



Executive summary

Flight Mechanics Model Development For A Kamov KA32T Helicopter Training Simulator



Problem area

A KA32T flight mechanics model was developed and tuned as part of the KA-32 Helicopter Training Simulator Development Program, managed by the Korea Aerospace Research Institute (KARI).

Description of work

Within this program, the Netherlands' National Aerospace Laboratory (NLR) developed the flight model and executed the flight tests in close co-operation with KARI and the helicopter operator. In this paper a description is given of the development of the basic flight mechanics model and several additional models required for training, such as the water tank and sling load. Subsequently the

techniques are described that were used to tune the flight model to AC120-63 level C requirements, and the challenges that were encountered in the process.

Results and conclusions

The very successful flight test campaign provided good quality data for the AC120-63 tuning process, thanks to good cooperation between Korean and Dutch engineers and the Korean helicopter operator.

During the model tuning process, a very good result was achieved, providing a simulation model that has a high (Level C) fidelity in representing the KA32T and an almost 100% fit to the flight test data.

Report no.

NLR-TP-2009-545

Author(s)

J. van der Vorst
K.D.S. Zeilstra
D.K. Jeon
H.S. Choi
H.S. Jun

Report classification

UNCLASSIFIED

Date

October 2010

Knowledge area(s)

Helikoptertechnologie

Descriptor(s)

Helicopters
Simulation

**Flight Mechanics Model Development For A Kamov KA32T Helicopter
Training Simulator**

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl



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J. van der Vorst and K.D.S. Zeilstra, D.K. Jeon¹, H.S. Choi¹ and H.S. Jun¹

¹ Korea Aerospace Research Institute

This report is based on a presentation held at the 35th European Rotorcraft Forum, Hamburg, Germany, September 2009.

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This publication has been refereed by the Advisory Committee AEROSPACE VEHICLES.

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Owner NLR
Division NLR Aerospace Vehicles
Distribution Unlimited
Classification of title Unclassified
 October 2010

Approved by:

Author	Reviewer	Managing department
		

Summary

A KA32T flight mechanics model was developed and tuned as part of the KA-32 Helicopter Training Simulator Development Program, managed by the Korea Aerospace Research Institute (KARI). Within this program, the Netherlands' National Aerospace Laboratory (NLR) developed the flight model and executed the flight tests in close co-operation with KARI and the helicopter operator. In this paper a description is given of the development of the basic flight mechanics model and several additional models required for training, such as the water tank and sling load. Subsequently the techniques are described that were used to tune the flight model to AC120-63 level C requirements, and the challenges that were encountered in the process. The final result is a comprehensive KA32T model that is a high-fidelity representation of the real helicopter, suitable for the KA32T training simulator.

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1 Project background

The objective of the KA-32 Helicopter Training Simulator Development Program, executed by the Republic of Korea Government, is to acquire a helicopter simulator which meets level C requirements in accordance with the FAA AC 120-63. The Korea Aerospace Research Institute (KARI) managed the development program and was in charge of developing and validating the flight dynamics model based on simulator design data and flight test data. The helicopter chosen for this project was the Kamov KA32T, operated by the Korean Forest Aviation Office (FAO). KARI was presented with the challenge of finding sufficient data for the flight dynamics model. The Dutch National Aerospace Laboratory (NLR) was awarded a contract to develop the flight model and flight test data, due to its experience with flight simulation development and flight testing.

The result is an interesting project with an international touch, including some distinctive logistical challenges: Korean and Dutch engineers working on a Russian helicopter.

Key innovations for NLR for this project are the non-intrusive measurement system and the setup of a flight test program with restrictions in operation and instrumentation. The project has been successfully finished in a short time and on a tight budget.

The KARI/NLR project consisted of three phases: flight mechanics model development, flight testing and model tuning. This paper presents the initial flight mechanics model development and the tuning to AC 120-63 Level C requirements.

2 Flight mechanics model

The Kamov KA32T is an 11-tonne twin engine helicopter with a co-axial rotor system (see Figure 1). It is operated by the Korean Forest Aviation Office, mainly for the fighting of forest fires.



Figure 1: The Kamov KA32T test helicopter

A comprehensive flight mechanics model had to be created to drive the KA32T training simulator.

For all rotorcraft simulation work the National Aerospace Laboratory NLR uses the comprehensive software suite FLIGHTLAB from Advanced Rotorcraft Technology (ART). Besides the default FLIGHTLAB models, some highly customized models have been created to suit the needs of the training simulator.

