MISSION ORIENTED INVESTIGATION OF HANDLING QUALITIES THROUGH SIMULATION

D. Braun, K. Kampa, D. Schimke
Messerschmitt-Bölkow-Blohm GmbH
Helicopter Division
Munich, Germany

Abstract

In the present paper, a survey of the simulation tool and its application is given. After a short description of the simulation facility, the main features of the simulation model are explained. Special emphasis is laid on engine, landing gear, noise, and vibration modelling. The validation of the model was performed by use of trim values, time histories, derivatives, and frequency responses. A mission analysis is discussed using the example of an EMS mission. The main part of the paper covers some exemplary investigations for the evaluation of mission effectiveness, control response behaviour, and system failures.

Introduction

From experience, development cost of new helicopters grow extensively in the test phase of the prototype. Due to a late detection of deficiences, expensive modifications of hardware elements are necessary and additional test campaigns delay the development and certification tests. Besides wind tunnel, component, and system testing, the off- and on-line simulation from the early beginning on helps to decrease such cost significantly.

In the past, simulation was only sporadically but not consequently used during the design process of a new helicopter. In most cases, after the first flight tests, pilots were surprised comparing the behaviour of the simulated and the real aircraft.

Nowadays, with the additional demand for increased mission effectiveness, the pilot-in-the-loop investigation of handling qualities is of increasing importance in the whole design process. The definition of handling qualities for future helicopters becomes even more decisive by the application of Active Control and fly-by-wire/light technology. The modification of the response and handling characteristics by control laws with full authority and advanced inceptors enable the designer to "program" handling qualities.

Presented at the 17th European Rotorcraft Forum, 24 - 27 September 1991, Berlin, Germany

Through pilot-in-the-loop simulation, a mission oriented optimum response characteristic can be specified and the handling qualities of the ACT helicopter can be evaluated. The demanding future tasks explain the increased importance given to the ground based simulation activities at all helicopter companies.

At MBB, a big effort is made to improve the simulation tool in order to be prepared for future development programs.

Simulation Facility

The MBB simulation facility is located at and operated by the military aircraft division. Both, helicopter and military aircraft division share the utilization of the simulator. It was laid out and purchased according to the requirements of the two users and has the following features:

- exchangeable cockpit
- large field-of-view computer generated image
- fixed base with provisions for buffeting and g-seat
- vibration and noise generation.

The general architecture of the MBB simulation facility is shown in Figure 1. The heart of the facility is the General Electric COMPU-SCENE IV visual system consisting of a spherical screen (dome) with a diameter of about 10 m and a six channel projection system (A), a computer image generator

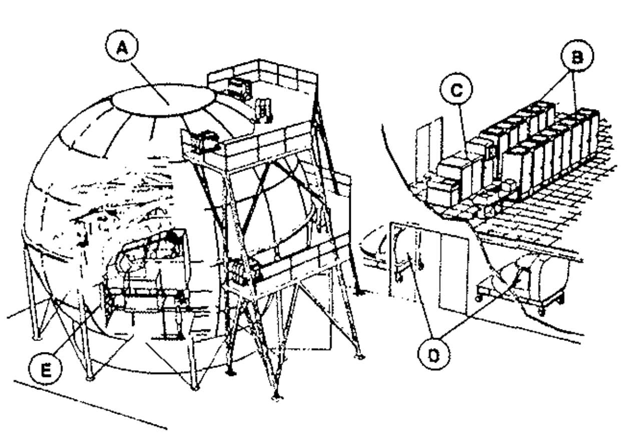


Fig. 1 Simulation facility

using the photomapping method (B), a powerful HARRIS Nighthawk simulation computer (C), three easy-to-exchange helicopter simulation cockpits (D), and an interface computer as a link between cockpit and simulation computer for I/O operations and signal converting (E).

The field of view of the projection system is adapted to the requirements of helicopter simulation: ± 70° in azimuth and + 70°/- 40° in elevation (Figure 2).

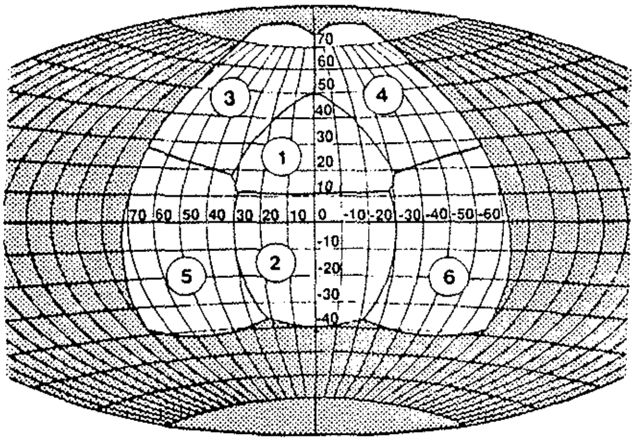


Fig. 2 Field-of-view for compu-scene 4

In Figure 3, the TIGER simulation cockpit is shown. It is equipped with the original inceptors, control panels, and programmable displays, etc. and is also used as a cockpit simulator mainly for the definition of the man-machine interfaces.

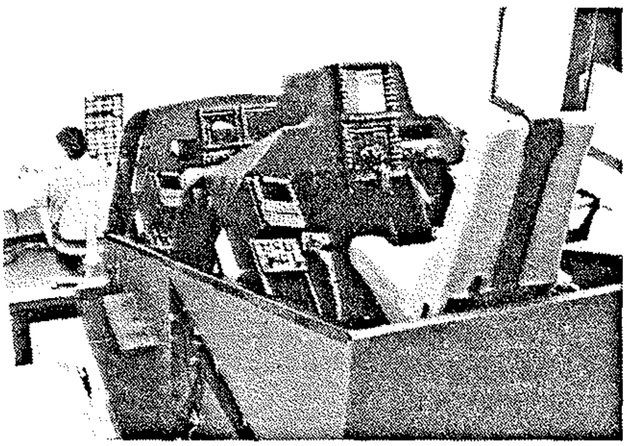


Fig. 3 Tiger simulation cockpit

A photograph of the NH90 cockpit is shown in Figure 4. It is provided with A320 displays and two active side arm controllers (cyclic plus collective).

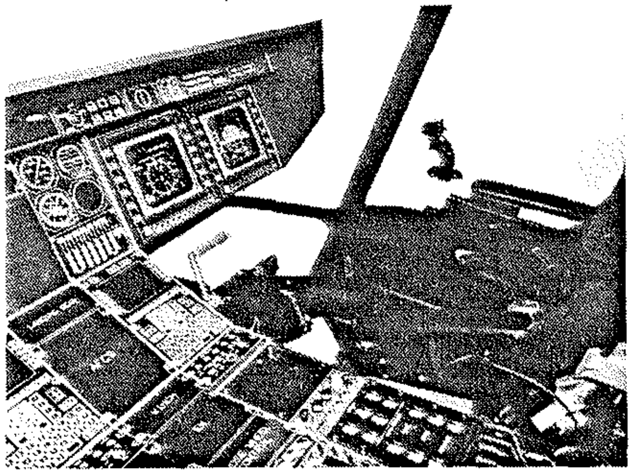


Fig. 4 NH90 simulation cockpit

Several data bases for the visual system are available. Apart from relatively low detailed large size areas developed for fighter aircraft simulation, a 15 x 15 nautical miles more detailed area is used particularly for helicopter trials. Figure 5 gives an impression of this so-called enhanced area looking through the windows of the BO108 simulator cockpit.

