Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection

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Executive Summary

Several aspects of future trends for A/RPC were presented in connection with aircraft/helicopter design and certification requirements, technical solutions, evolution of modelling and simulation techniques. Evolution of certification requirements and increase of manoeuvrability together with stability requirements is specified as the major source of future A/RPC analyses importance. Prediction of possible future aircrafts/helicopter design analyses areas is considered. Increase of the A/RPC problems importance for future aerial vehicles design is finally emphasized.

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1. Introduction

As described in ARISTOTEL Project Annex I - "Description of Work" [1], the main challenge of the program is to "ensure of aircraft/helicopter safety and aims to reduce the aircraft and rotorcraft accidents caused by a particularly unfavourable category of phenomena: aircraft-pilot-couplings and rotorcraft-pilot-couplings (A/RPCs)".
Because not all of the A/RPC aspects are fully taken into consideration during today's aircrafts/helicopters design process, the correct identification of possible future needs for results of ARISTOTEL Project is requested.
Present analysis try to answer on the question which areas could be predicted where A/RPC problems can affect future design of aircrafts and helicopters.

2. Summary of Work Performed

2.1 Evolution of new helicopter design requirements

2.1.1 Stability vs. manoeuvrability

Increasing of the manoeuvrability requirements for aircrafts and rotorcrafts could be easily observed in evolution of mission requirements to pass which are introduced during aircrafts and helicopters are ordered by customers. For rotorcrafts it is visible for both civil and military customers but for aircrafts these requirements are mostly expressed by military customers.
Analysis of flight missions requirements trends requested by civil customers reveals increase of flight time over urban and mountainous area. Because of obstacles and because of low flight profile which is necessary to pass missions – (law enforcement, passengers, medical transport and also sling load missions are requested) increase of the helicopter manoeuvrability qualities is highly recommended. Specially the EMS and medical transport missions request from helicopter possibility to land on short fields with limited area and high obstacles around the landing area [2].
For military customers the correct helicopter handling qualities for Near of Earth (NoE) flying conditions are compulsory to increase the survivability on the battlefield. Possibility to perform dynamic manoeuvres attract helicopter design for military purposes [3].
For both operational usage cases, environmental conditions and helicopter flying paths request increase of manoeuvrability qualities. It lead usually to decrease of static stability margins for the helicopter and as the effect to decrease necessary reaction time requested from pilot. To prove of safe operational use for these NoE conditions the RPC analyses importance will increase.
For fixed wings planes increasing of the manoeuvrability seems to be most important for military purposes – decrease of the manoeuvres radius and increase angular speed increase chance to survive for fighters, assault planes and tactical bombers specially for NoE flights.
For civil purposes the manoeuvrability could be also expressed specially for low speed near take-off and approach conditions to avoid the collisions with other flying vehicles and ground obstacles. Growing of the urban areas will also decrease the clearance around airfields.
One of the method to meet systematically increased manoeuvrability requirements for the new aircrafts/helicopters is to design them with more reasonable stability factors which can

produce faster response on control input. This approach needs more reliable prediction of A/RPC dynamics to proper design with enough stability within whole flight envelope.

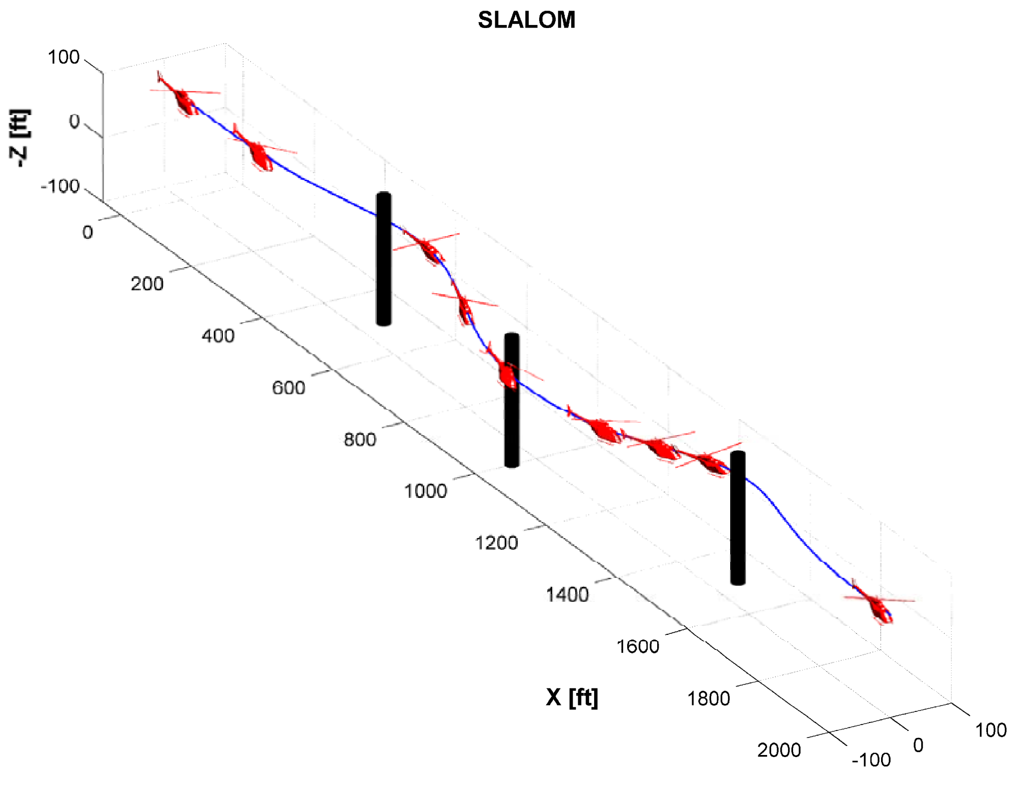

Fig. 1. Numerical simulation of the ADS-33 required flight manoeuvre – slalom [4]

Civil transport aircraft policy which had been conservative in retaining enough stability to ensure control of the aircraft, has accepted since the last three decades the idea of improving efficiency by relaxed static stability, with compensation through stability augmentation. With reliability increasing onboard computers, this trend will continue in the future. The potentials for adverse aircraft-pilot couplings are then similar to those encountered earlier on military aircraft. The evolution of the design and manufacturing of fighter aircraft is marked by superaugmentation. The basically unstable airframe is highly augmented by fly-by-wire systems and the handling qualities are thus dominated by the characteristics of the flight control system. In military aircraft the push towards the limits concerning performance and maneuverability leads to high inputs, both in positions and rates, driving the flight control system and the aircraft to its limits. The aircraft-pilot interactions are then characterized by highly nonlinear dynamics and the pilot behaviour itself is highly nonlinear and time varying. This highlights the need for the development of nonlinear control design techniques and nonlinear analysis methods.