The KA32T Flightlab model consists of the following main components:

- Rotors

The rotors have been modelled using a blade element approach, with rigid blades (no elastic blade model). The induced velocity model is a six state Peters-He model. The rotor blade aerodynamic data has been created by KARI using CFD, from airfoil shape data measured on the KA32 blade. Blade element aerodynamic forces are calculated from a nonlinear function of dynamic pressure, angle of attack, and Mach number, with a correction for cross-flow.

- Interference

Interference from both rotors was calculated from the Peters-He induced velocity model, and interacts with the other rotor, empennage and fuselage.

- Fuselage and empennage

The fuselage aerodynamic coefficients, as a function of angle of attack and angle of sideslip, have been calculated by KARI using CFD and complemented with wind tunnel measurements.

The vertical tail and horizontal stabiliser geometry was measured and used as input for the CFD calculation, providing tables with lift and drag coefficients as a function of angle of attack, Mach number, and rudder deflection.

No elastic models have been used for empennage and fuselage.

- Landing gears

The landing gears were modelled as non-linear spring and dampers, with generic data that has been updated after the flight test campaign.

3 Engine model

The KA32T's TB3117 engines have been modelled using a piece-wise linear approach with lookup tables. Data for the model has been gathered from flight and maintenance manuals and was later supplemented with flight test data.

The engines' control system (Engine Automatic Control System, EACS) is a hydromechanical unit providing gas generator speed governing, main rotor speed governing and starting

functions. The EACS is supplemented by an electronic gas generator speed limiter and temperature limiter.

The EACS is a mechanical system controlling the fuel flow by means of fuel pressure. For simulation purposes the controller model was built on the functional specifications from the maintenance manual and is based on fuel flow instead of fuel pressure. The system included the main rotor governor, the gas generator governor (mechanical and digital), the temperature limiting system and the starting system.

CSGE is ART's 'Control System Graphical Editor', a Matlab-Simulink-like tool for building control systems in FLIGHTLAB. The EACS functional specifications were translated into CSGE block diagrams, providing easy integration with the FLIGHTLAB model.

Due to the systematic approach it was easy to implement the malfunctions required for training purposes.

Additionally, a model was created of the KA32T's fuel system. Components with variable distributed mass represent the fuel tanks. Input to these components is mass flow, both between tanks and to the engines. The fuel flow is calculated from a diagram with switching logic to simulate pump and valve selection and relevant malfunctions.

4 Flight control system model

The KA32T has a flight control system with analog autopilot, called Integrated Flight System (IFS). The IFS provides the following functions:

- Attitude hold
- Control & stabilization
- Altitude hold
- Hover hold
- Flight director for altitude, heading, speed and sling load damping

Information about the IFS control laws and computer switching logic was found in the KA32T maintenance manuals. The gains were initially also estimated from the manuals. After the flight test campaign flight test data was used to update these values.

The flight control law diagrams are readily available in the maintenance manual, however without gains and switching logic. The switching logic was derived from analysing the IFS electrical diagrams together with the functional description in the manual. Even though this was a difficult puzzle to solve, it resulted in a very accurate model with the correct behaviour for use in training, including realistic response to malfunctions.

Switching logic and electrical diagrams were created in FLIGHTLAB's Control System Graphical Editor (see Figure 2).

5 Additional models

A number of additional models that are required for the training function of the KA32T simulator had to be developed. These models were added to the flight mechanics simulation, but are only tested subjectively by pilots, because no flight test data for those configurations and equipment was available.

Most of the following models are not standard models in the FLIGHTLAB development environment. Due to the flexible nature of FLIGHTLAB they could be implemented in a very efficient way by using pre-existing components. The structural part (e.g. masses and springs) was coded in scripts, whereas the switching logic and electrical diagrams were created in FLIGHTLAB's Control System Graphical Editor.

Combining all of these models into one FLIGHTLAB model was a challenge: only one binary FLIGHTLAB model is created for use in the simulator. This means all elements are always present in the model, but not active. For example: the bambi bucket and water tank model are always there, but have zero mass when they are not used. Activation of the models in the simulation consists of 'electrically' switching on the appropriate systems by setting the correct switches and circuit breakers and by filling the tanks with a water load.

Due to the scope of the models a complex interaction existed with other simulator components, like motion base, control loading system, cockpit, etc. To manage these interactions, an extensive Interface Control Document was realised.

