NH90 HELICOPTER MODEL ROTOR AND ENGINE INSTALLATION WIND TUNNEL TEST IN DNW

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Abstract

In the framework of the Design & Development (D&D) Phase of the NH90 helicopter programme, a wind tunnel test project is being carried out using various sub-scale models to determine the aerodynamic behaviour of the vehicle. The NH90 helicopter is being developed in a co-operative programme by four European nations: France, Germany, Italy and The Netherlands.
NLR, in close cooperation with DLR and DNW has successfully completed testing of a powered NH90 helicopter model (scale 1:4) in the Large Low speed Facility of the German Dutch Windtunnel DNW. A unique feature of the wind tunnel model was the integration of a scaled down powered rotor system and engine flow simulation module in one test set-up. The model allowed simultaneous gathering of both rotor and installed engine performance data.
Prior to wind tunnel testing, the model was subjected to a series of elaborate functional tests.
The wind tunnel tests were primarily aimed at evaluating the engine air intake characteristics, exhaust gas recirculation and IR signature. Testing was performed in a wide range of forward, sideward and rearward flight conditions. A large number of test parameters were acquired, ranging from rotor quantities like hub and blade loads, and rotor blade angles (pitch, flap and lead-lag) to air intake pressure distribution, exhaust gas and fuselage skin temperature.
A high level of repeatability of the most import test parameters was achieved, demonstrating the quality of test results gained.

Notation

CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CCD	Charged Coupled Device
D&D	Design & Development
DLR	Deutsche Versuchsanstalt für Luft und Raumfahrt
DNW	Duits Nederlandse Windtunnel (German Dutch Wind tunnel)
ECD	Eurocopter Deutschland
ECF	Eurocopter France
FFT	Fast Fourier Transform
IR(S)	Infra Red (System)
LLF	Large Low speed Facility
MWM	Modular Wind tunnel Model
NAHEMA	NATO Helicopter Management Agency
NFH	NATO Frigate Helicopter
NH90	NATO Helicopter for the 90-ties
NLR	Nationaal Lucht- en Ruimtevaart Laboratorium
OA	ONERA
PCM	Pulse Code Modulation
PCB	Printed Circuit Board
PT	PorT
SB	StarBoard
TTH	Tactical Transport Helicopter

Introduction

The NH90 helicopter is being developed in a co-operative programme by four European nations: France, Germany, Italy and the Netherlands. In February 1992, the four participating governments constituted an international programme office, the NATO Helicopter Management Agency (NAHEMA). The four companies sharing the Design and Development of the NH90 programme (Agusta, Eurocopter Deutschland, Eurocopter France and Fokker Aerostructures) established a joint venture, the company NHIndustries, to ensure international industrial programme management. The Dutch industrial participation is shared between Fokker Aerostructures, SP Aerospace and Vehicle Systems and the National Aerospace Laboratory NLR.

Fig. 1 - Prototype of the NH90 in flight (photo: NHI)

The NH90 (figure 1), a twin engine helicopter in the 9-ton class, is characterized by a wide use of composite materials, a high level of system integration, an advanced aerodynamic design and low detectability. It is an integrated weapon system, being developed in two mission variants, the Tactical Transport Helicopter (TTH) and the NATO Frigate Helicopter (NFH). The TTH is designed for high manoeuvrability in Nap of the Earth operations. The NATO Frigate Helicopter, the naval version, is primarily intended for autonomous Anti-

Submarine Warfare and Anti Surface Unit Warfare missions.

During the Design & Development phase wind tunnel tests are carried out by NLR and ECF on various sub-scale models to support the helicopter design process and reduce development risks.
In December 1996 a second test campaign, managed by NLR, was successfully performed with a 1:4-scale powered main rotor model in the Large Low Speed Facility of the German Dutch Wind tunnel (the original DNW at NLR Noordoostpolder now named DNW-LLF). The model, designed and manufactured by NLR, featured a powered main rotor system and a fuselage with engine air intake and hot exhaust gas simulation. The main rotor system was driven by the Modular Wind Tunnel Model (MWM), a rotor test rig of the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR).
While subsystems such as these have been tested in wind tunnels previously, their concurrent application to a large helicopter model is believed to be unique.

Test objectives

The experiment carried out in DNW-LLF focused on low speed engine installation and high speed rotor system behaviour.
During the engine installation related tests, the main rotor system acted as a representative downwash generator, distorting engine intake and exhaust flow. Tests have addressed engine air intake behaviour, exhaust gas recirculation effects and exhaust gas infra red signature in a wide range of operational test conditions.
To investigate the global helicopter behaviour in flight, specific high speed tests were performed, addressing rotor performance and stability.

Wind tunnel model and its instrumentation

Model development

Early 1995 first preliminary main rotor system design studies were conducted by NLR, based on stringent design criteria. After the summer of 1995, the first model rotor components were taken into production. The design driver for the composite material rotor blades was the matching of the natural frequencies. The blade development is characterized by an iterative approach. Calculated mass and stiffness distributions were converted to a blade core material lay-up. A sample blade was manufactured and its clamped-in natural frequencies were determined experimentally. The structural properties of the blade were adapted, and a second development loop was entered. This process was repeated as to comply with the requirements for the blade characteristics. Then the actual production of the blade set was carried out.
After the assembly of the complete rotor system, that included also wiring of electrical components (figure 2), the rotor system sensors were calibrated in their intended use range. As part of the design substantiation, the susceptibility of the test set up to ground resonance was investigated at this stage of the development process analytically.

