RETRACTING BLADE STALL PHENOMENON – REVIEW OF INVESTIGATIONS PERFORMED DURING THE PZL W-3A SERIAL AND NEW BLADE PROJECTS

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Abstract

One of the key phenomena of importance for the final determination of the operating envelope of classic design helicopters is the flow separation appearing on the retracting blade. This study presents specific issues related to the occurrence of this phenomenon on the main rotor of the PZL W-3A “Sokół” helicopter, which blades are characterized by relatively low torsional stiffness. Aspects related to the prediction of the conditions for the occurrence of the stall phenomenon using different levels of complexity of aerodynamic models in comparison with the test results are presented. The results of selected flight tests of the PZL W-3A “Sokół” helicopter conducted to determine it’s safe operating envelope are presented. The results of measurements carried out in the conditions of a developed phenomenon of retracting blade stall and the identified influence of external parameters on the intensity of the phenomenon are noted. Selected analyzes carried out to determine the limitations for the newly designed main rotor blades for the PZL W-3A helicopter are presented, showing the possibility of the helicopter operating envelope extension. The results of these analyzes was the starting point for the anticipated flight tests of the helicopter and will be checked for the final MR blade configuration.

1. SYMBOLS AND ACRONYMS

Symbols

μ	Nondimensional forward speed, advance ratio
c_t	Main Rotor thrust coefficient
R	Rotor radius, m
P_i	Induced power, kW
β_p	Precone angle, deg
Ω_{MR}, Ω_{TR}	Main rotor, tail rotor speed of rotation, rad/s
Ψ	MR blade azimuth, Ψ=0 for blade over the tailboom

Acronyms:

AHS	American Helicopter Society
ERF	European Rotorcraft Forum
IoA	Institute of Aviation (Currently part of the Łukasiewicz Research Network)
MR	Main Rotor
NACA	National Advisory Committee for Aeronautics
PZL	Polish Aviation Factory (currently part of Leonardo Helicopters)
ToW	Take of Weight
VFS	Vertical Flight Society

2. INTRODUCTION

The various requirements for operation of the main rotor in flight of the classical scheme helicopter (producing thrust, side forces to ensure stability and controllability of the helicopter) makes it necessary to increase the blade pitch angles in the area of azimuth angles Ψ=270deg as the forward speed increases. Increasing the flight speed is accompanied by an increase of the required power level necessary for the forward flight, limited by the available engine power. This may be accompanied by the appearance of lateral instability symptoms, deterioration of controllability and increase in blade, shaft and control system loads. These phenomena are related to the appearance of flow separation around the rotor blade in the area of the blade azimuth angles close to Ψ=270deg.

Many aspects related to the appearance of retracting blade stall have been described in the known literature, e.g. [1], [2] or [3]. However, due to the complexity of the phenomenon, accurate analytical prediction of its intensity is very difficult. The final answer regarding the boundary conditions of retracting blade stall for the rotor and helicopter design requires rotor testing in flight. The flight tests conducted during the qualification process of the PZL W-3A helicopter were performed during type qualification. They allow to properly determine the flight envelope limitations for the helicopter operation also due to the potential occurrence of the stall phenomena.

3. ANALYSES AND FLIGHT INVESTIGATION OF THE W-3A HELICOPTER WITH SERIAL BLADES

3.1. General characteristic of the object

The PZL W-3A "Sokół" helicopter is compliant with FAR-29 airworthiness requirements version of the PZL W-3 helicopter. The originally designed MR blades (named in this paper as "serial blades") were characterized as relatively low torsional stiffness, fully glass epoxy composite parts (first elastic torsional frequency placed below the 4^{th} harmonic of MR speed). Blades are rectangular shape with trapezoidal tip parts. They use classical NACA 230xx airfoil section family to design geometrical shape of the blades. They are attached to the fully articulated hub with hydraulic dampers.

The choice of this concept allowed to reduce the base vibration level of the helicopter structure without using any additional passive vibration damping units across the structure. However, the low torsional stiffness of the blades made it necessary to extend the scope of analyzes and tests for both, the aeroelastic stability of the rotor and the determination of the envelope of external conditions related to the operation of the main rotor blade at high angles of attack.

