Predicting The Loads Of Autopilot Executive Systems Based On Digital Twin Strategy Modeling

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INTRODUCTION

The presented publication discusses aspects of designing and validating an autonomous control system from the point of view of the loads on the executive system. The research object is a helicopter with a Max Gross Weight =1800 kg with a classic articulated rotor and a classic control system equipped with actuators minimizing loads. The executive system of the automatic control system consists of electromechanical actuators connected in parallel to the control system. Ensuring mission safety relies on the interaction of the actuator system and on-board hydraulics. The aim of the following analyses is to evaluate the loads that flow onto the autonomous executive systems both in the case of normal, failure-free operation and in the case of a support failure. The load validation will be determined based on the actual loads recorded during the flight and adapted to the numerical control model. The presented approach is defined as a digital twin strategy.

SYMBOL

AoA	Angle of Atack
CAD	Computer Aid Designe
CFD	Computational Fluid Dynamics
Coll1/2	Collective control actuator
EASA	European Union Aviation Safaty Agency
Eta 1/2	Lateral control actuator
FEM	Finite Elements Metod
F7XX	Forcing forces
Kappa1/2	Longitudinal control actuator
OAT	Outside Air Temperature
RFM	Rotor Flight Manual
SP	Swash Plate
TQ/MQ	Torque moment on actuator
ToW	Take of Weight

ABSTRACT

Table 1. PZL SW4 General information

Characteristic	English	Metric
Engines	1 x RR 250 turboshaft	
Passengers	3 pax + 1-2 crew	
Engine Power	1 x 450 hp	1x 328 kW
Length	46 ft	9.075 m
Height	10,26 ft	3,13 m
Rotor Diameter	29,5 ft	9 m
Max Gross Weight	3968 lb	1800 kg
Range	370 nm	700 km
Service ceiling	16,400 ft	5,000 m
Vmax (at cruise)	140 kt	260 km/h

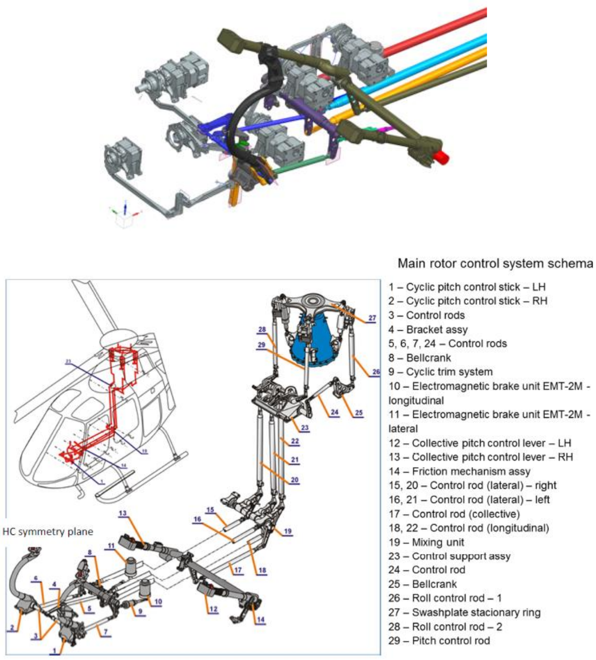


Fig. 1. Visualization of the PZL SW4 helicopter control system in the unmanned variant. Credits: PZL – Świdnik (Ref. 1)

One of the significant problems related to the implementation of autonomous flight control and stabilization systems in unmanned rotorcraft is the load on the control system. The research object on which the systems are tested is a classic helicopter with a maximum take-off weight of 1800 kg, with a control system equipped with hydraulic actuators. The design parameters of the rotorcraft are presented in Table 1 below. This means that in order to ensure safety, it is necessary to confirm that in the event of a failure of the on-board hydraulic system, the autonomous executive systems are able to take over the load and bring the helicopter to landing. The adopted assessment methodology assumes the use of a numerical model of the control system corresponding to the adopted configuration of the control system. The numerical model has inertial properties of elements such as masses and moments of inertia consistent with the design documentation. In order to improve load prediction, the numerical model takes into account the friction resistance to motion of control elements such as bearings and joints. The analysis strategy assumes the use of a validated control system model, consistent with the design documentation, in the process of analyzing the loads (require moment) on the executive systems. The safety assessment assumes verification of the autonomous control system in terms of assessing the control capabilities in the event of increased load resulting from a hydraulic failure. The analysis assumes verification of the autonomous system for the flight envelope, taking into account different masses, centers of gravity, and external conditions. For each of the analyzed cases, the time histories of the swash plate positions and the current forces in the individual control directions will be determined. Figure 2 a) shows the numerical visualization of the rotor and the control disk with the main axes of motion marked.