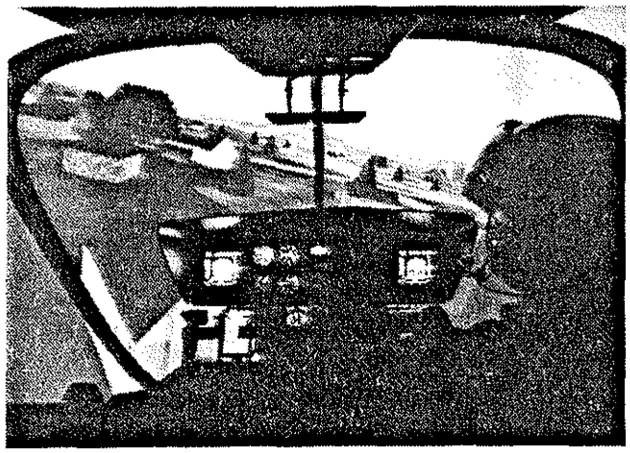


Fig. 5 Enhanced area scenery and BO108 simulation cockpit

Simulation Model

Basic Flight Mechanics Model

The flight mechanics approach is based on a comprehensive, interdisciplinary overall helicopter model for calculation of trim condition, stability characteristics, loads, and simulation of manoeuvres. A special on-line application of this model family is the generic program GENSIM for simulation trials. Figure 6 shows a block diagram of the code.

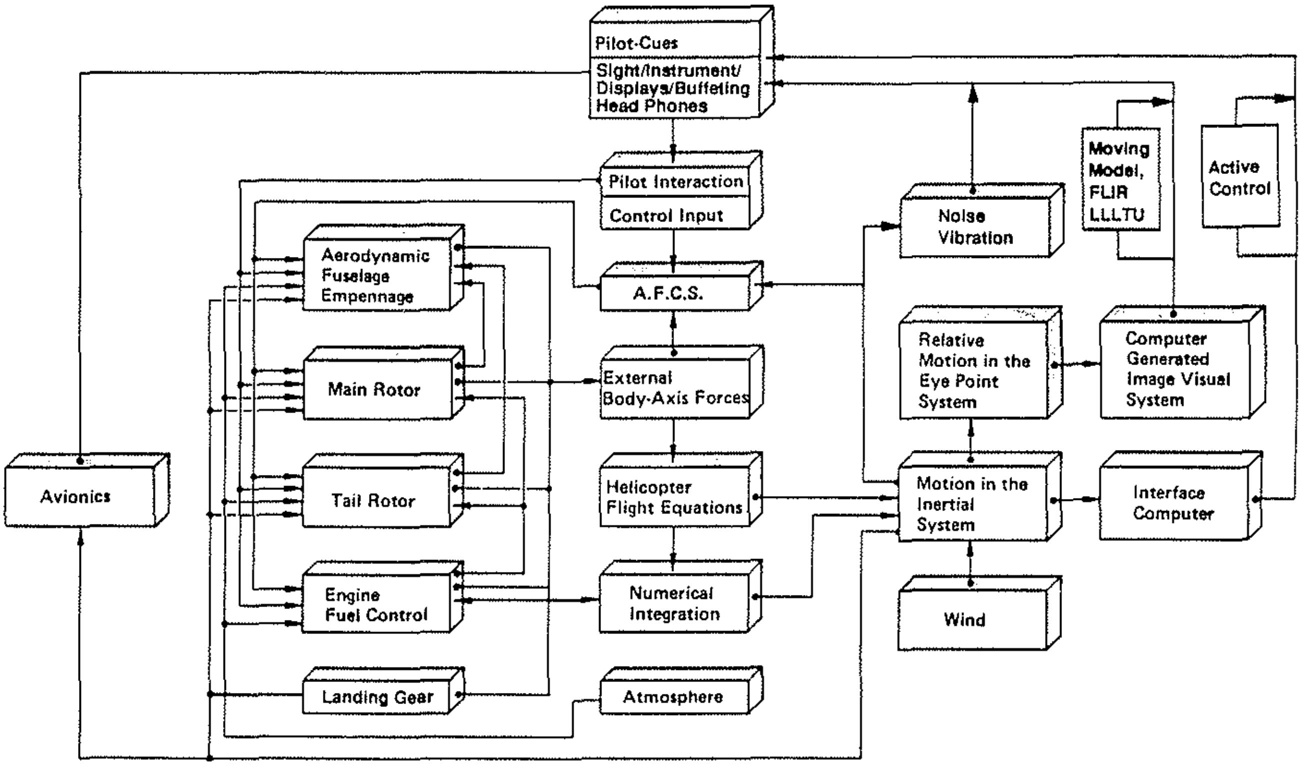


Fig. 6 Block diagram of generic simulation model

All the external forces and moments of the individual components like main rotor, tail rotor, fuselage, wing, and stabilizer are calculated using non-linear aerodynamic coefficients and wind tunnel data respectively.

Special emphasis is laid on the rotor model, which has following features:

- single blade dynamics (up to 6 blades)
- blade element theory (up to 15 elements, 3 different airfoils, variable planform).
- flapping DOF (lead lag and torsion are deleted for on-line simulation).

Gust models can also be applied.

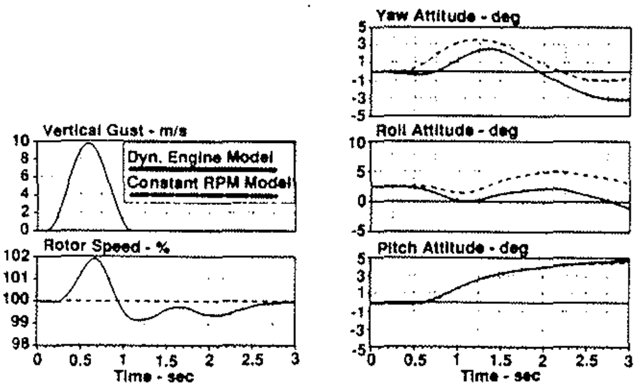


Fig.7 Calculated time histories due to vertical gust influence of rotor speed DOF

Figure 7 shows a comparison of flight responses with constant and variable rotor speed after a heavy vertical sine squared gust of about 10 m/s. With the engine model activated, an effect on attitudes can be noticed which has an influence on handling qualities.

<u>Rotor Speed/Engine Model</u>

Future engine governors do not allow large rotor speed variations for normal or moderate aggressive flight manoeuvres. Hence, rotor speed dynamics are not necessarily required for many handling quality tasks. Only in power-off flight conditions, extreme manoeuvres, or due to strong gust disturbances, motion response of the aircraft is apparent in consequence of varying rotor speed.