Documentation of the model (design description, stress report, user manual, etc.) is extensive, to allow easy and safe operation.

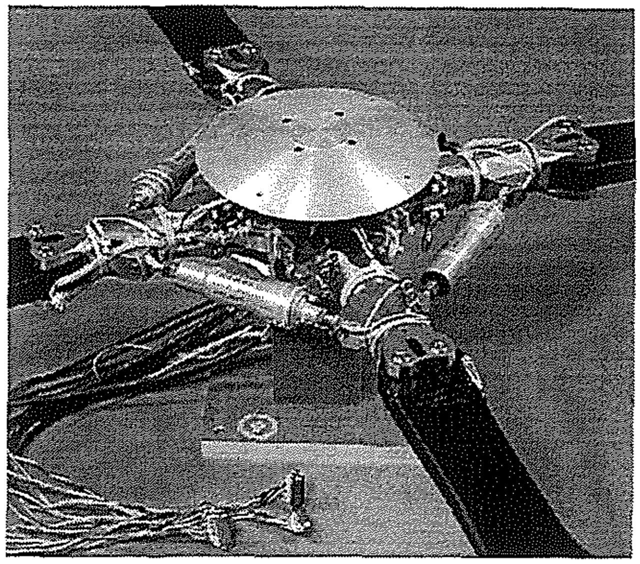

Fig. 2 - Main rotor hub of the model (photo: NLR)

In parallel the development of the engine installation model hardware was performed at NLR on a dedicated contract for ECF. Development work for the model support and exhaust gas burner system, including angle-of-attack mechanism, was subcontracted to DNW. For the design of the complete engine installation set-up, the Computer Aided Design tool CATIA was used. Because of the complex nature of the test equipment and potential risks during operation, a structured approach was applied to identify hazardous failure modes, in order to reduce the risks to an acceptable level and to guarantee safe model operation during the execution of the wind tunnel test.
In the summer of 1996 the manufacturing of engine installation components was started, followed by sensor development and calibration activities. Subassemblies were made for most of the major model and support system components. Final assembly work started mid-October 1996 at DNW.

Set-up description

The model test set-up developed and applied during the second NH90 test campaign in the DNW-LLF, consisted of three major subsystems:

- main rotor hub, blades and rotor test rig MWM of DLR;
- fuselage skin, horizontal tail surface and vertical fin;
- engine air intake and engine exhaust subsystems.

The model rotor system is a geometrically and dynamically scaled replica of the actual NH90 rotor. The model rotor hub contour follows the full-scale hub geometry closely to ensure representative rotor system wake and related drag characteristics of the full-scale

NH90 aircraft, and to represent its high speed behaviour accurately.
The hub utilizes Lord Corp. spherical elastomeric bearings, which allow the blades to pitch, lead-lag and flap. Elastomeric inter-blade dampers, located between two sleeves, have been included in the hub design. The dampers provide lead-lag damping to the rotor system, which is necessary to control the rotor system ground resonance.

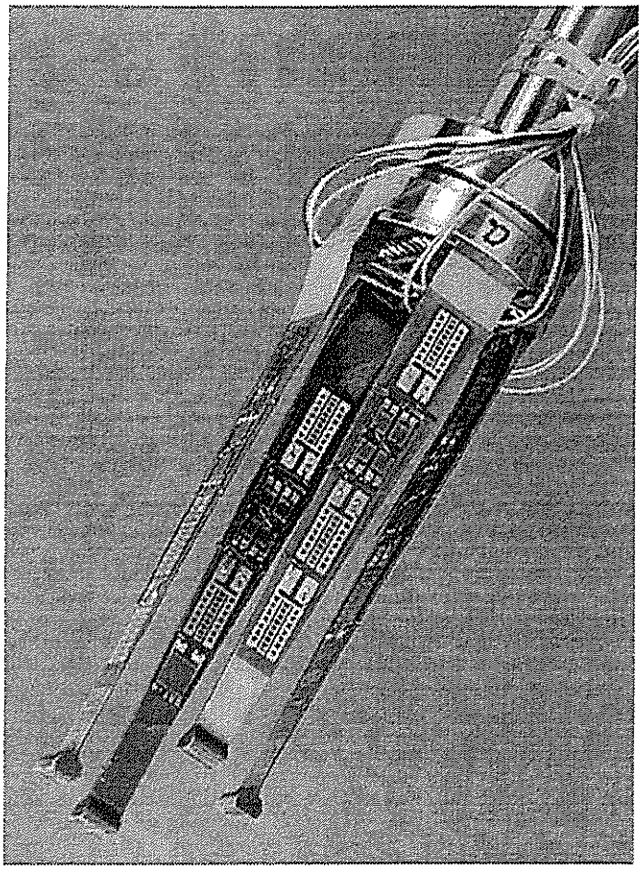

Fig. 3 - Blade angle measurement system (photo: NLR)

The sleeve attaches the rotor blade to the rotor hub. It also provides attachments for the pitch lever and flapping stops that limit the blade flapping angles. The rotor torque is transmitted to the rotor drive system MWM via the rotor mast, by bushings. Rotor hub and mast can be separated at the flange. The mast is hollow to allow for internal routing of the instrumentation cables.