DESCRIPTION OF THE PROPOSED PAPER

Currently, research is being conducted on the broader use of Digital Twins technology, which allows for the development of engineering analysis capabilities with high convergence with real results. The possibilities of Digital Twins technology have also been noticed by EASA, which allows for the certification of products using the CIVIP

(Continued Integrity Verification Programme) evidence path. The information gained during the verification of computational models will be used to develop general knowledge about the methodologies and thus help provide the necessary data in future evidentiary processes.

PRIOR PUBLICATION

Currently, many aspects of engineering problems are analyzed using the Digital Twins strategy, which has been widely presented in scientific publications describing many technical aspects (Ref.2). Currently, in the analyses conducted in PZL Świdnik, the Digital Twin strategy was not used. The results obtained will be used to assess both the quality and quantity of the results obtained, and the project itself is treated as a test.

SAMPLE RESULTS

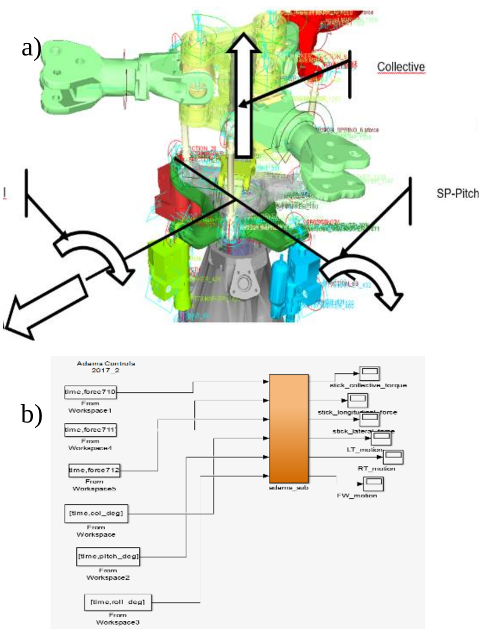


Fig. 2. a) Visualization of the PZL SW4 helicopter Swash Plate. Credits: PZL – Świdnik b) Conceptual diagram of data flow

The numerical model of the control plate reflects the kinematics and dynamics of operation. It also allows for the introduction of analysis automation through the Matlab Simulink environment, allowing for the simulation of data recorded in real flights. Figure 2 b) shows the schematic diagram of the helicopter numerical model operation and actual measurement data. According to the data flow diagram, the central element is the numerical model of the control system, for which the input data are the angular values of the control disc position and the time-correlated values , and the output data are the angular values of the actuator positions. Time courses determined based on actual courses recorded during the flight are the starting point for determining the loads of the executive systems. Reconstruction of the flight state using a digital twin consists in introducing time courses to individual executive systems performing movement in a particular control channel

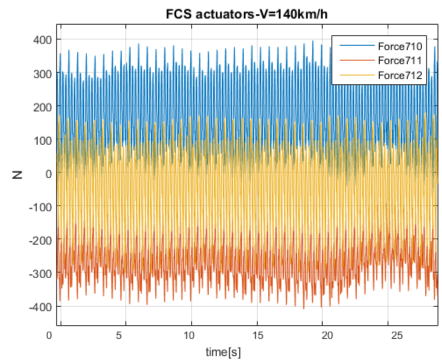


Fig. 3. Visualization of the PZL SW4 Time plot of swashplate forces during real flight. Credits: PZL - Świdnik

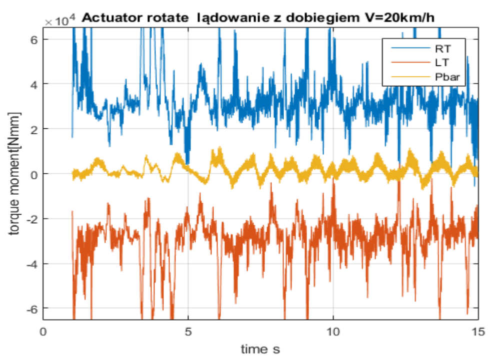


Fig. 5. Visualization of the PZL SW4 Time plot of actuators loads. Credits: PZL - Świdnik

