Executive summary

Korean-Dutch Cooperation for the KA32 Helicopter Training Simulator Flight Mechanics Model Development

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. The flight test campaign performed in the summer of 2007 in Korea to gather data to complete and validate the flight mechanics model is presented. 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.

Korean-Dutch Cooperation for the KA32 Helicopter Training Simulator Flight Mechanics Model Development

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Contents

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. 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 provide engineering services to develop the flight model and flight test data, due to its experience with flight simulation development and flight testing.

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

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. See (ref. [1]).

The comprehensive software suite FLIGHTLAB from Advanced Rotorcraft Technology (ART) was used for KA-32T flight mechanics model. 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 analogue 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.

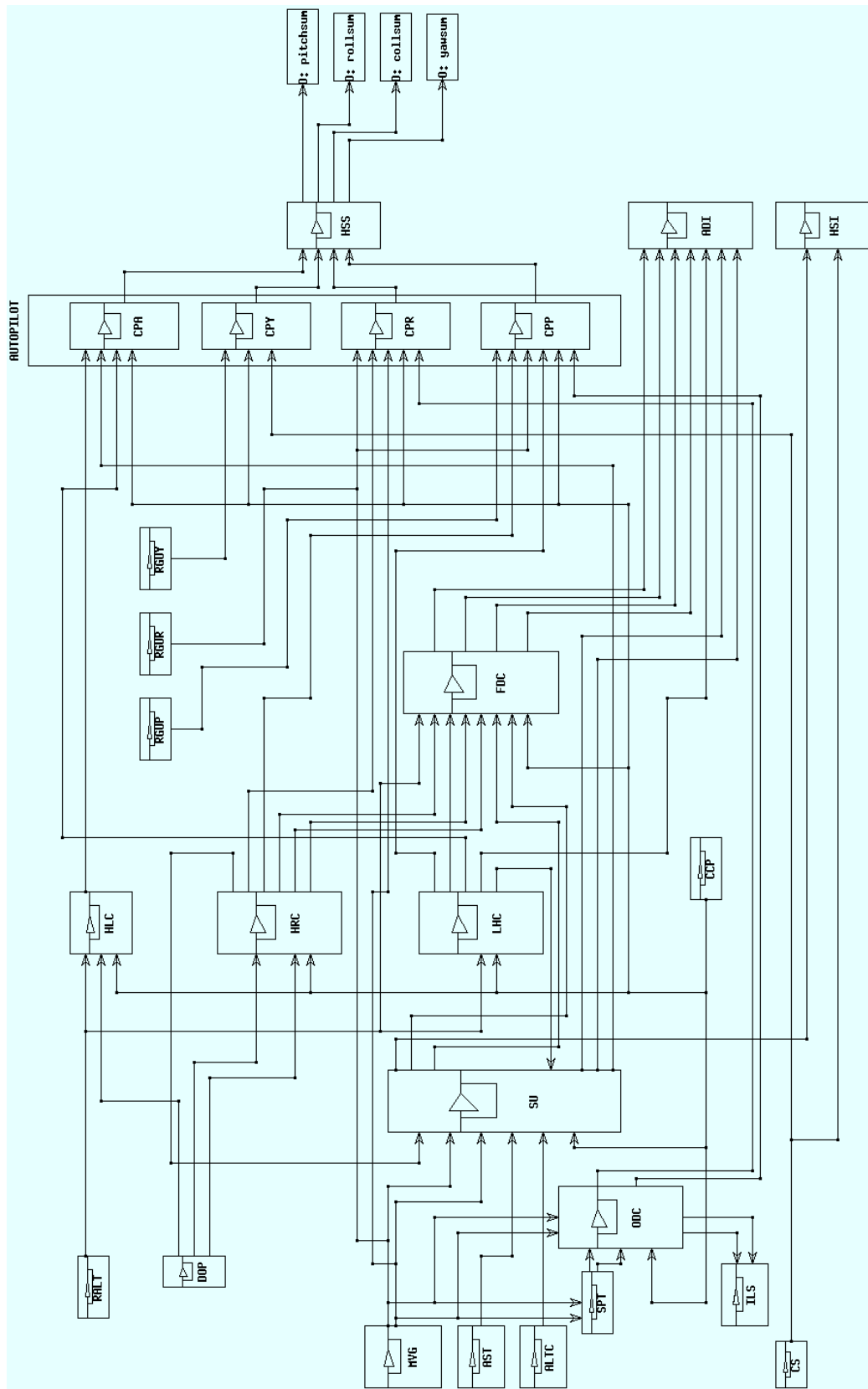Switching logic and electrical diagrams were created in FLIGHTLAB's Control System Graphical Editor (see Figure 2).