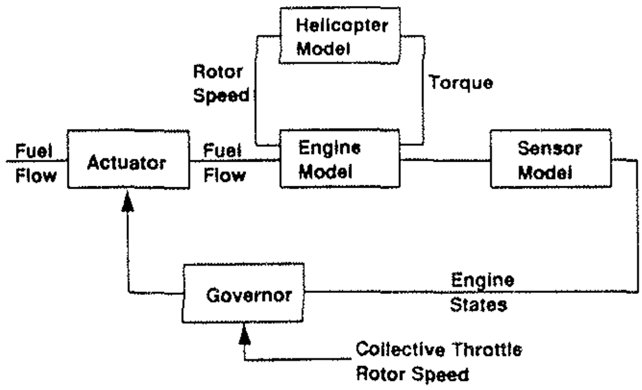


Fig. 8 Block diagram for the engine simulation model

Figure 8 characterizes the engine model used. To describe the dynamics of the gas generator and the power turbine, data tables are used dependent on the gas generator speed/acceleration, fuel flow, turbine outlet temperature, ambient pressure, rotor speed, and torque.

Landing Gear Model

Landing, take-off, and operations on ground are important for a complete mission simulation.

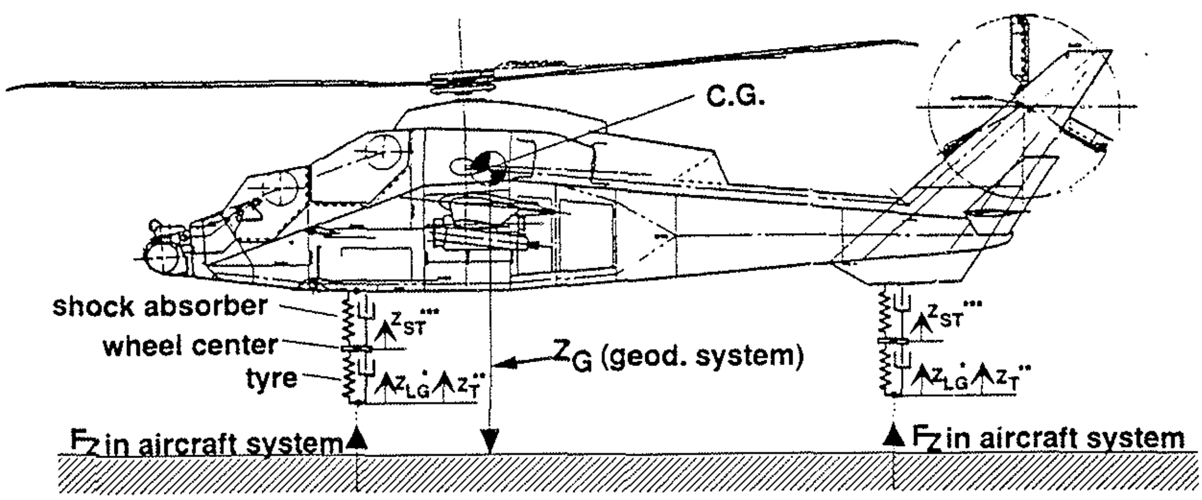
Analytical landing gear models describing both, the skid and the wheel landing gear, have been developed.

The skid landing gear has been modelled as a one DOF system (Ref. 1) with linearized bending tube characteristics and also linear kinematics. Elastic and plastic bending tube deformations as well as damping effects due to the friction between the skid and the ground surface have been considered.

The wheel landing gear model was mainly based upon Milwitzky's and Cook's model (Ref. 2), which is a two DOF system as shown in Fig. 9.

The shock absorber contains a gas spring and a hydraulic damper. The tyre is also modelled as a gas spring and additionally, structural damping effects caused by the tyre deflection can be considered.

Figure 10 presents the calculated time histories of characteristic aircraft values during a landing impact simulation of a tail wheel type helicopter.



* Z_{LG}: Deflection of landing gear including tyre deflection with reference to the aircraft

** Z_T: Tyre deflection with reference to the wheel center

*** Z_{ST}: Shock strut deflection: $Z_{ST} = Z_{LG} - Z_T$ in the helicopter system

Fig. 9 Schematic model of wheel landing gear

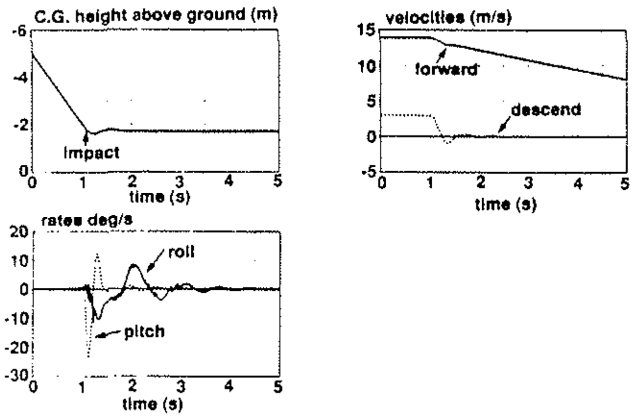


Fig. 10 Time history of landing impact

Starting condition for this simulation was a trimmed flight with v_x = 50 km/h and a rate of descent of v_z = 3 m/s. Due to the high damping capacity of the shock absorbers, the oscillation was nearly completely damped two seconds after impact.

Noise

Visual cues alone do not provide the pilot with adequate indications of flight conditions. Therefore, to enhance the overall quality of the helicopter simulation at MBB, a simulation of the noise environment in the helicopter cockpit is necessary. This can be particularly valuable for the assessment of certain flight conditions, as high g maneuvers, flares, and steep descents. For the simulation of autorotations and engine failures, it is even more important since acoustic cues provide an essential indication of rotor speed.

The noise simulation is achieved by the synthetic regeneration of the helicopter noise frequency spectrum. For that purpose, a data base through comprehensive measurements was established with a BK117 of the German police. To simulate the effects of noise attenuation by the pilot's headset, all measurements were performed with a microphone installed, under a headset which was mounted on an artificial head located between the front seats.

Due to the specific acoustics in the simulator dome, headphones are used instead of loudspeakers for transmitting the noise to the pilot.

The described noise simulation was developed for mission simulations of the Tiger and is already used in combination with the cockpit simulator.

Vibration

Another important parameter for a realistic helicopter environment is vibration. Like noise, vibration gives the pilot vital information about the flight condition of the helicopter and when used in a simulator, helps to increase the degree of realism. Both, noise and vibration are dominated by the blade passage frequency and both have a more or less similar dependence on the flight condition.

Therefore, in a feasibility study, the simulated noise signal was simultaneously used for vibration simulation. This was furthered by the availability of a relatively cheap and simple vibration system in the form of an inflatable vibration cushion that can be easily placed on the pilot's seat. An additional argument for the combined simulation of noise and vibration is that the lower frequencies in the noise spectrum are likewise felt through the body and through the ears. Pilots have assessed the integration of the inflatable pillow as a positive supplement.

Limitations of Real-Time Simulation

In real time simulation trials, it is essential that the lag between the pilot's input and the visual cue is not too large compared to the reality. Otherwise, the pilot will be bothered by tendencies of pilot induced oscillations, e.g. in tracking tasks, which is not in accordance with flight tests.

If the time delays in the system are too high, the simulator is limited in his bandwidth. This typical lag of simulators is caused by summing up the individual processing times of the several computers used.