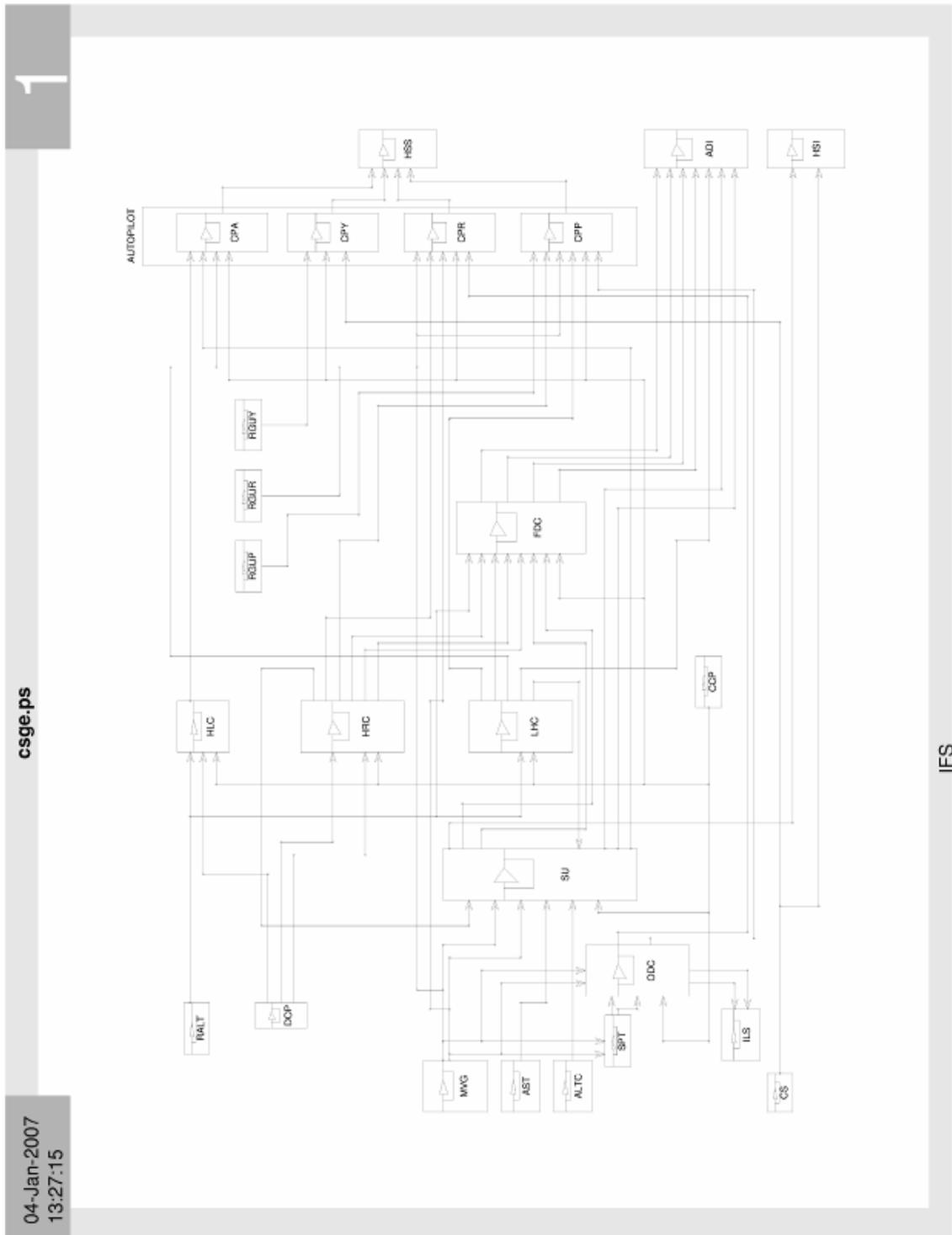


Figure 2: Overall structure of the Integrated Flight System model

5.1 Sling load

A 3 degree-of-freedom sling load was added to the flight mechanics model, consisting of a mass on a cable which can roll and pitch with respect to the helicopter. The third degree-of-freedom is the length of the cable, which can be changed by the instructor. The model also includes the possibility to pick up and drop the load. Connection of the load during pick up is enabled by the instructor, and is possible when there is slack in the cable. In-flight emergency release is also possible.

Generic aerodynamic coefficients are used for the forces on the sling load.