Figure 2: Overall structure of the Integrated Flight System model

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.

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 instable 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:

- SALVO/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 ¾ 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.

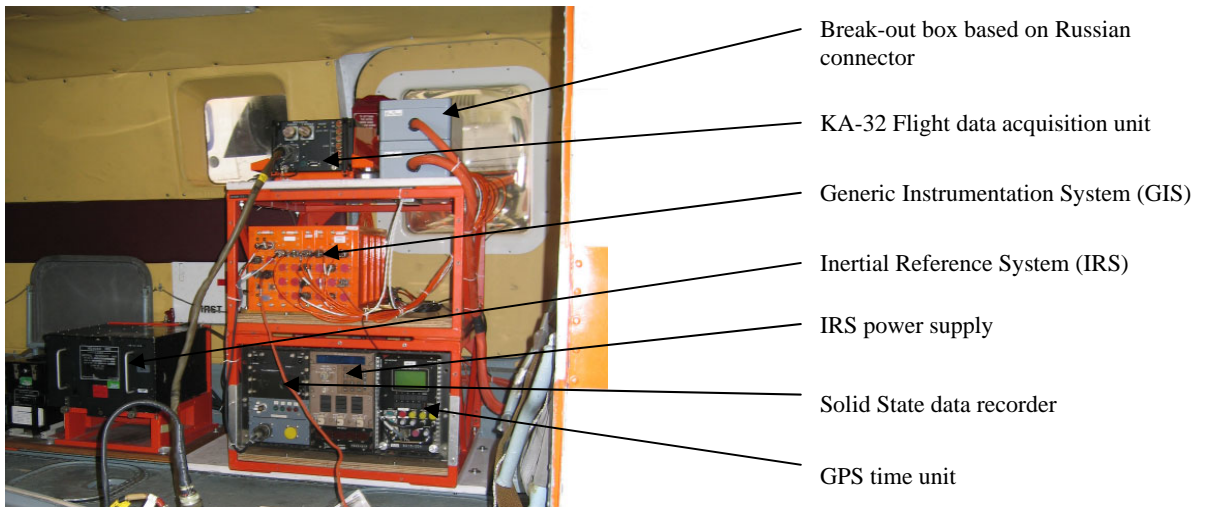# 6 Flight testing

6.1 Helicopter configuration

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.

All flights have been performed with a crew of 2 pilots and 1 flight test engineer, complemented during several flights with a flight mechanic. The pilots of the test aircraft were senior pilots within the Forest Aviation Office, however without a formal test pilot training. The flight test engineer from KARI was in charge of the in-flight organization of the tests, managing the instrumentation system and recording of events using the event marker and flight test cards.

6.2 Instrumentation system

After several preparatory visits to South-Korea, the preliminary design of the instrumentation system was started, using NLR's "Generic Instrumentation System" (GIS) as a basis. The GIS is an advanced airborne measuring and recording system. It is capable of adequately measuring, conditioning and recording analogue signals, discrete signals, digital signals, synchro signals and manual data entry (i.e. record number).

A constraint for the instrumentation system design from the operator was to install equipment with as little impact on the helicopter as possible, both mechanically and electrically. For both operational reasons and safety the system had to be 'non-intrusive'. Therefore, the approach for the design of the instrumentation system was to use as many parameters going to the KA32's Flight Data Recorder (FDR) as possible. This required the design of a 'breakout box', which enabled recording these parameters by the NLR data acquisition system, while the Flight Data Recorder remained in operation. A second major part in the instrumentation system was a dedicated test Inertial Reference System (IRS), providing ring laser based attitudes, rates and accelerations.