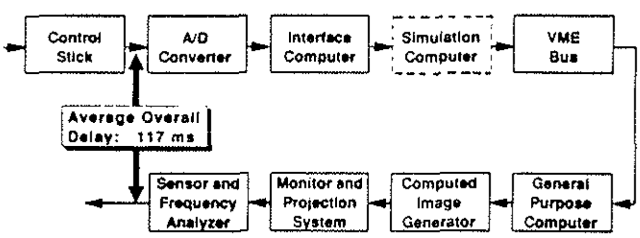


Fig. 11 Analysis of the simulator latency

These time delays minus the time in which the real aircraft responds to the same pilot input are usually quantified as a latency. Figure 11 shows the signal path and the measurement point of intersection. The result of this time delay analysis was a mean latency time of about 117 ms. In this case, the sampling time for the flight mechanical computation was 25 ms, indicated as a dashed box in Figure 11. For the most complex on-line flight mechanical model (GENSIM), a slightly higher sampling time of 30 ms to 40 ms is necessary. If the latency time is too high for mission tasks which require a high bandwidth, following improvements or adaptions can be performed:

- optimization of parallel or vector processing;
- *quickening the response dynamics of the helicopter* model by adding lead dynamics in the control system;
- clearing up the simulation model by eliminating time delaying effects of secondary importance.

Another important boundary for *simulation trials arises* from the computer generated scenery. At the fixed base simulation facility of MBB, a dome projection system is used as described above. Pilots seldom complain seriously about the global scenery or the brightness in performing their tasks. But, typical for hover and low speed tasks near the ground, they feel a lack in the range of field-of-view and in reference points. Therefore, distance, position, or speed estimation is very difficult, what is especially disadvantageous in precision hover, hover turn, side-steps, or bob downs.

It is the experience from helicopter simulation at MBB that for the above mentioned mission task elements, a mean decay of two points occur in the Cooper-Harper handling quality rating scale if simulation is compared to flight test. This result is in accordance with other investigations, e.g. Ref. 3 and 4.

Verification and Validation

The verification implies a comparative and quantitative assessment of the simulation models by use of flight test data. Aim of the verification procedure is to build up the essential mathematical model structure.

Validation is understood as a more comprehensive procedure involving all aspects of rotorcraft simulation as the flight mechanical model, motion system, and visual/aural environment. Main goal of the validation is to establish the flight envelope in which enough accuracy exists to perform successfully the simulation task.

To assure a maximum advantage from simulation application, a thorough verification and validation is strongly recommended. This is best to be done by comparing trimmed states, control responses, derivatives, and frequency responses with flight test data of an existing aircraft. The following chapters give a short and exemplary discussion of this task.

Verification using Derivatives and Frequency Responses

The simulation code is a special application of a basic flight mechanical code for use of off-line simulation, trim, and stability calculations. This comprehensive code was used to perform a perturbation analysis to extract derivatives. An important argument to verify the linearized model is based on the fact that on-line simulation is also used in the control system design. *Because of this possible application, it is indispensable* to check the accuracy of the linear representation of the flight mechanical model.

Figure 12 presents lateral derivatives vs forward speed resulting from the 8 x 8 system matrix compared to system identification values (Ref. 5).

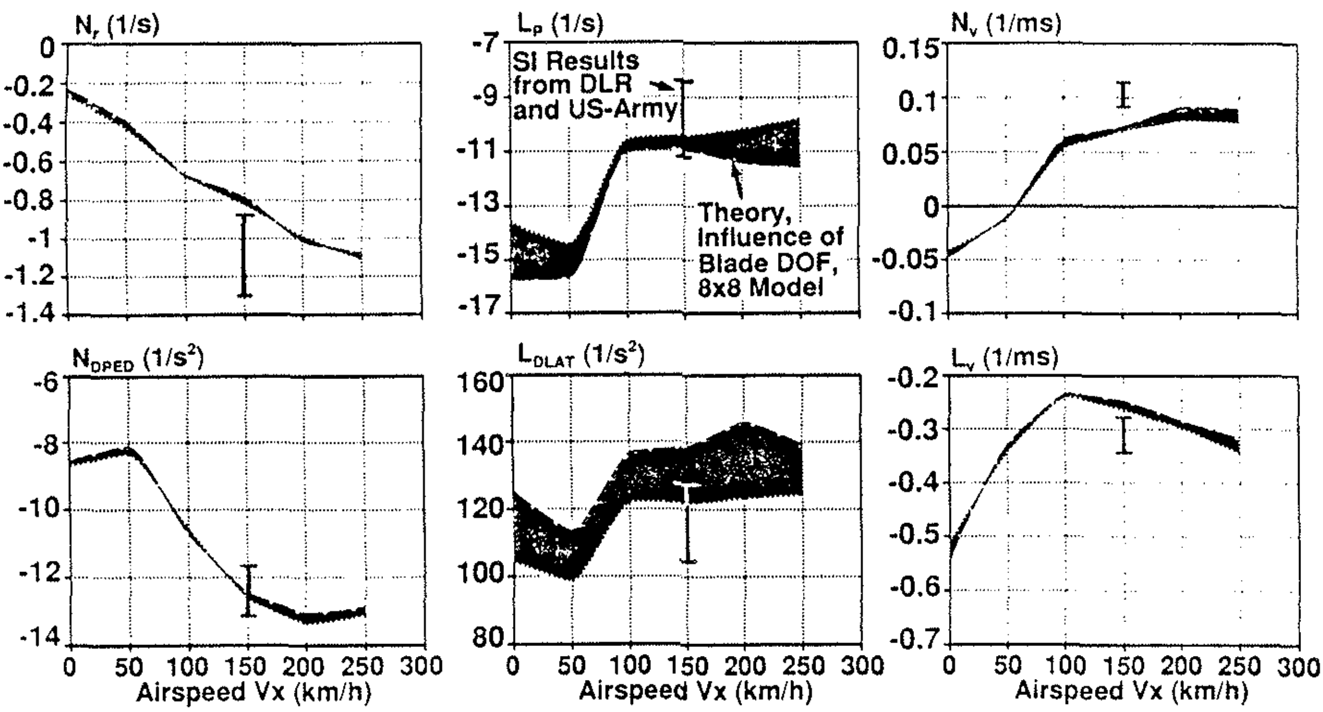


Fig. 12 Lateral derivatives for BO 105 system identification vs theory

The variation of identified results originates from different identification techniques. DLR used a time-domain method and US Army a frequency-domain identification procedure. The scatter band for the theoretical derivatives indicates the influence of the blade DOF applied. One linearization was performed with the flapping DOF only and the other one with flapping, lead-lag, and torsional degrees of freedom for the main rotor blades. To get a 8 x 8 system matrix, the blade DOF were treated in a quasi-static perturbation analysis. Predicted and identified derivatives are in an acceptable agreement. In particular the offset of the calculated derivatives is small compared to the variation of system identification values.

Figure 13 shows a comparison of the BO105 roll rate frequency responses between theory and flight test results (see Ref. 5) using the linearized model.