The external load lock control functions of the electrical system (pilot emergency release, etc.) are included in the FLIGHTLAB model, together with the automatic disengagement of the mechanical lock. This is accomplished automatically at the moment of contact of the load with the ground. When the load on the hook is lower than 5 kg the hook opens.

5.2 Bambi bucket

A special case of the sling load is the bambi bucket. It is a bucket used for fire fighting which can hold 1590 liter of water. It is modelled just like the sling load, but has a variable mass. The water is released from the bucket in 2 seconds upon activation of the release switch. When the bucket is lowered into water, it automatically fills in 30 seconds.

The location and height of the water drop provides the instructor with information on the fire-fighting performance of the pilots (see Figure 3).



Figure 3: KA32T simulator 'Fire View'



5.3 Hoist

A rescue hoist model has also been added in FLIGHTLAB. It is the same type of sling load model as used for the external load, with an additional input from the instructor for cable speed to reel the hoist in or out. Ground contact of the load on the hoist is also included.

During development of the hoist model it was found that the hoist load became unstable during reeling in of the hoist cable. The aerodynamic forces on the hoist load were not sufficient to dampen the increased motion due to the conservation of angular momentum. This was solved by adding an artificial damping, representing damping from the cable and steering of the load by the load master when it is close to the cabin.

Attaching and detaching loads is performed by the instructor, as well as the emergency cable chop function.

5.4 Water tank

The FAO's KA32Ts can be equipped with a Simplex FireAttack system. This is a water tank which is installed below (and partly inside) the helicopter. It consists of two compartments with two doors each that can be opened independently to release the water. It can contain 3000 liters of water. The system is capable of hover refilling through two hoses that extend below the helicopter.

The retardant system consists of 2 foam tanks externally mounted, one on each side. One foam pump/filter assembly feeds each compartment of the main tank. Both foam tanks contain 332 lb of retardant.

Water drops can be made in three modes:

- SALVE/ONE: By activating the doors open switch once both left-hand doors open. By activating the DOORS OPEN SWITCH again both sides doors open
- SALVO/BOTH: Both sides doors open
- TRAIL/BOTH: By activating the DOORS OPEN SWITCH once, both aft doors open.

When the water level drops to $\frac{3}{4}$ both forward doors open too.

Both compartments of the water tank as well as the two foam tanks are modelled as time-varying distributed masses. Changes in helicopter mass and centre of gravity are automatically accounted for.

The mass in the tanks will change during a water drop, hover refilling or foam injection. The flow into or from the tanks during these phases is controlled by a complex logic diagram representing the FireAttack control box in the cockpit.

As for the bambi bucket the trajectory of the dropped water load is calculated for analysis by the instructor.

5.5 Atmosphere with fire simulation

Simulator instructor controls are required for the atmosphere model. The instructor can set sea-level temperature, pressure and temperature lapse rate.

FLIGHTLAB's default atmosphere model consists of the standard atmosphere, with different tables for off-standard conditions. Temperature lapse rate is ordinarily not an input that can be changed in real-time. Therefore FLIGHTLAB's default tables for lapse rate were replaced with a customized solution connecting the lapse rate to the instructor input.

Besides the instructor inputs, a model has been added for the local influence of a forest fire on ambient temperature. This model was based on simplified functions derived from 2-dimensional line heat source model and represents a change in ambient temperature as a function of the size of the fire and the distance of the helicopter to the fire, and its height above the fire.

5.6 Centre of gravity calculation

Since FLIGHTLAB is a modeling environment based on 'multi body dynamics', a parameter like 'current mass' or 'current centre of gravity' is not available. The helicopter model consists of many separate components representing mass, like the rotor blade elements, fuel tanks, empty mass, cargo, etc. The combination of these components results in a total mass and centre of gravity.

In order to provide the instructor with a tool to monitor the simulator's weight and balance, a diagram has been implemented in CSGE to continuously calculate the helicopter's total mass and centre of gravity.

Due to this approach, the instructor cannot set mass and centre of gravity directly, but has to set the amount of fuel and cargo mass and location to obtain the required configuration.

6 Tuning process

During the tuning process the flight mechanics model was updated and changed to match the level C requirements in FAA AC-120-63 (ref. [1]). These requirements describe tolerances on data for flight test manoeuvres and for steady flight test conditions. This chapter illustrates the process followed to adapt the flight mechanics model to comply with the tolerances from AC-120-63. References [3], [4] and [5] provide a good overview of the complexity of the tuning process and the associated challenges. These references have been used as a guideline during the KA-32 tuning process, although the limitations in available data and the helicopter's co-axial configuration provided some unique challenges.