The rotor blades are constructed of a D-spar wrapped with layers of uni-directional graphite epoxy material and a foam trailing edge core covered with layers of aramid epoxy fabric material. Airfoils of the OA series are applied. Blade tip shape is parabolic with anhedral. All rotor blades are equipped with 'safety-of-flight' strain gauge bridges in the blade root area; two opposite blades are equipped with additional strain gauge bridges for the measurement of flapwise, chordwise and torsional bending at four positions along the span.

Rotor control is supplied by a typical swash plate configuration, driven by three actuators of the MWM. Two pitch links are instrumented with piezo-electric transducers. A scissor assembly interfaces the rotor mast and rotating star of the swash plate system.

A novel measurement system has been developed, and installed in the blade sleeve, to measure the blade pitch, flap and lead-lag angles (figure 3). A unique feature of the system is that it only senses blade root rotations but no translation caused by the flexibility of the elastomeric bearing. The electronic component used to measure blade pitch is a resolver. Strain gauges, glued on the system flexures, are used to measure blade flapping and lead-lag. Two sets of instrumentation are located at opposite blades. The elastomeric bearings and dampers are equipped with thermo-couples to monitor heating during rotor operation.

Instrumentation wiring is plugged onto a dedicated printed circuit board (PCB), which is mounted inside the rotor beanie. This PCB is the front-end of the DLR data acquisition system (PCM unit).

The rotor is driven by the rotor test rig MWM, operated by a crew of the Flight Mechanics Department of DLR. The MWM drives the rotor system with a hydraulic motor, which is connected to the drive shaft through an intermediate gearbox. Loads generated by the rotating rotor are measured by means of a built-in balance system, composed of six strain gauge load transducers. Remote control of both the speed of the rotor and the settings of the swash plate enables the required model load conditions to be achieved.

A light-weight, but stiff glass fibre fuselage is mounted to the MWM structure. It consists of a nose section, a centre section (cabin), engine cowlings and a tail section. .

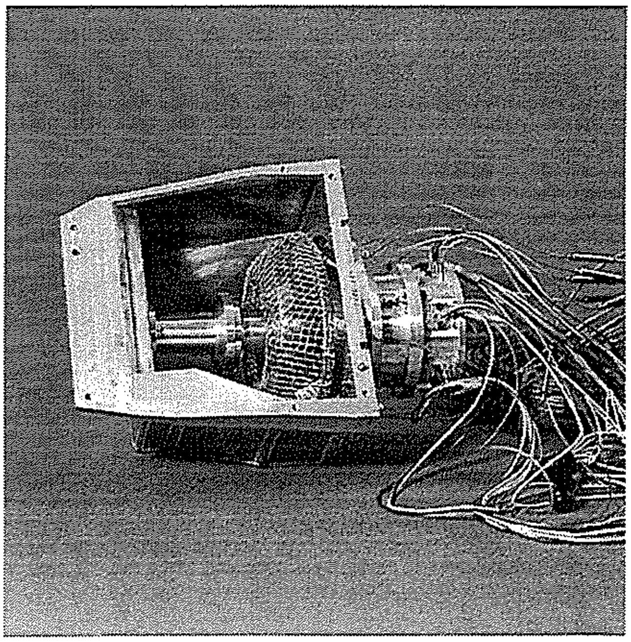

Fig. 4 - Air intake module (photo: NLR)

Because the sense of rotation of the main rotor is reversed as compared to the actual NH90 main rotor, the aft part of the tail and empennage are mirrored images of the actual fuselage. The fuselage was equipped with 76 thermocouples to measure the temperature of the circulating air.

The engine installation model hardware is integrated in the fuselage hull. It contains engine air intake and exhaust modules with both external and internal geometries to scale, capable of simulating representative engine intake and exhaust gas flow conditions (for both the left and right hand side engines).

The air intake subsystem consists of the intake opening recess (intake plate), a caisson air intake, bellmouth with a screen and the engine duct (figure 4). Behind the compressor entry, the cross section area has been adapted to obtain the scaled mass flow capability. The exhaust subsystem consists of a plenum settling chamber connected to the hot air supply pipe, a perforated stainless steel plate located between the nozzle, settling chamber, and a stainless steel nozzle Thermocouples are applied in the air intake, to detect exhaust gas recirculation. Data on total pressure drop, flow direction and velocity inside the engine air intake is obtained using six five-hole probes and twelve total pressure probes.

The model is mounted on the so-called DNW common support system, which allows for testing in a wide range of crosswind conditions (270°) and a limited angle of attack range (+/-10°). The model support basically consists of the DNW-LLF open jet common support housing structure, a vertical mast, an angle of attack hinge joint and a vertical sting. A MWM mounting adaptor interfaced the support system to the MWM rotor drive system. The vacuum duct connects the intakes to a vacuum pump located in the test hall. Pressurized air is supplied by an air supply system, transferred through flexible hoses to the air heating system located above the hinge joint. The central component of the air heating system is the burner can, in which propane gas is burned to heat the pressurized air to 500°C. All supply pipes, including MWM hydraulic lines and measuring cables are routed along the vertical strut and covered with a cylindrical fairing between the fuselage model and the hinge joint.