Break-out box based on Russian connector

KA-32 Flight data acquisition unit

Generic Instrumentation System (GIS)

Inertial Reference System (IRS)

IRS power supply

Solid State data recorder

GPS time unit

Figure 4: Measurement system in the KA32T

To complement the parameters from the FDR and the NLR IRS, several additional sensors have been installed:

On the landing light bracket a probe for outside air temperature has been installed.

To satisfy concerns about flight safety, non-intrusive optical (laser) sensors have been used for longitudinal and lateral cyclic position, with reflectors installed on the longitudinal and lateral push-pull rods below the cockpit floor (see Figure 5):
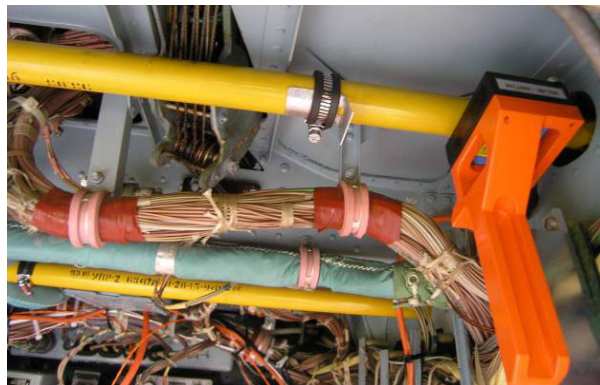
Figure 5:Non-intrusive laser sensor (on orange bracket) and reflector (on yellow push-pull rod) below cockpit floor to measure stick position

To measure engine temperature, a break-out connector was installed in the signal from the engine thermocouples. Because it was not possible to measure the cold junction temperature, the measurement will vary with cold junction temperature. This deficiency has been solved by correcting the measurement with observations of the cockpit instruments from video (for ground tests) and from the flight test engineer (for flight tests).

A temporary transducer, for ground test only, was connected to the engine throttles to measure the deflections during engine start up, (ground) operation and shut down.

The engine pressure ratio, an indication of engine power, has been measured by installing a breakout connector in the signal to the cockpit instrument.

In order to create the breakout connectors for Flight Data Recorder, engine pressure and temperature, several Russian connectors had to be purchased, which proved to be a very critical part of the design.

A video camera was used to record engine instruments during ground runs in the engine start procedure.

All flight test data was recorded on a Solid State data recorder, and was processed direct after the flight in the Omega data processing system to enable analysis of the data before the next day. The Omega system contains all the calibration data of the individual parameters and calculates the engineering units from the raw recorder data. The instrumentation design was concluded with a safety analysis report, showing that the instrumentation design has a high degree of reliability and damage tolerance and that it has provisions to protect the helicopter signals in the event of a failure.

A ground station was located at the FAO base at Iksan. It consisted of a KARI portable office container, in which the NLR ground station was installed.

The NLR ground station is based on a WYLE Omega processing system in a server-client network environment. The server is operated by the instrumentation engineer and processes and distributes all available data from helicopter and ground instrumentation.The Omega system contains all the calibration data of the individual parameters and calculates the engineering units from the raw recorder data. The system design allows for quick configuration changes for different test programmes. A shared hard disk unit is used for securely archiving the acquired data. The specialists were provided with client laptop computers, enabling them to analyse the distributed data on- or offline as necessary. The network is completed with a network printer. Weather data was gathered with a mobile meteo system, consisting of temperature, pressure, humidity, wind speed and direction sensors. These transducers are mounted on a transportable 10 meter high meteo mast. The system can be powered by a car. The data is logged onto a PC. The meteo system was used during several hover trials at the FAO base at Iksan and the low speed trials at Jeonju airbase (see Figure 9).

6.3 Data processing and analysis

Data from the instrumentation system is processed directly after flight and, after calibration in the Omega data processing station, converted to Matlab®- data files. Several tools have been developed for quick post-processing and analysis of the flight test results:

A Matlab®-based graphical user-interface (see Figure 6 for fast presentation of flight test data. This tool can represent both steady state data (average values and standard deviations) as well as time history data (parameters as a function of time). The appropriate parameters are displayed, depending on the type of test. Additional parameters can easily be added manually. A provision has been made to show AC120-63 tolerances. Figure 6 shows data for an approach and landing. Shown are, in the left column of graphs, from top to bottom: airspeed, radio altitude, lateral stick position, pedal position, roll angle, engine 1 power. In the right column of graphs, from top to bottom: pressure altitude, collective stick position, longitudinal stick position, pitch angle, true heading and finally main rotor RPM.
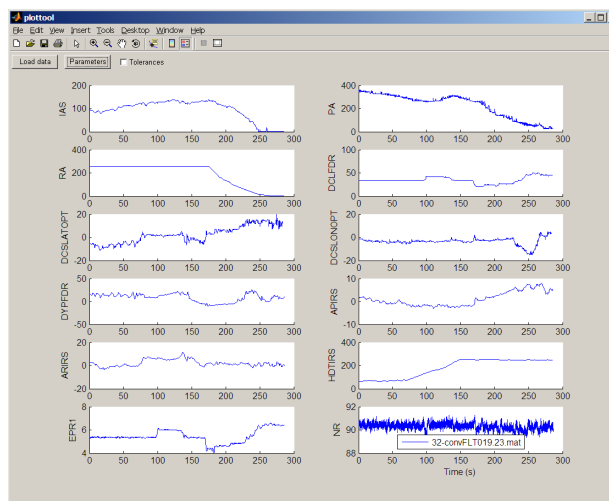

Figure 6: Flight test data plotting tool

A Matlab®-based graphical user-interface (see Figure 7) for the selection of steady state (trim) data. From time history data selections can be made manually, automatically showing the average value and standard deviation. Figure 7 shows indicated airspeed in the top graph, and pitch attitude in the lower graph. The two grey bands are manually selected areas. The red dot and lines indicate the average value and standard deviation. The result from this selection would be two test points, with flight parameters like pitch attitude as a function of airspeed.
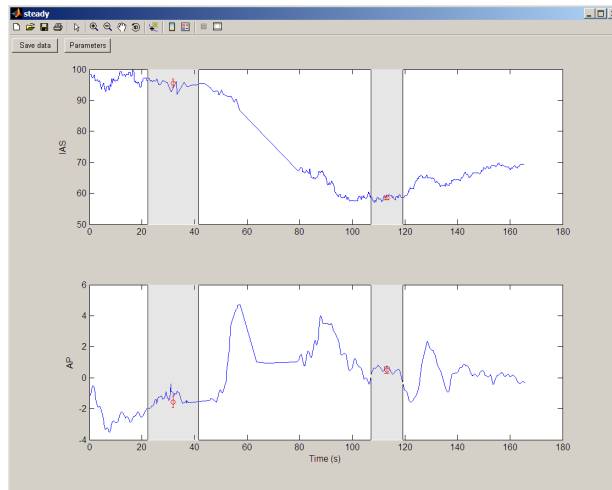
Figure 7: Steady state data selection tool

Flight test replay tool: HeliX is a 3-D representation of flight path and helicopter motion (see Figure 8), both from an outside view or a cockpit view with head-up display, including stick positions, enabling the replay of test data. This was found to be a highly valued aid in the post-flight data analysis.
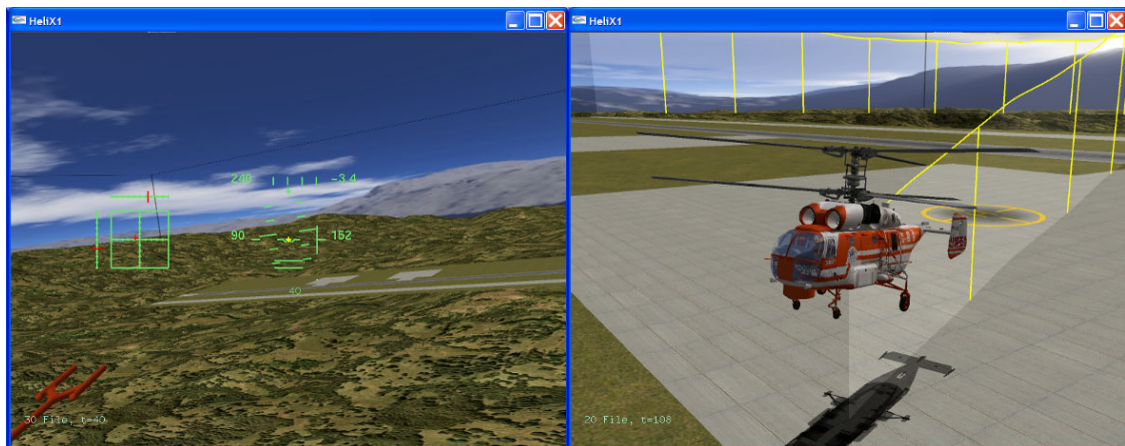