3.2. Analyses of the retracting blade stall for serial blades before flight tests

The set of analyses for MR equipped with serial blades were performed using PZL created, own code named OBW. This code, originally based on blade element method for blade aerodynamics, simple Glauert method to obtain induced velocity distribution across the MR disk, the Galerkin method for modeling of blades elastic motion and published in [4] methodology to obtain airfoil dynamic stall characteristics based on steady airfoils coefficients taken from wind tunnel tests performed at IoA.

Due to simplified modeling methodology and computational limitations at the time of serial blades design (end of 70thies), the main emphasis was put on flight trials investigations.

3.3. Flight trials of the serial blades

The extensive flight trials campaign was performed up to the end of 80thies and was finalized by obtaining the FAR-29 type certificate for W-3A helicopter equipped with serial blades.

Flight trials were performed in various climate conditions including far Siberia (Yakutsk) forlow temperature trials and Kazakhstan and Pakistan locations for high temperature trials. Retracting blade stall investigations were performed for full envelope of barometric altitude, helicopter ToW and MR speed. The gradient methodology of flight parameters increase was used to ensure safety of trials with on board loads and flight parameters measurements and telemetry.

During the flight trials it was found that the first symptoms and the most critical indication parameters of the retracting blade stall were oscillatory loads of the non-rotating part of MR swashplate. Increase of the flight forward speed, reduction of the MR speed, as well as increase of the density altitude and/or helicopter ToW lead to the higher amplitude of the oscillatory loads. The swashplate limit loads margin was established for longitudinal and lateral swashplate moments to ensure safety of in-flight investigations and was found as main determinant of the retracting blade stall. During trials, the specific behavior of the swashplate oscillatory loads variation was identified. Apart of usually relatively slow increase of the oscillatory loads, for several cases the high gradient of loads amplitude vs. forward speed was noted (see Fig.1).

This behavior was observed more frequently for the lateral swashplate control moment.

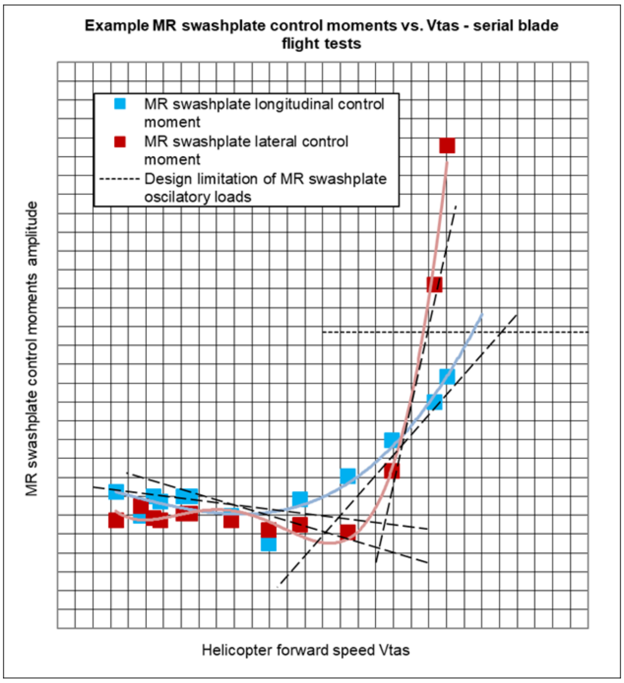

Figure 1: The PZL W-3A Sokół MR swashplate oscillatory loads slope vs. helicopter forward speed obtained during flight trials. Credits: PZL-Świdnik.

It was the base for conservative decision to cut drastically the helicopter forward speed envelope vs, ToW, MR speed, ambient temperature and barometric altitude to ensure safe usage of the helicopter. This restriction keeps oscillatory loads of the MR swashplate within the bandwidth used to obtain guaranteed fatigue loads (unlimited fatigue life for MR control elements). Although, applied speed limits cut off significant part of the feasible flying conditions allowed by the balance between power required for flight vs. power available resulting from installed engines (Fig.2).