Experimental approach

Rotor system functional testing at DLR

After the completion of the model rotor system and engine installation development, an elaborate test preparation period preceded the actual wind tunnel test campaign. Dedicated rotor system functional tests were performed by the Flight Mechanics Institute of DLR at Braunschweig. During these tests, the rotor system was prepared and completely checked-out for testing in the DNW-LLF.

After arrival at Braunschweig, the rotor was fitted to the rotor drive system MWM which was mounted to a dummy sting in the DLR testing hall (figure 5).
Model sensor wiring was plugged in the DLR data acquisition system and all data streams were checked. Sensor calibration results provided by NLR were implemented in the data processing software. A number of calibration activities were repeated to include the effects of the complete measurement chain in the calibration and for redundancy purposes. These calibrations were limited to sensor 'on-axis' excitation, without any cross coupling effects, to allow sensor read-out in case of failure of one of the other sensors.

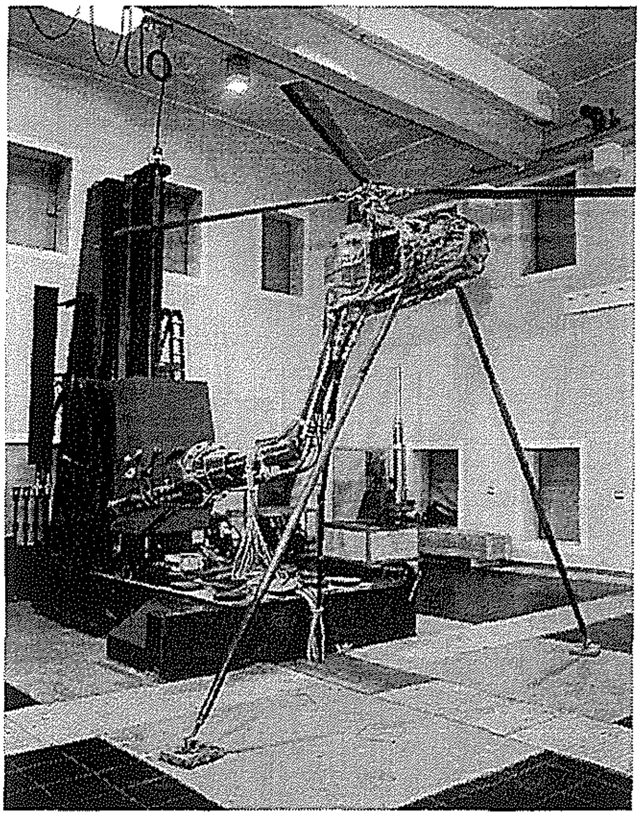

Fig. 5 - Model rotor system set up during testing at DLR Braunschweig (photo: NLR)

To verify controlled running down of the rotor system after a potential complete loss of the blade angle information, the kinematic characteristics of the control system were determined. Blade angles were measured for a large variety of actuator settings and stored in the control matrix. This was done experimentally, since control system kinematics are non-linear and difficult to be predicted accurately.
Relevant model rotor operating limitations were implemented in the on-line monitoring system.
When these data acquisition activities were finalized, the test set-up was equipped with a number of accelerometers to perform rotor rotating balancing. First test runs (without rotor blades) showed very low vibration levels. Next, the rotor blades were mounted and the rotor system was operated (in hover conditions at nominal rpm) at 50% thrust level. Rotor behaviour showed to be very smooth and the familiarization tests could be performed in a short period of time. Blade tracking was checked by a strobe light. Rotor testing was resumed by correlating lateral and longitudinal control inputs to rotor bending moment read-outs of both the shaft gauges and rotor balance. The rotor operation time accumulated during these functional tests

was only five hours. After completion of the functional tests, early November the rotor drive system and rotor hub were shipped to DNW-LLF for integration with the engine installation hardware and fuselage hull.

Engine installation and test set-up preparation

The air intake suction system was laid out to provide the mass flow required for the simulation of the air intake flow. In an early stage of the development phase, the required capacity of the air suction system was predicted by calculations. As soon as the model air intake was manufactured, a function test was performed to verify the system capabilities, using the piping that would be used in the actual tests. The capacity of the air suction system proved to be sufficient.