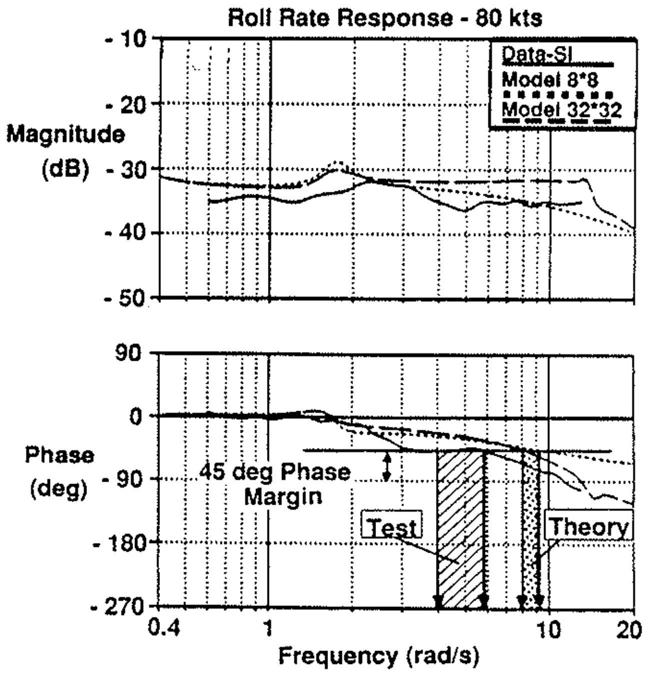


Fig. 13 Frequency responses for BO105

From the more complex model with four blade DOF (32 x 32 model), a benifit arises only at high frequencies beyond 10 rad/s. Both theories show less decay in gain and amplitude resulting from non-included dynamic effects, e.g. control system time constants. The theoretical representation of the aircraft leads to a bandwidth of 8 to 9 rad/s whereas the test gives values of 4 to 6 rad/s. This difference, obviously due to an incompleteness of the model used, however, gives a chance to regain frequency response behaviour by reducing the simulator time delays.

Static Validation

It is necessary to cover the whole flight envelope of possible steady-state flights as level flight, quartering flight, climb/descent, turn, torque range, and autorotation for all weight, CG, altitude, rotor speed and atmospheric conditions. As an example for the trim validation, Figure 14 shows the static control positions vs cruise speed for the BO105.

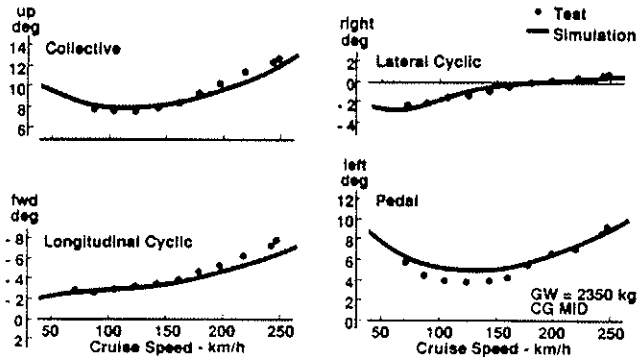


Fig. 14 Simulation validation with BO105 data - control positions

A good correlation exists between predicted and measured control angles. Generally, this is true for static trim values. Noticeable differences occur only in tail rotor control for medium speed, resulting from the simplified tail rotor model (e.g. no flapping DOF and hence no pitch-flap coupling).

Dynamic Validation

The procedure for the dynamic validation is to add the time histories of the perturbations of all four controls to the trim of the simulation model. In this way, differences in initial control do not effect the motion response. Furthermore, it is important to initiate the helicopter motion from trimmed steady flight states at known wind and gust conditions. All these preconditions are sometimes difficult to achieve in flight test.

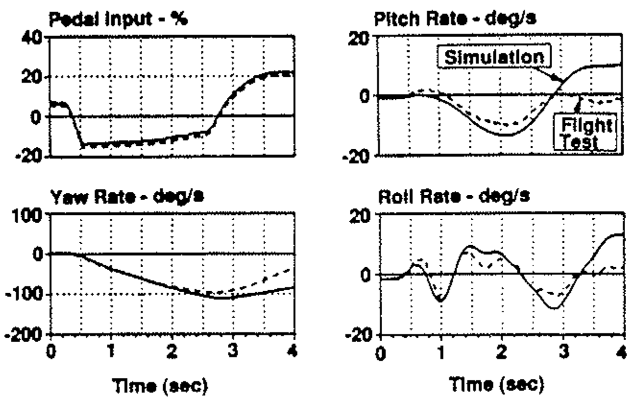


Fig. 15 Validation of a hover turn manoeuvre

Figure 15 shows the yaw motion after a pedal input in comparison to the calculated reaction using the off-line simulation model. The yaw rate as an on-axis response is slightly overestimated as well as the coupled reaction in the pitch and roll rate. Further adjustments of the yaw response may be performed in the simulator.

Definition of the Mission Oriented Task

The progress in real time simulation with the pilot in the loop allows to consider apart from the pure specification of the response to a test signal (step input, frequency response, etc.) more mission oriented handling qualities requirements already during the design phase. An example for this tendency is presented in the LH specification (Ref. 6). An important statement from this specification is the definition of the mission task element: "An element of a mission that can be treated as a handling qualities task. ...". This definition assumes the derivation of the mission task elements from the existing helicopter missions.

Looking at the variety of helicopter roles in civil or military missions, a large amount of missions or mission phases can be listed. An effective use of mission tasks for the investigation of handling qualities can be achieved if three main demands are fulfilled:

- Relationship to the real mission through a mission analysis including the pilot;
- Selection of important mission phases using an handling qualities oriented criterium like the pilot workload;
- Reduction of mission phases to well defined and reproducible mission tasks.

According to these demands, an analysis of a lot of missions was performed at MBB. As an example, Figure 16 shows the general procedure for the EMS (Emergency Medical Service) mission.

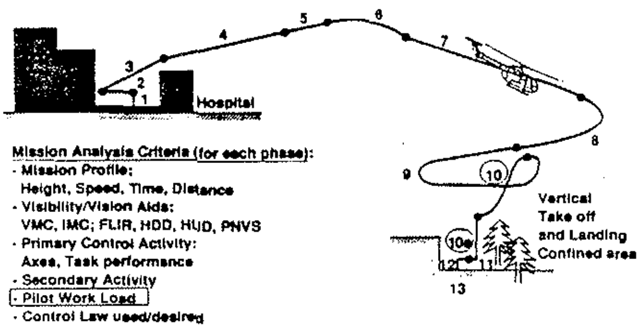


Fig. 16 Analysis of an emergency medical service (EMS) mission

The EMS mission was derived from the nationwide air rescue system founded by the German ADAC. The mission results mainly from ADAC pilots, experienced in EMS and SAR missions. Each mission phase was described by important parameters like the mission profile (height, speed, time, distance), typical visual conditions, the cockpit equipment, the pilot activity and the pilot workload respectively. For the selection of specific phases, the pilot workload was the decisive criterium. The discussion and the analysis with pilots showed that above all, the vertical take-off and landing in a confined area (phase 10 in Figure 16) is the most attentive phase and a typical demand for this mission. About 30% of all external take-offs and landings in Germany are in a confined area. The identification of phases with high pilot workload in a realistic mission environment is the basis for the definition of the task elements.