The visualization of the course of the control disk positions, which is the result of processing the time histories of the actuators by the digital twin, is presented in Figure 3. By analyzing the individual mission states using the digital twin methodology, we are able to determine the envelope of the motion kinematics, as well as the envelope of the actuator torque demand. The load demand analysis can be performed continuously, which means that continuous courses are used during load simulation. An example of loads for horizontal flight at a speed of V=140 km/h is shown in Figure 4. Figure 5 shows the dynamic response of the load curves of the actuator system. Using a digital twin in analyses allows for shortening the optimization time. Based on the flight state group, as well as the boundary envelope of the control disk positions, it is possible to determine the ranges of movement for individual actuators. Figure 6 shows the visualization of the swash plate position in relation to the limitation envelope. Currently, work is underway to improve computational models and to accelerate numerical analyses. The target digital twin model will not only analyze load levels, movement speeds and kinematic ranges, but will also allow for the optimization process of the actuators' work concept. Based on “Big Data” sets, we take into account the effect not only of a single helicopter, but also of the entire fleet of helicopters operating in different climatic conditions with different mass configurations and external equipment. The use of the digital twin approach enables statistical analyses to be carried out to verify the levels of variable stresses that limit fatigue life, and thus to verify the hourly service life assigned to individual components. An additional advantage of the Twin strategy approach to analysis is the possibility of co-simulation, using FEM (Fine Element Methods) and CFD (Computational Fluid Dynamic) tools and their coupling. The analyses performed so far have allowed us to identify a combination of flight states that significantly affect the performance of the executive systems. This information will allow us to further minimize their presence in the spectrum of flight states, as well as facilitate modification of the piloting procedure in automatic mode. To summarize the scheme of the operation schematically, three basic groups can be distinguished, i.e., input data being a sequenced set of data, Digital Twins numerical model, being an executive element and output data, in this case the load of the executive system. Additionally, the control stage includes a detailed validation process, which allows to tune the numerical algorithms to real conditions.

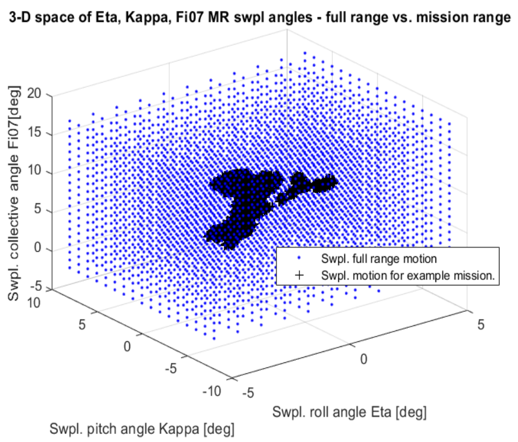


Fig. 6. Visualization of the swashplate position envelope depending on the mission being performed: PZL - Świdnik

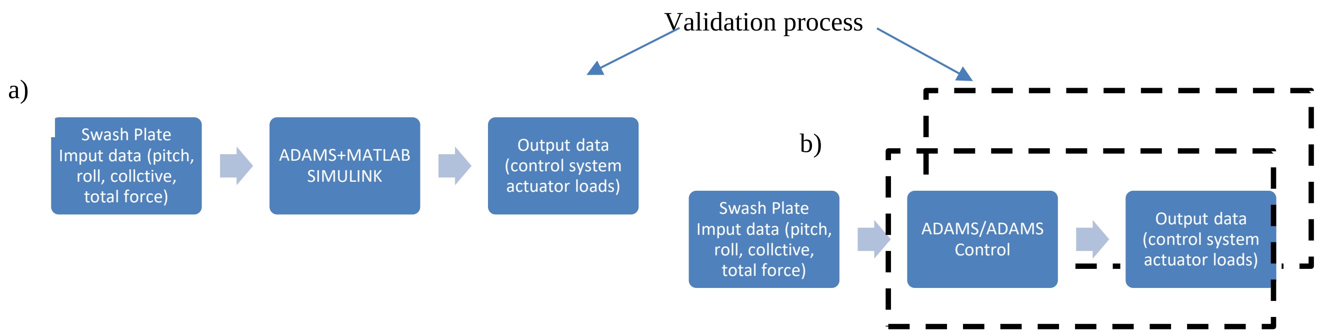


Fig. 7. Schematic diagram of the process. Credits: PZL Świdnik

The diagram below (Fig. 7) shows the interpretation of the process. The diagram above shows the validation process using two models a) Matlab Simulink and parallel b) Adams Control/ Akimow splain.

