AEROMECHANIC ASPECTS IN THE DESIGN OF THE EC135

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Abstract

In mid 1996 the EC135 received its type certification from LBA, DGAC and FAA as the first helicopter commonly developed and certified by Eurocopter Germany and France.

This paper highlights the design work for optimised dynamics, aerodynamics, flying and handling qualities taking into account the experiences gained during the development of the EC135 and also the BO108 prototypes.

New design features such as the bearingless main rotor and advanced main rotor profiles were preliminarily evaluated on the technology demonstrator BO108. Based on these theoretical evaluations and flight test experience, Eurocopter started in 1991 with the development and design of the EC135 with fan-in-fin tail rotor, leading to the first flight of a pre-production aircraft in February 1994.

First a brief description of the helicopter and a presentation of the development schedule is given, followed by a discussion of interesting topics like rotor dynamics, vibration, rotor/airframe aerodynamics, dynamic stability, manoeuvrability, gust sensitivity, flight envelope, agility and controllability.

The paper describes theoretical and experimental investigations carried out in the design, development and certification process from the aeromechanic point of view. For each problem area, significant parameters are discussed and tendencies are shown.
In addition, the methodology used today in the design process of a helicopter is addressed.

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Fig. 1 EC 135 helicopter in flight

Helicopter description

The EC135 is shown in Fig. 1. An optimum combination of aircraft architecture and advanced technology components was realised on this aircraft. The most significant items in this sense are:

- rear loading capability with clam shell doors and one level floor
- hybrid airframe structure (composite, sheet-metal)
- aluminium alloy MGB with long dry run capability
- passive vibration isolation system [1]
- automatically controlled variable rotor speed [2]
- twin engine configuration with a digital electronic engine control (FADEC) [3]
- choice between Turbomeca Arrius 2B(1) and Pratt & Whitney PW 206 B engines
- yaw SAS (simplex) for VFR operation, dual/single pilot IFR certification planned [4]
- cockpit layout with high visibility
- modern MMI technologies (Avionique Nouvelle)
- the bearingless main rotor system
- composite blades with parabolic blade tip and advanced DM-H3/H4 airfoils
- fan-in-fin tail rotor (Fenestron) with unequally spaced blades [5]

In combination of all these listed technology features the EC135 promises to be one of the most modern light twin engine helicopter on the present and future market.

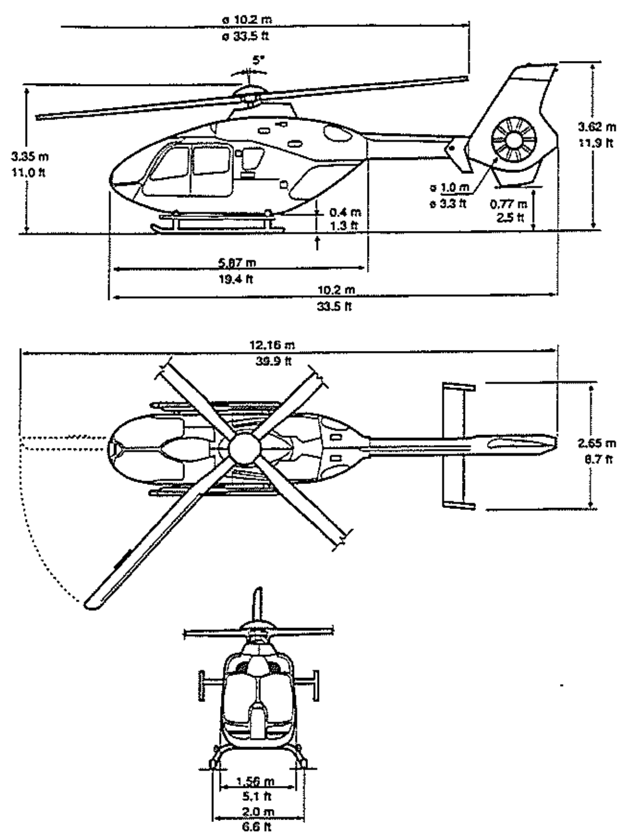

Fig. 2 General dimensions of EC135

The actual configuration of the EC135 is shown in Fig. 2 and key parameters are collected in Table 1.

General		Main Rotor	
MTOW	2630 kg	Type	BMR
MTOW (sling load)	2900 kg	Radius	5.1 m
Empty weight	1420 kg	No. of Blades	4
MCP	2x283 kW	Tip Speed	211 m/s
TOP	2x308 kW	Equiv. Chord	0.288 m
2,5 min OEI	410 kw		
Vcruise	141 kts	Fenestron	
Vne	155 kts	Diameter	1.0 m
Seat capacity	1+6	No. of Blades	10
Max HIGE/HOGE	4300m/3700m	chord	0.05 m
Max ceiling	6000 m	Tip Speed	188 m/s

Table 1 Main data (mostly SL std)

The EC135 is a multi-role helicopter designed for missions like EMS, police/paramilitary, external loads, off-shore and executive transport.

Short development schedule

At the end of the eighties it was planned to develop a new light twin helicopter, initially called BO108 [6], [7]. But the Commercial Helicopter Advisory Team (CHAT), in which major customers and operators were involved, worked out recommendations, leading to an extensive redefinition of the helicopter. Finally, the improved design resulted in the EC135. Although the design of the EC135 has changed in many aspects, the BO108 has served as a technology demonstrator in a decisive and beneficial way.

In addition, the merge of former Aerospatiale and MBB helicopter groups has made available the full range of technology and experience from both companies for the EC135.

Fig. 3 shows the time schedule for the definition, development and certification phases of the EC135. Until the end of 1997 the certification for IFR in combination with an increased MTOW will be completed.

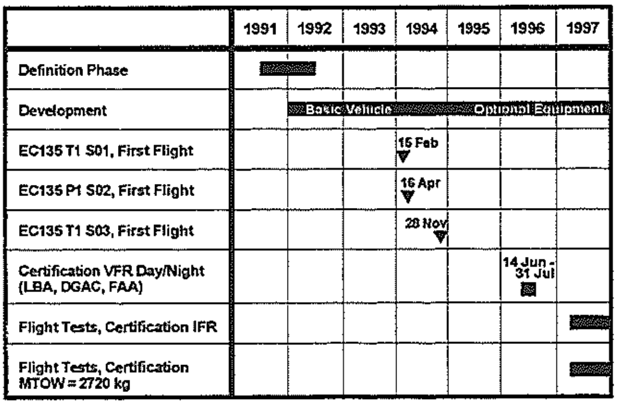

Fig. 3 Time schedule for development and certification

Dynamics

Basic dynamic layout

The hub design of the main rotor influences the aeromechanic and aeroelastic characteristics of the helicopter basically. In the case of a bearingless system the stiffness distribution at the most inboard beam sections determines the ability of the rotor to carry moments to the hub.

Fig. 4 shows the flap bending stiffness distribution of the flexbeam. The double bolted blade attachment is followed by a flat structure, which represents the „flapping hinge" (for illustration see Fig. 5), [8].

The moment capacity of the rotor amounts approximately 2000 Nm per degree of cyclic flapping. This corresponds to an equivalent hinge offset of 8.7% rotor radius.