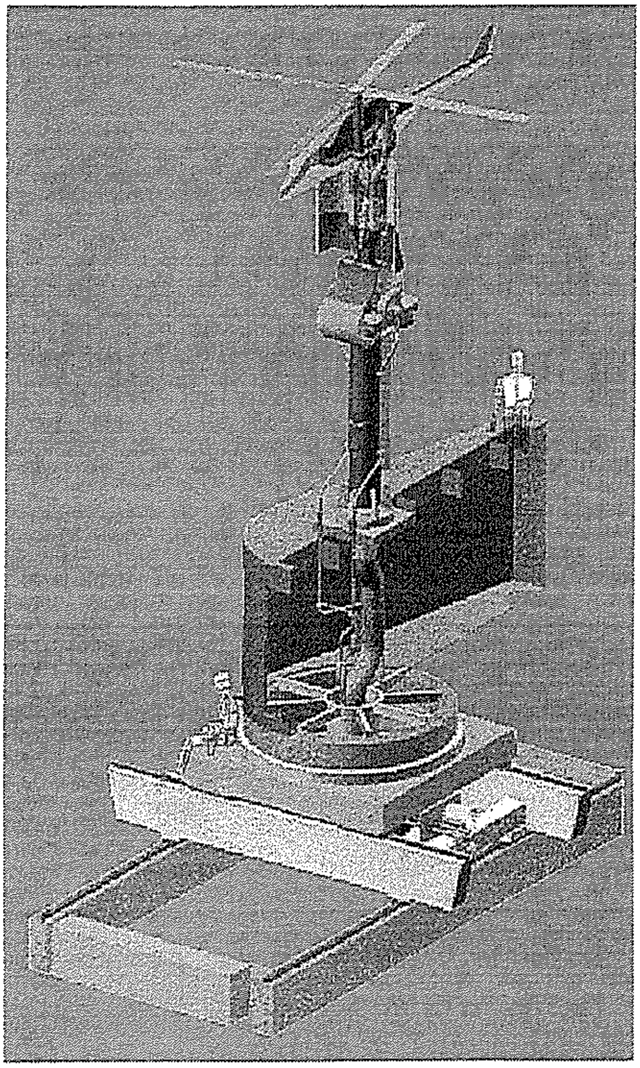

Fig. 6 - Schematic CAD/CAM model to aid assembly of the test set up

During this test the instrumentation, including five-hole pressure probes in the air intake, was checked also. A so-called zero measurement run was performed for this instrumentation, to be used as a reference for the actual tests. This test set-up allows the flow speed and direction, which are influenced by the shape of the engine bellmouth only, to be measured, with all disturbing effects of the NH90 air intake eliminated. Deviations from the 'clean' measurement can be regarded typical for the NH90 configuration.

The engine exhaust flow was heated by a propane burner located in the support system, just below the fuselage bottom. The original burner system has been developed by Boeing. DNW has adapted this system to the test set-up for the NH90 model. The system was pre-tested separately in the DNW-LLF parking hall. The burner was connected to the pipes supplying the hot air to the exhausts. The optimal gas pressure and air mass flow were determined and set. The gas mixture is ignited with a spark plug. The required temperature and mass flow can be established by controlling the gas pressure and air mass flow. Increasing the gas pressure had to be performed very carefully to avoid the propane gas mixture to become liquid, which would be highly explosive. A dedicated computer code was developed to monitor the propane and burner conditions. All critical parameters were displayed on-line.

Because of the limited space available and the large numbers of equipment to be integrated, the routing of pipes and cables had been prepared using 3D design tools including CATIA (figure 6). This equipment includes oil supply and return pipes to cool the hydraulic drive unit, insulated hot air supply pipes, air suction pipes, measurement cables for the rotor, engine and fuselage instrumentation, reference pressure tube, fire extinguisher cables and cables for a CCD camera inside the model. Prior to wind tunnel testing, the model was completely pre-assembled in a model preparation hall of the DNW-LLF, to check the interfaces between the parts supplied by DLR, DNW and NLR. The pre-assembly started with mounting the sting on a dummy support. After lifting the DLR rotor drive system on this sting, the engine simulation hardware was built-in (figure 7) and the burner system was connected to the sting.

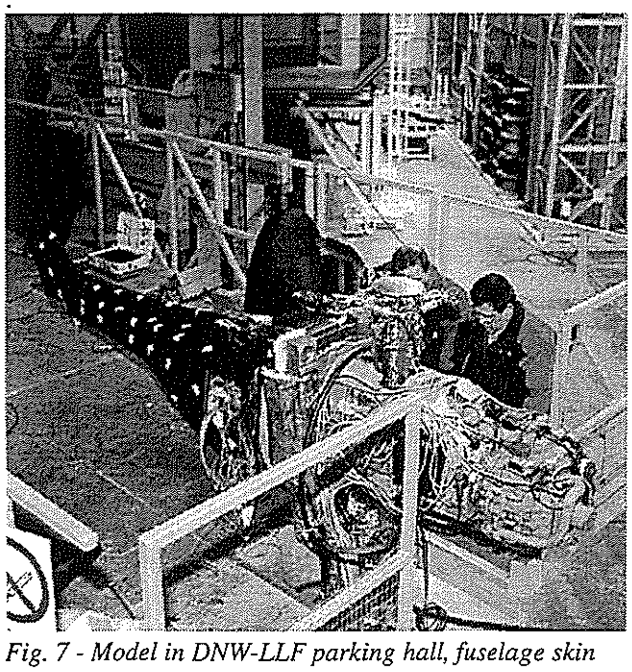

Fig. 7 - Model in DNW-LLF parking hall, fuselage skin and rotor blades removed (photo: NLR)

Having completed the assembly of the engine installation and rotor modules, the sting with the model was lifted from the dummy support and mounted on top of the alpha mechanism which on its turn was connected to the common support of the wind tunnel. In parallel with the model pre-assembly, all cabling and piping was already mounted on the common support.

Test execution in DNW-LLF

The test preparation and execution was a major collaborative effort of NLR, NH90 partner representatives (guiding the test programme), DNW and DLR. NLR was responsible for overall test co-ordination and IR signature measurement (in cooperation with ECD). The DNW team was responsible for the operation of the wind tunnel, the model support system and the burner control, and for the acquisition of the sensor data related to the engine installation. The rotor system was operated by DLR personnel, who also took care of the rotor system data acquisition.