For a complete Helicopter mission analysis, similar tasks from different missions must be harmonized in order to reduce the overall number of tasks. With a detailed definition of the requirements, the mission element becomes a reproducible mission task element as defined in Ref. 6. An example for this definition derived from the EMS mission is shown in Figure 17.

Vertical Landing in Confined Area	
Task description	• Final approach on a visual glide path from 300 ft agl to 100 ft agl and deceleration from 45 kts to about 30 kts • Flare to HOGE at 100 ft agl and continuous vertical descent to HIGE at about 5 ft agl
Condition	• Wind: ≤ 30 kts (Sideward dir. most critical) • Gusts: ≤ 30 kts
Required/Desired Precision	• Horizontal Position: ± 2 m/± 1 m
Level of Task Aggression *High/Medium/Low*	• Rate of vertical descent: *200-300/100-200/≤ 100 ft/min*
Extracted MTE-Segments	• Decelerating descent flight • Flare to HOGE • Continuous vertical descent • Stabilized HIGE

Fig. 17 Definition of a mission task element

Besides the description of the task and the ambient condition, a division into demands for precision and aggression have proven to be useful. In addition, for both types of parameters, a margin of two or three levels was defined in order to record the achieved performance together with the pilot rating. Thereby, the influence of the increased task performance could be evaluated. A further division into several segments can be useful to receive a pilot assessment for different control strategies within one mission task element (e.g. high control power and precise tracking phases).

Evaluation of Handling Qualities

In the following chapters, three typical simulation applications are discussed. Firstly, a pilot-in-the-loop investigation of mission task elements is presented using the Cooper-Harper rating scale. Secondly, a basic study on design parameters is given influencing the controllability. And thirdly, the use of the simulator for accident simulation is high-lighted.

Investigation of Mission Task Elements

The specification of a future military helicopter will require handling quality ratings of level 1 at day-light missions. For the demonstration of such a requirement, mission task elements similar to the ADS-33 C (Ref. 6) specification may be applied. Figure 18 presents some exemplary pilot ratings for the most important mission task elements.

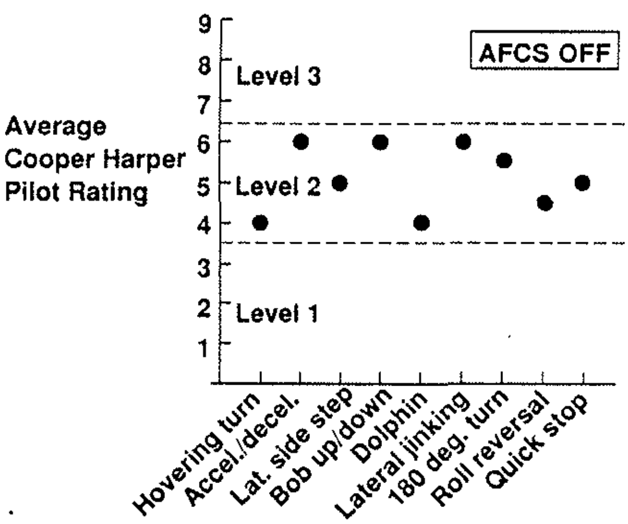


Fig. 18 Pilot ratings for some mission task elements - simulation tests

The ratings are derived from one pilot only. As most of the mission task elements are multi-axis control tasks, the pilot was asked to rate each control axis separately. That is the reason for the scatter in the pilot ratings of Figure 18. It is important to note that all manoeuvres are flown with CSAS on but AFCS off. Upper AFCS functions like attitude hold, doppler hover hold, line of sight, radar height hold, and decoupling mode may improve handling qualities to level 1.

As an example, in Figure 19, characteristic performance data are collected for the lateral jinking manoeuvre. The aim of the manoeuvre is to roll rapidly to ± 50° bank angle with a minimum lateral amplitude of ± 15 m from the centerline of the runway. The test is flown at 75 ft AGL and 70 KIAS. Mainly the precision in height control was a problem in the simulator because of not sufficient visual cues. In spite of this, the overall Cooper-Harper rating was level 2.

No. of test	peak bank angle - deg	peak roll rate - deg/s	speed - kts	altitude deviation - m
1	+ 90	31	70 - 115	± 12
2	+ 65	34	55 - 75	± 15
3	- 83	30	65 - 100	± 14
4	- 68	32	50 - 80	± 12
5	+ 72	36	55 - 70	± 6
Requirement	≥ 50	n.a.	≥ 60	± 3

Lateral displacement > 15 m

Fig. 19 Manoeuvre data for lateral jinking - simulation

The identical lateral jinking manoeuvre was performed in flight test with the BO108-V1 by the same pilot. Figure 20 summarizes the analog characteristic manoeuvre data. Now, precise height control within the required accuracy is not a problem.

No. of test	peak bank angle - deg	peak roll rate - deg/s	speed - kts	altitude deviation - m
1	46	46	66 - 62	± 2,5
2	48	64	80 - 75	± 0,4
3	52	64	60 - 67	± 4
4	45	64		± 0,8
5	48	63		± 1,5
Requirement	50	n.a.	≥ 60	± 3

Lateral displacement > 15

G = 2360 kg, CG MID
1000 ft, + 2,5°C
5 kts Wind

Fig. 20 Manoeuvre data for lateral jinking - flight tests for BO 108-V1

Cooper-Harper ratings given for the individual control axes of the BO108 are:

- control of roll attitude : CHR 3
- control of yaw axis : CHR 4
- control of altitude : CHR 2
- control of airspeed : CHR 2.

The relatively high Cooper-Harper rating for the yaw axis is attributed to a non-optimum engine governor which is used in this prototype.

The complete manoeuvre was rated with respect to the specified limits at an average CHR of 3 which is three points better compared to the simulator trials. Taking into account the different sizes of the simulated helicopter and the test helicopter (BO108-V1), an assumed deterioration of about two points from flight test to simulation seems reasonable as already mentioned in a previous chapter.

Controllability

For the investigation of the optimum control sensitivity, two mission task elements turned out to be the most essential: the quickhop task for the longitudinal axis and the lateral unmask and remask task for the lateral axis. Both are typical hover and low speed tasks. The damping values coming from the linearized theory without any delay time, were held constant for both tasks: -1.5 1/s for the pitch axis and -4.0 1/s for the roll axis.

Figure 21 shows the results for the longitudinal axis. An increase of the sensitivity up to 0.8 does not deteriorate the pilot rating.

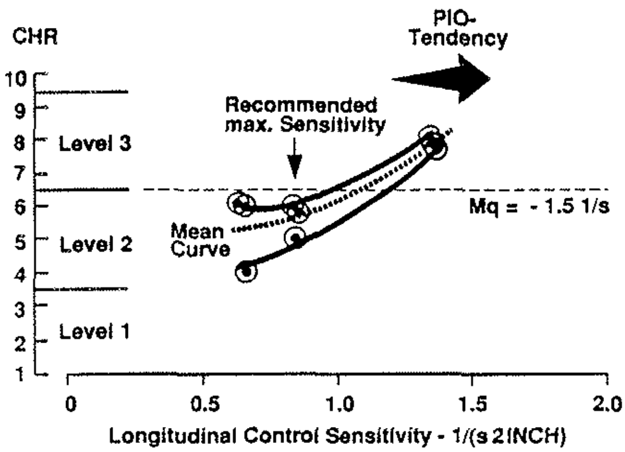


Fig. 21 CHR for a quickhop task

Above the control sensitivity of 1.0, a tendency to pilot induced oscillations was noticed, which is in accordance with the crossing of the boundary from level 2 to level 3 in Figure 21.