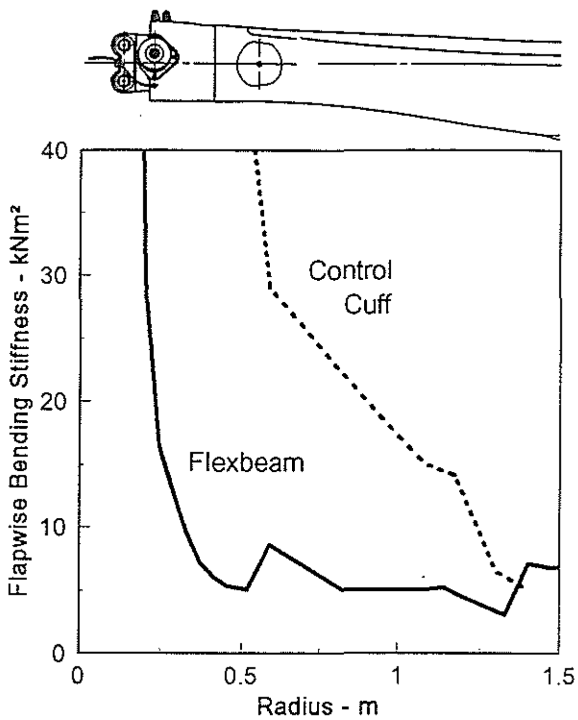

Fig. 4 Flap bending distribution of the flexbeam

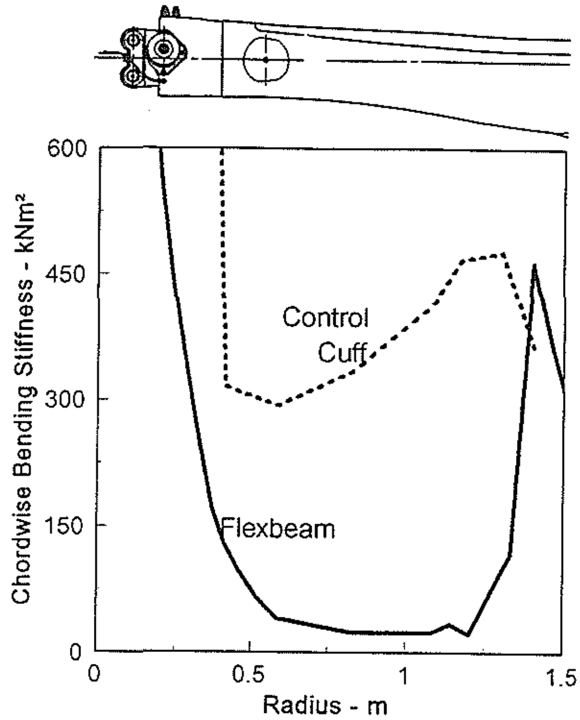

Fig. 6 Chordwise bending distribution of the Flexbeam and the control cuff

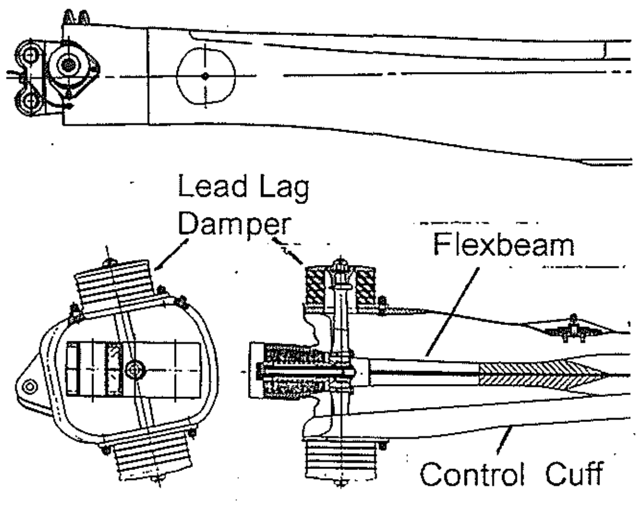

Fig. 5 Design of flexbeam and control cuff

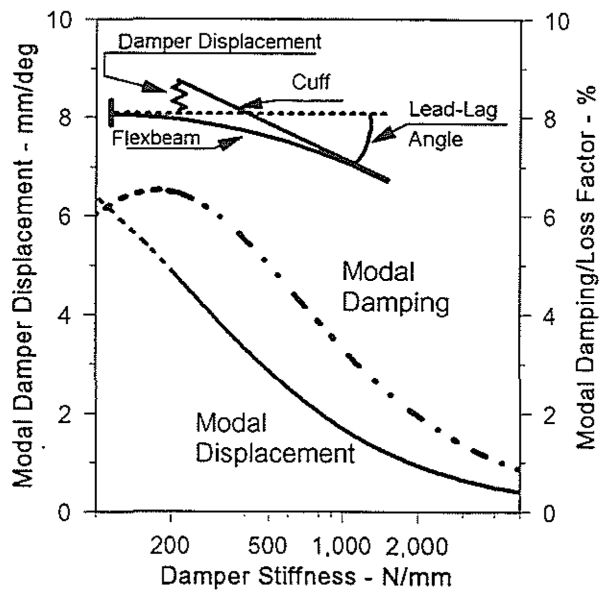

Fig. 7 Chordwise kinematics determines displacement and damping of the damper

A thorough tailoring of the chordwise stiffness distribution (see Fig. 6) is mandatory for a proper placement of the fundamental inplane frequency as well as for the lead lag kinematics which are driving the lead lag damper. Both are decisive for stability and load aspects.

Fig. 7 shows the displacement between cuff and flexbeam at the location of the damper due to inplane bending as well as the available lead lag damping. Both strongly depend on the damper shear stiffness. The inplane damping has been optimised step by step during the development process of the BMR, always keeping in mind life time requirements. Besides material and geometrical properties, the shear stiffness depends on environmental conditions and axial loads as well as on the displacement amplitude [9].

Therefore, the inplane frequency of the blade also becomes a function of the lead-lag amplitude. The calculated fundamental frequency and the damping provided by the damper is shown in Fig. 8.

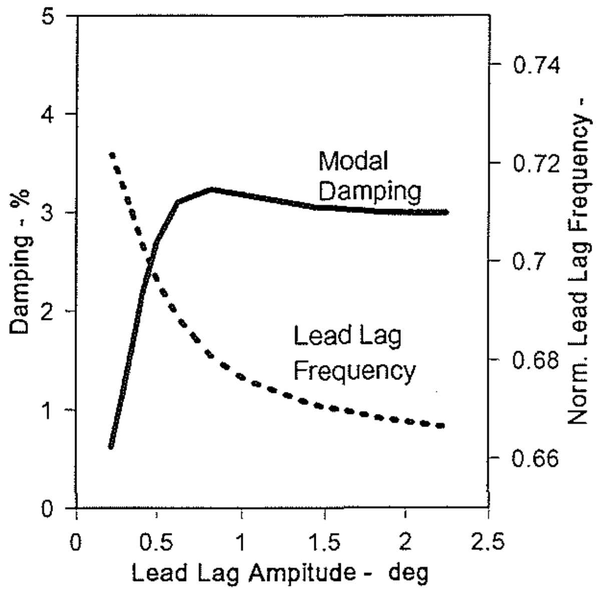

Fig. 8 Modal damping and lead lag frequency versus lead lag amplitude

Due to kinematic effects between the lead-lag motion of the cuff and the pitch control, a pitch lag coupling occurs (Fig. 9). It is stabilising when the coupling parameter is negative and depends mainly on the control angle and on the modal displacement. That kinematic coupling is superposed by an elastic pitch lag coupling caused by an elastic torsion due to bending moments which in principle is well known from hingeless rotors [10]. In general a stabilising coupling is ensured during all operation conditions of the rotor.

A coning angle of 2.5 deg is incorporated in the hub design to reduce the static flapwise bending loads in the flexbeam. A chordwise unloading is reached by an offset of the blade attachment of 20 mm. The geometric arrangement of the control rod and the control shear restraint leads to a positive flap/pitch coupling of approximately 7.5 deg.