Figure 8: HeliX flight test replay tool

6.4 Flight test execution

In preparation of the flight test campaign, the test plan was drafted, as well as a 'flight test execution guide'. The test plan described in detail which configuration and maneuvers were planned, while the flight test execution guide provided guidelines to the pilots on how to perform the maneuvers. Due to FAO operational limitations, no autorotation or (simulated) single engine flights could be performed. Also, 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).

The majority of the test plan consisted of AC120-63 validation tests (see ref. 2). Additional tests were included in the test plan for validation outside the AC120-63 requirements, like accel-decel maneuvers and hover turns. These maneuvers were based on ref. 4. Other tests, like autopilot and engine performance checks were performed to provide additional data for the simulation model.

The flight test campaign in the summer of 2007 was started with the installation and calibration of the instrumentation system. Because most of the design was performed in the Netherlands, some minor adjustments had to be made in Korea to the mechanical interface.

After the instrumentation installation, the parameter calibration was started. As far as possible parameters were calibrated on the ground. For example: the fuel gauge was calibrated through a weight and balance procedure at several fuel weights, the airspeed and pressure altitude were calibrated with a pitot-static test set and the flight control rigging was checked through a ground test with hydraulic power. Other parameters were calibrated during a ground run, like the engine temperatures, gas generator speeds and rotor speed. The engine pressure parameters (substitute for engine torque) could only be calibrated in flight.

After the first ground runs for a general instrumentation check and EMI/EMC test, a first test flight took place for instrumentation check and final calibration. Several runs have been included to determine the error in the pitot-static system.

The actual test campaign started at the Iksan airbase of the Forest Aviation Office on 1 August 2007. Nearly 5 weeks of flight tests followed. The flight tests were performed in a daily schedule of up to two flights a day. After acquiring the actual meteo information, the test cards were selected for each flight, based on:

- Weather conditions
- Progress of the test program based on analyzed test results
- An efficient combination of maneuvers with respect to helicopter mass, required altitude and airspeed, pilot's workload etc.

The test program of the flight consisted of the sequence of the selected test cards.

The resulting test program was briefed to the KARI flight test engineer by NLR in English. Subsequently, the helicopter crew was briefed by the flight test engineer in Korean.

Next, the flights were executed by the helicopter test crew. During the test flight, previously acquired data was analyzed by NLR on the ground. The main objective of the analysis was approval or rejection of the data as a source for tuning. The approval of data defined the status and progress of the test program.

After landing, the acquired data was processed by the NLR instrumentation engineer while the other NLR engineers were debriefed by the KARI flight test engineer.

Since the FAO base at Iksan has only a helicopter platform, the low-speed flight tests requiring a runway were performed at the Jeonju air force base, which is only 4.5 nautical miles from the FAO base. For these tests a mobile meteo team deployed to Jeonju air force base to set up the 10 m wind measuring mast just outside the base perimeter for security reasons, in close proximity of the runway (see Figure 9). This team operated from a car with power supply, laptop and data acquisition system, connected to the measuring mast.

Figure 9: Meteo mast at Jeonju air force base

6.5 Flight test results

In the period from 1 to 31 August 2007, the flight trials at the Iksan airbase of the Forest Aviation Office yielded the following results:

A total of about 30 hours of flight time has been performed in 22 flights. A distinction was made between 'performed' tests and 'approved' tests: A test was 'performed' once it has been executed during a flight. Only when the data of the test shows that it has been executed satisfactorily and provides sufficient data for model tuning, it was approved. 99% of the test program has been executed. Of the planned tests only the engine start/shutdown at altitude was not performed (low priority).