In December 1996, the actual wind tunnel campaign was carried out during a 3 week period in the open jet test section of DNW-LLF. The test set-up was transferred from the parking hall to the test hall, and all supply systems (hydraulic, air suction and supply, propane gas) were connected (figure 8). A stroboscope system was installed to be used for blade tracking. All instrumentation signals were checked and fire extinguishers were connected. Final functional checks of all major systems, such as the rotor, air suction, exhaust gas burner were first done separately and finally collectively. The scanners of the infrared measurement system were installed on special mounting platforms in the testing hall.

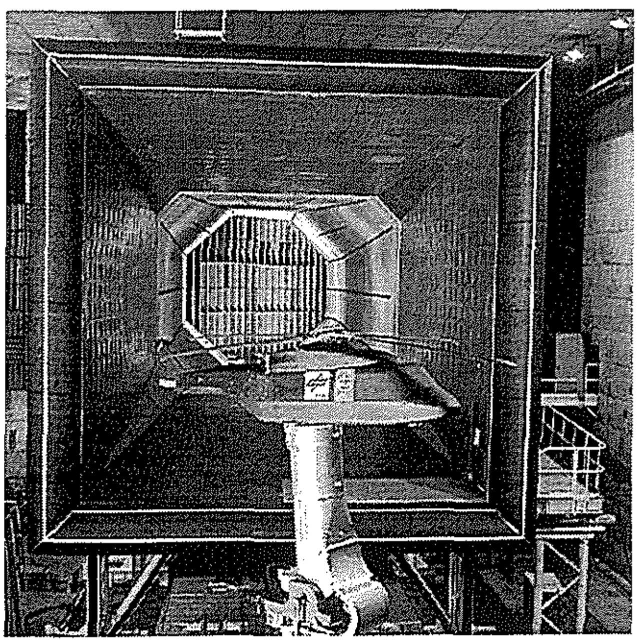

Fig. 8 - NH90 model in the open jet test section of the DNW-LLF (photo: DNW)

When all systems were operational, the first measurement production runs were made, according to a predefined detailed test programme. Rotor system hover and low speed tests were performed to familiarize with the new test set-up.

The test procedure was such that first the rotor system is engaged. Rotor speed is increased gradually until the requested blade tip Mach number is reached. Thrust is increased to a moderate level at zero (cyclic) blade flapping. Next, the burner system is engaged by spark plug ignition at the proper propane gas pressure, and exhaust mass flow. Gradually the exhaust gas mass flow and temperature are brought to the requested level.

Fig. 9 - Sample IR image

In parallel, the air intake mass flow is set. As soon as the burner is on condition, the model angle of attack, sideslip and tunnel wind speed are set to the specific values Finally, the rotor thrust is set to the predefined thrust coefficient and the cyclic pitch is adjusted to achieve the required longitudinal and lateral flapping level.

As soon as a test condition is settled completely, data acquisition starts by recording the parameters related to the engine installation, pressures and temperatures. In parallel infrared recordings are made (figure 9). Then, a data point number is assigned by DNW, and passed to the DLR crew, performing rotor system data acquisition.
The average testing time needed for one test condition, according to the above approach was five to six minutes. The above procedure was repeated for all test conditions of the test programme.

Test results obtained

Data acquisition and processing
During testing the most important parameters were displayed on-line for monitoring purposes and test programme guidance. It allowed the tests to be executed efficiently and with a high productivity.
Data postprocessing and storage were performed by DNW (engine installation related data), DLR (rotor system related data) and NLR/ECD (infrared data).

All rotor system related instrumentation and the corresponding data acquisition and processing was handled by DLR, using DLR data acquisition and processing equipment (figure 10).
The DLR data acquisition system discerns in sensors in the "rotating system" (up to 64 signals) and sensors in the "fixed system" (up to 100 signals).