The structural tuning of the higher blade bending modes determines the capability of the rotor to carry vibratory moments and shear forces to the hub. Fig. 10 shows the resonance diagram based on a

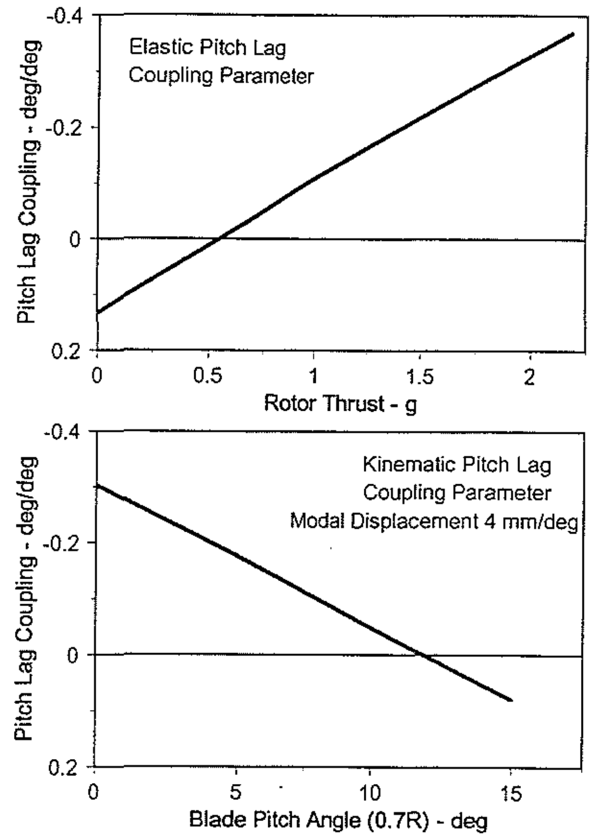

Fig. 9 Pitch lag coupling

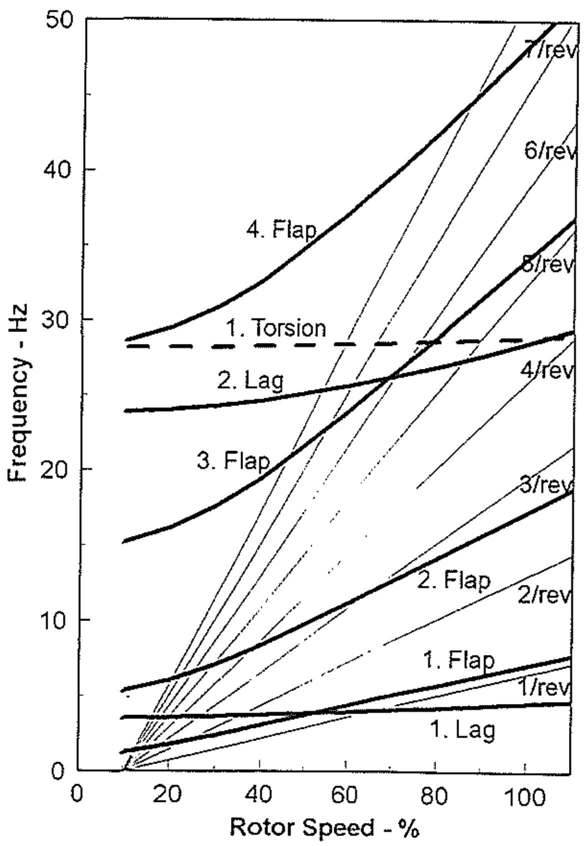

Fig. 10 Tuning of the higher blade modes

uncoupled calculation. The separation of the eigenfrequencies from the higher harmonic excitation frequencies at inflight operation rotor speeds is performed by a thorough mass and stiffness tuning of the blade.

Aeromechanic stability

The rotor is designed to ensure the aeromechanic stability of the EC135 in the entire operation envelope without any further provisions. With skids

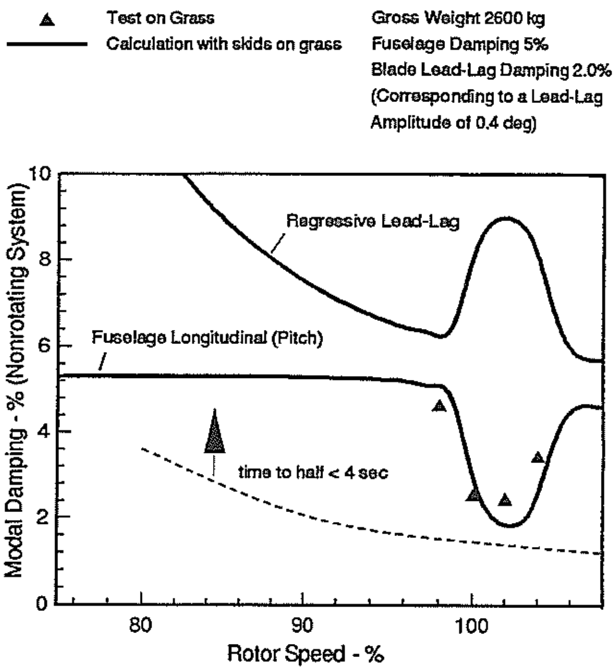

Fig. 11 Ground resonance stability

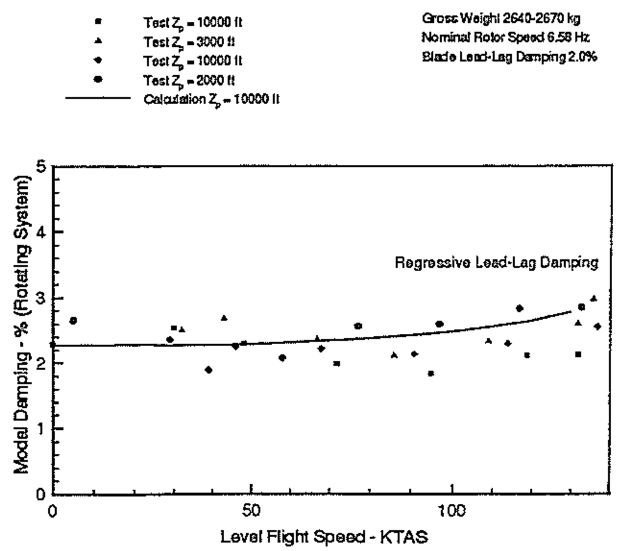

Fig. 12 Air resonance stability

on a soft surface the resonance condition exists slightly above nominal rotor speed. As is shown in Fig. 11 calculations and system tests demonstrate stability with an adequate margin at small lead-lag amplitudes of approximately 0.4 deg. Even under the most unfavourable conditions (e.g. failure of a damper) the stability is guaranteed due to the nonlinear damping characteristics of the elastomeric dampers (see Fig. 8).

Fig. 12 shows the modal damping in level flight. The damping ratio was determined from decaying lead lag oscillations after cyclic whirl excitation. It amounts to approximately 2.5% in the rotating frame and matches the calculation well. Further tests were performed in autorotation with different rotor speeds, in the torque range, and during g-turns.

Vibrations

To keep uncomfortable vibrations away from the cabin, a passive isolation system between gear box and the airframe is installed in the vertical direction. In conjunction with a lateral underfloor absorber in the cockpit, the cabin floor vibrations remain below 0.1g at 4/rev during steady flight conditions. Fig. 13 gives an impression of the vibration level.

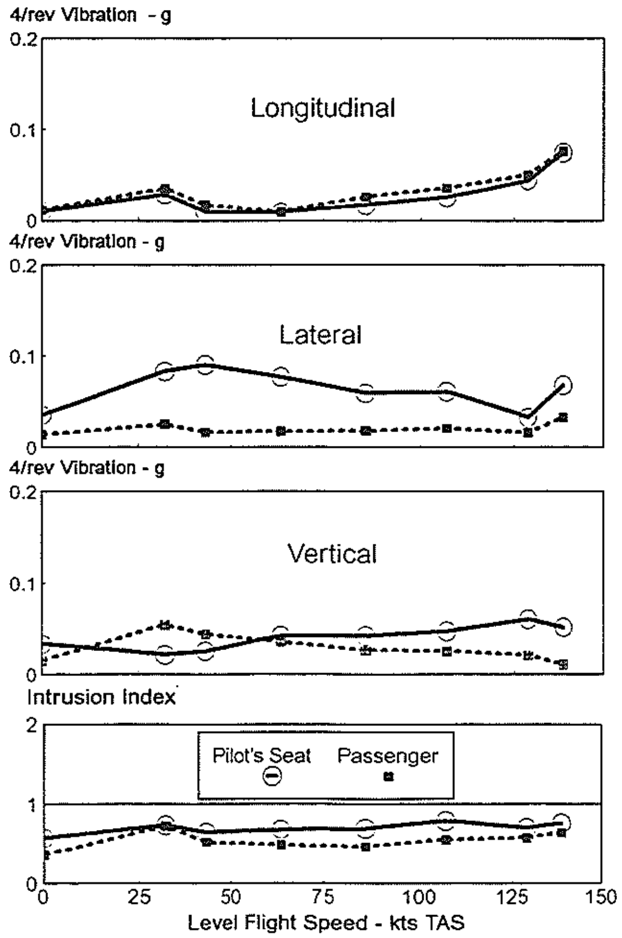

Fig. 13 Cabin vibrations during level flight

The Intrusion Index is a criteria which describes the ride quality taking into account human factors in dependence of frequency and direction. It should stay below 1 in steady flight conditions.