As described above, the adaptation of the calculation model and validation to real conditions takes place in two stages. In the first part, a model is built, the purpose of which is to generate a transition function, allowing to determine the angular position of actuators of the actuator in relation to the current position of the control disc. For this purpose, an algorithm will be used to sweep the angular range of the steering disc in the kinematic limits ranges. Figure 8 shows an example of the use of the sweep function

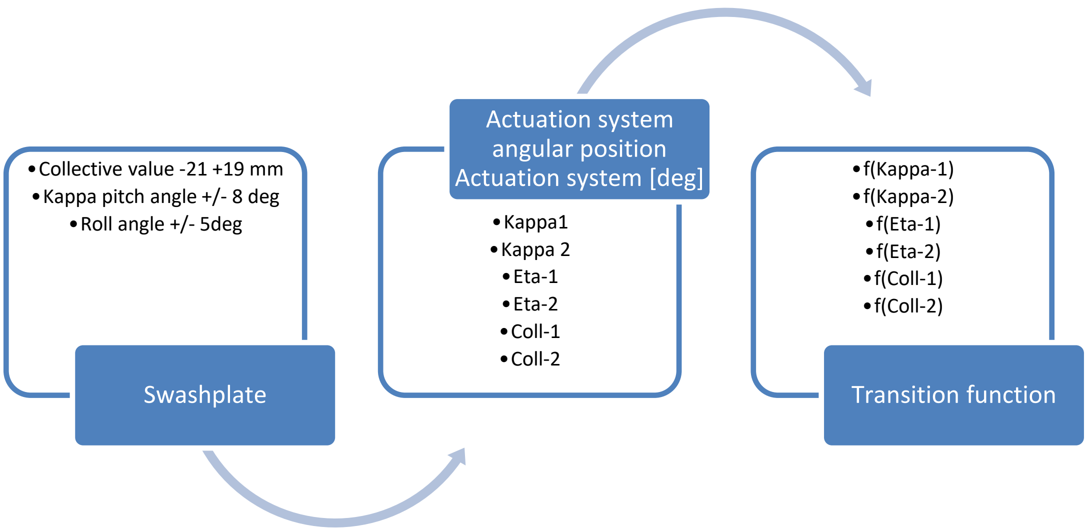


Fig. 8. Visualization of the data adaptation process. Credits: PZL Świdnik.

Figure 9 shows an example of the use of the sweep function and the response on the actuators. The response on individual actuators is measured depending on the current position of the steering disc. The movement of the steering plate is simulated using the STEP function.

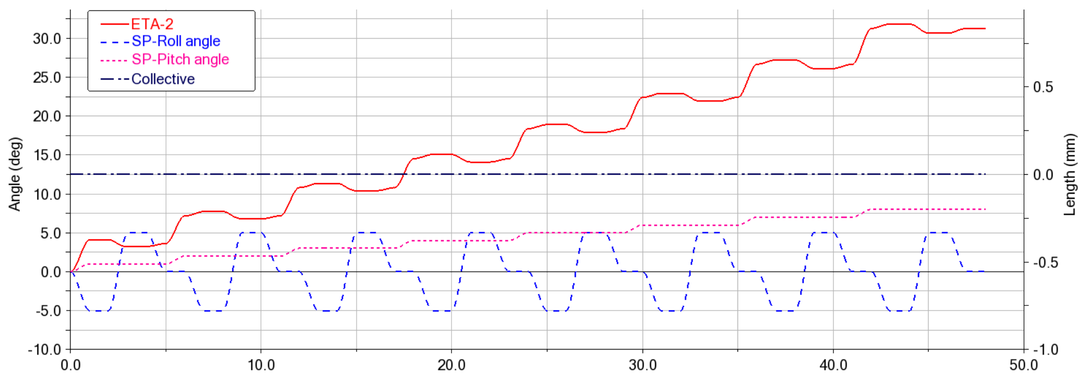


Fig. 9. Visualization of the sweep function. Credits: PZL Świdnik.

Depending on the control channel being analyzed, the end result is a matrix that defines the control envelope. Figure 10 below shows a visualization of the envelope of the positions of the control disc and the corresponding positions of the actuators.