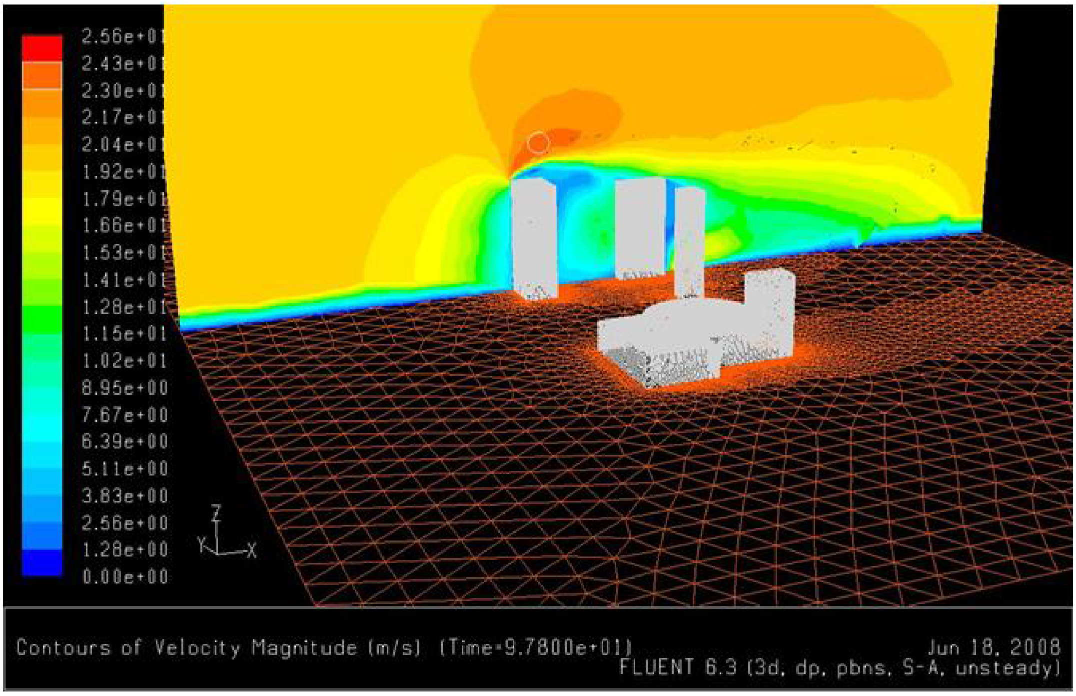

Fig. 2. Calculated airflow fluctuations behind group of buildings due to wind – possible source of troubles during flights over urban areas [2].

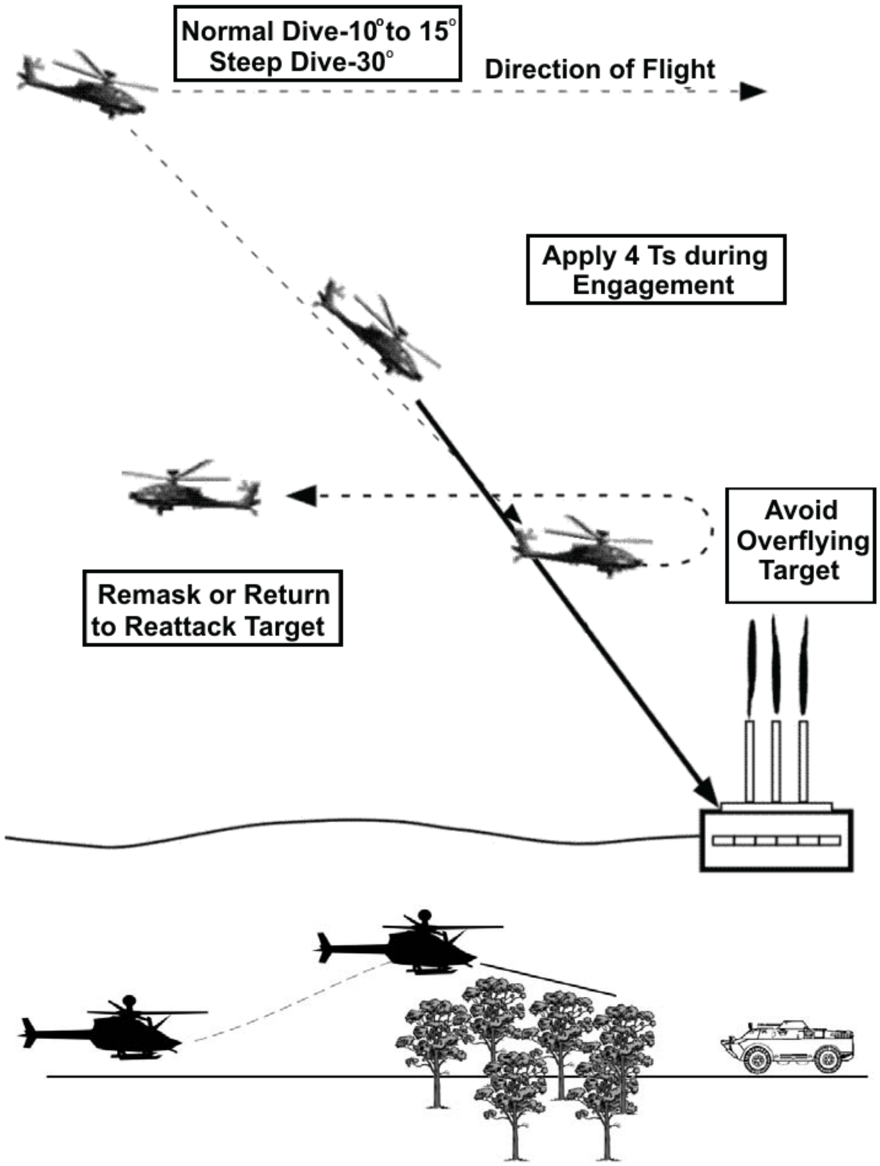

Fig. 3. Examples of required tactical manoeuvres for attack helicopters [3]

2.1.2 Increase of the flight envelope

Another trends could be observed for both aircrafts and helicopters – this is tendency to extend the flying condition envelope – increase of flying speed (also decrease of approach speed for fixed wing planes), altitude, ambient temperature range. Also the transportation quality factors Several areas of customers interest could be observed which could increase RPC:

increase or maintain of the VNE and flight altitude with actual and future trends to MR and TR tip speed decrease (for „green" reason) could cause the RPC problems earlier than for classical solution (rotors closer to the stall conditions)
„A" category rotorcraft capabilities improvements (necessary airfield size reduction through specific control strategy - closer to the „vortex ring" state) increase possible RPC problems.

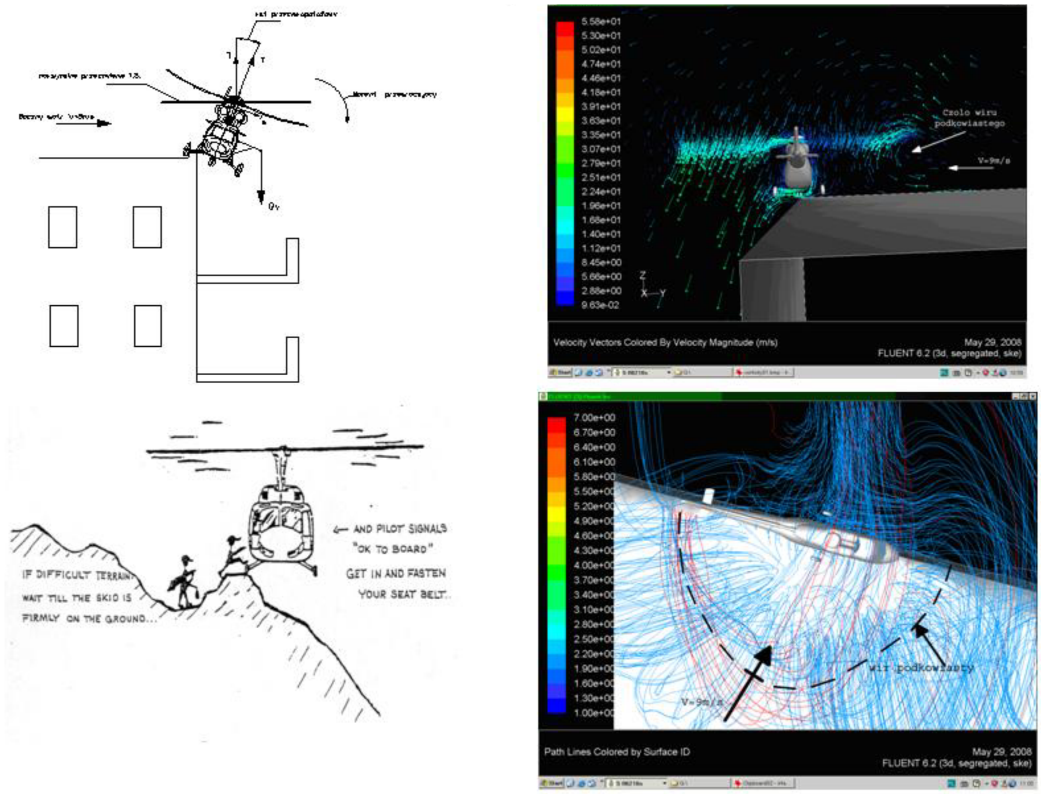

Fig.4. Example of airflow disturbances over building and mountain as possible source of RPC problems [2].