Aerodynamics

Rotor aerodynamics

The BO108 prototype helicopter as EC135 predecessor was equipped with main rotor blades similar to the advantageous one of the helicopters BO105 CBS-5 or BO105 LS A3 Superlifter.
This improved rotor blade was fitted with a trapezoidal blade tip beginning at 80% radius and a chord reduction towards 2/3 of the inner blade chord at the tip (Fig. 14)

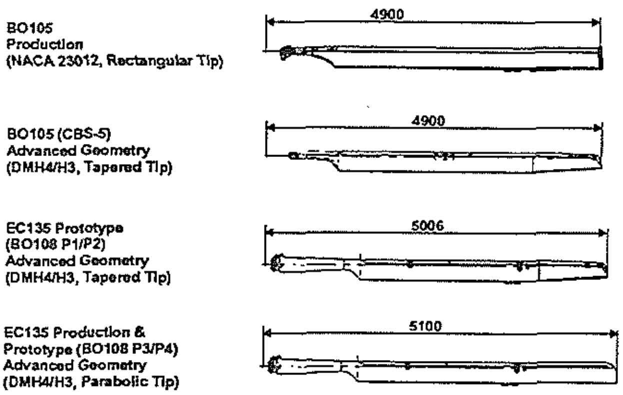

Fig. 14 Advanced blade planforms developed for BO105 CBS-5 and EC135

Specifically developed airfoils DM-H4Tb (12% thickness) and DM-H3Tb (9% thickness) [11] were used for the inner blade part and for the tip. With this layout, the rotor had an impressive hover and low speed performance [12].
During the development of the BO108 and with the change over to the EC135 the TOW was increased step by step, demanding for additional blade area.

This area had to be added to the tip region because of its high efficiency in blade thrust. Thus the trapezoidal planform was changed to a rectangular one with a parabolic leading edge sweep back at the outer blade tip. In addition, the region covered by the 12% thick inner airfoil was extended from 80% up to the 88% radius, whereas the region of the thinner tip airfoil was increased from 98.5% to 94% radius (Fig. 15) The modifications resulted in a small loss of hover performance, but a great advantage at higher flight speeds and in high-g manoeuvres.

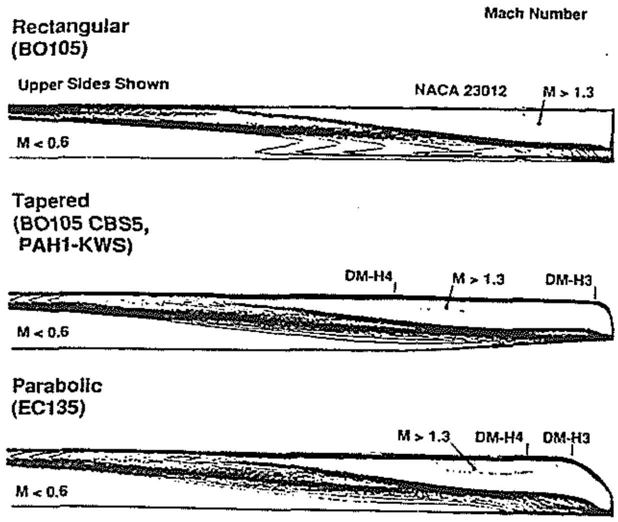

Fig. 15. Reduction of transonic effects with advanced blade shape and airfoils

Theoretical studies have been performed with a CFD method based on 3D Euler equations [13] to estimate the local Mach number distributions over the upper blade surface.
Fig. 15 shows the improvement of unfavourable transonic effects compared to the rectangular blade, achieved by the sweep back of the leading edge and the reduced airfoil thickness at the blade tip.

The blade twist is generally a compromise between the requirements of hover (high twist angle) and forward flight (lower twist angle). At the latter condition, the optimum twist increases with rotor disk inclination, i.e. with the aerodynamic drag of the aircraft.

Due to the low aerodynamic drag of the EC135, a blade twist of 10 deg was chosen, measured from rotor centre to the blade tip. To avoid a too negative angle-of-attack for the thin tip airfoil in high speed

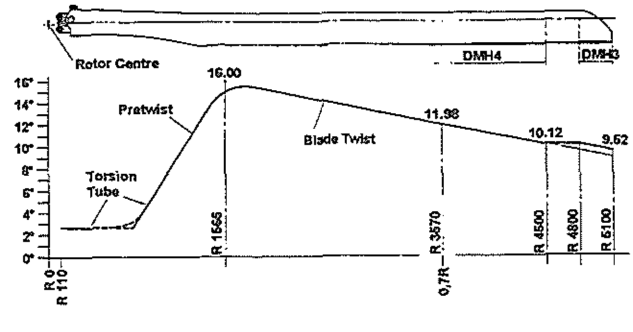

Fig. 16 Twist distribution along blade span

flight on the advancing blade, the aerodynamic twist at the blade tip was slightly reduced (Fig. 16).

Airframe aerodynamics

The aerodynamics of the fuselage are affected by a number of contradicting requirements, such as visibility, accessibility of cabin and cargo door etc.. Also the arrangement of the engines with their inlet and exhaust openings influences the aerodynamic layout and behaviour of the fuselage. For the EC135, a high position of the fuselage nose gives a low negative angle-of-attack and, therefore, a low fuselage drag in cruise flight.

The slenderness of the afterbody was limited by the requirement of a rear cargo door, but it was possible to maintain a completely unseparated flow on the afterbody over a large range of flight conditions.

Tail shake

During the first flights with EC135 a pronounced tail shake was reported by the pilots [14], [11]. Based on experiences with the BK117 it was assumed that this flow-induced lateral oscillation of the tailboom was caused to a large amount by the wake of the hub, pylon and engine cowling.
In order to find a quick and low cost solution measurements were performed with several hub caps and pylons on a 1:7.126 scale model of the EC135 in the wind tunnel of Eurocopter France. The wake of hub pylon cowling and fuselage was identified by a grid of pitot tubes and microphones in a lateral plane near the Fenestron/fin compartment.

In the two upper plots in Fig. 17, areas with constant dynamic pressure are indicated. The shaded area show regions where the dynamic pressure is reduced to 60% due to wake effects.

Based on these results, the EC135 was fitted with an optimised hub cap and a mast fairing/pylon having a specifically shaped "surfboard". Due to these devices, the tail shake, which was discovered during the first test flights, could be almost completely eliminated (Fig. 17).

Dynamic Stability of the Helicopter

For the design of good flying qualities it is necessary to achieve adequate dynamic stability of the basic helicopter. The most important eigenmodes of the helicopter, dutch roll and phugoid, will be discussed in the chapters below, skipping e. g. spiral mode, short period and roll/flap mode.

Dutch roll

This typical mode for fixed wing and also for all types of helicopters in forward flight occurs mainly in the yaw and roll axis. Superimposed to this typical motion is a small pitch reaction.