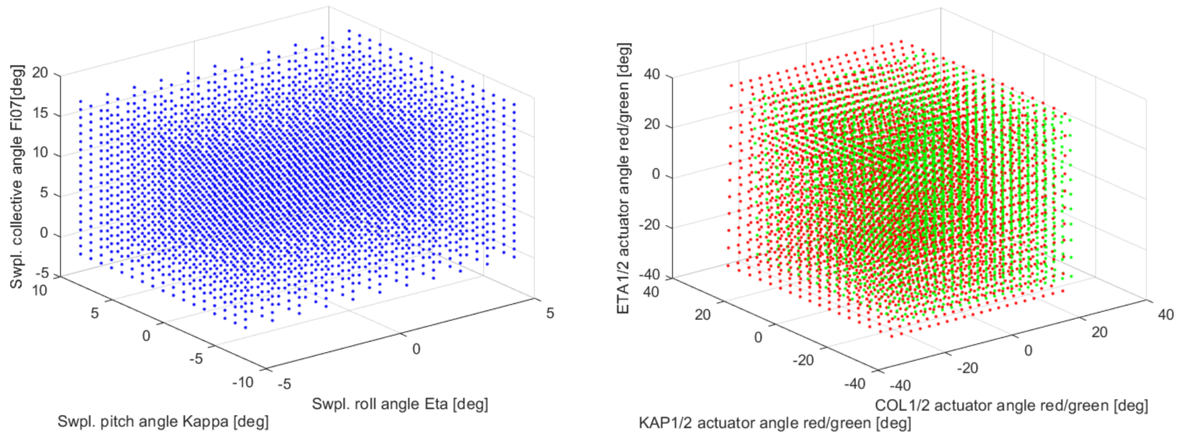
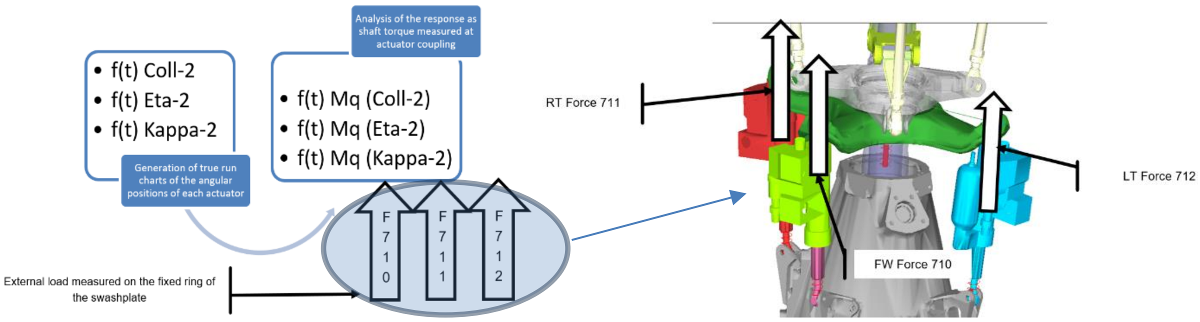


Fig. 10. Visualization of the boundary of angular position of the actuators covering full motion of the swashplate. Credits: PZL Świdnik

The control matrices created in this way allow you to easily determine the values of angular displacements of actuator systems depending on the combination of positions of the control plate.

In the second stage, a block of algorithms was introduced into the control model, responsible for introducing loads directly from the main rotor and loads generated by the internal inertia of the system. The diagram shown in Figure 11 presents the ideas of information exchange between the kinematics of the swash plate and the kinematics of the actuator system (f(t)) and the resulting torque demand of the actuators (f(t) Mq). The numerical model of the control system allows for the modification of loads by introducing additional components resulting from aerodynamics and flight mechanics (Ref. 3). In the presented model, the load from the rotor is represented by forces measured in real time on the fixed element of the control plate, which take into account the inertial and aerodynamic aspects of the main rotor.



Figs. 11 Schematic Diagram of Numerical Interpretation and Definition of Digital Twin Loads. Credits: PZL Świdnik.

The torque demand directly depends on the current rotor load, determined by the current flight condition. The current power requirement is directly correlated with the load and the position of the control plate. External data are standardized to a common time base. In figure 11, the load block is represented by F710, F711, F712. The initial tuning of the numerical model is based on the determination and appropriate distribution of friction coefficients in individual bearings, so that the total force measured on the cyclic and collective rods corresponds to the actual values measured on the helicopter.