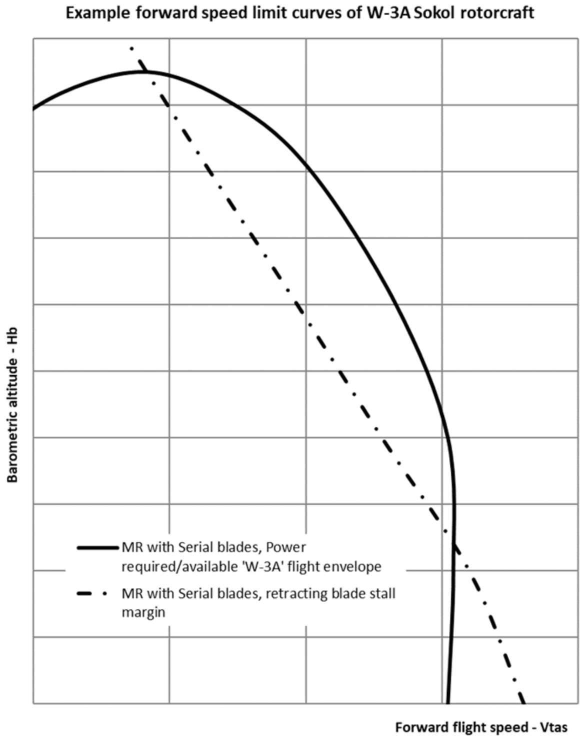

Figure 2: The graph shows the comparison between power required/available flying envelope vs. restriction established due to retracting blade stall behavior. Credits: PZL-Świdnik.

3.4. Retracting blade stall indicator investigations

Due to severe effects of the restrictions applied to the allowed flight speed envelope, the several ideas of the stall indicator were proposed to suppress conservativeness of the cut off rule.

First proposed solution to apply an indicator based on strain gauges installed on the swashplate was rejected due to anticipated problems related to high dependency of this kind of measurements on ambient conditions which requires precise calibration of sensors and verification of system status. The more promising system was based on the swashplate vibration. It consists of the piezoelectric vibration speed sensor installed on the non-rotating component of the MR swashplate. The idea was to find experimentally the correlation between the swashplate oscillatory loads and amplitude of swashplate vibration. The optimal location of the vibration sensor was also investigated (Fig.3).

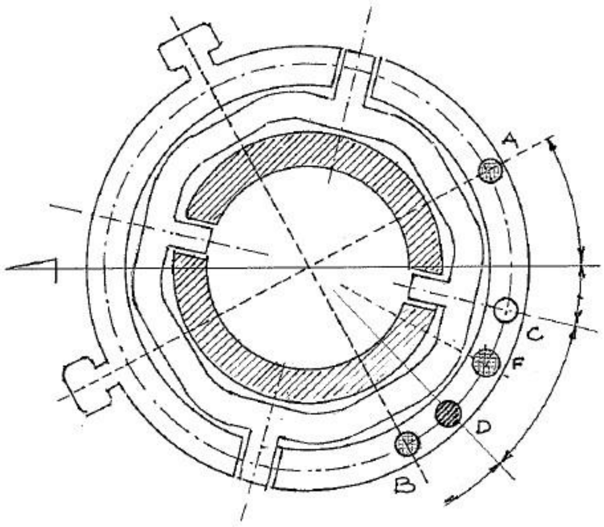

Figure 3: Sketch of the vibration sensor positions investigated to establish optimal position for retracting blade stall indicator. Credits: PZL-Świdnik.

In-flight investigations results show a significant correlation between oscillatory loads and swashplate vibrations (Fig.4). However, due to limited benefit of the sensor application on the speed limit extension (up to 10km/h limit shift) vs. anticipated complexity of the helicopter equipment, the idea was abandoned.

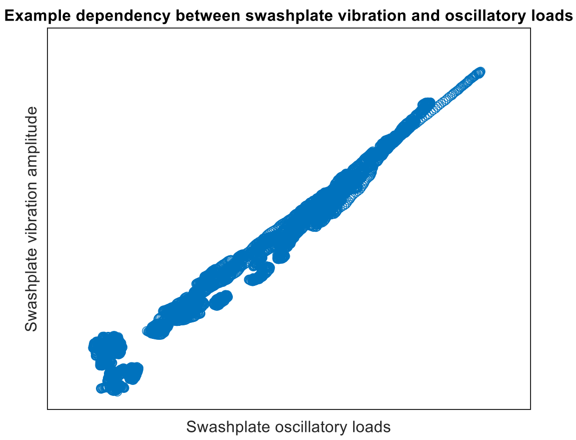

Figure 4: Example results of in-flight investigations showing dependency between the retracting blade stall indicator – MR swashplate vibration level vs. oscillatory loads. Credits: PZL-Świdnik.

