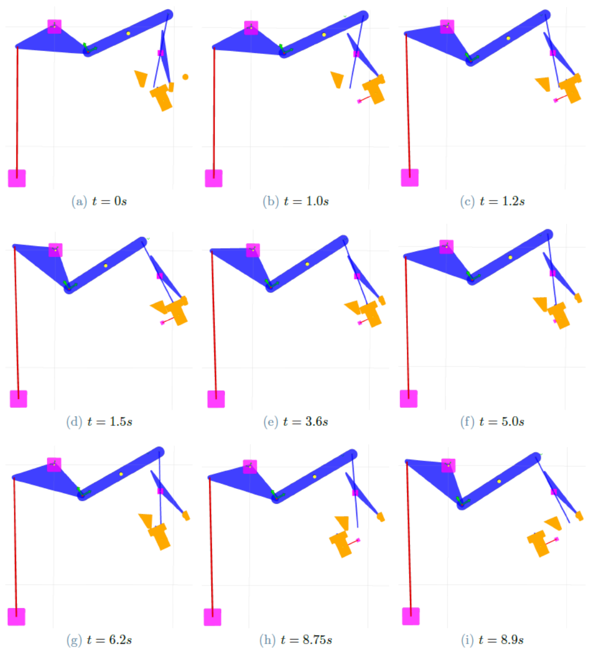

Figure 12. Spring Orientation Parametric Analysis

4.4. Siemens Amesim Parametric Analysis

Siemens Amesim was also used to perform a parametric analysis to evaluate the Locking Mechanism performance and its sensitivity to design parameters, with the intention to optimize the design. The parameters studied are related to the spring properties, to the kinematic angles and to the rolling pin velocity.

Also cases that do not fulfil the tightening space constraints of the NGCTR Morphing Wing system were taken into account: these non-compliant cases are still analyzed for future applications of the Locking Mechanism besides the NGCTR Morphing Wing.

In first place, the velocity of the rolling pin movement was varied. It resulted that, in the Morphing Wing deflection phase, the higher is the desired deflection velocity, the higher the force required to the rolling pin to disengage the Locking Mechanism (Figure 13). Increasing the unlocking time, the unlocking force lowers, however the reduction becomes progressively less significant. The best trade-off is a rolling pin velocity in the MW deflection phase three times lower than the MW retraction phase.

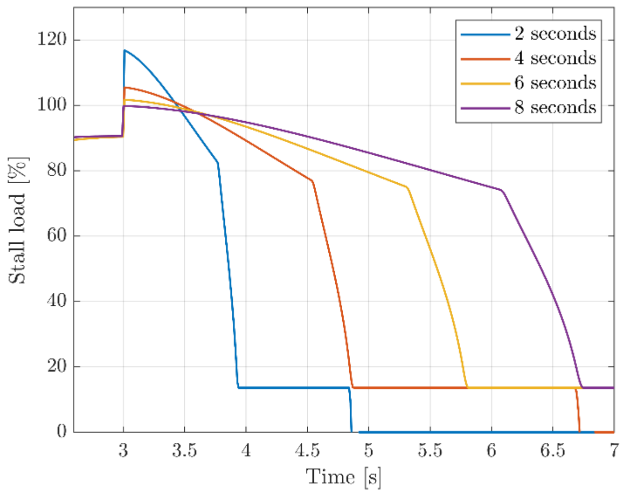

Figure 13. LM unlocking force varying unlocking time

In second place, the spring orientation was considered: a variation in the spring force direction modifies the transmission ratio that amplifies or attenuates the spring force. More precisely, the parameter studied is the angle β, defined as shown in Figure 14, as the bellcrank orientation of the LM when MW is deployed.

The Amesim model was then executed for the seven bellcrank orientations: the more the angle β is increased, the less the spring expansion is allowed by the lever system. Figure 15 displays the trend over time of the roller force for the seven bellcrank orientations. Increasing β, the preload provided by the Locking Mechanism on the rolling pin increases, then it reaches a peak and finally decreases. Looking at the unlocking phase, (from t = 3.1s to t = 5.75s), it can be noticed that the bellcrank orientation affects the curves peak and slope (Figure 15).

The Locking Mechanism requirements demand the highest possible preload on the upstop but simultaneously low unlocking force. The best tradeoff would be given by β = 38.9°.