Input for the tuning phase were the results of the flight test campaign, which was held in South-Korea in the summer of 2007, to gather data for flight mechanics model improvement and data for the comparison between model and flight test (ref. [2]).

The flight test campaign has been successfully executed from 1 to 31 August 2007 at the Iksan airbase of the Forest Aviation Office. The installation and calibration of the instrumentation (see Figure 4) was accomplished within 2 weeks. A total of 22 flights have been performed, in about 30 hours of flight time.



Figure 4: The test instrumentation package

Before starting the tuning phase, the flight mechanics model was updated with data measured during the flight test phase. This included:

- airspeed calibration
- flight control rigging
- engine performance data
- autopilot performance (gains and limits)

The tuning process consisted of an iterative loop, shown in Figure 5. Together with post-processing the flight test data, an appropriate selection of the flight test data was made: for example selection of the most successful control inputs or best steady data.

This data was input for the creation of scripts that enabled automatic (batch) simulation of all test points in FLIGHTLAB. The subsequent data analysis led to changes in the model, or changes in data selection, after which another iteration was performed.

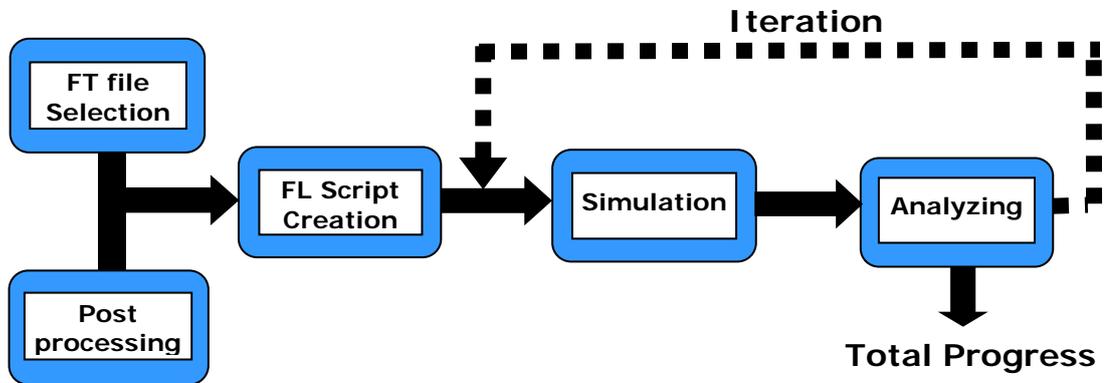


Figure 5: The tuning process

For selection of flight test data, comparison of flight test and simulation results and automatic pass/fail analysis several tools have been created, for example:

A replay and simulation tool (see Figure 6): HeliX is a 3-D representation of flight path and helicopter motion, both from an outside view or a cockpit view with head-up display, including stick positions, enabling the replay of test data and simulation runs. This was found to be a highly valued aid in the post-flight/post-simulation data analysis.



Figure 6: Helix replay and simulation tool

Automatic plot generation for the Qualification Test Guide (QTG, see Figure 7 and Figure 8). This is the same tool that was used for analyzing flight test data. It has analysis functions, such as zooming, panning, parameter selection, etc. Also the AC120-63 tolerance can be plotted for

those parameters that have a tolerance. Multiple simulation results can be loaded, such that changes in model parameters can be evaluated.