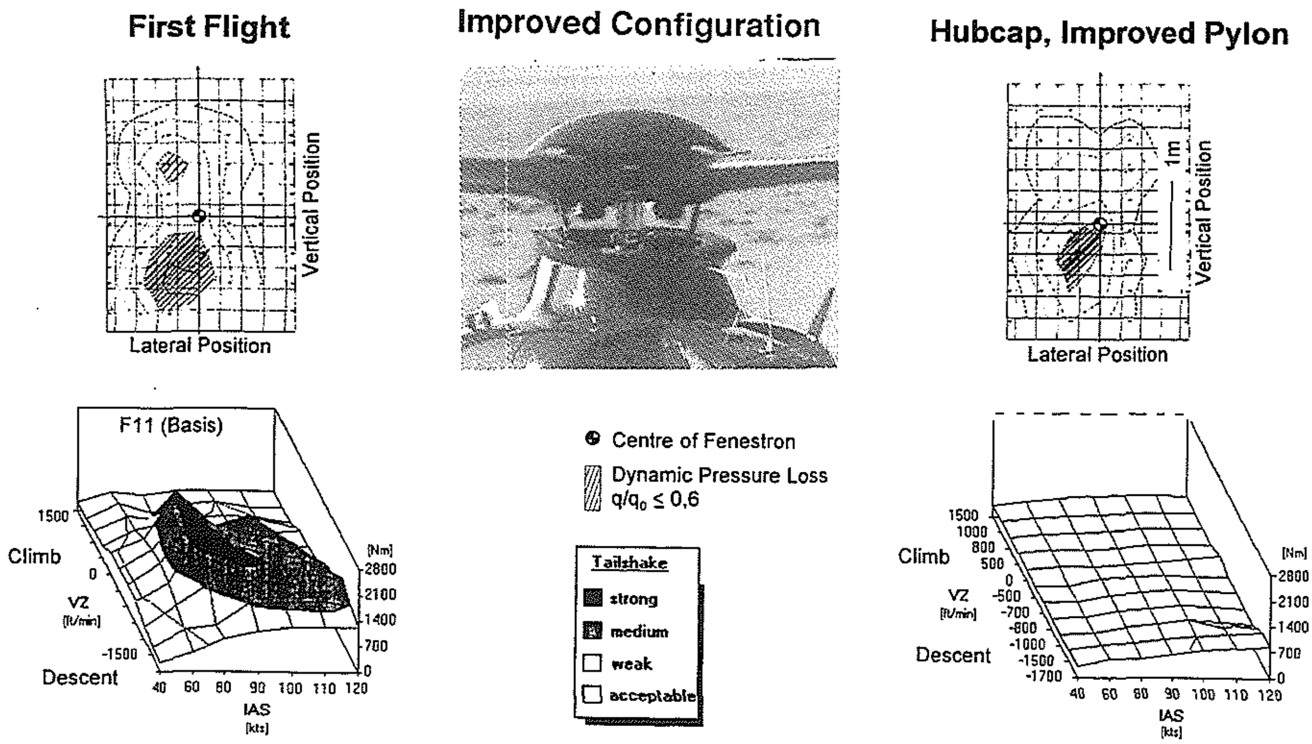

Fig. 17 Reduction of tail shake with hub cap and pylon

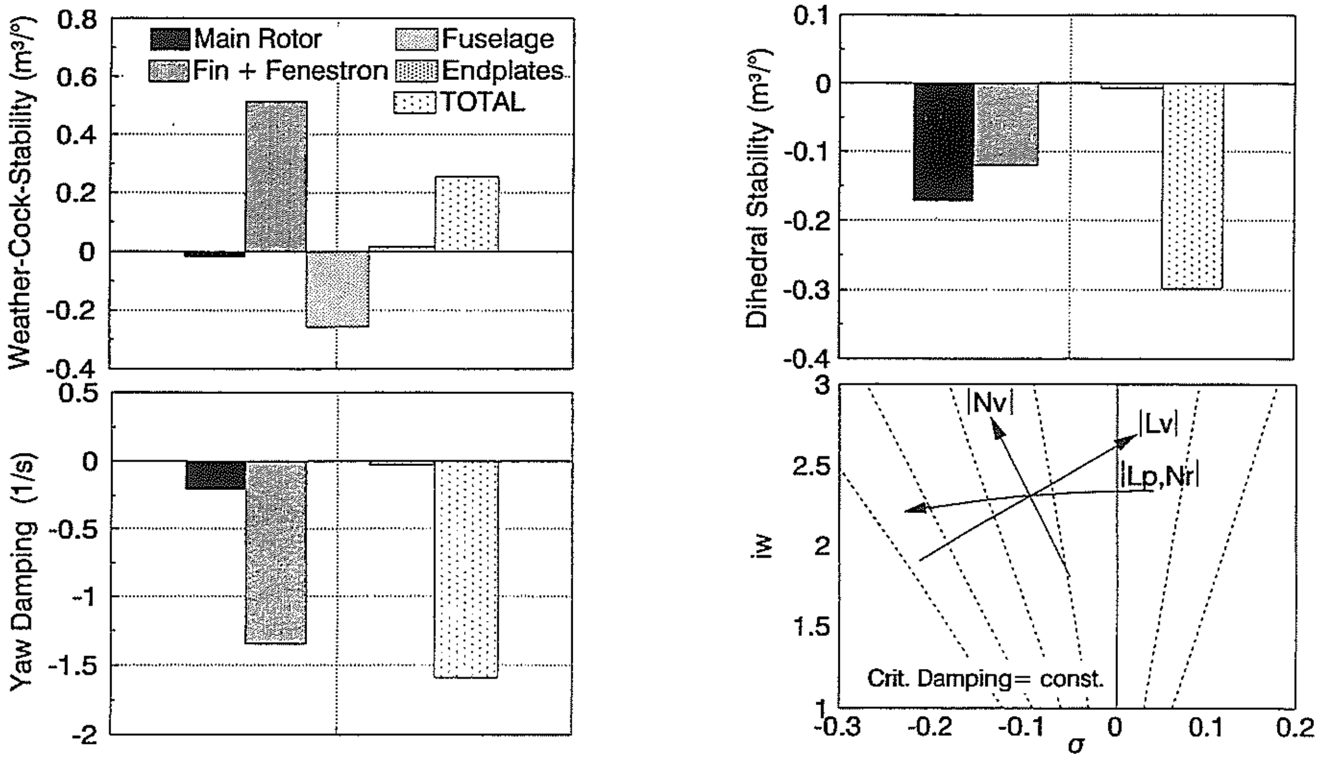

Fig. 18 Significant derivatives for dutch roll and their influence on critical dutch roll damping

The pilot and passenger noticed a low dutch roll damping by increased work load and unpleasant ride qualities. This feeling will be directly intensified by occurrence of lateral gusts.

Though complex linear and non-linear flight mechanic models are available, it is still challenging to design good dutch roll characteristics under the constraint of minimal helicopter weight and costs.
The demanding modelling task arise from many important physical effects like

- aerodynamic configuration of fuselage and stabilising areas,
- impingement of tail areas and the anti-torque device in the wake of the fuselage and rotor,
- influence of sideslip,
- rotor dynamics (flap, blade/control torsion) and coupled body/rotor modes.

Based on the experience with the helicopters BO105, BK117 and also the development platform BO108, a linear and non-linear aeromechanic modelisation was carried through, using approved Eurocopter codes (STAN/BWVL, HOST).

For explanation the results of the linearized model investigation are discussed. All the derivatives mentioned below are theoretically derived from a validated model, based on flight test results and partly by low order system identification.

Fig. 18 shows a breakdown of derivatives influencing mainly the damping of the dutch roll mode.
The directional stability Nv is influenced basically by the fin, Fenestron, end plates or fuselage, and not by the rotor system. The fuselage has typically the large destabilising part which must be counteracted. The aerodynamic optimisation in the design of the fuselage contour is strongly influenced by operational requirements like pilot's view, seat capacity, or rear load capability. Thus the aerodynamicist is forced to compromise.

Below the picture for the directional stability, the derivative yaw damping Nr is shown in Fig. 18. It does not suffer under the deteriorating influence of the fuselage, because no significant moment is created due to yaw rate. The Fenestron/fin component contributes mostly to yaw damping.