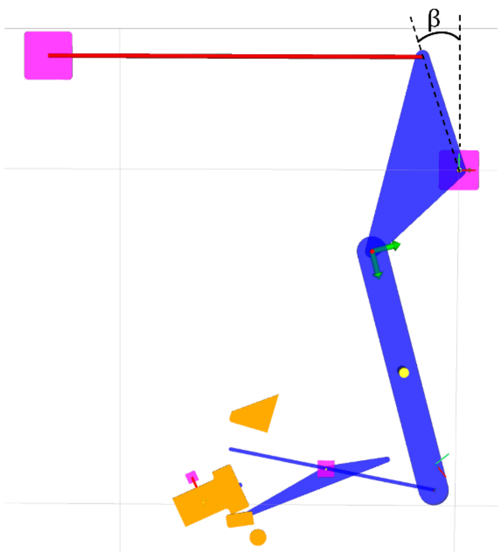

Figure 14 Definition of spring orientation

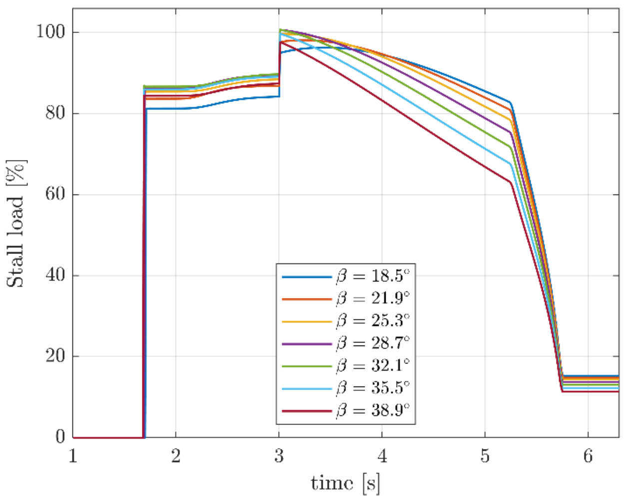

Figure 15 Roller force varying bellcrank orientation

The locking mechanism performances are very sensitive to the bellcrank features: arms length and angle between them. For an application with less tightening space constraints, it might be possible to replace the current bellcrank with a more suitable one: with either both rod and spring arms equally longer or with only the spring arm longer. However, the choice of the bellcrank for the NGCTR Morphing Wing Locking Mechanism was driven by the space available on the Morphing Wing frames.

A variation in spring properties can change heavily the locking mechanism operability as well. The spring parameters that can be modified in a different application of the Locking Mechanism are the spring length, stiffness and the initial compression. Modifications in spring properties are the most simple way to tune the Locking Mechanism preload, keeping unchanged the Locking Mechanism design.

5. CONCLUSIONS

The present article purpose is to describe the design and the numerical analysis of a fully mechanical system able to guarantee aeroelastic stability of a wing movable surface named Morphing Wing Locking Mechanism. This device is aimed to backup the two hydraulic servoactuators of Next Generation Civil Tiltrotor Morphing Wing ensuring the Triple Redundancy typical of Civil Aviation rules. During normal operation, the Morphing Wing aeroelastic stability is guaranteed by the hydraulic actuators. In case of a single or double hydraulic failure, the Locking Mechanism keeps the Morphing Wing in position ensuring aeroelastic stability. While looking for a backup system, the state of the art was deeply investigated, nevertheless none of the existing solutions results suitable. The solution identified exploits a Spring element and a system of levers which provides a preload to a rolling pin integral to the Morphing Wing.

The device was designed in order to provide a preload to the Morphing Wing rolling pin equal to the 80% of actuator stall load. Simultaneously, the load required to disengage the locking mechanism and to allow the Morphing Wing deployment has been kept lower than the hydraulic actuators stall load. Notice that the minimum preload equal to the 75% of actuator stall load is the value required to ensure a sufficient connection stiffness between the morphing wing and the fixed wing, hence the aeroelastic stability is guaranteed.

The reversibility of the Locking Mechanism has been achieved thanks to a detailed design of the levers system. The levers system is able to amplify the spring force to the rolling pin when preload is needed: a spring force of about 70% is increased up to 80/86 % at the rolling pin, satisfying the requirement of 75% of the stall load. The same levers system decreases the spring force while the Morphing Wing moves from stored to deployed position: a spring force of about 80% is decreased to 55/60% at the rolling pin, showing an instantaneous peak near to the stall load at the very start of the movement. In this way the power available from the Morphing Wing hydraulic actuators is optimized.

