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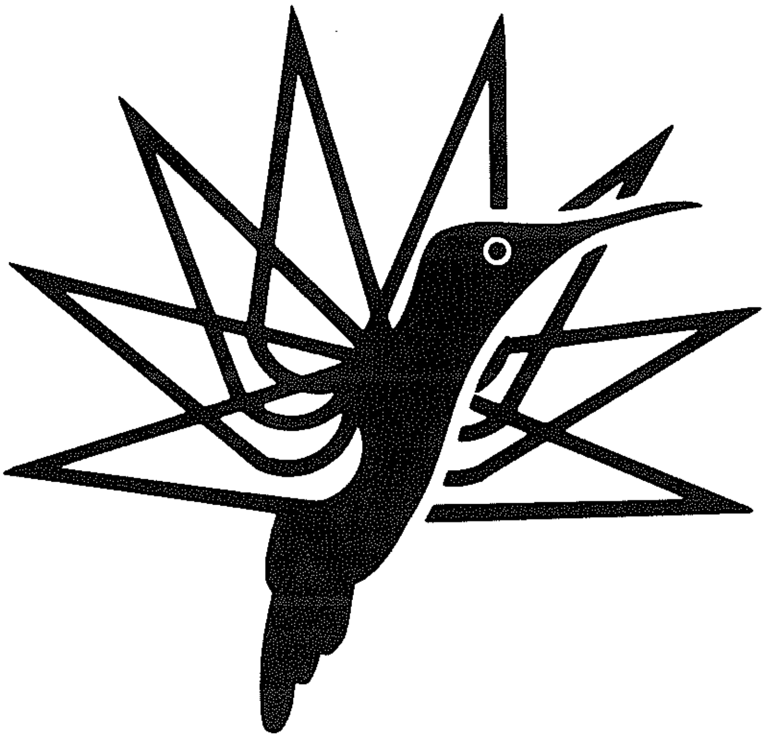

BK 117 FOR DUAL PILOT IFR OPERATION

BY

A. FAULKNER AND H. KÖNIG

MESSERSCHMITT–BÖLKOW–BLOHM GMBH
MUNICH, GERMANY

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Abstract

The growth in helicopter roles increasingly demands operations beyond the basic VFR flight envelope. In keeping with the FAR Part 29 Category A status, the BK 117 is now being certified to cover IFR operation. The variety of missions very often dictates special customer fits of navigation, radio and perhaps radar equipments, however, a basic avionic installation including the flight control system is the central building block. This paper describes the BK 117 basic IFR installation with the major emphasis on the flight control system and stabilisation aspects. The stabilisation system concept is presented and a short description of the hardware is given. The results of theoretical analysis and optimisation of the stability augmentation system are presented together with the design aims. Results of the system flight testing and certification, dynamic and static stability measurements are described, including time history responses. Cockpit layout, current flight envelope and planned IFR development are included in the paper.

1. Introduction

In order to extend its operational envelope towards an "all weather" capability, the BK 117 helicopter has been certified for dual pilot IFR. The jointly developed MBB/Kawasaki BK 117 is a twin-engined aircraft designed to meet FAR Part 29 Transport Category regulations. The basic VFR certification for both Cat. A and Cat. B operation was granted by the Federal German authorities (LBA) and the Japanese civil airworthiness board (JCAB) in December of 1982. This was followed a few months later by the USA FAA certification in March 1983. In February 1984 the LBA and the FAA carried out an assessment of the aircraft for IFR and formal approval was given in August of 1984.

The growing operational demands on helicopters extend beyond the conventional Visual Meteorological Conditions (VMC) to include instrument flying (IMC). With this in mind, many design safety aspects such as system duplication and failure characteristics were considered during the early concept and development stages and their design solutions already included in the basic helicopter.

For IFR operation, however, additional avionic aids are necessary to assist navigation and reduce the existing pilot workload to compensate for the increase owing to the IFR tasks. It is unlikely though that the IFR fit will be the same for all missions.

For example, IFR may be required by an operator since IMC are often encountered, owing to fog or mist, at the take-off or landing airfield only, with the rest of the mission being conducted under VMC. In this case, a minimum avionics complement might be sufficient. On the other hand, in situations where poor weather is regularly encountered, e.g. on an offshore route, additional aids such as Weather Radar, Flight Directors, Flight Management System, Rad. Alt., Doppler, HF Comms. etc. could be essential.