An interesting contribution to dutch roll is given by the dihedral stability Lv. Both, the main rotor and the fin/Fenestron compartment have a strong input on this derivative. It can be changed by a vertical shift of fin/endplate areas and the anti torque device with respect to the helicopter CG, or the moment capacity of the main rotor.

The fourth important derivative for dutch roll is the roll damping Lp (see Fig 23). It is only dependent on the highly damped bearingless main rotor system and, therefore, no break down of derivatives is given.

With these four key derivatives the direct influence on damping and the eigenvalue of the dutch roll mode can be optimised, as shown in Fig 18 bottom right.
The figure visualises clearly the strong influence of the dihedral effect Lv on dutch roll damping. It is of advantage, that this derivative can be optimised without additional areas, what was aspired for the configuration of the EC135. Following this evaluations the design for small Lv is expressed by the low attached end plates, the tail bumper and of course by the fan-in-fin design of the anti torque device, which can be attached lower than a conventional tail rotor without compromising safety.

It should be mentioned that a reduction of Lv in order to improve dutch roll is limited, because of its influence on lateral static stability and spiral mode stability.

The attempt to reach specified dutch roll characteristics purely by means of additional areas for fin or endplates may have a contradictory effect on the derivatives directional stability Nv, dihedral stability Lv and yaw damping Nr. This can be derived from Fig. 18. I. e. larger vertical tail areas increase directly Nv, meaning increased frequency, but improve only marginal the critical damping. Of course Nr is improved, what is a benefit for dutch roll damping. However, if this additional area is placed high with respect to the helicopter centre of gravity, than the dihedral effect Lv will contribute negatively to dutch roll damping.

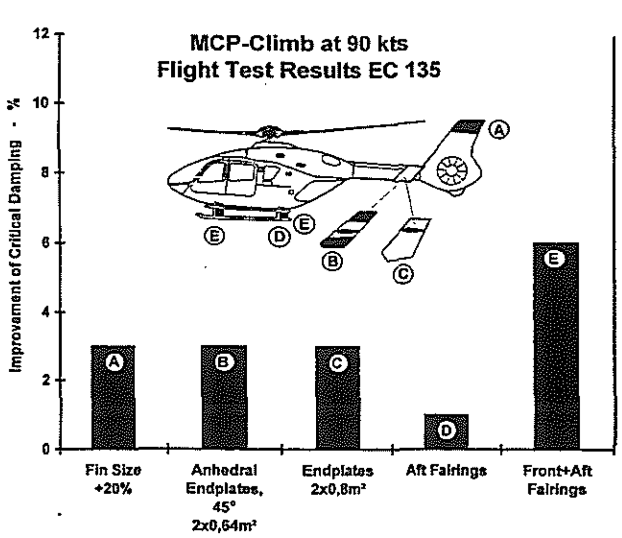

Fig. 19 Aerodynamic measures to improve critical dutch roll damping

During the development phase of EC135, several configurations have been tested to check the influences on dutch roll stability. These configurations and their influences on stability parameters and critical damping are shown in Fig. 19 for the most adverse flight condition climb at 90 kts with MCP.
From the flight test, two results can be derived: firstly, looking to the improvement due to landing gear fairings, it exhibits the beneficial effect of optimised Lv, secondly, it shows the possible margin of damping improvement by passive measures, lying in the order of about 10% of critical damping.

For the VFR certification without yaw SAS it was not necessary to use the possible potential of improvements shown in Fig. 19 . The basic EC135 has no fairings at all, a small fin (0.9 m²) without 20 % increase as indicated in the figure and small endplates (0.36 m²). Further discussion for this decision is given in the chapter for gust response.

<u>Dynamic stability and control response for the longitudinal axis</u>

For some portions of the flight envelope any helicopter has an unstable phugoid mode. Hingeless rotor systems and also bearingless rotor systems contribute to this system characteristics more than articulated rotors. On the other side, helicopters with hingeless and bearingless rotors have advantages in agility, controllability, small and moderate amplitude requirements, as stressed in the military requirement ADS33. The development of the BMR for the EC135 is an attempt to find a good compromise between both characteristics.

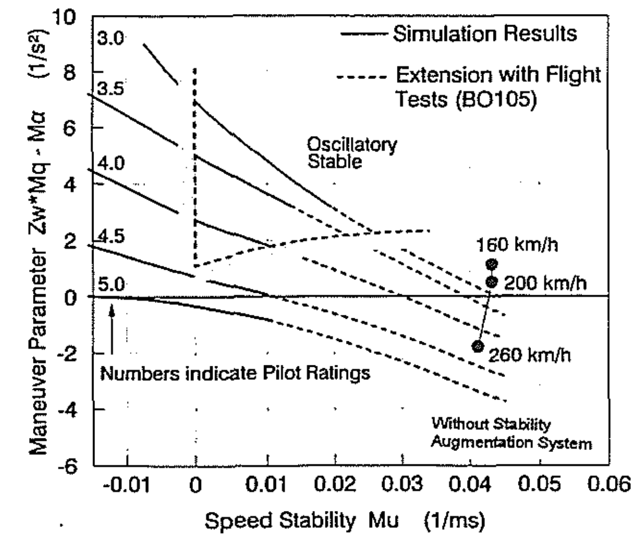

Fig. 20 Relationship between longitudinal derivatives and pilot ratings

Fig. 20 correlates the stability parameters of the longitudinal axis as speed stability Mu and manoeuvre parameter ZwMq-Mα with handling qualities ratings. The speed stability plotted on the horizontal-axis represents the control response behaviour and is also of importance for the stick position stability.
The manoeuvre parameter on the vertical axis can be interpreted as a measure for the dynamic longitudinal stability.
With respect to these parameters and derivatives which are theoretically evaluated, handling qualities pilot ratings (CHR) have been obtained through flight tests and also simulator trials for the selected flight conditions [15]. This figure substantiates for the EC135 in forward flight level 1 to level 2 pilot ratings without augmentation.

The speed stability Mu is positively influenced by the BMR design with its optimised flapping stiffness, the pitching moment distribution c_m of the profiles chosen along blade span and the design of the horizontal stabiliser.

Design Improvement	Favourable Influence on Derivative
optimised flapping stiffness aβ≅8.7% (w/o spring)	Mq, Mu, Mα.
c_m of blade airfoils DM-H3/H4 less negative	Mu
flap-torsion coupling δ3=+7.5 deg	Mα
increased horizontal stabiliser area (2.6m span, 0.52m chord, inverted NASA GAW(1) airfoil)	Mα, Mq
Gurney flaps (5% stabiliser chord)	Mα
limited blade loading in cruise (see Fig 22)	Zw

Table 2 Design improvements and influence on characteristic derivatives

Table 2 summarises the measures of design improvements realised on the BMR and horizontal stabiliser and denotes the favourably influenced longitudinal derivatives.

Concerning the manoeuvre parameter Z_w*M_q-M_α the fuselage, the horizontal stabiliser and the BMR were optimised to reach the good to acceptable stability characteristics.

E. g. to minimise the necessary horizontal stabiliser area, it is fitted with the inverted NASA GA(W)-1 airfoil and additional Gurney flaps (Fig. 21) to achieve a high lift curve slope. In addition, the effective aspect ratio of the stabiliser is increased by endplates and further improves the efficiency.