4. NEW MR BLADES DEVELOPMENTS FOR THE PZL W-3A HELICOPTER

4.1. General overview of improvements

Within the new blade development program, apart from the retracting blade stall limits suppression, also other improvements are expected (increase of the fatigue life and introduction of full blades interchangeability). Thanks to analytical methods improvements currently available, the design of the new blades was supported by significant number of numerical analyses. To reduce risk of the project failure and simultaneously to increase the numerical analyses prediction precision, the initial step was added to the project for methods validation and tuning. Large database of in-flight tests results obtained for retracting blade stall investigation was used to perform this step.

4.2. Analytical methods tuning and validation for serial blades

Several activities were performed to increase accuracy of correct prediction of the aeromechanical behavior of new blades and whole rotor. The various methods were tested in the following areas:

- induced velocity distribution prediction (Mangler-Squire [5] and various prescribed wake geometry)

- dynamic stall prediction (Leishman-Beddoes method [6])

- finite element method used to predict elastic motion with more coupling effects supported by extended blades modal tests [7].

First of all, the non-dimensional retracting stall curve was predicted for serial blade by simulation of the set of level flights and comparing control loads from analysis vs. oscillatory load criteria for MR swashplate (Figs. 5-6). The condition where level of swashplate loads amplitude exceeds overload criteria was interpreted as potential retracting blade stall indicator. Additionally, the MR and control system loads were analyzed and compared for cases which are before stall margin vs. stalled conditions (Figs. 7-10). Example results shows significant increase of oscillatory loads which are result of visible additional blade torque oscillations for blade azimuth values Ψ=270-350deg. It could be interpreted as a main source of sudden oscillatory loads increase when the deepest stall phenomenon occurs at the blade azimuth angle opposite to the particular swashplate control chain.

The non-dimensional curve obtained from numerical analyses was compared with the one obtained from in-flight tests data with satisfactory prediction level (Fig. 11). This level of prediction allows to use the same tools and methodologies to obtain the retracting blade stall critical conditions for the new designed W-3A helicopter MR blades.

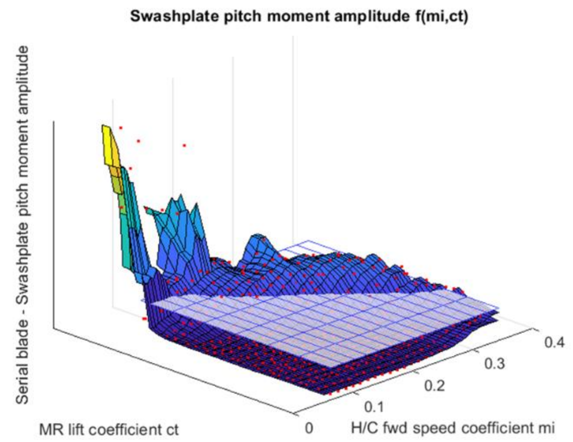

Figure 5: Summary plot of level flight simulations performed to obtain non-dimensional retracting blade stall curve – MR swashplate oscillatory loads – longitudinal channel. Credits: PZL-Świdnik.

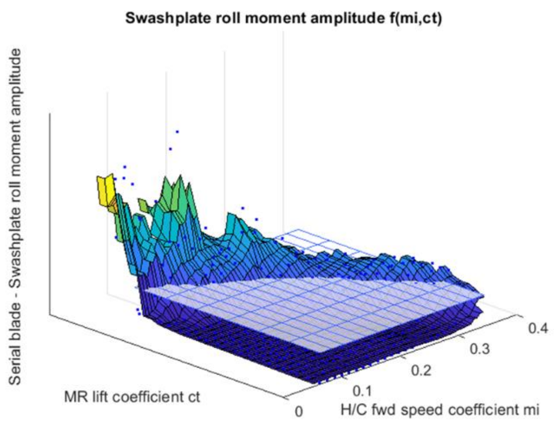

Figure 6: Summary plot of level flight simulations performed to obtain non-dimensional retracting blade stall curve – MR swashplate oscillatory loads – lateral channel. Credits: PZL-Świdnik.