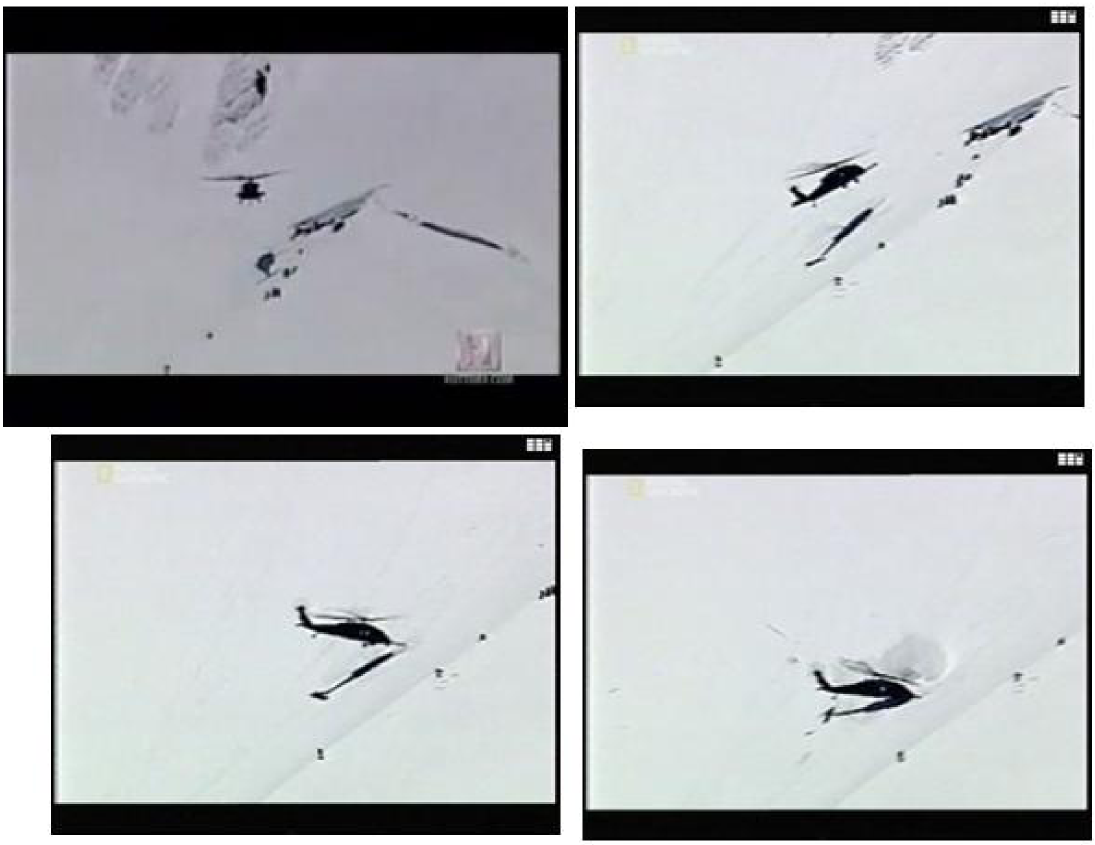

Fig.5. Sikorsky S-70 helicopter accident due to RPC problem near mountain surface.

2.1.3 Increasing of the AFCS autonomy

Visible present tendency to increase capabilities of AFCS with larger possible class of manoeuvres which could be performed lead to the optionally, fully autonomous vehicle. Cooperation between pilot on board with more sophisticated control system and vehicle equipped with these type of AFCS could be the source of possible A/RPC problems. Implementation of pilot mathematical models together with flight mechanics helicopter model allows more reliable investigation of failure modes. It will increase chance to avoid A/RPC induced problems, specially during emergency situations when pilot should react on hardware faults or not expected situations during flight [5].

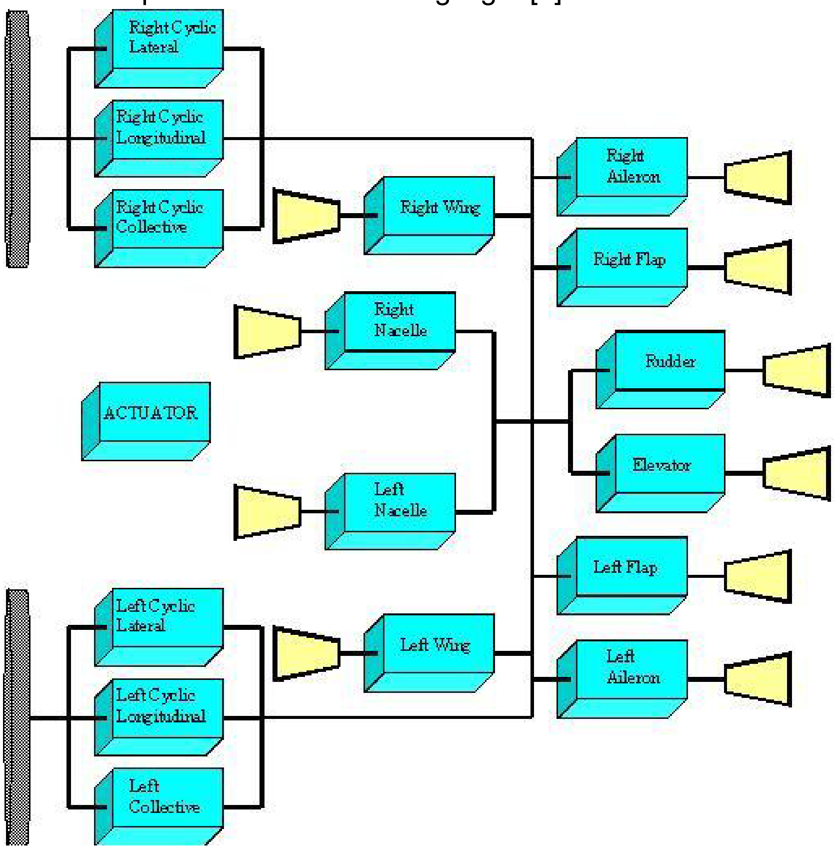

Fig. 6. Tilt-Rotor/Wing actuator schematic example – future complication of AFCS systems will cause more A/RPC effects. [5]

Failure-Severity	Maximum Probability of Occurrence / Flight Hour	Failure Condition Effect
Catastrophic	Extremely Improbable $< 10^{-9}$	All failure conditions that prevent continued safe flight and landing.
Hazardous	Extremely Remote $< 10^{-7}$	Large reduction in safety margins or functional capabilities. Higher workload or physical distress such that the crew could not be relied upon to perform tasks accurately or completely. Adverse effects upon occupants
Major	Remote $<10^{-5}$	Significant reductions on safety margins or functional capabilities. Significant increases in crew workload or in conditions impairing crew efficiency. Some discomfort to occupants.
Minor	Probable $< 10^{-3}$	Slight reduction in safety margins. Slight increases in crew workload. Some inconvenience to occupants.

Fig. 7. Table with classification of possibile failures. [5]

2.1.4 Decrease of the noise and vibration levels

Design of new helicopters which meet the „green" requirements could lead to the more flexible structures – lower natural frequencies could increase RPC problems. The evolution of the design and manufacturing of civil transport aircraft become larger and their structures become more flexible. The flexible dynamics of civil transport aircraft thus tend to be more and more low frequency and occurs APC effects.