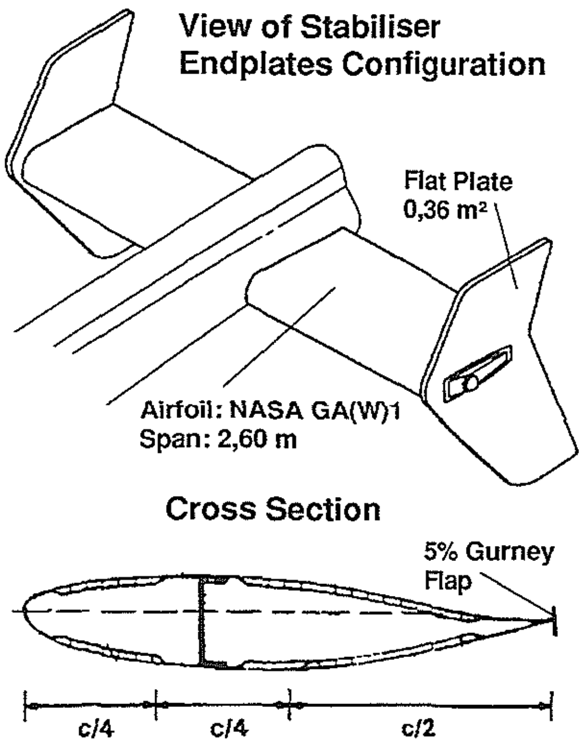

Fig. 21 Configuration of horizontal stabiliser with Gurney flaps

Handling Qualities

Layout boundaries in the blade loading diagram

A general objective for the design of the EC135 was to enlarge the operational flight envelope [2]. An important limitation of manoeuvrability is given by the load factor capability depending on the speed. In Fig. 22 the operational improvements and design guidelines for the EC135 are visualised in the blade loading diagram.

On the vertical axis, the maximum thrust is plotted in a normalised way as blade loading coefficient, and the horizontal axis shows the speed of the helicopter normalised by the blade tip speed.
A remarkable increase of main rotor thrust can be seen by comparing the stall limit curves of the EC135 and the BK117.

This improvement is achieved by the BMR concept and the advanced aerodynamic blade design with respect to blade plan form, twist and use of improved profiles, as discussed above.
Additionally, the design guideline for HQ used for the EC135 is given in Fig. 22, addressed as 'handling qualities limit for cruise flight'. The boundary was

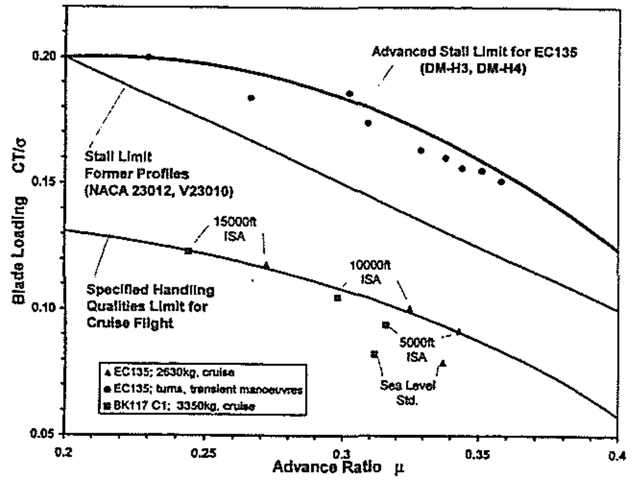

Fig. 22 Operational limits in the blade loading diagram

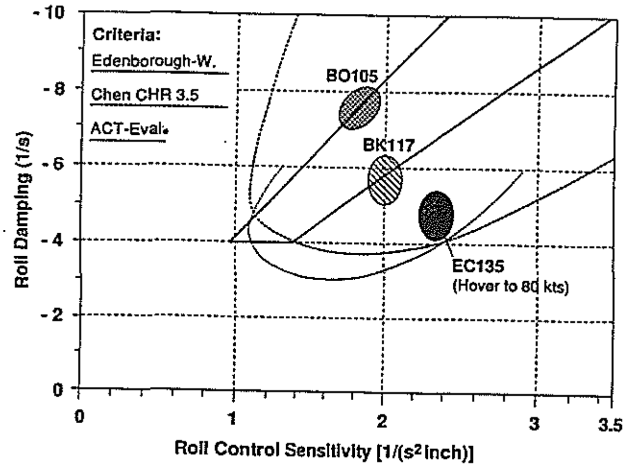

Fig. 23 Controllability chart for the roll axis

defined with help of BO108 flight tests in a way to guarantee at least acceptable pilot ratings.
The HQ boundary curve is typically reached during high speed cruise flight in high altitudes. Due to extreme high available power of the installed engines, an override collective stop was implemented to stay on or below the recommended blade loading [2]. As a positive side effect, also dynamic loads of the rotor and control system are reduced, increasing the life time of parts. The BK117 and BO105 LS already use this mechanism of collective stop with success.

Controllability for the roll axis

Good handling qualities ratings depend strongly on the control response characteristics. Helicopters with hingeless rotor systems and with BMR as the EC135 have well-known advantages concerning control power and controllability.
Many investigations have been performed in the past on simulators and also in flight test, to identify the optimum relationship between control sensitivity and damping for the pitch and roll axis (see [15], [16]). In Fig. 23 the values of the EC135 are plotted together with those of the BO105 and BK117.

Due to the lower flapping stiffness and the increased lateral cyclic control range, the EC135 lies below the BK117 within the recommended area. This design for the EC135 control response behaviour is the result of an optimisation process.
It was on one side the goal to reduce the control power of the BMR to a still excellent level, searching for a favourable compromise between control response and (longitudinal) dynamic stability. On the other side, the demanding requirements for manoeuvrability, e.g. hover in wind or quartering flights, lead to increased lateral cyclic control range overlaid by the pilot's wish for small control stick travel.

	Lateral Cyclic		Longitudinal Cyclic	
	Angle	Travel	Angle	Travel
EC135	15 deg	160 mm	21.8 deg	215 mm
BK117	11 deg	160 mm	18.3 deg	265 mm

Table 3 Cyclic control ranges and stick travels for EC135 and BK117

Theoretical studies and flight tests resulted in a definition of blade control angles and cockpit stick travels for the lateral and also for the longitudinal cyclic controls, summarised in Table 3 for the BK117 C1 and EC135.

Bandwidth and phase delay criteria for the roll axis

Connected to the above discussed controllability parameters is the small amplitude criteria for attitude changes, proposed by the military requirement ADS-33D.
Fig. 24 reflects the proposed parameters bandwidth and phase delay for the roll axis in forward flight. The EC135 fulfils all addressed civil and military recommendations for level 1 handling qualities [18].
If the transfer functions for pitch and roll motion are simplified to a first order equation with time delay

$$\frac{\text{Rate}}{\text{Input}} = \frac{K}{T_1 * s + 1} e^{-\tau * s},$$

then the parameters of Table 4 characterise the small amplitude requirement of ADS33D for cruise with 75 kts.

	Time Delay	Phase Delay	Bandwidth
Roll Axis	80 ms	55 ms	3.7 1/s
Pitch Axis	125 ms	92 ms	1.84 1/s

Table 4 Parameters for small amplitude attitudes changes of the EC135 (75 kts)

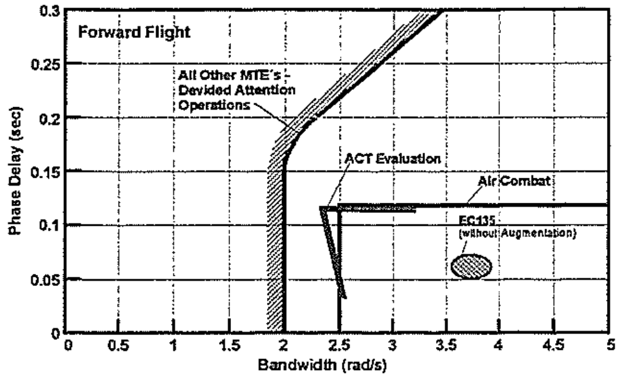

Fig. 24 Phase delay vs. bandwidth for the roll axis (small amplitude criteria of ADS-33D)

For the pitch axis, the EC135 shows level 1 handling qualities according to the requirement for fully attended operation and level 2 to 1 for air combat and divided operation. This excellent result is realised by the design of BMR with its high control power and a control system with high cuttoff frequency.

<u>Gust sensitivity for yaw and roll axis</u>

Of importance for high ride comfort of passengers and low pilot workload during precision manoeuvres is the sensitivity of an helicopter to spatial gusts.
Gust perturbations are typically felt in vertical axis but occur also in yaw, pitch and roll axes.
Difficulties in the design optimisation process arise, as other design goals like controllability, agility, static and dynamic stability lead often to contradictory consequences.