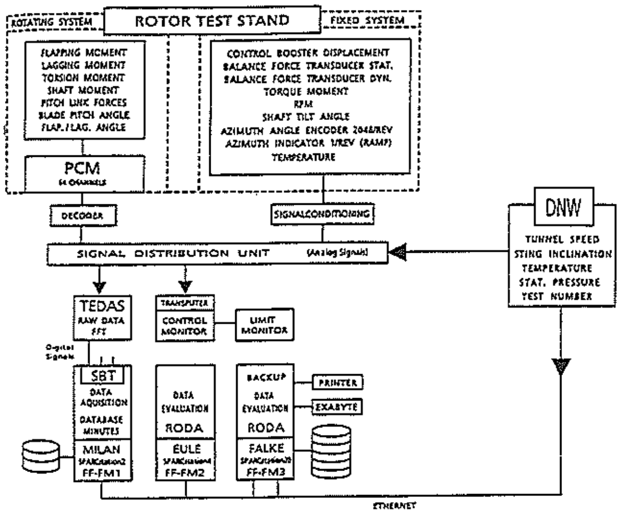

Fig. 10 - Flow diagram of DLR data acquisition and processing chain

The sensors in the "rotating system", e.g. strain gauge bridges on the main rotor blades, are first amplified in close vicinity of the sensor. Next each measuring signal is fed through a 250 Hz low pass filter to ensure a proper signal analysis up to the 8th harmonic of the rotor rpm. After the filtering, the signals are presented to a Pulse Code Modulation (PCM) system to reduce the number of channels to pass through a slip ring from the "rotating system" into the "fixed system". Once in the "fixed system" (on ground) the PCM serial signals are transformed back to obtain the original signals. The sensor signals originating in the "fixed system" are fed straight away into the signal conditioners (amplification and filtering). At this point the data of both the rotating and non-rotating system, together with DNW tunnel relevant reference data are joined and are available for further processing. A SUN workstation, the main computing element, is linked to the DNW computer via ETHERNET. It triggers a data point, performs signal processing, analysis (off-line) and stores the data. Via calibrations engineering units are calculated from these values. The duration of each time series equals 32 main rotor cycles, or approximately 2 seconds.

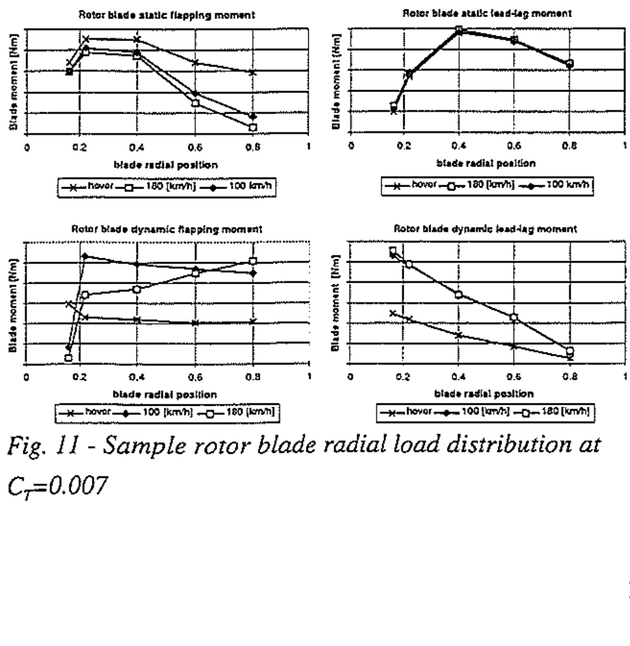

Fig. 11 - Sample rotor blade radial load distribution at C_T=0.007

In the data processing computer the raw data are reduced off-line by performing a Fast Fourier Transform (FFT) for 32 rotor revolutions (figure 11 shows sample blade load results).

In a second (on-line) data loop selected signals are monitored. These signals are used as a status indicator for the rotor and wind tunnel condition, and to monitor actual blade and balance load limits with respect to pre-defined curves and values.
DNW carried out the data acquisition and control of all engine installation sensors (air intake five-hole probes, pitot probes, thermocouples) via a HYSCAN system. These data have been sampled during 10 seconds. Separate transducers have been used for the static exhaust pressures in both engines. The data of the temperature sensors is sampled during 3 seconds.
For the determination of exhaust gas recirculation in the air intakes the (non-dimensional) reingestion and distortion temperatures are calculated. The so-called re-ingestion temperature relates the mean air intake temperature increase to the exhaust gas temperature, while the distortion temperature relates the local maximum temperature to the exhaust gas temperature.

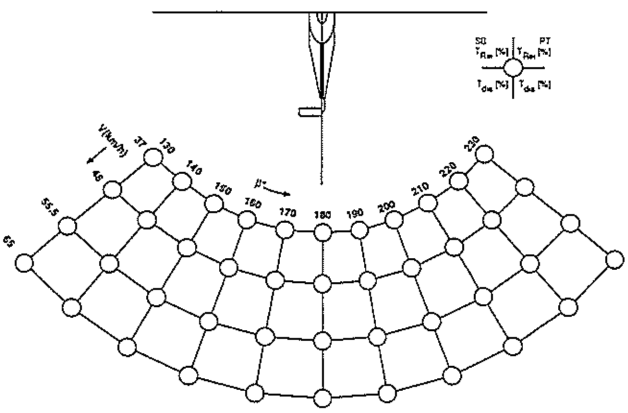

Fig. 12 - Presentation of recirculation parameters

In order to ease analysis and enable to adapt the test conditions on-line during testing, a special data presentation format was applied (figure 12).

Quality of test results: repeatability
The accuracy of the blade flapping angle measurement (during operation) was verified by analysing the DNW blade tip position tracking system (stroboscopic light) data. For a series of thrust levels (at hover and nominal rpm) blade tip position and flap angle sensor data were correlated.

Figure 13 shows that the flap angle sensor information is quite accurate (appr. 0.1°), even if the rotor rotates i.e. when centrifugal loads are acting on the blade flap sensor.