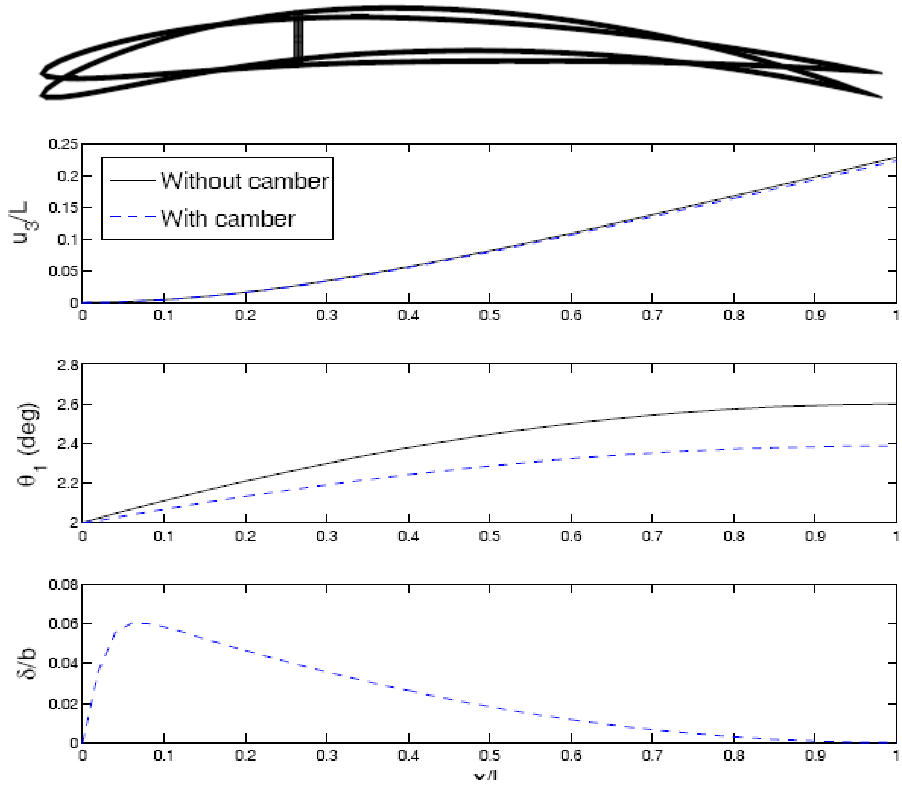

Fig. 7. Example of flexible wing structure – possibile source of the new type of Pilot – Aircraft interaction modes. [6]

Application of vibration and noise suppression systems could increase number of DOF which have to be included into RPC analyses

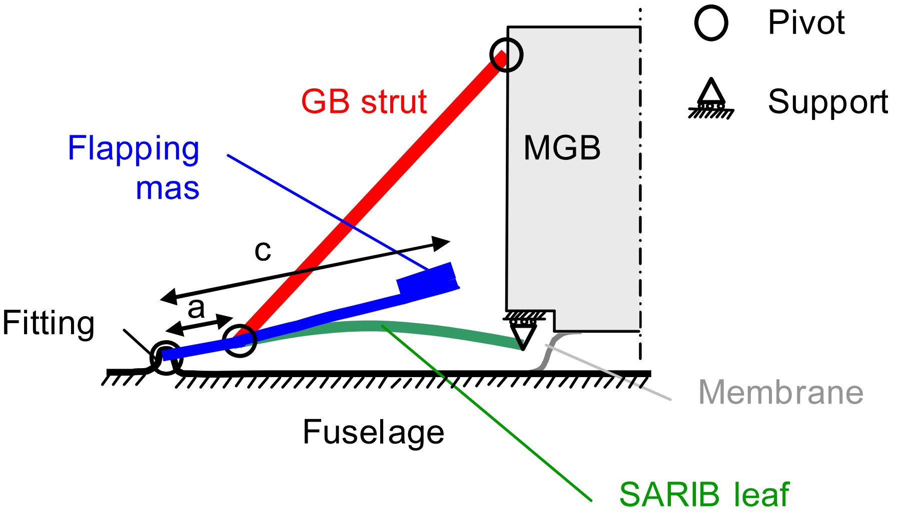

Fig 8. Scheme of flexible MR gearbox suspension - SARIB concept, NH-90 helicopter [7].

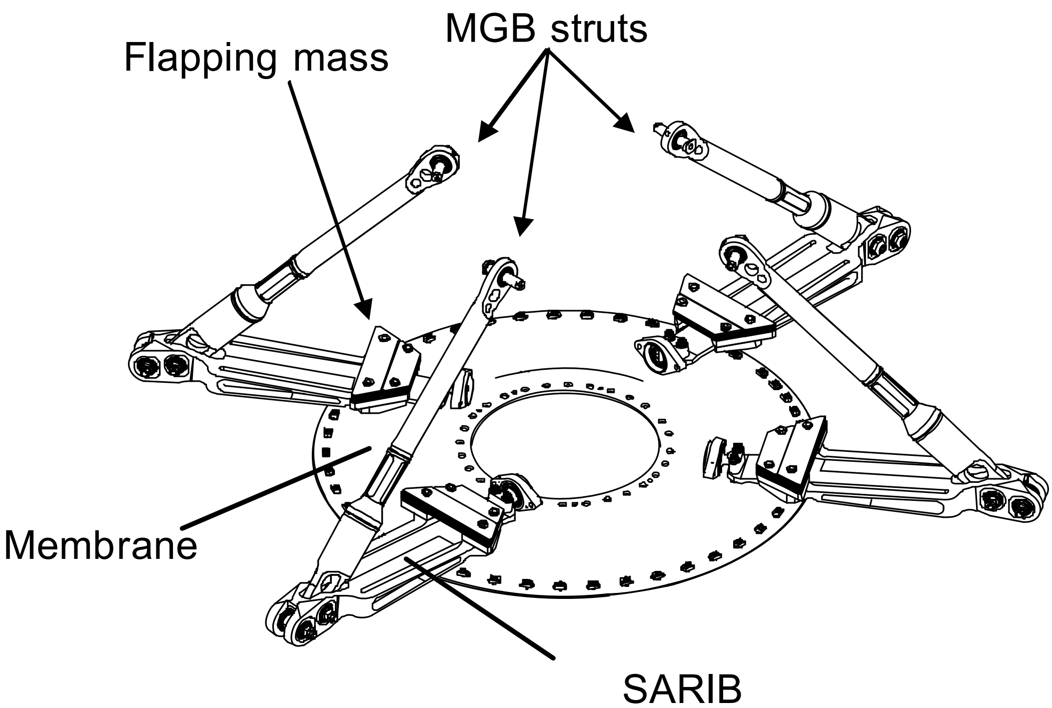

Fig 9. Example of flexible MR gearbox suspension - SARIB concept, NH-90 helicopter [7].

2.2 Evolution of possible technical solutions

2.2.1 Advanced main and tail rotor schemes

To design more controllable helicopter the more stiff structure of MR hub could be performed. Time line from fully articulated, through bearingless rotors up to the higless rotor increases number of modes which could be affected by pilot response.

Implementation of new rotor control techniques (HHC, individual blade control) also increase necessity to analyses of eventually RPCs also with „pilot in the loop” technique.

Tail rotor replacement by Fenestron, NOTAR and other solutions also need RPC analyses specially to discover additional critical conditions different than for classical TR solutions

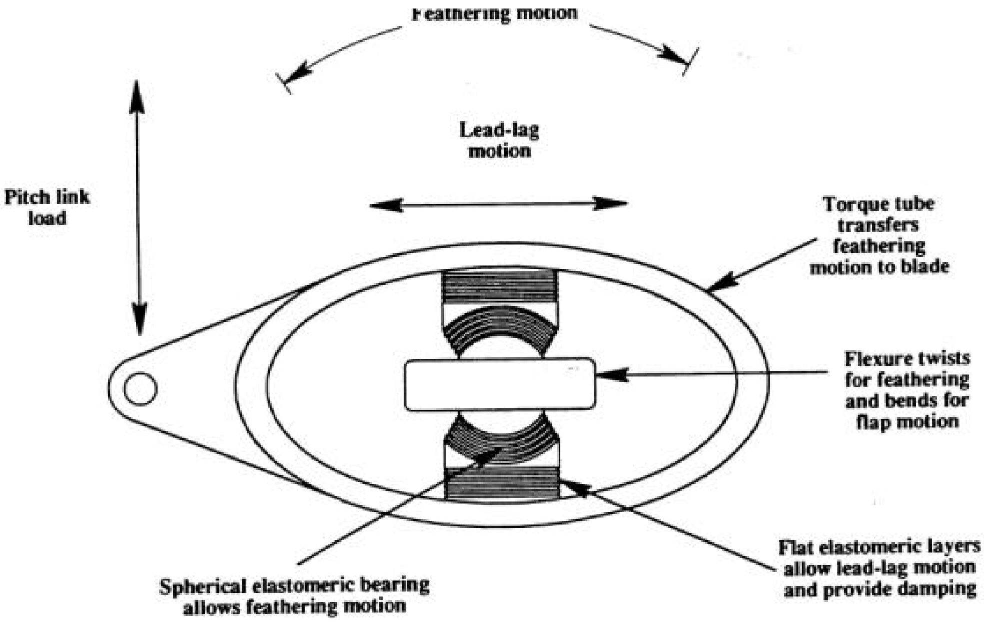

Fig. 10. Typical installation of elastomeric bearings on helicopter hub arm – increases number of rotor modes which could cause RPC problems [8].