Figure 22 shows a similar investigation for the lateral axis.

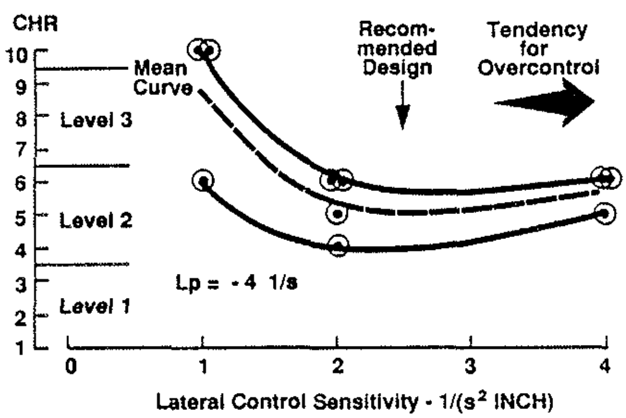


Fig. 22 CHR for a lateral unmask and remask task

The optimum control sensitivity was achieved between 2 and 3. At higher control sensitivities, a tendency for overcontrol was noticed.

Figure 23 shows the well known controllability diagram for the roll axis. In the figure, some flight test results for BO105, BK117, and BO108 with two control

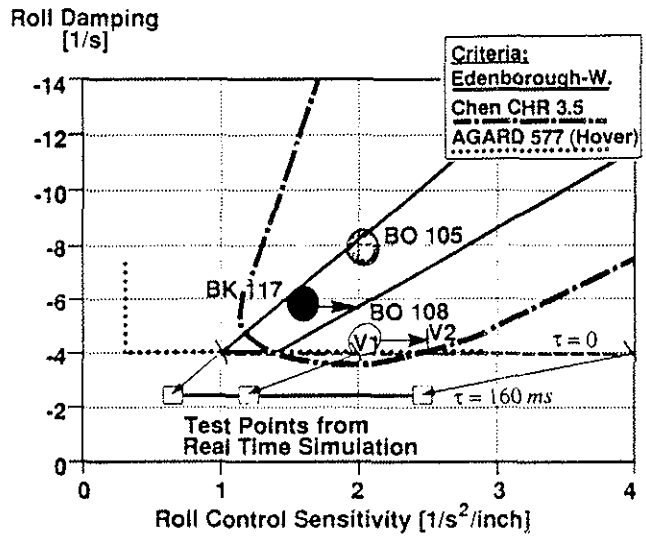


Fig. 23 Controllability - roll response

sensitivities for Prototype 1 and 2 are indicated. In addition, the simulation results from the sensitivity study mentioned above are presented. The evaluation of the simulation test points have to be corrected due to the time delay of the simulation facility. This shift may be one of the reasons for the Level 2 assessment.

During the simulation tests and also during the BK117 and BO108 flight tests, as high as possible control sensitivities were prefered by the pilot. In addition, the increased control sensitivity reduces the stick travel, which supports a positive assessment.

However, the format of the controllability diagram has deficiencies which result from the simple representation of the helicopter as a pure first order system (Ref. 7). Especially for higher frequencies, this representation is not adequate. The best way to check the response characteristic in high frequency ranges is to define the requirements by the frequency response of the helicopter, as done in Ref. 6. An evaluation of this criterium from flight test and two simulation models is already presented in Figure 13. The problem of this method is, that reliable theoretical models for the high frequency domain are not available before a prototype is flying.

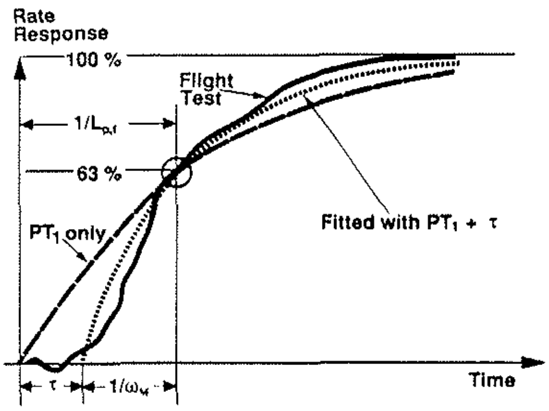
Bandwidth and Time Delay

In this chapter, a connection between controllability and frequency domain parameters is discussed. The rate response of a helicopter per control input can be written as

$$\frac{Rate}{Input} = \frac{K}{\frac{1}{\omega_M} \cdot s + 1} \cdot e^{-\tau s}$$

where a first order system is completed by a time delay term. This time delay is mainly used for the simulation of dynamic effects which are not included in the model.

Figure 24 explains for the rate response after a control step input the parameters used above.



$L_{p,f}$: Roll damping fitted to flight test without time delay
ω_M : Roll damping in a first order approximation with time delay

Fig. 24 Definitions for rate response time histories

Not visualized in the diagram is the roll damping derivative L_p which is known from the linearized models, e.g. the 8 x 8 system matrix representation. It is calculated with 8 body DOF and without a time delay term and therefore, has values between ω_M and $L_{p,f}$.

The relation between the damping $L_{p,f}$ of a pure first order system used in the controllability diagram, the time constant $1/\omega_M$, and the time delay τ for the roll axis is

$$L_{p,f} = \frac{1}{1/\omega_M + \tau}.$$

Figure 25 correlates the parameters ω_M and τ with bandwidth and time delay (see also Ref. 8) and establishes a useful tool in the preliminary design process.

In the simulator investigation for the roll control sensitivity mentioned above, a roll damping $L_{p,f}$ of 2.4 1/s was identified (see Figure 23), connected with a measured value of 160 ms for the time delay resulting in $\omega_M = 4\ 1/s$. These values are plotted into Figure 25 which allows to estimate the phase delay and bandwidth. From this consideration results a

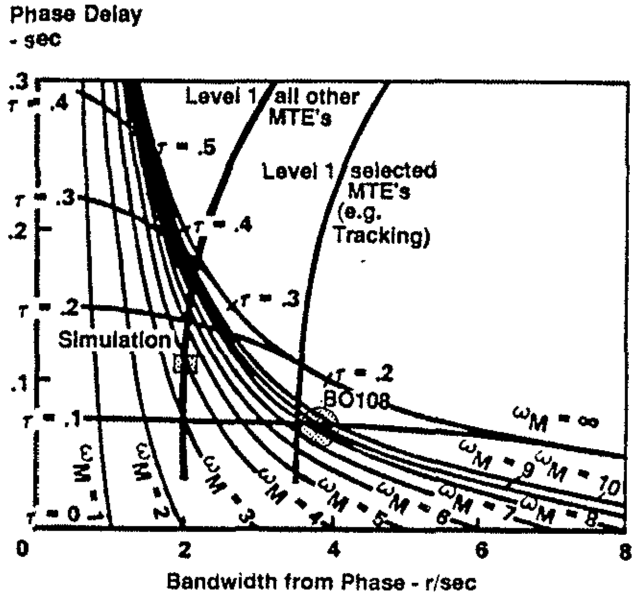


Fig. 25 Correlation of bandwidth low order equivalent system

handling qualities rating according to level 1 - 2. This rating is almost identical to that one given during the simulator test for lateral mission task elements.