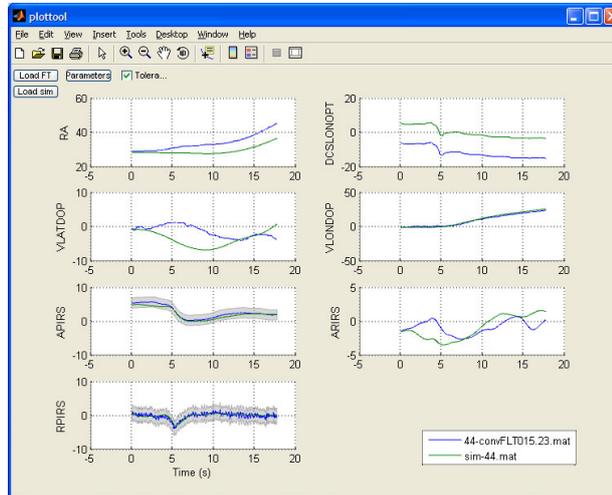


Figure 7: Flight test and simulation plotting tool

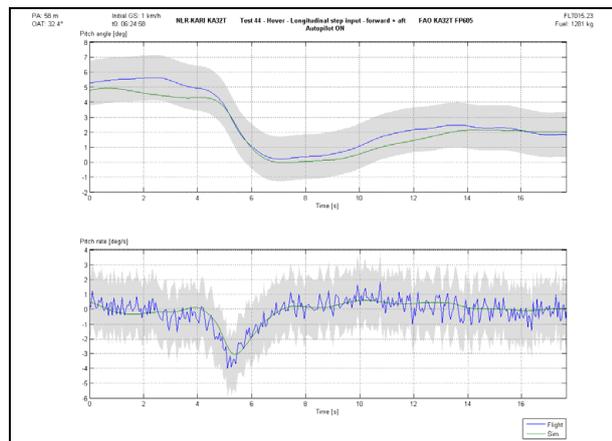


Figure 8: Example of QTG plot

The output of the automatic pass/fail analysis is a large table, indicating the percentage of match, which is calculated as follows: points inside the tolerance are counted as 100%, points outside two times the tolerance are counted as 0% and between 1 and 2 times the tolerance the count decreases linearly from 100% to 0%. This applies both to time traces and points of a trim analysis.

The pass percentage is calculated for each applicable parameter in a test, averaged for each test and averaged over all the tests. This approach provided a quick and detailed overview of progress of the tuning effort.

6.1 Tuning tools

The engineers had several instruments at their disposal for tuning the flight mechanics model:

Parameter sweeps

By sweeping one or more parameters, the effect of these changes can be quickly examined.

Results were analysed per test case in a plot, or for all tests at once by evaluating the effect on the total pass/fail percentage.

Typically several parameter sweeps were defined and run overnight for analysis the next day.

Parameters that have been adjusted using this approach are for example: helicopter inertia, flight control settings, empennage and fuselage aerodynamic data, landing gear spring and damping characteristics

Automatic parameter optimization

The tables used for engine startup and shutdown have been created by application of an automatic parameter optimization algorithm. Matlab-Simulink's Parameter Optimization Toolbox was used for this purpose. Measured data of an engine's gas generator speed and engine temperature during startup and engine shutdown

Part of the engine model had to be rebuilt as a Matlab-Simulink diagram, because the original engine model exists as a FLIGHTLAB CSGE diagram. An example of the Simulink parameter optimization setup is shown in Figure 9.