The Matlab and Amesim analysis revealed a very adjustable and versatile system. By changing the spring mechanical properties and the levers system peculiar angles and arms, the Locking Mechanism can be tuned in order to provide the desired preload and working stroke still ensuring its reversibility. This solution appeared to be particularly suitable where limited envelopes are available. Moreover, this Locking Mechanism eliminates the need of an additional couple of actuators to provide the preload, allowing a great weight saving.

Steps forward concern some tests in order to validate the entire design. A functionality test procedure has been set up to evaluate the correspondence between the numerical identified working points and the real ones. The preload required to ensure aeroelastic stability and to move the rolling pin will be recorded together with the required rolling pin stroke to move from the two working positions. A vibration test is also being detailed in order to evaluate the robustness of the system when subjected to the H/C vibrations. Fundamental is to evaluate the performance of the system while shaking before its application on the H/C, ensuring none of the components will fail.

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APPENDIX A

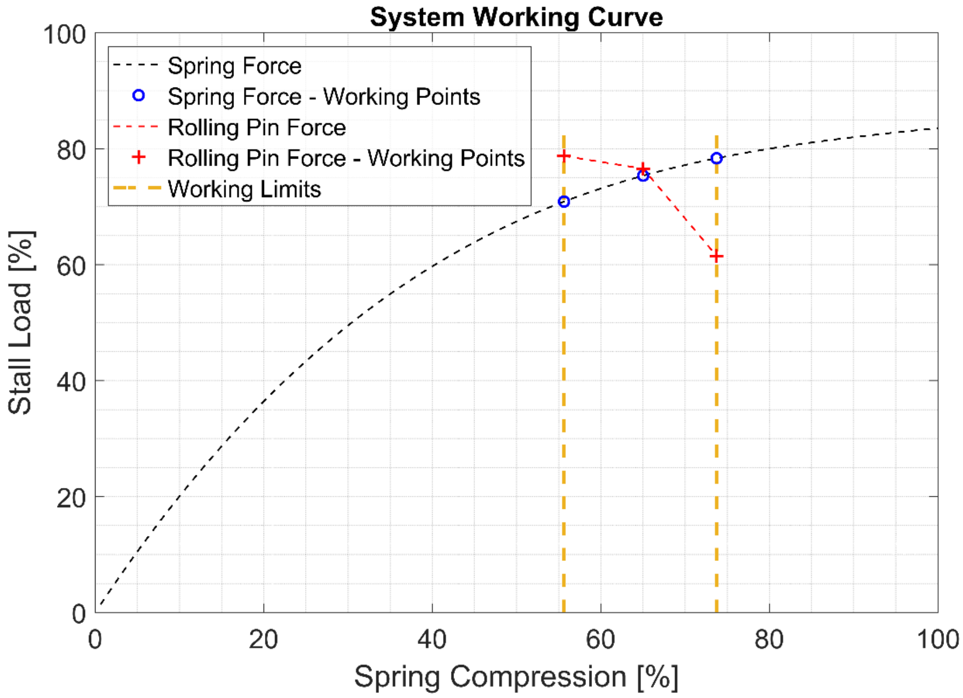


Figure 6

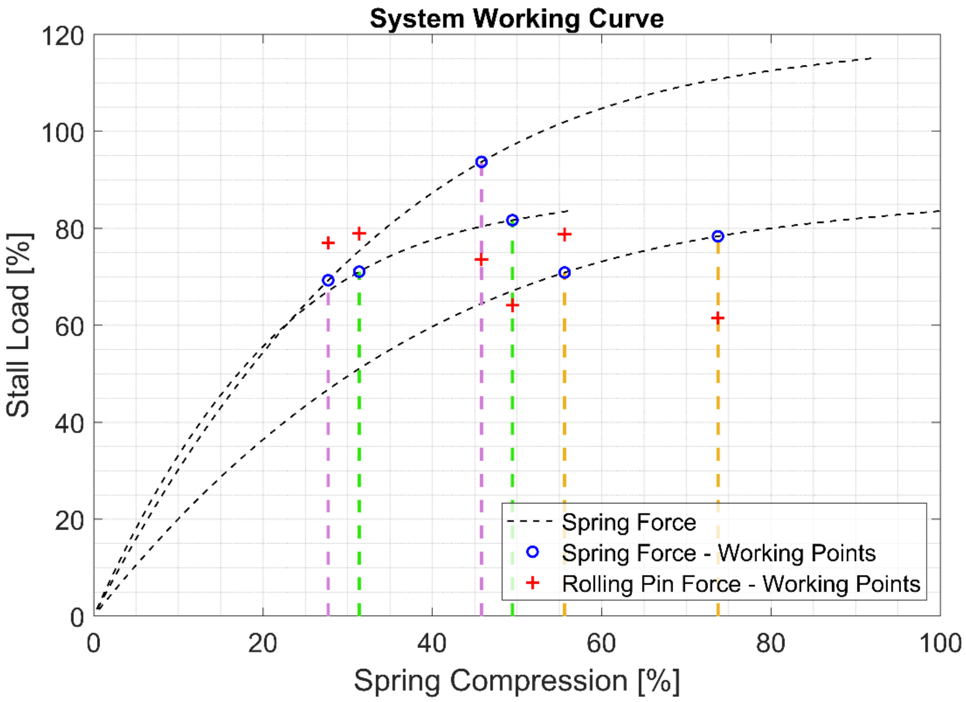
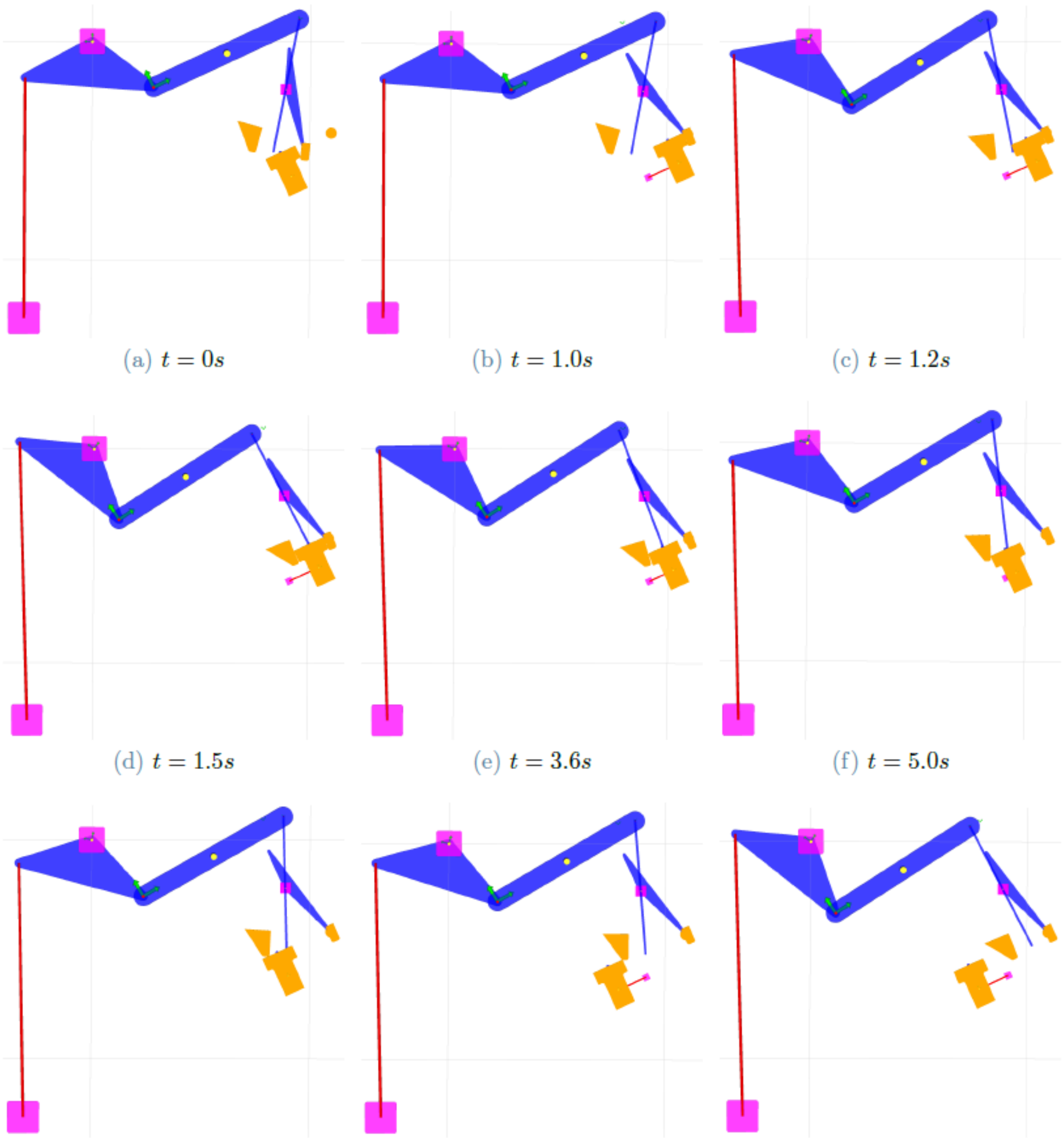