This can be detected for the yaw and roll axis from Fig. 25 and 26, which have been created through linear simulation.

The used linear model describes the rigid body motion

$$\dot{x} = \begin{bmatrix} \text{System} \\ \\ \text{Matrix} \end{bmatrix} * x + \begin{bmatrix} \text{Control} \\ \\ \text{Matrix} \end{bmatrix} * u_c$$

$$\dot{x} = \left[\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}, , \dot{\theta}, \dot{\Phi}\right]^T,$$

$$u_c = \left[D_{col}, D_{\alpha}, D_{\beta}, D_{ped}\right]^T$$

and was derived by perturbation analysis from a non-linear simulation model with the basic modes of four blade degrees of freedom (flap, lead lag, 2 torsional DOF).

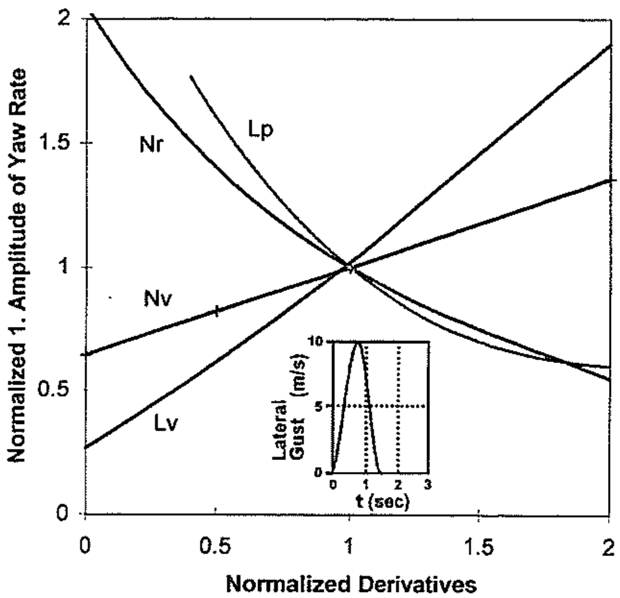

Fig. 25 Influence of characteristic derivatives on gust response for yaw axis (90 kts MCP)

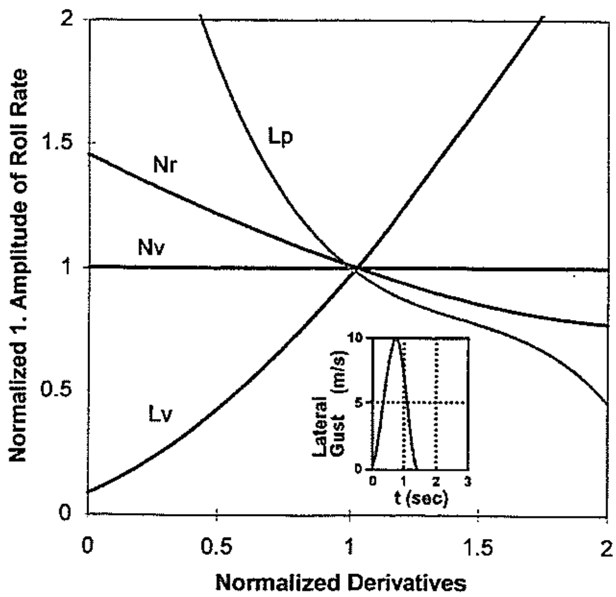

Fig. 26 Influence of characteristic derivatives on gust response for roll axis (90 kts MCP)

After a sin²-gust with an amplitude of 10 m/s, as indicated in the figure, the initial amplitudes of yaw rate and roll rate have been analysed and plotted versus normalised characteristic derivatives. Climb with 90 kts at MCP was taken as demanding flight condition, similar to the above discussed dutch roll evaluation.
Both figures show an improvement of gust induced yaw and roll motion with increasing yaw damping Nr, decreasing dihedral stability Lv and also decreasing or constant directional stability Nv, what are opposing tendencies, if the yaw damping would be improved by a larger fin area. In this case the directional stability Nv would have a worse net influence. The influence of the dihedral effect Lv is ambivalent being not only dependent on the size, but also on the vertical position of the area.

The roll damping (Fig. 23) should be high to achieve low gust sensitivity in yaw and roll and is only dependent on the rotor design. The BMR with adequate flapping stiffness and Lock number is favourable in this respect.

Based on these theoretical investigations and later verification through flight test, the EC135 has been configured with a tail bumper and endplates. Similar as for the dutch roll investigation, not all evaluated favourable measures have been realised in the EC135's final configuration.

For example, a clear potential for an improvement of dutch roll stability as well as for gust sensitivity concerning the roll and yaw axis exists through fairings on the landing gear, if implemented without deterioration of directional stability, and also with enlarged bumpers and increased low situated endplates.

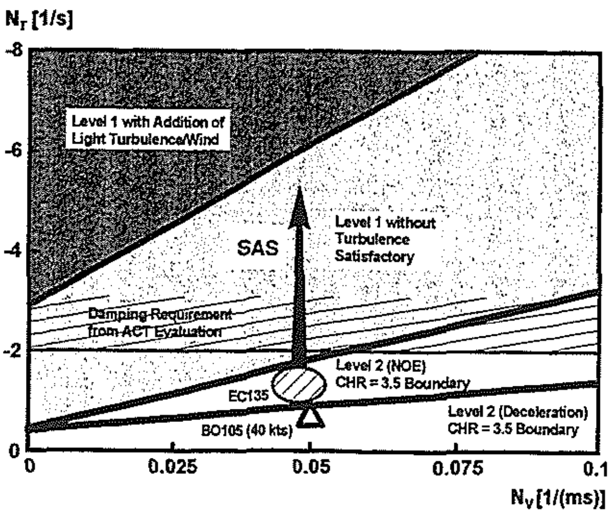

Fig. 27 Yaw damping requirements in gusty flight conditions (from [19])

The reason why these possible configurational improvements were not implemented on the basic EC135 is explained with help of Fig. 27.
It shows a correlation of handling qualities level to the derivatives yaw damping Nr and directional stability Nv if turbulence occurs.

In Fig. 27 the recommendations of [19] for NOE tasks and NOE deceleration tasks have been combined. Two important messages valid for all helicopters result from this figure and were also experienced in EC135 flight tests:

- the helicopter, stabilised with passive means, can hardly reach handling qualities level 1 even in calm atmospheric conditions,
- under light turbulence level 1 handling qualities are only to reach with a very high value of yaw damping, which is not attainable by stabilising areas.

Because of that, the decision was made to equip the basic sales version of the EC135 with a yaw SAS. Consequently the unaugmented EC135 was designed with as much as possible reduced vertical stabilising areas, still guaranteeing acceptable handling qualities and enabling the VFR certification. This design offers advantages also with respect to loads and has favourable impacts on the interrelated topics weight, lifetime and maintenance.
As the basic certification was performed without augmentation, a failure of the yaw SAS will not enforce flight envelope restrictions, an important fact for the customer.

Summary

A wide range of dynamic, aerodynamic and flight mechanic subjects have been addressed in this paper which have been relevant for the design of the EC135. It was tried to present not only the result, but also to explain the method and guiding thoughts during the development process.

Following topics should be highlighted in a retrospect:

- The dynamic layout of the BMR was discussed in terms of stiffness tailoring, blade damper optimisation, pitch-lag and pitch-flap coupling.
- A margin for ground and air resonance stability was demonstrated.
- The cabin vibrations were reflected on recommended comfort limits.
- The design of dynamic stability in combination with the on-axis control response behaviour was evaluated relating on the longitudinal stability derivatives, which are fundamental in the development process.

- Concerning the dutch roll stability, the theoretical background and interesting flight test results have been discussed.
- The dutch roll stability together with gust sensitivity was optimised leading to a configuration with a minimised size of fin/endplates and a yaw augmentation system.
- The operational envelope was enlarged (cruise speed, load factor flight) due to the aerodynamic optimisation of the blade planform, the twist and use of improved blade airfoils.

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