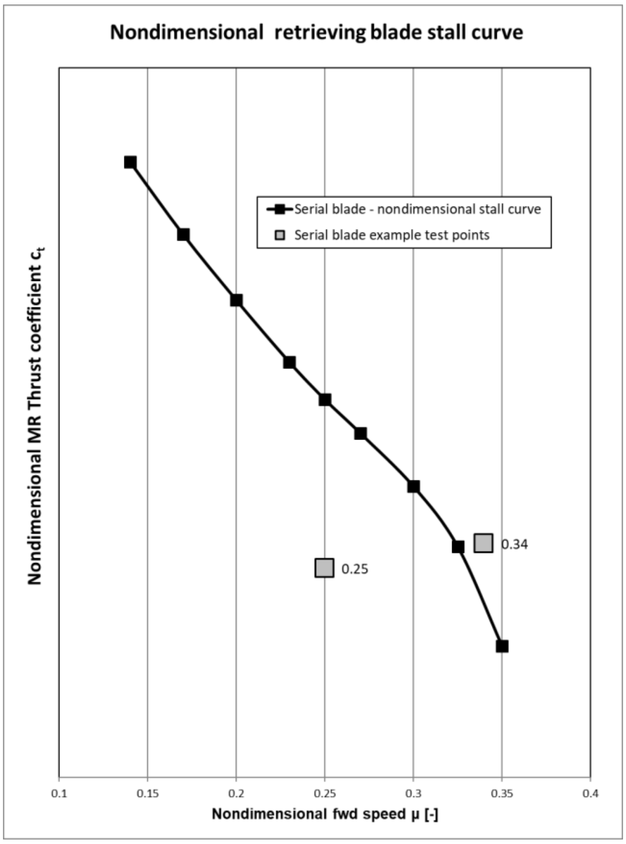

Figure 7: Example analysis test points to compare rotor loads and behavior with and without presence of retracting blade stall. Credits: PZL-Świdnik.

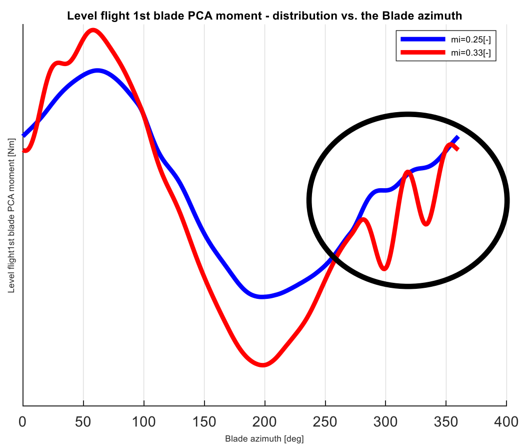

Figure 8: Comparison of the blade control moment variation vs. azimuth angle for serial blade – visible loads oscillations in the area of retracting blade stall Ψ=270-350deg. Credits: PZL-Świdnik.

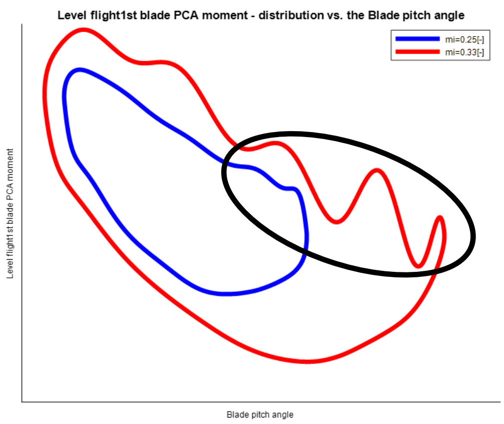

Figure 9: Comparison of the blade control moment variation vs. blade pitch angle for serial blade – visible loads oscillations starting from the area of high blade pitch angle values. Credits: PZL-Świdnik.