2.2.2 Increase role of the electronics in PID design

Commercial aircraft manufacturers are turning more and more towards fly-by-wire control technologies which enhance significantly the aircraft manoeuvrability both in the time domain and in the frequency domain, thus increasing the controller bandwidth. This trend increases the potential for adverse interactions between the human pilot, the flight control system and the aircraft dynamics. The interactions become even more critical in the occurrence of structural spillover instabilities due to poor control laws designs or incompatible airframe-flight control system updates. This highlights the need for the development of robust control design techniques and effective analysis methods [11].

Design of more autonomous AFCS with larger authority margin lead to future RPC analyses which should answer on several questions:

- is pilot capable to maintain partial/full AFCS out of order?
- what is appropriate parameters tuning of AFCS during design stage for safe operation because of delay time necessary for pilot to take control of helicopter?
- which flight states are most critical when malfunctions of AFCS occur?

To correctly answer on these questions future implementation of appropriate pilot mathematical models could reply or/and complement extensive simulations with real human pilot participation.

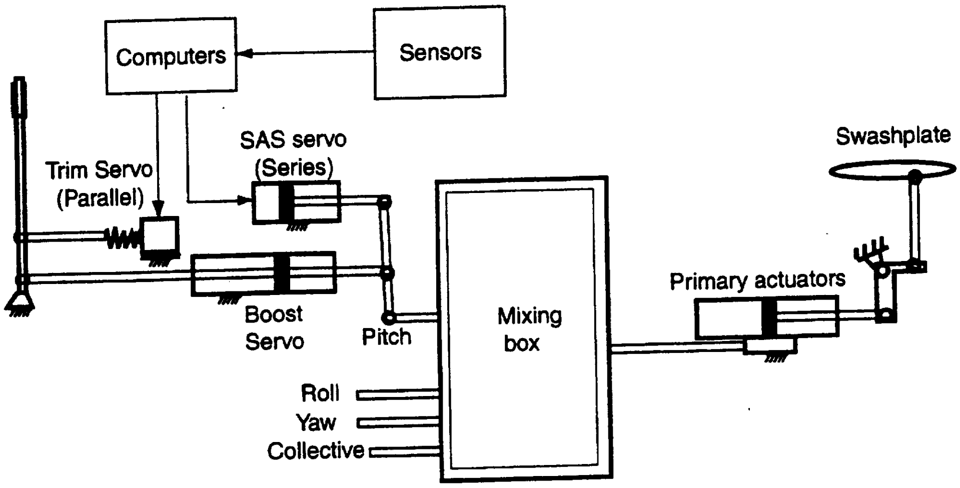

Fig. 11. Functional schematic of Limited Authority SCAS (LASCAS). [9]

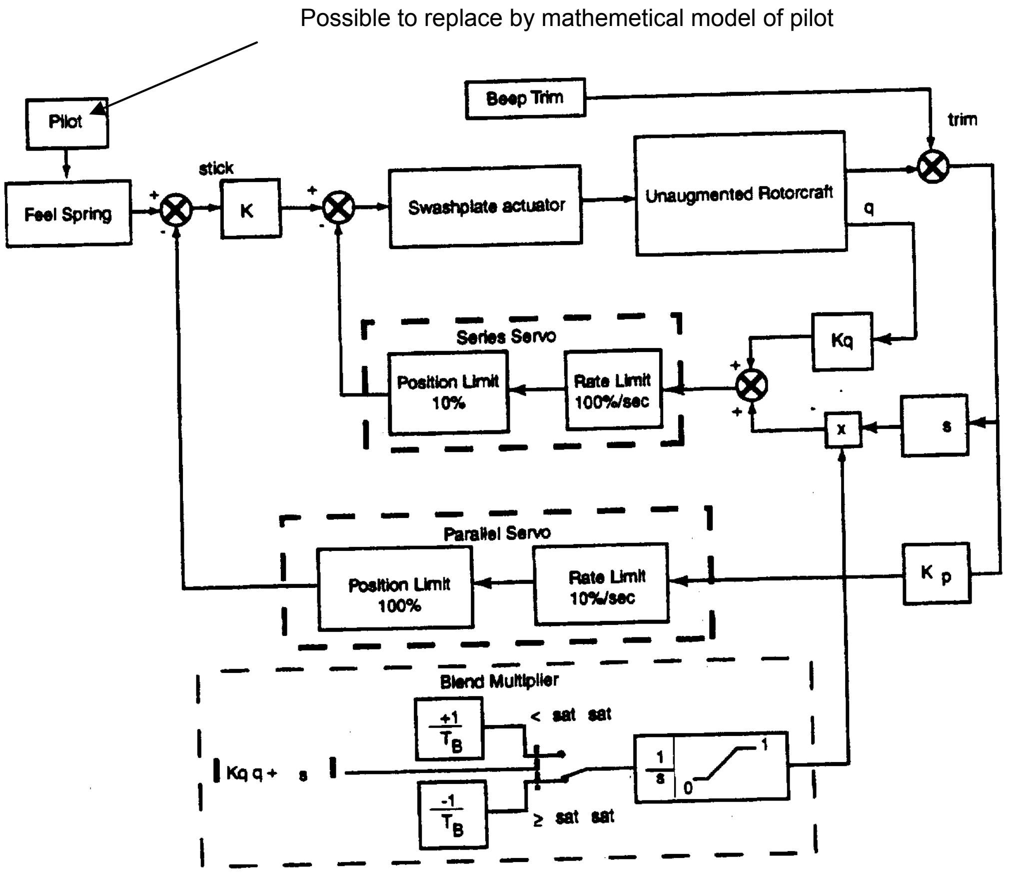

Fig. 12. LASCAS control system architecture. [9]

2.2.3 Smart structures and smart materials incorporation into design

New type of adaptable structures used on helicopter as additional controls or to optimize automatically vehicle characteristics could add new DOFs into the RPC analyses

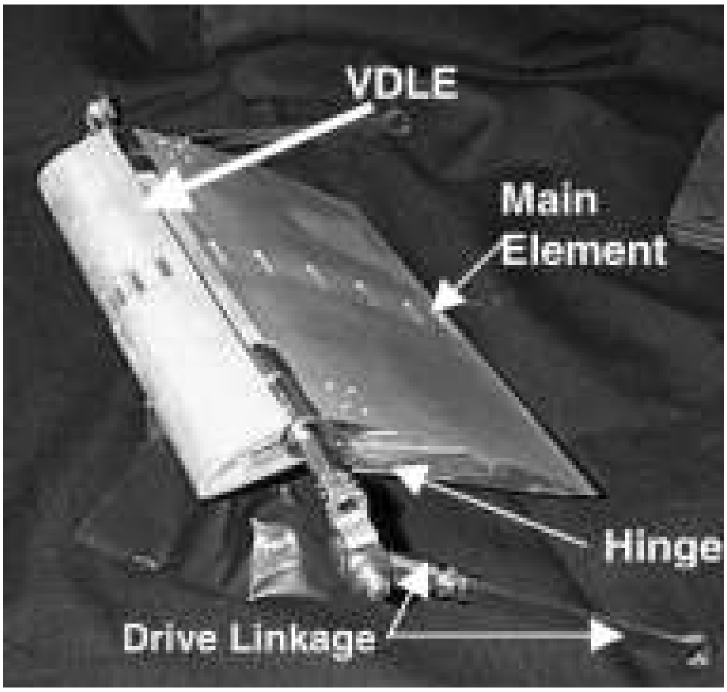

Fig. 13. Example of the variable droop nose (part of helicopter blade). [10]