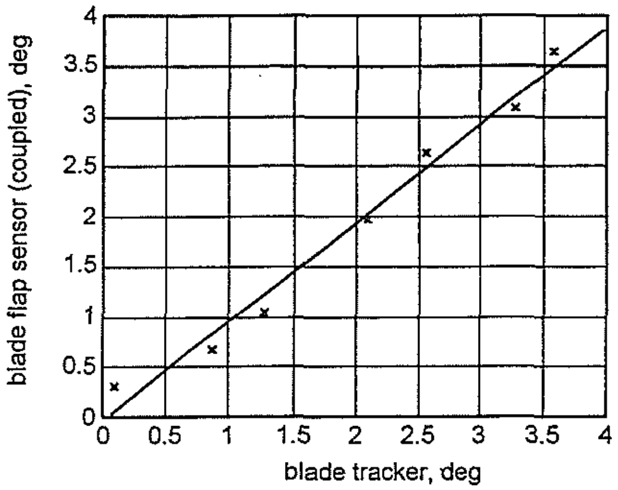

Fig. 13 - Blade coning angle measurement accuracy

Quality of test results can be quantified by assessing the level of repeatability of the most important test parameters.

Repeatability of rotor system related test results is very much dependent of the ability to set equal test conditions (environment, tunnel and rotor setting), which in general was good. The standard deviation (as a percentage of the average value) is given for the most important rotor setting parameters:

- tip Mach number (rotor rpm): 0.2 %;
- blade pitch: 0.1°;
- blade flap angle: 0.1°.

Resulting rotor thrust (shown in figure 14), torque and lead-lag angle repeatability was:

- thrust coefficient: 1.0 %;
- torque coefficient: 1.0 %;
- blade lead-lag angle: 0.1°.

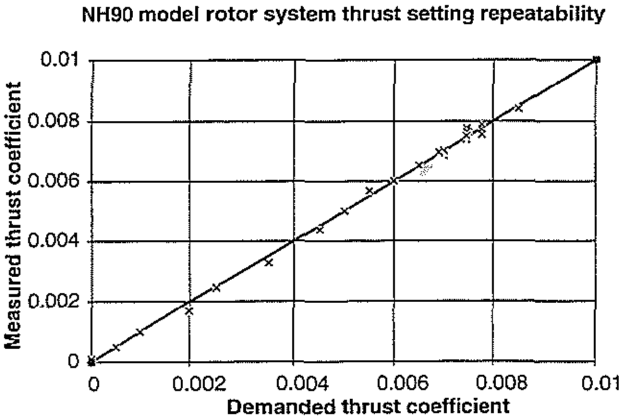

Fig. 14 - Repeatability of thrust setting

Average rotor blade bending moment repeatability for the hover (static only) and forward flight cases was:

- flapping moment (stat,dyn):
  2.5 %/0.5 [Nm] and 2.5 %/1.0 [Nm];
- lead-lag moment (stat,dyn):
  1.0%/1.0 [Nm] and 5.0 %/5.0 [Nm];
- torsion moment (stat,dyn):
  1.0%/0.2 [Nm] and 2.5 %/0.2 [Nm].

The air intake temperature profile showed to be very uniform outside of the re-ingestion conditions (within ±0.5 °C). Outside the re-ingestion conditions, repeatability is achieved of about 0.1% (0.5 °C).

Re-ingestion could already be discovered when the relevant parameters were higher than a threshold of 0.4% (corresponding to a 2 °C intake temperature increase). The re-ingestion conditions could be observed clearly as shown in figure 15 and reproduced very well.

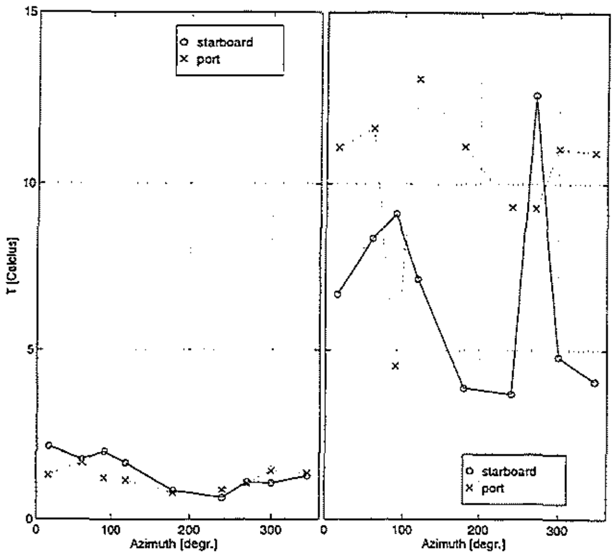

Fig. 15 - Sample air intake temperature change due to re-ingestion

The repeatability of the skin temperature sensors for test conditions without hot exhaust flow simulation is good. The temperature distribution is very uniform.

The occurring temperature differences were within the sensor accuracy (±1 °C).

During intake and exhaust simulation the mass flows were controlled to become equal (1.5 %). The total intake pressures (pitot and five-hole probes) showed repeatability values within ± 20 Pa, the intake flow angles within ±0.2° and the intake velocities within 0.2 m/s.

Generally speaking, a high level of repeatability of test parameters was achieved, which is an important condition for the measurement of high quality test results.

Conclusion

In the framework of the NH90 programme, a wind tunnel experiment was carried out in DNW-LLF.

A unique feature of the wind tunnel model was the integration of a scaled down powered rotor system and engine flow simulation module in one test set-up.

The tests provided high quality data on rotor behaviour, engine-air intake conditions, exhaust-gas characteristics and infrared signature during a range of test conditions.

Great commitment of all people involved of NLR, DNW, DLR and NH90 partner representatives was crucial to the successful development of the test set-up and execution of the test campaign.