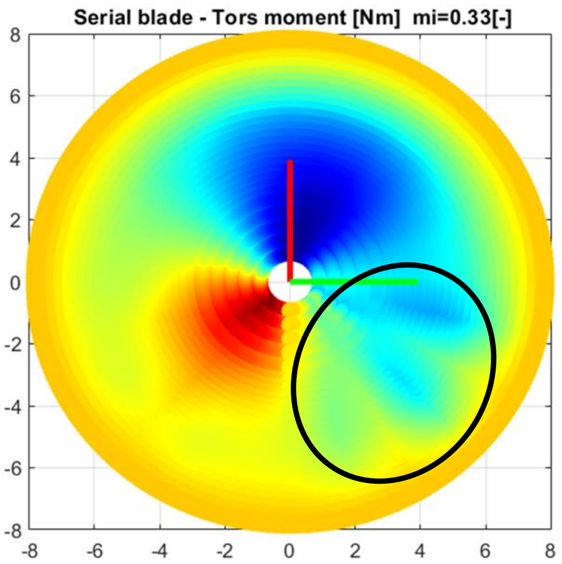

Figure 10: Example of blade torsion moment map of MR disk to visualize variation of the blade load vs. azimuth and along the radius. Oscillations are visible in the azimuth region Ψ=270-350 deg. Credits: PZL-Świdnik.

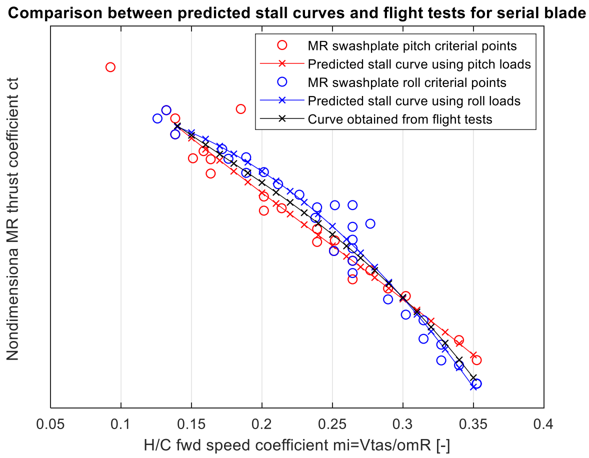

Figure 11: Comparison between predicted retracting blade stall curves based on swashplate limit oscillatory loads separately for longitudinal and lateral swashplate control channel. Satisfactory prediction level with better results using swashplate lateral loads. Credits: PZL-Świdnik.

4.3. Prediction of retracting blade stall margins for new blade.

Analyses of the serial blades recommended several improvements for blade geometry and properties to suppress and to shift retracting blade stall phenomenon to the higher speed and higher MR thrust values. Recommendations include moderate increase of the MR solidity, increase of the torsional stiffness and use of the modern airfoils to define blade geometry. Also the mass distribution along the blade was found as a noticeable parameter to suppress blade stall behavior.

In addition to the methodology improvements tuned and validated during serial blades analysis stage, the additional data gathering campaign was run to increase precision of the retracting stall prediction for new blades. The series of dedicated wind tunnel tests along with the CFD calculations were performed to obtain new airfoil sections family (ILH 4xx family) developed by IoA. This airfoils family was used to define new blade geometry. Both, static and oscillatory characteristics were investigated for core thickness airfoils (Figs.12-13).