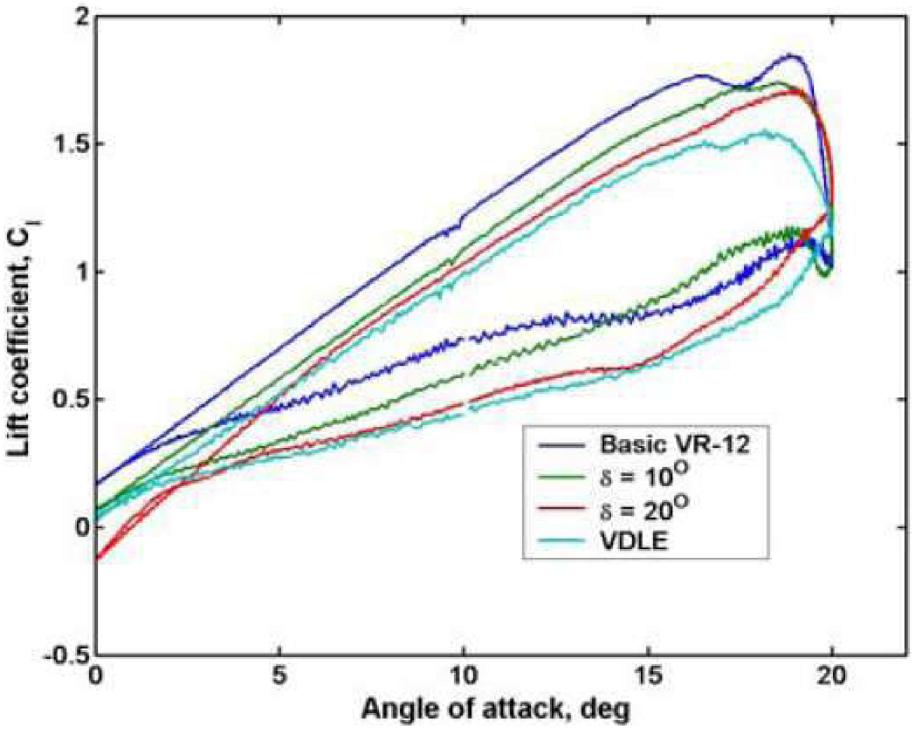

Fig. 14. Lift curves modifications for variable nose drop positions and motion – possibile additional DOF necessary to take into the consideration for future A/RPC analyses.

2.3 Evolution of certification requirements

2.3.1 Manoeuvrability requirements evolution

Tendency to increase of the requirements for ability to perform specific manoeuvres are visible when amendments and new issues of military documents is traced.

MIL-H-8501A [12] and later MIL-F-83300 [13], which were applicable in the past had defined limits for helicopter response on control input. Present ADS-33E [14] requirements define manoeuvres which should be passed to meet the controllability checks. [15]
Both types of approach increase importance of correct RPC analyses to predict helicopter manoeuvrability. Future implementation of adequate mathematical models into the analyses used to show helicopter fulfil manoeuvrability requirements will decrease the assessments costs [4].
For fixed wing planes the manoeuvrability requirements are expressed inside MIL-F-8785C document [19] which evaluated and was replaced by MIL-STD-1797A requirements [20].

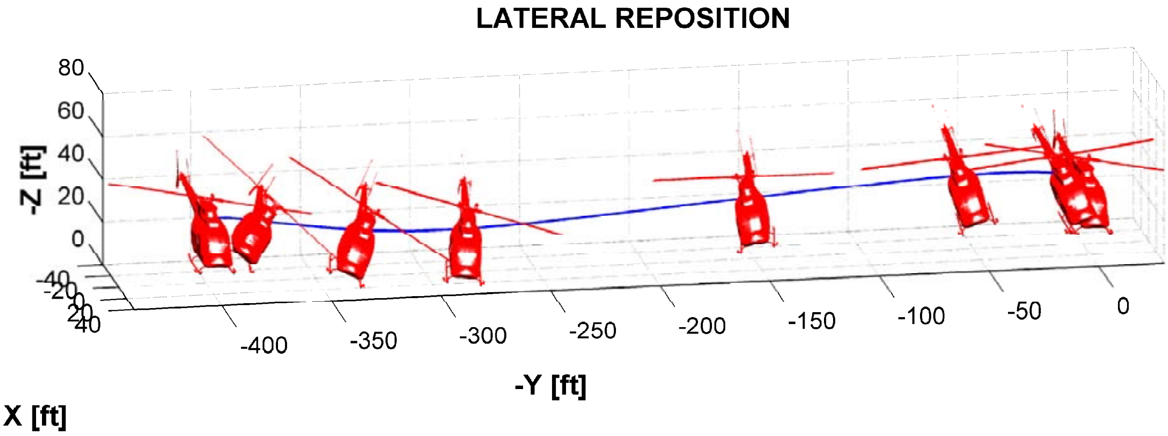

Fig. 15. Example of ADS-33E required manoeuvre simulation. [4]

2.3.2 Civil design requirements evolution.

Trace of civil helicopter design regulations - FAR 27/29, JAR 27/29, CS 27/29 for helicopters and FAR 23/25, JAR 27/29, CS 27/29 through time scale lead to the conclusion of increasing stability requirements for designed helicopters (damping requirements, pilot response delay time when AFCS is present).
This approach increases troubles to common fullfil civil and military requirements.
Future RPC analyses could help to predict both characteristics of future helicopter and to find optimal control strategy within physical pilot capabilities

2.3.3 Environmental requirements evolution

These aspects not directly define the helicopter design, however to meet more restrictive noise, vibration, pollution requirements, the future vehicles shall to incorporate features (new structures, materials, systems, control strategies etc.) which increase RPC level (as described above). One of the future example of new “green” requirements impact on helicopter design is published futuristic environmental helicopter project – VOLTERRA [16]. Inside the design study which is focused on environment friendly solutions, the implementation of most of mentioned above technical innovations is requested (innovative rotor, gearbox mount, vibration suppression systems, smart materials eyc.). All of this solution could increase of the RPC possibility.
The JTI “Clean Sky” initiative lead to the complex implementation of technology, smart structures, materials and also control strategies and flight paths for aerial vehicles. One of important idea is to implement new take-off and approach flight paths for fixed wing and rotorcraft planes (increased manoeuvrability, higher climb and descend ratios near airfields and helipads). These solution should decrease noise pollution around the airfields by

decreasing of the time period of low altitude flight above populated areas. This concept possible affect the A/RPC problems.