With the Matlab®-based analysis tools, described earlier, the acquired test data was analyzed. The analysis consisted of verifications of:

- data quality
- steady initial conditions

- steady data i.e. correct performed maneuver
- control inputs applied conform the definition required for tuning.
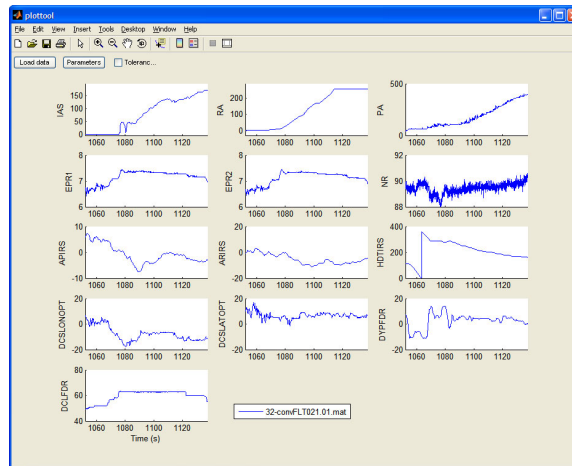

Figure 10: Example of parameter plots used during analysis of the acquired test data

In Figure 10 an example is given of a graphical presentation of a take–off. To save space on the screen, only the acronyms without engineering units are listed at the vertical axes.

Presented in Figure 10 are:

IAS: Indicated airspeed (km/h)
RA: Radio altitude (m)
PA: Barometric altitude (m)
EPR1: Engine Pressure Ratio 1 (-)
EPR2: Engine Pressure Ratio 2 (-)
NR: Rotor speed (%)
APIRS: Pitch angle (deg)
ARIRS: Roll angle (deg)
HDTIRS: Heading (deg)
DCSLONOPT: Longitudinal cyclic stick pos. (%)
DCSLATOPT: Lateral cyclic stick pos. (%)
DYPFDR: Pedal position (%)
DCLFDR: Collective stick position (%)

7 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.

References [5], [6] and [7] 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.

This chapter illustrates the process followed to adapt the flight mechanics model to comply with the tolerances from AC-120-63.

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 11. 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.

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:

The earlier described HeliX, 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.
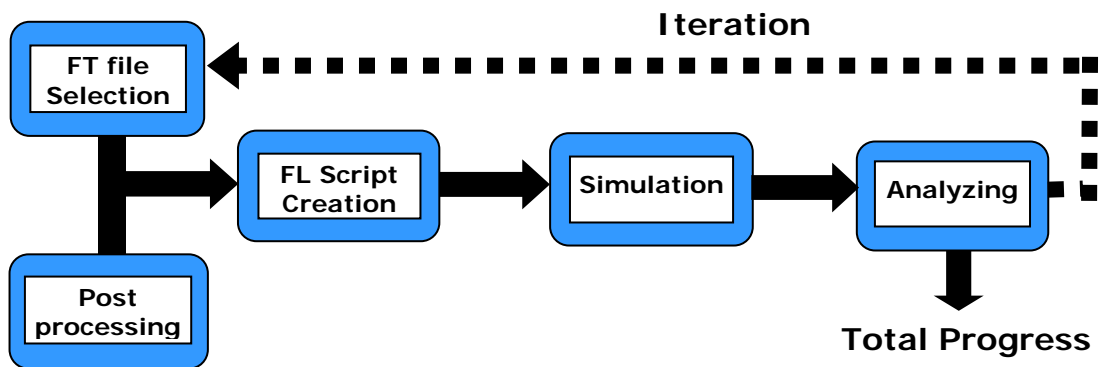
Figure 11: The tuning process

Automatic plot generation for the Qualification Test Guide (QTG, see Figure 12 and Figure 13). 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.
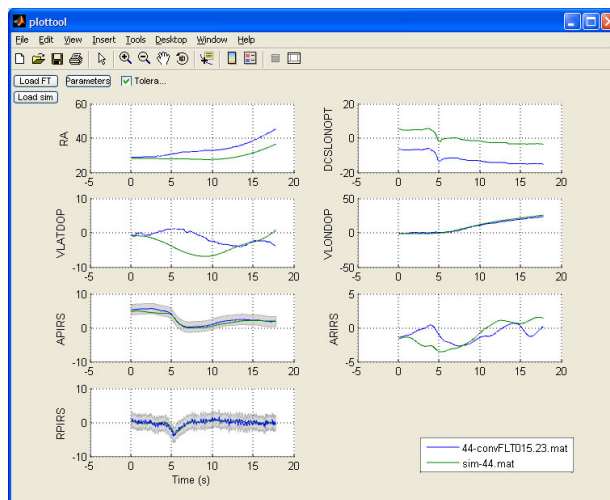