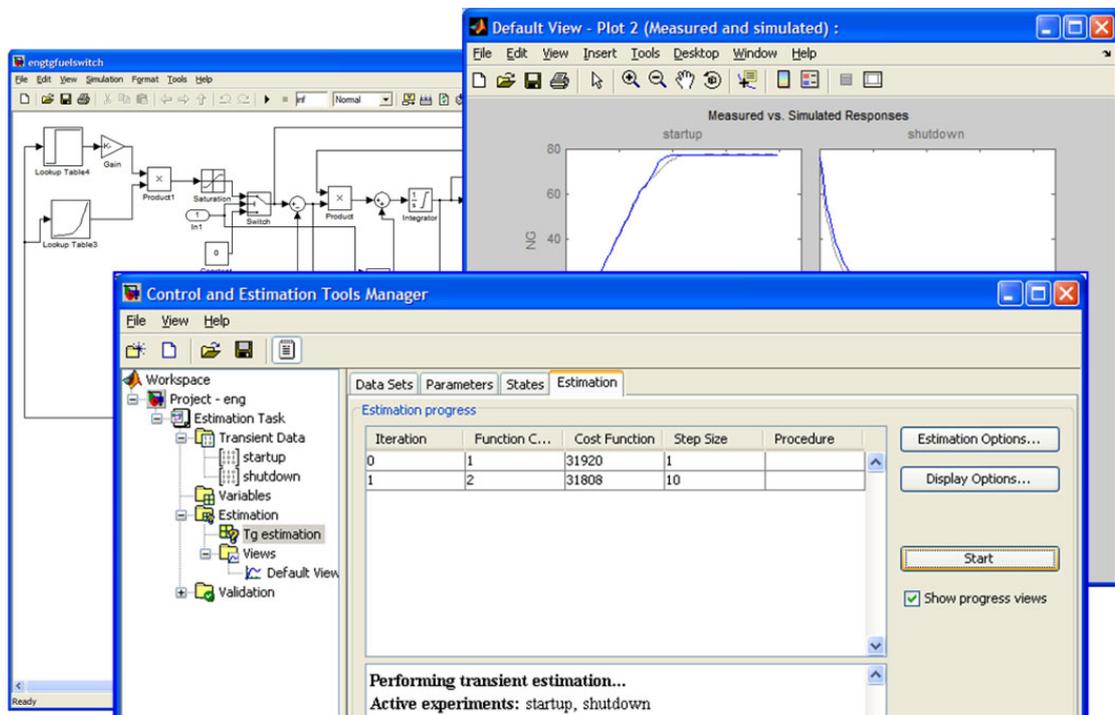


Figure 9: Screenshot of engine startup/shutdown optimization in Matlab-Simulink

Interference

Interference from the coaxial rotors on each other and on the fuselage and empennage is taken from the 6-state Peters-He inflow model. The influence of the interference modelling on the overall tuning result is large, especially for low speed tests. Application of the interference from the Peters-He proved to be a challenge. In the end an acceptable result has been achieved.

Several aspects of the interference model have been adjusted:

- Inflow correction factor
The 'inflow correction factor' tabel (kappa.tab) for both rotors has been changed, influencing the magnitude of the interference as a function of the wake skew angle
- 'Effective rotor wake skew'
A table for 'effective rotor wake skew' has been used in the model, for both rotors. This table defines the actual 'wake skew angle', as a function of the current theoretical value. from the inflow calculation. The effective wake skew angle has been adjusted for low speeds to improve the match with the flight test data.
- 'Rotor wake contraction ratio'
A table for the wake contraction ratio has been used for both rotors. This table defines the amount of contraction of the rotor wake as a function of the distance from the rotor. This ratio has been adjusted for low speeds.

Engine performance

By adjusting the engine data tables, in particular the torque produced by the engines, a better match could be obtained for those tests involving engine power.

Since no torque measurements are available in the flight test data, engine power is represented by Engine Pressure Ratio (EPR). A linear relationship is assumed between EPR and engine power. Besides the engine performance, changing the Engine Automatic Control System parameters has been used to match rotor speed for most tests.

Automatic test driver

For those tests where a tolerance exists on the flight controls (like the take-off and landing) a "flight test driver" was used.

This consisted of a tool that automatically adjusts the controls to obtain a closer match for the take-off and landing manoeuvres, while staying inside the AC120-63 tolerances for stick position. Note that this controller does not represent a pilot or auto-pilot: it merely changes the stick position measured during flight test within the AC120-63 tolerance (+/- 10%) to get a

closer match. For example: the measured longitudinal stick position is slightly changed to get a better match in pitch attitude.

Data selection

Sometimes a better match between flight test and model was achieved by selecting data from a different flight or even by changing the starting time, and consequently initial condition, of the manoeuvre.

6.2 Tuning challenges

During the tuning phase, a number of challenges have been encountered:

Due to operational restrictions some of the flight test data was limited. For example, no single engine or autorotation tests could be performed. Obviously this limits the operational flight envelope where the model has been validated. Autorotation and single engine flight has only been tuned subjectively. Unfortunately, NLR was not involved in that phase of the project. For some of the aerodynamic properties (rotor airfoil data, horizontal stabiliser and vertical fins) only CFD data was available. Also no (wind tunnel) data was available about interactional aerodynamics.

No torque measurement was available. Due to the KA32's design philosophy it has no torque indicators in the cockpit. The gearbox is designed to absorb all engine power at all times, also with one engine inoperative. Therefore, a torque indication is not required. To provide the pilot with a measure of engine power, 'Engine Pressure Ratio', is displayed instead of torque. This is a measure of engine power, but cannot be converted to horse power directly.

Sideslip angle has not been measured, due to limitations on flight test instrumentation by the operator. This makes judging the initial condition for cruise flight difficult. For dynamic tests with a tolerance for sideslip angle it was decided to replace it by rate of yaw, with a tolerance of 2°/s (similar to the directional step inputs in cruise).

6.3 Tuning result

Despite the above limitations a very good result has been achieved, providing a simulation model that has a high fidelity in representing the KA32T and an almost 100% fit to the flight test data within the tolerances of AC120-63. An example of the result of the tuning phase is shown in Figure 10: the 'All Engines Take-Off'.