CURRENT STATUS OF THE WORK

At the moment, work is being carried out on the construction of a numerical model reflecting the full control system, taking into account friction resistance and inertia of the system. Over the next 2 months, work will be carried out on the construction of coupling algorithms and filling data sets. At the moment, the state of advancement is about

85%. A significant risk that we may encounter at the final stage is the computational efficiency as well as the speed of interpretation of results.

Flights in which the hydraulics were intentionally switched off will be used to assess the effectiveness of the control system and validate the numerical model. Selected flights cover the entire operational envelope of the helicopter, both mass and temperature. An important problem in the evaluation of functionality is the impact of the steering speed on the level of loads, as well as the confirmation of sufficient reserve to ensure controllability and stability. The following figure 12 shows the load and velocity curves of the random flight state of the lateral control actuator (a) and collective control actuator (b).

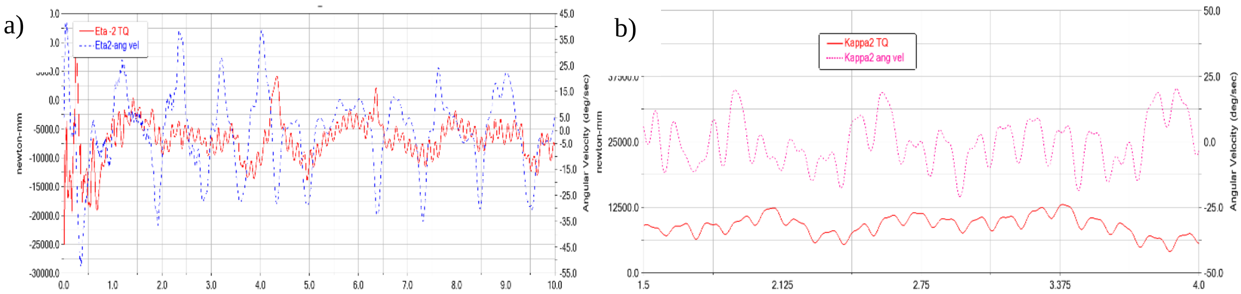


Fig. 12 Visualization of load course on lateral a) control actuator, collective control actutor b). Credits: PZL Świdnik

Determining the maximum loads limiting the size of the actuator systems requires an analysis of a set of flights, both emergency (hydraulic assistance off) and normal states (hydraulic support on). On the basis of the above assumptions, a "BIG DATA" database was created, allowing to determine the envelopes. The chart below shows the case of a combination of flights without hydraulic assistance. The red and green lines symbolize the maximum efficiency of the actuators as a function of the speed of movement, while the blue dots represent the current torque demand. Using the methodology of control performance assessment, it is easy to determine flight states for which the maximum efficiency of actuators has been exceeded by analyzing areas in which outside the envelope lines. The use of the above methodology allowed to determine and select hazardous conditions, which is important for the correct formulation of RFM restrictions.

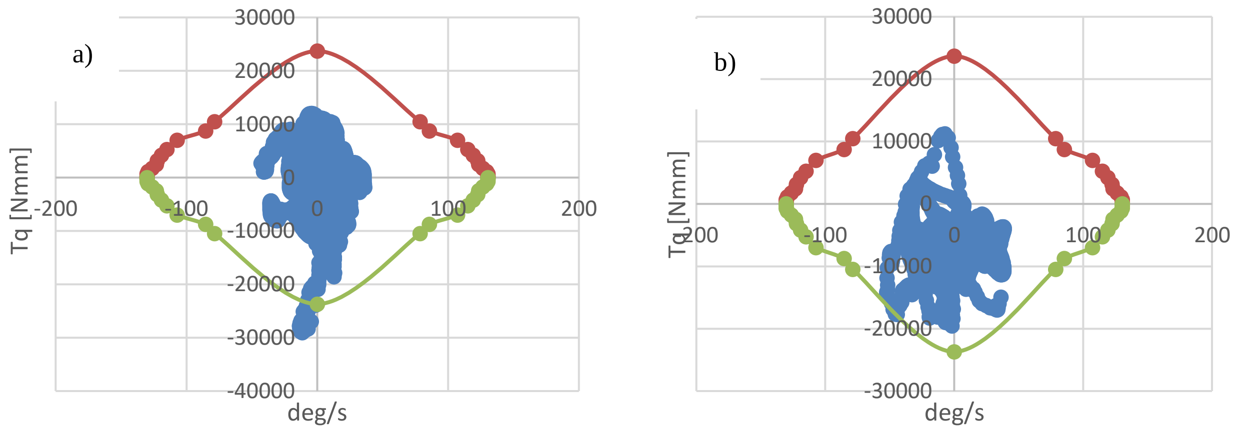


Fig. 13 Visualization of actuator loads for level flight case a), close ground maneuvers b). Credits: PZL Świdnik