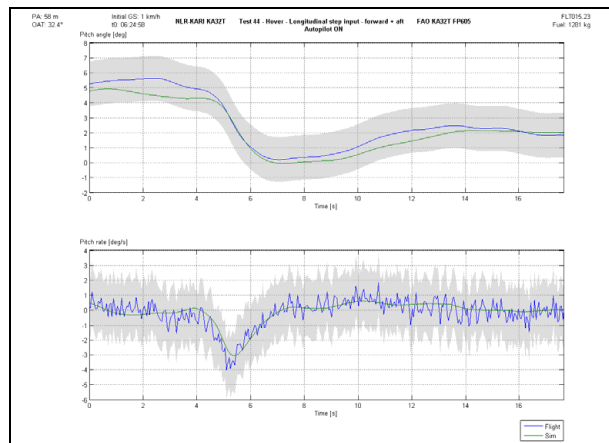*Figure 12: Flight test and simulation plotting tool*

Figure 13: 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.

7.1 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 rebuild 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 14.

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.
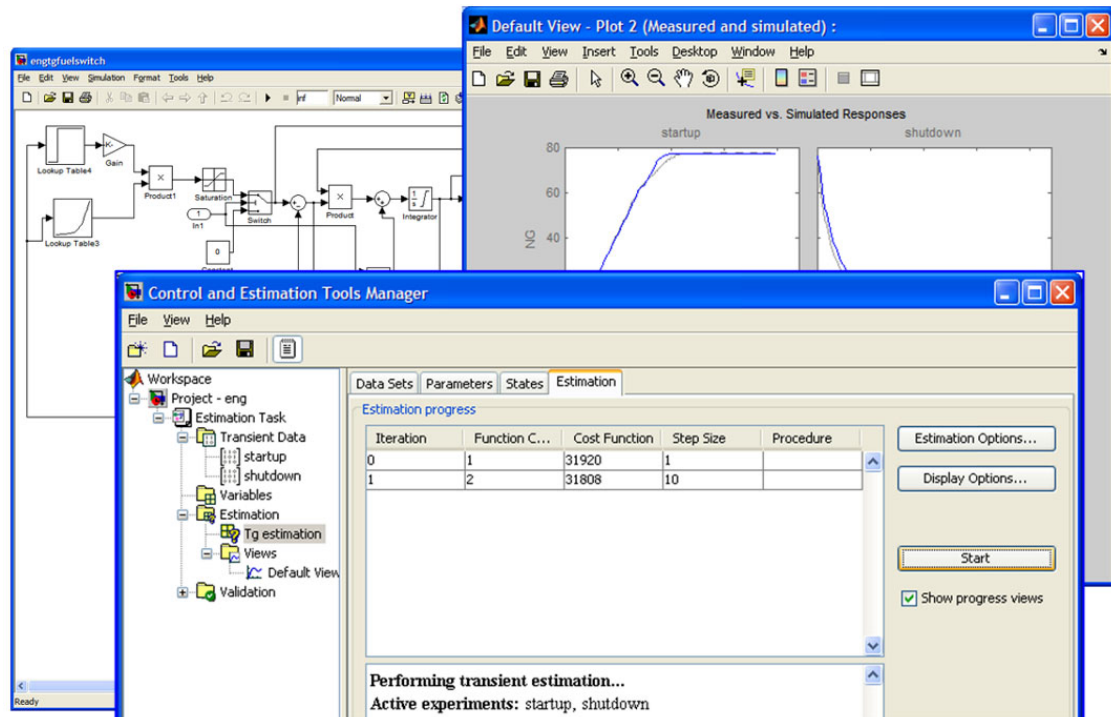
Figure 14: Screenshot of engine startup/shutdown optimization in Matlab-Simulink

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.

7.2 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

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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).