The same procedure was applied to BO108 flight test data. An identification of the test results from step inputs leads to a roll damping of $L_{p,f} = 4.7\ 1/s$ and with a time delay of $\tau = 100$ ms to $\omega_M = 9\ 1/s$. These parameters are also plotted in Figure 25 and show level 1 behaviour for the BO108.

This representation has the following advantages:

- Experience from the controllability diagram is included in the handling qualities requirements;
- Recommendations or requirements for the control sensitivity are included;
- Extension of the requirements to the high frequency domain by the specification of an equivalent time delay on the basis of a first order system is possible;
- Already in an early design phase, the overall time delay can be estimated or specified by a breakdown of time delay terms (rotor dynamics, actuator computer...).

Sidestick controllers have to be treated in a different way and are also excluded in Ref. 6 up to now. Due to additional features like nonlinear shaping, the increased influence of the breakout force, the force gradient, etc., the sidestick configuration will require another more detailled approach.

Study on Tail Rotor Loss

One important domain of simulation is the investigation of failures which would lead to dangerous flight conditions in real testing.

Typical examples for such malfunctions are engine failures, hydraulic hard overs, or run-aways of the automatic flight control system. While these types of emergency conditions may be performed at least to a certain degree also in flight tests, this is not possible for a tail rotor loss. A complete tail rotor malfunction or a damage of all tail rotor blades results in a zero anti-torque moment and a strong reduction of yaw damping and directional stability. In flight test, it is possible with a refined measurement equipment to control the tail rotor for zero thrust. But then it still acts as a yaw damping and directional stability device.

As a preliminary study for the Tiger, real time simulations were performed to optimize the design of the fin and end plates and to check the survivability after a tail rotor loss. As after such a tail rotor failure, large angles of attack and sideslip angles may occur, causing strong nonlinear aerodynamic effects, an extensive measurement campaign in the wind tunnel was performed before the simulation.

As an example, Figure 26 shows the flight envelope in terms of climb/descent vs forward flight after tail rotor loss for an early configuration of the anti-tank helicopter.

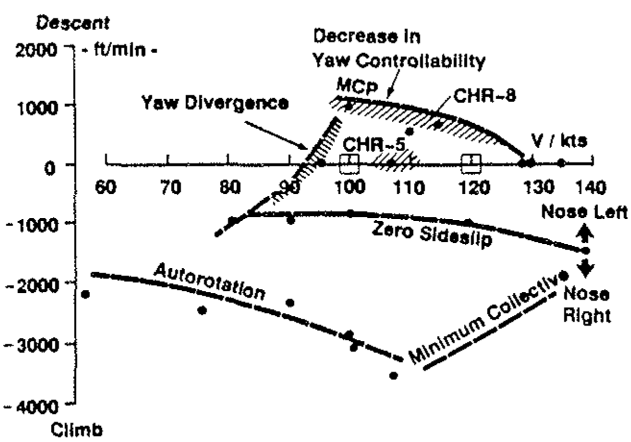


Fig. 26 Simulator study on flight envelope after tail rotor failure

During simulation tests the pilot was attentive but did not know the time of failure which was activated unexpectively in the simulation computer system by an external simulation engineer. The pilot was allowed to counteract as soon as he perceived the helicopter reaction.

Four boundaries are limiting the possible flight conditions from which a tail rotor loss can be survived. On the left hand side of Figure 26, the low speed limitation for cruise at which yaw divergence occurs, is shown. With decreasing dynamic pressure, the anti-torque moment can not be generated by the sum of all aerodynamic devices.

If the pilot increases the speed, a moderate climbing flight is possible. But due to a large sideslip angle and a large angle of attack, the drag force increases. At about 130 kts, only level flight is possible. This boundary was accompanied by an early decrease of pilot ratings.

The lower boundary of the flight envelope without tail rotor represents an auto-rotational flight with small sideslip angles according to a zero yaw moment of the helicopter. The maximum auto-rotational speed is limited by the available minimum collective control and the minimum rotorspeed. This boundary is indicated below right in Figure 26.

For all flight conditions, ratings using the Cooper-Harper scale were given by the pilot. The whole flight envelope was rated at level 2 with CSAS engaged in roll and pitch, except for the two upper boundaries where the yaw controllability deteriorates drastically without the tail rotor.

Conclusions

In the paper, the methodology of simulation application in the design process of a helicopter is discussed. The following experiences and results can be concluded:

- The quality of the computer generated image turned out to be acceptable. A lack of visual cues (field-of-view) is detected only in hovering and low speed tasks with high precision and aggressiveness demands.
- Aural and vibratory cues are valuable for the assessment of flight manoeuvres like flare, turn, steep descent, and auto-rotation.
- Validation proved good agreement between simulation and flight test results. But the most complex simulation model may not always be the best fitted for simulator trials. Because of the inherent latency of the simulation facility, a deletion of time delaying effects of secondary importance or quickening the response dynamics is necessary to improve the simulator's bandwidth.
- An outstanding application of real time simulation is the investigation of emergency and failure conditions. As an example, a total tail rotor failure was discussed.
- The real time simulation demonstrated its importance for handling qualities design in the preliminary phase of the Tiger.

References

(1) Chernoff, "Analysis and Design of Skid Gears for Level Landing", Republic Aviation Corporation Farmingdale, New York

(2) Milwitzky, B. and Cook, F.E., "Analysis of Landing Gear Behaviour," NACA-Report 1154 p. 1079 a.f.

(3) Warren F.Clement, William B.Cleveland, David L.Key, "Assessment of Simulation Fidelity Using Measurements of Piloting Technique in Flight", AGARD Guidance and Control Panel 38th Symposium, Monterey, May 8, 1984, Paper No. 55

(4) Gregory W. Condon, "Simulation of Nap-of-the-Earth Flight in Helicopters", 50th Symposium - Computer Aided System Design and Simulation, Izmir, May, 1990, Paper No. 63

(5) Jürgen Kaletka, Wolfgang von Grünhagen Mark B. Tischler, Jay W. Fletcher "Time and Frequency-Domain Identification and Verification of BO105 Dynamic Models", Fifteenth European Rotorcraft Forum, September, 1989, Amsterdam

(6) Aeronautical Design Standard "Handling Qualities Requirements for Military Rotorcraft", August, 1989

(7) K.Kampa, D.Schimke, "Examples For Good Handling Qualities Design of MBB Helicopter Projects", Helicopter Handling Qualities and Control, Conference Papers, 15-17 November 1988, London

(8) David L.Key, Branch Chief, "A Handling Qualities Specification for U.S. Military Rotorcraft", Ames Research Center, Moffett Field, CA