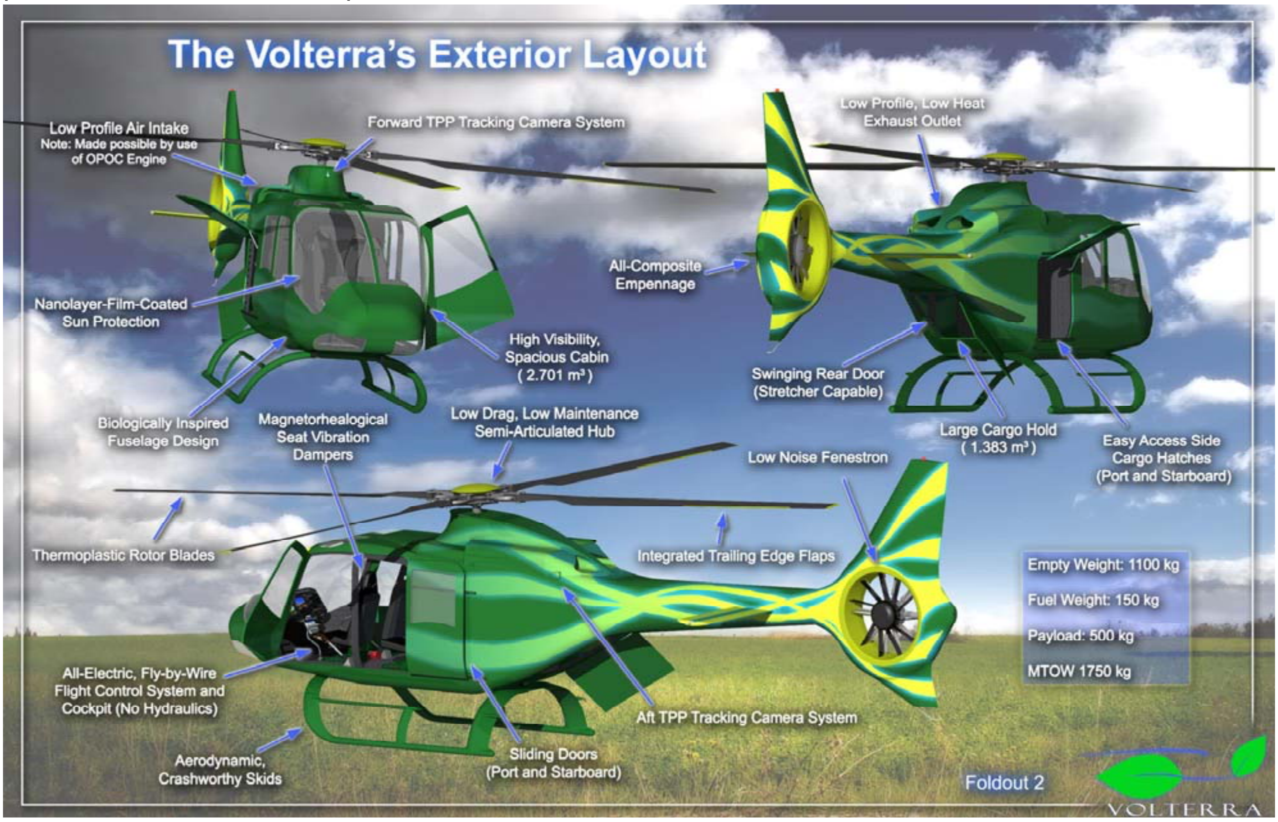

Fig. 16. VOLTERRA “green” rotorcraft concept. [16]

2.4 Evolution of modelling and simulation techniques

2.4.1 Rigid body modelling and separate rotor stability analyses

This approach is the standard for preliminary stability analyses and for classical helicopter design schemes is still valuable to determine helicopter basic characteristics.
In the future analyses will be still usable to test new approach for pilot modelling and for partially implemented into the model.
Rigid body models are also suitable to validate more sophisticated models [17, 18, 21].

2.4.2 Coupled rotor-fuselage aeroelastic analyses

It is today approach to investigate stability of modern helicopter solutions. This type of modelling needs carefull flight results database to validate model parameters.
This modelling method can incorporate new futures as smart structures and control strategies. Correct assessment of new designs needs improvements in aerodynamics couplings between rotors and fuselage with empennage. This can be managed through application of methods known from isolated rotor analyses methods into the flight mechanics models.
Future increase of the DOFs number to cover new possible coupled aeroelastic modes seems to be suitable for future modelling improvements.

2.4.3 Pilot-rotor-fuselage coupled analyses

This method looks as the most promising to determine correctly every aspects of helicopter handling characteristics and RPC prediction. It will allow to find possible problems which could be raised by new technologies before physical demonstrators will be build.
Needs to include all improvements of coupled aeroelastic approach to correct prediction of helicopter as the part of model.
APC-free objectives can be incorporated at different phases of an aircraft development. Present trends focus on APC-free verification and compensation. For example, adverse effects of actuator rate saturation on APC can be alleviated by rate limiter concepts such as phase compensation filters. Future trends would integrate APC-free requirements into the early phase of conceptual design.

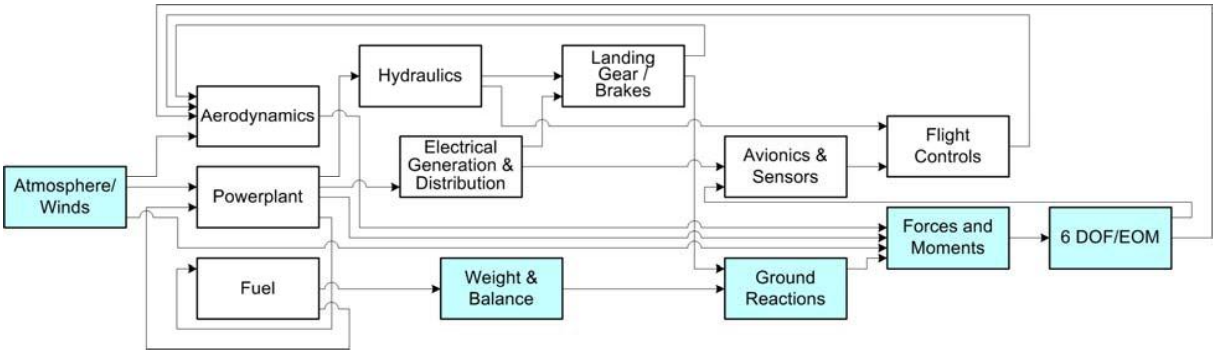

Fig. 17. Basic simulation architecture of Gulfstream pilot_in_the_loop concept [22]

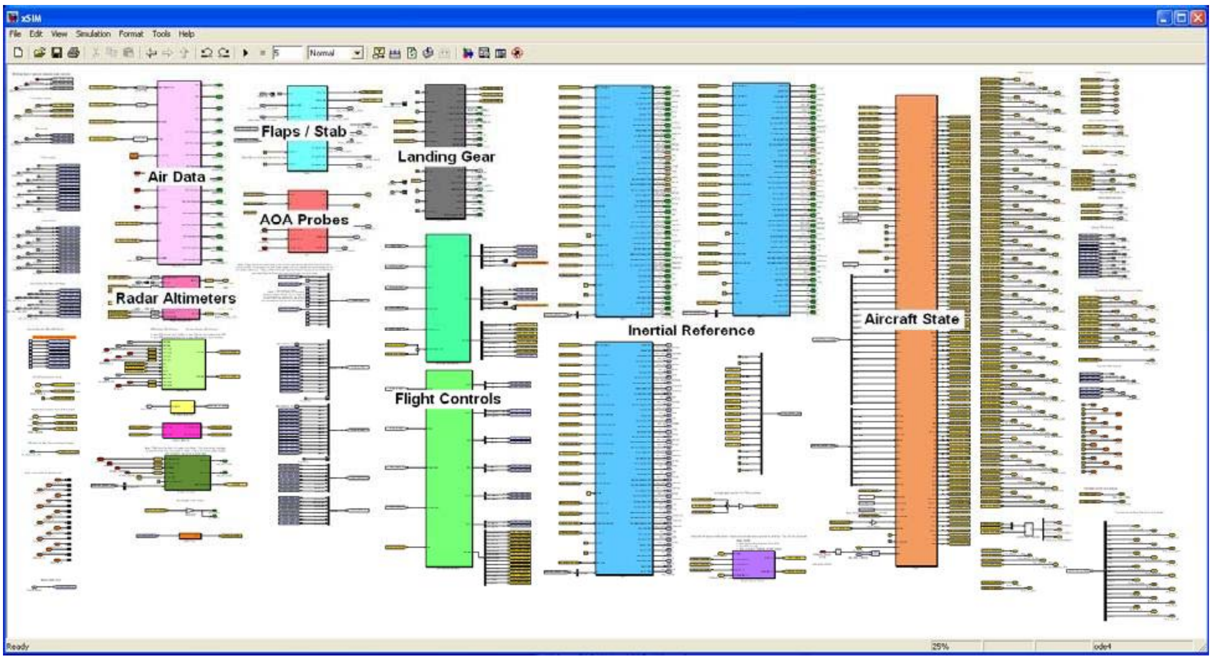

Fig. 18. SIMULINK representation of Gulfstream pilot_in_the_loop simulation architecture [22]