7.3 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 15: the 'All Engines Take-Off'.
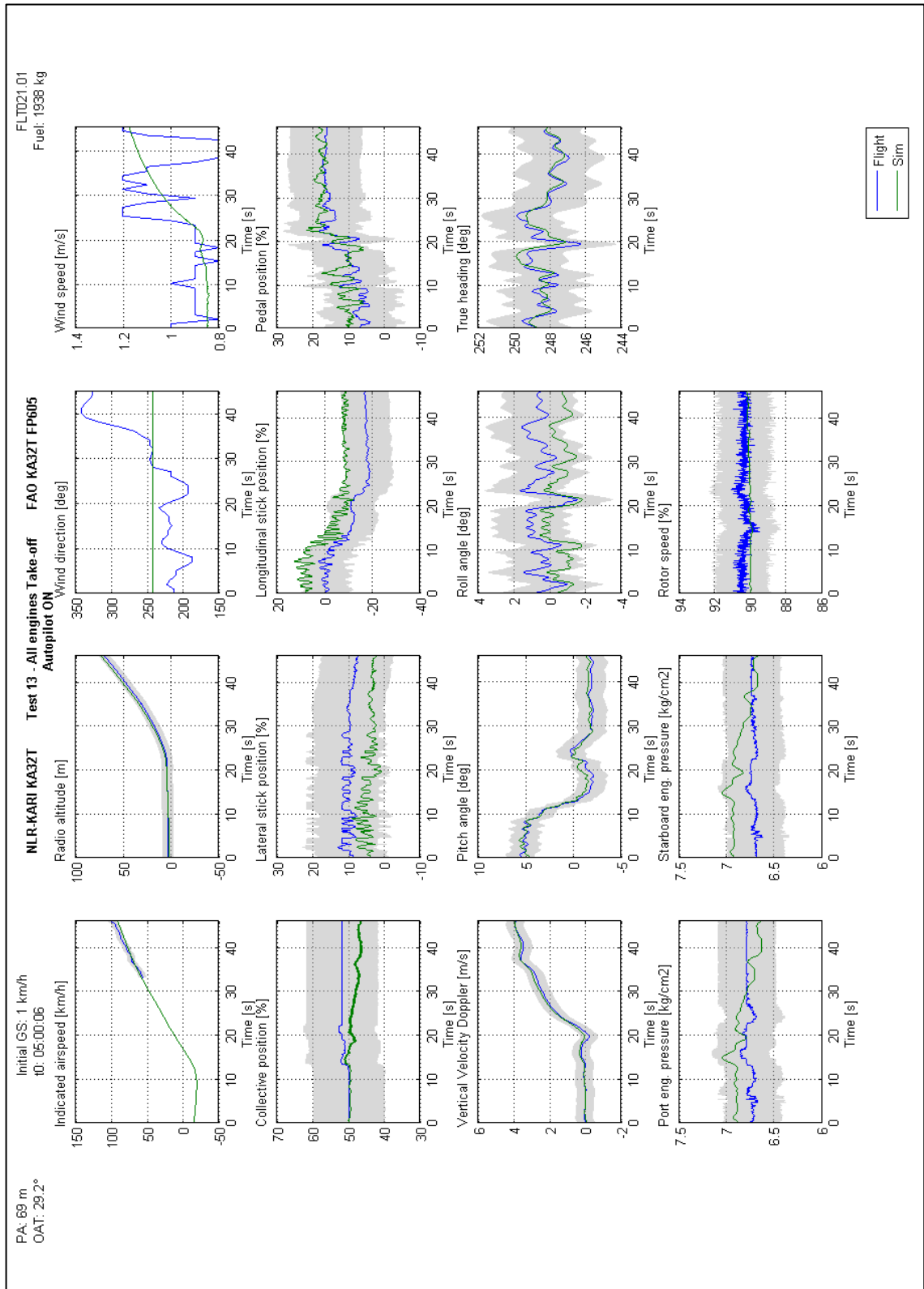
Figure 15: Example of comparison between model and flight test data for the take-off maneuver

8 Conclusion

The KARI/NLR cooperation project "Engineering services for developing Simulator Design Data and Flight Test Data" has been running since May 2006 and started with the development of a comprehensive simulation model. The successful flight test campaign in Korea was a crucial element to complete the model and provide a database for validation. 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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