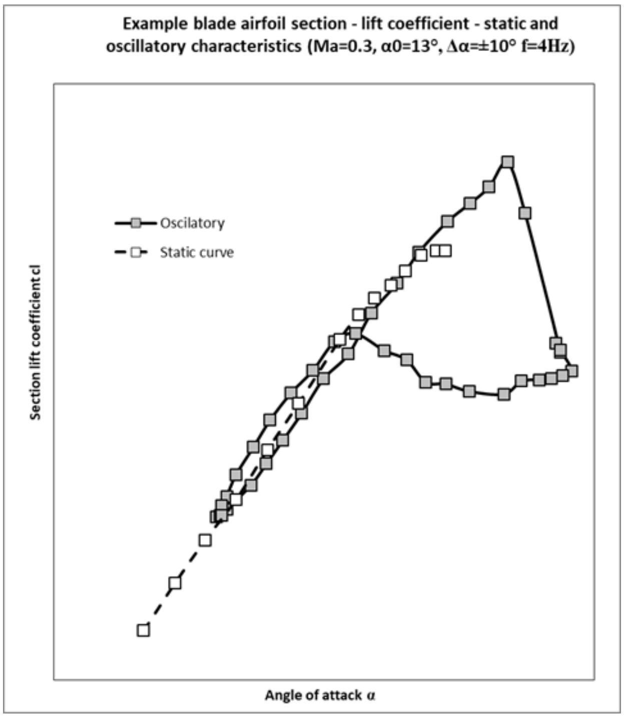

Figure 12: Example results of wind tunnel investigation of airfoil characteristic – section lift – static/oscillatory. Credits: PZL-Świdnik/IoA.

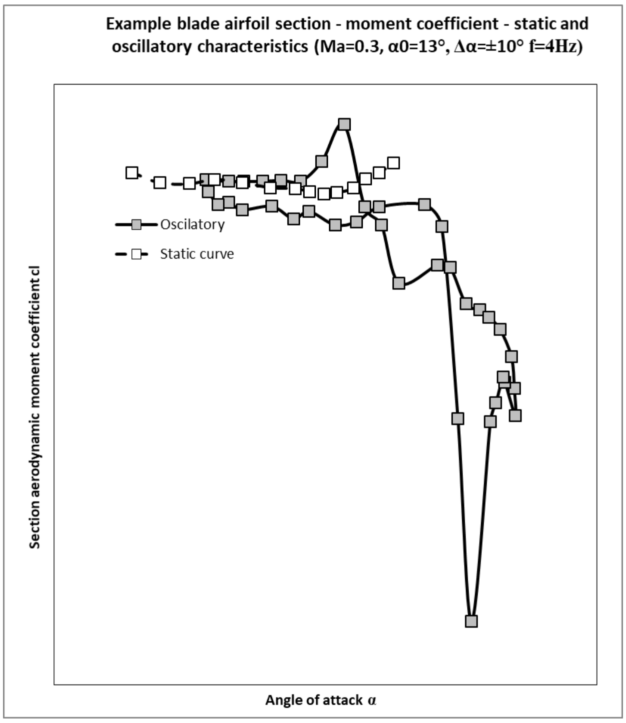

Figure 13: Example results of wind tunnel investigation of airfoil characteristic – section aerodynamic moment – static/oscillator. Credits: PZL-Świdnik/IoA

Also the set of complete blade stiffness/inertia parameters verification campaign followed by ground modal tests was run as described in [7].

Finally the similar analysis campaign as for serial blades was run and promising results were obtained including better power required vs. power available limitation curve fit (Figs. 14-).

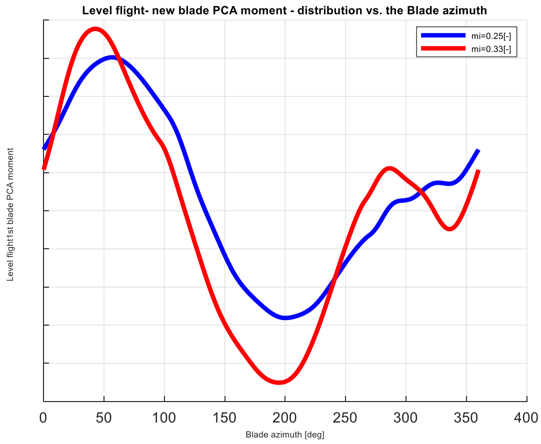

Figure 14: Comparison of the blade control moment variation vs. azimuth angle for new MR blade for check points as for serial blades (Fig. 8). Credits: PZL-Świdnik.

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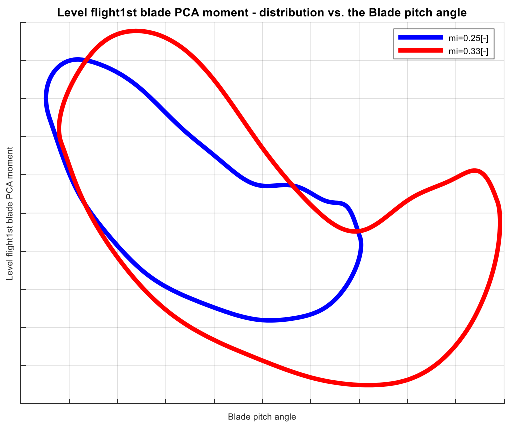

Figure 15: Comparison of the blade control moment variation vs. blade pitch angle for new blade for check points as for serial blades (Fig. 9). Credits: PZL-Świdnik.