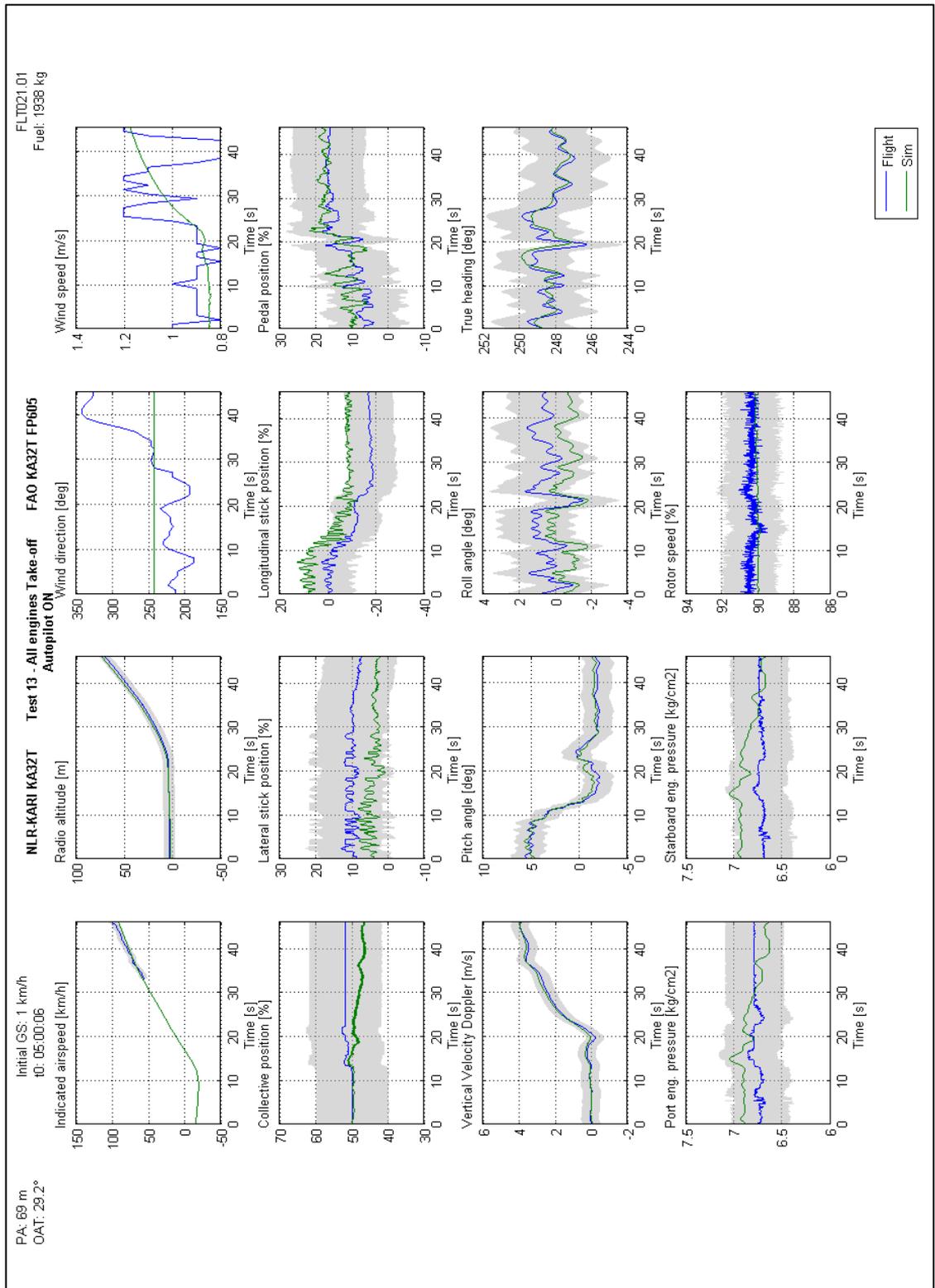


Figure 10: Example of comparison between model and flight test data for the take-off maneuver



7 Conclusion

The project "Engineering services for developing Simulator Design Data and Flight Test Data" has been running since May 2006. After development of a comprehensive simulation model a flight test campaign was performed. The final phase consisted of tuning the simulation model to the flight test data within the tolerances of the 'Helicopter Simulator Qualification' Advisory Circular AC120-63. The final result is a Flightlab model that is a high-fidelity representation of the KA32T, suitable for the KA32T training simulator.

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