Figure 7



(a) $t = 0s$ (b) $t = 1.0s$ (c) $t = 1.2s$

(d) $t = 1.5s$ (e) $t = 3.6s$ (f) $t = 5.0s$

(g) $t = 6.2s$ (h) $t = 8.75s$ (i) $t = 8.9s$

Figure 12

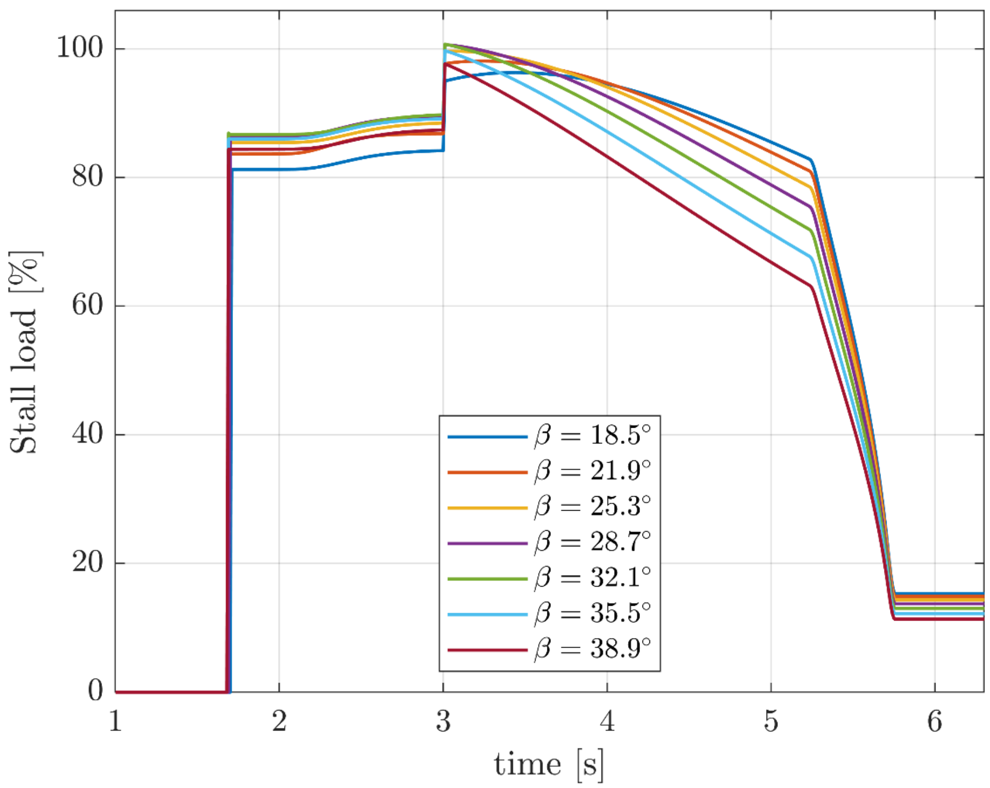

Stall load [%]
100
80
60
40
20
0
1
2
3
4
5
6
time [s]
β = 18.5°
β = 21.9°
β = 25.3°
β = 28.7°
β = 32.1°
β = 35.5°
β = 38.9°

Figure *15*