The use of the above methodology makes it possible to analyze a large number of cases for different helicopter configurations, taking into account parameters such as take-off weight, ambient temperature, flight altitude. The use of the digital twin approach makes it possible to easily reconstruct the entire course of the flight by analyzing the current load values. Figure 14 below shows a visualization of the time course on the individual actuators of the actuator.

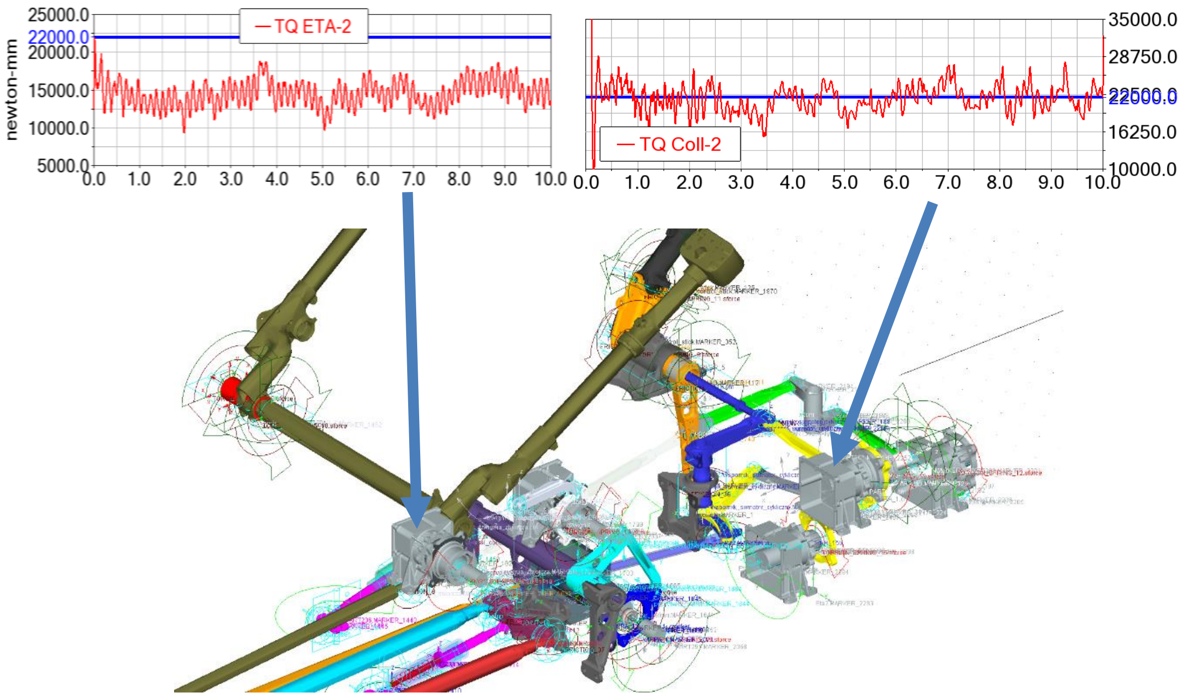


Fig. 14.Graphic interpretation of the Digital Twin. Credits: PZL Świdnik

CONCLUSION

The use of the methodology of analysis of the autonomous control system, using the Digital Twin as a reference model, significantly reduced the calculation time, allowing to analyze a number of flights in different helicopter configurations. Tuning the model from a real object made it possible to use its capabilities in the analysis of intermediate phenomena, such as the smoothness of the control system or the analysis of collisions and deadlocks. The figure below shows a visualization of analyses in which a collision of the collective control thrust was found.