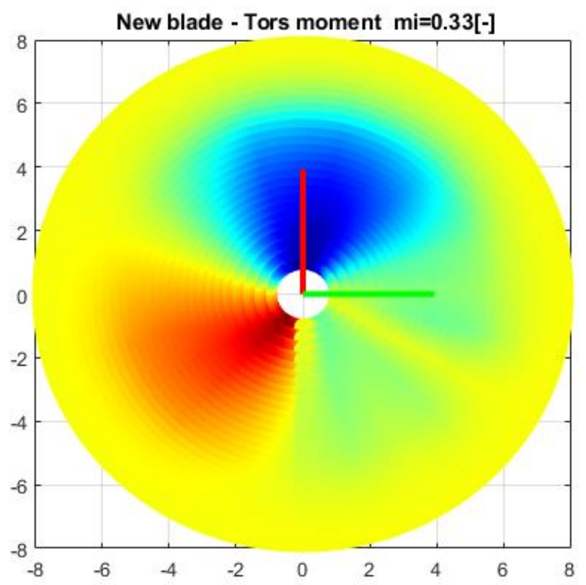

Figure 16: Example blade torsion moment map of MR disk to visualize variation of the blade load vs. azimuth and along the radius new MR blade. Credits: PZL-Świdnik.

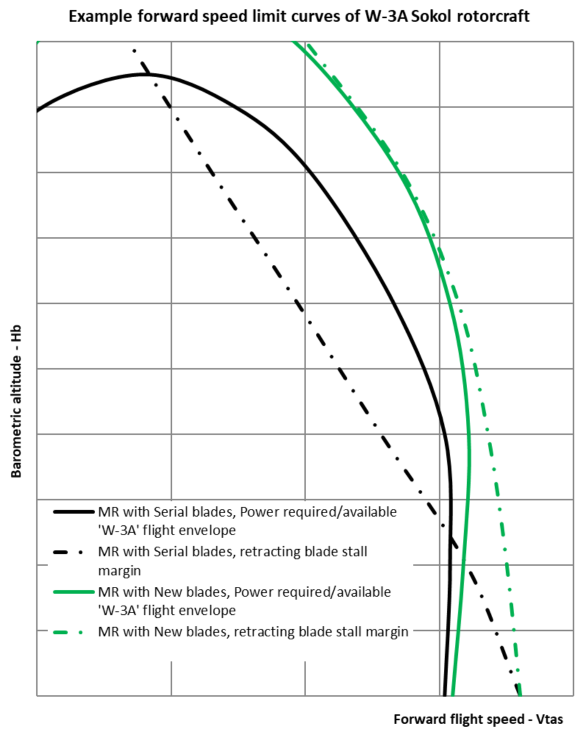

Figure 17: Comparison between fitting of retracting blade stall curves vs, power required/available limitations for serial and new blade. Credits: PZL-Świdnik.

The suppression of the retracting blade stall was confirmed during preliminary flight test campaign while flight tests for finally tuned blade geometry and properties are planned for the end of this year.

5. CONCLUSIONS

Long time investigations of the MR retracting blade stall phenomenon, performed on the PZL W-3A "Sokół" helicopter leads to the following conclusions:

1. The increase of MR swashplate oscillatory loads is the first indicator of the retracting blade stall phenomenon.
2. Using of the MR swashplate vibration shows high correlation with the stall loads but due to the sudden increase of loads vs. speed, it does not allow significant extension of the flying envelope.
3. Low torsional stiffness of the MR blade could be a source of fly speed envelope reduction due to the retracting blade stall phenomenon occurrence.
4. The simplest induced velocity distribution and dynamic stall models shall be improved and replaced by more sophisticated modeling for correct prediction of the retracting blade stall margins which, after improvements, would allow correct prediction of the retracting blade stall limit.

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