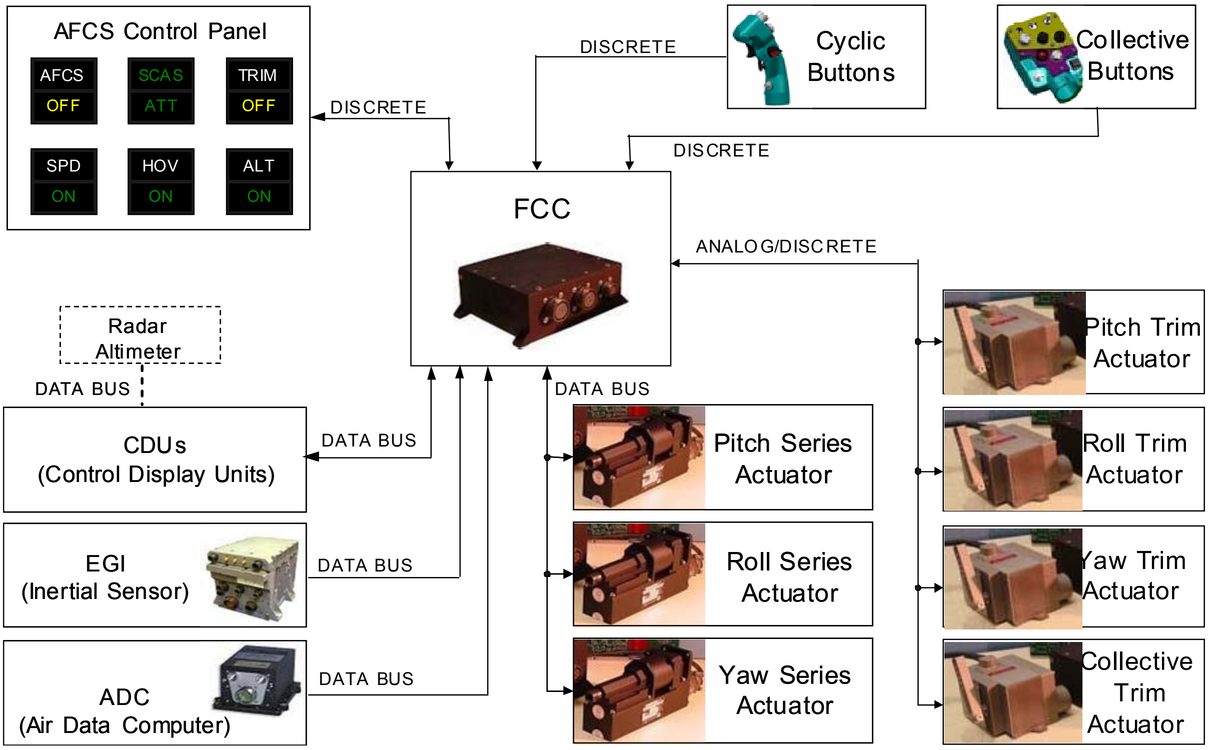

Fig. 19. ARH-70A helicopter Automatic Flight Control System (AFCS) overview [23]

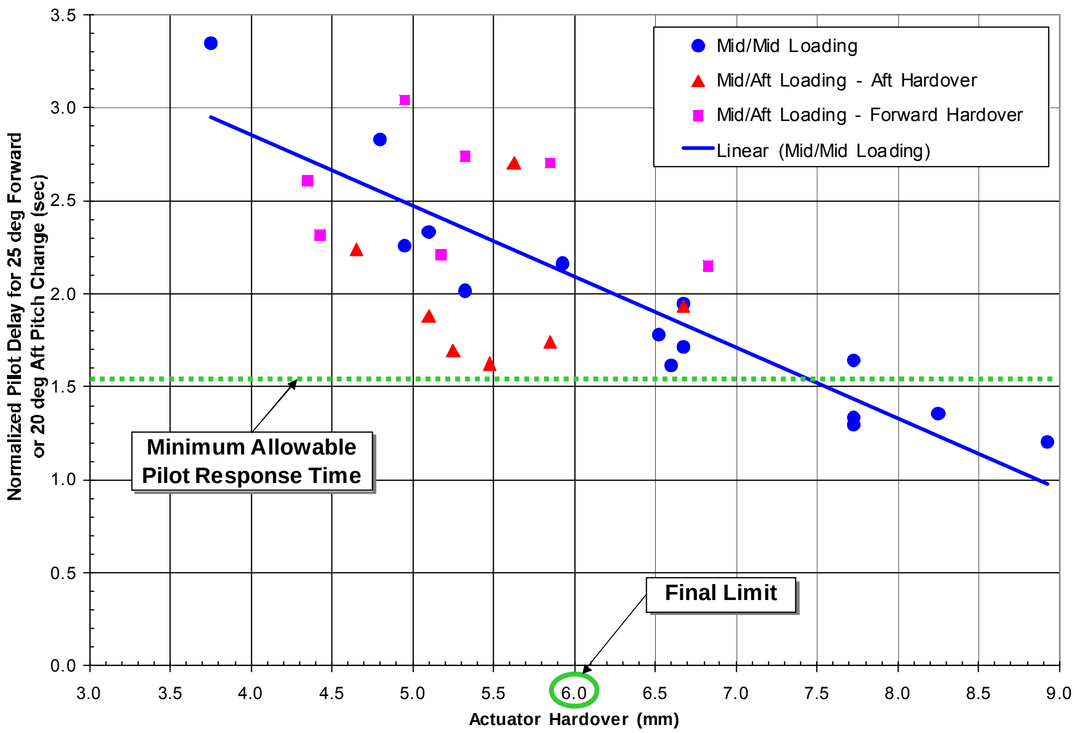

Fig. 19. ARH-70A helicopter Automatic Flight Control System (AFCS) pitch actuator hardover response analysis results – using Minimum Allowable Pilot Response Time (correct estimation of this value could allow to increase the AFCS authority) [23]

3. Results and Conclusion

Four main aspects are considered to investigate of the future trends for A/RPC importance evaluation:

- Evolution of new helicopter design requirements;
- Evolution of possible technical solutions;
- Evolution of certification requirements;
- Evolution of modelling and simulation techniques;

All of these subjects are identified as sources to increase of the A/RPC assessment importance in the future.
The main future sources of potential PIOs could be summarized as:

- future aircrafts/helicopters design lead to produce vehicles which work closer to the static stability margins with improved manoeuvrability;
- future structures become more flexible and complicated which induce more non negligible DOFs which can be close coupled with pilot reactions and behaviour;
- required future mission profiles impose close to ground manoeuvres which needs more precise control of the aircraft/helicopters
- certification regulations step by step incorporate additional, more restrictive and more precise safety requirements

Finally, incorporate of the pilot_in_the_loop analyses for future new aircrafts/helicopters design should be right way to perform correct assessment of vehicle safety and their handling qualities and to avoid negative A/RPC effects and identify potentially dangerous PIOs. Implementation of reliable pilot mathematical model in early stage of future fixed wing and rotorcraft designs should improve the effectiveness of process.

4. Deviations

Final significant delivery delay time of this paper was caused by unpredicted insufficient resources amount of partner (PZL) but should not affect overall Project time schedule.

5. References

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6. List of Abbreviations

APC Aircraft-Pilot Coupling
BDFT Bio-Dynamic Feed-Thru
PIO Pilot-Induced Oscillations
RPC Rotorcraft-Pilot Coupling
AFCS Automated Flight Control System