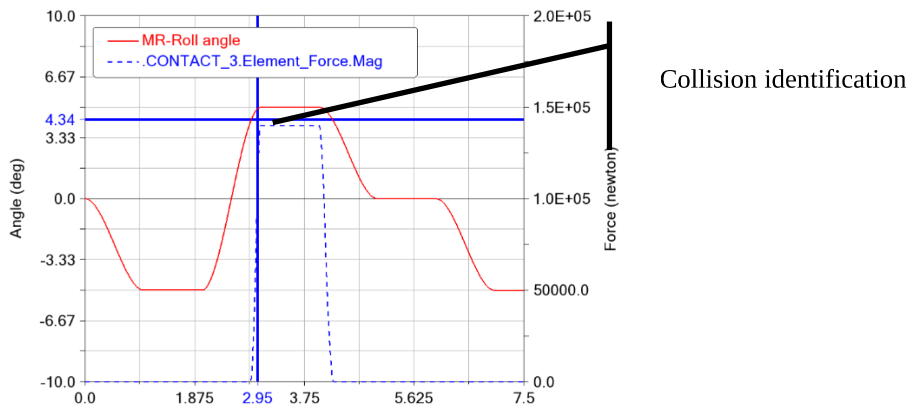


Fig. 15 Visualization of the collision hazard identification process. Credits: PZL Świdnik

Another example of the use of a digital twin in the design process is the assessment of the impact of individual modifications on the load level of executive systems. For this purpose, the numerical model was modified by introducing new assemblies into the tuned model. Using sets of helicopter flights and configurations analyzed on the baseline, their impact on load levels was determined. Figure 16 below shows the effect of structural modification on the load level of the collective control system.

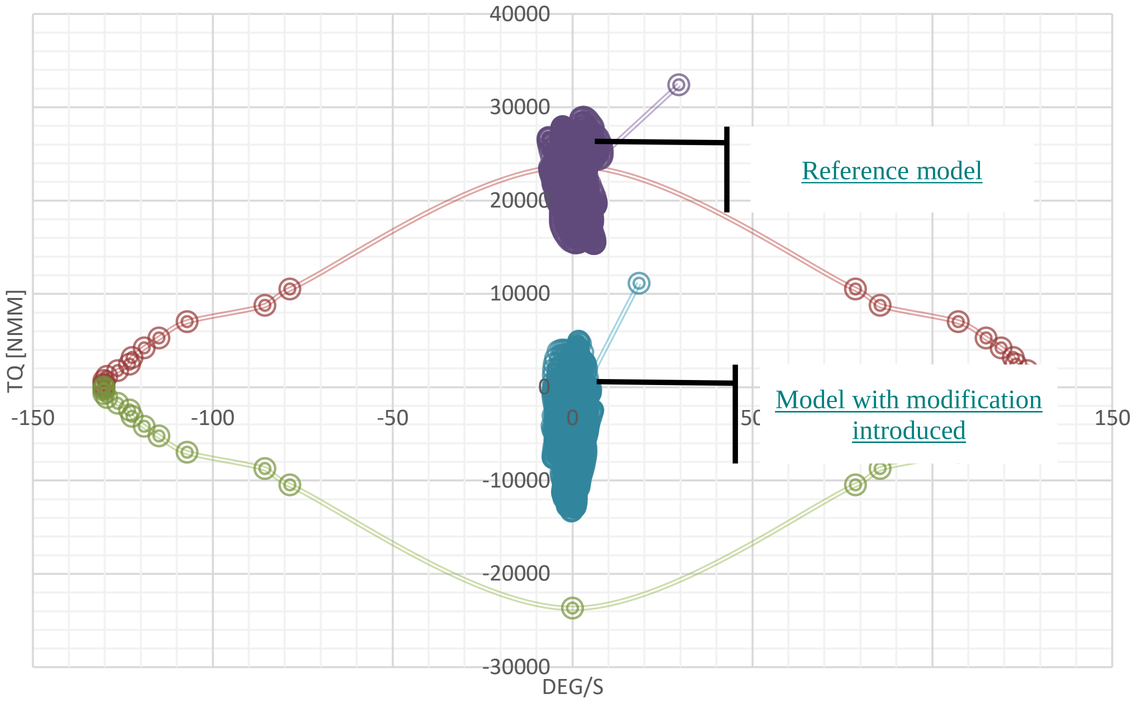


Figure 16 Effect of proposed modification on control system loads. Credits: PZL Świdnik.

ACKNOWLEDGMENTS

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REFERENCES

1. Fei Tao and Qinglin Qi, “Make More digital twins”, Nature, Vol 573, 26-09-2019.
2. PZL SW-4 Maintenance Manual AE 60.01.04.0, Control section.
3. Johnson, W., *Helicopter Theory*, Princeton University Press, Princeton, NJ, 1980, pp. 273-318.