In a paper such as this it is not feasible to cover all the possible IFR missions and equipment fits. However, basic standards are laid down by the airworthiness authorities with regard to stability, handling qualities and flight instruments, and these aspects will be discussed in the following sections, with particular emphasis on the aircraft specific qualities such as handling and stability.

There has been considerable activity by the FAA with the revision of the IFR airworthiness requirements under their Rotorcraft Regulatory Review Program and the recent formal issuing of an Appendix B to Parts 27 and 29, together with Advisory Circular 29-2. Certification of the BK 117 dual pilot IFR has been completed under the Interim Airworthiness Criteria for Helicopter Instrument Flight of Dec. 1978. However, many of the changes instroduced by Appendix B were taken into account during the flight testing phase.

2. Dual Pilot IFR Equipment

2.1. Cockpit Instrumentation, Navigation and Communications

As previously stated, the dual pilot IFR avionics fit will very much depend on the mission foreseen and individual customer requirements and preferences. However, the basic cockpit instrumentation would include the following,

- Artificial Horizon Pilot
- Artificial Horizon Copilot
- Standby Horizon (battery powered back-up)
- Horizontal Situation Indicator (HSI) Pilot, with NAV, Heading, ADF and DME
- Directional Gyro Copilot
- Encoding Altimeter Pilot
- Altimeter Copilot
- Airspeed Indicator Pilot
- Airspeed Indicator Copilot
- Vertical Speed Indicator Pilot
- Vertical Speed Indicator Copilot
- Nav. Indicator Copilot
- Marker

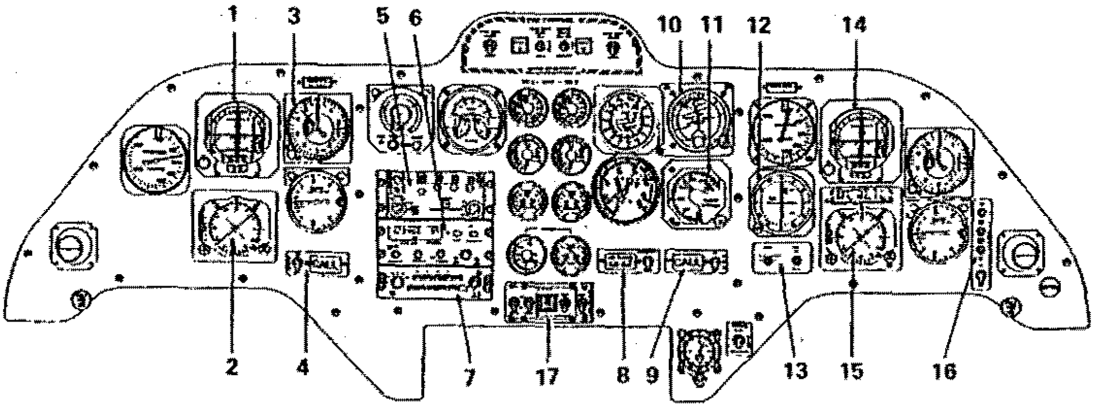
Alternative systems and/ or displays can include,

- Radio Magnetic Indicator (RMI)
- Radio Altimeter
- Copilot HSI as alternative to DG including NAV, Heading etc.
- Course Deviation Indicator (CDI)

For communication and navigation purposes, the following basic radio systems are available,

- VHF Comms. 1 and 2
- NAV 1 and 2 for VOR, ILS
- ATC Transponder
- Comm. Control System 1 and 2

A typical instrument panel layout is shown in Fig. 1



1	Artificial Horizon Copilot	GH 14 – 671
2	HSI	KPI 552
3	Enc. Altimeter	Kollsman
4	CALL Indicator / Switch (Copilot)	
5	VHF 1 Control Unit	VCC 186
6	HF Control Unit	KCU 951
7	Comm. Control Copilot	AS 3100
8	No Smoke + FAST BELT Indicator /Switch	
9	CALL Indicator / Switch (Pilot)	
10	Artificial Horizon STBY	AIM–510
11	Radar Altimeter Indicator	
12	CDI	KI 204
13	DME / HSI – Switch	
14	Artificial Horizon Pilot	GH 14 – 671
15	HSI	KPI 553 A
16	Marker Indicator	KA 35 A
17	CSAS Control unit	

Figure 1 Typical IFR Cockpit Installation

2.2. Control and Stability Augmentation System (CSAS)

For dual pilot IFR operations, the BK 117 is equipped with a 3-axis, pitch, roll and yaw CSAS. All three axes function independently of each other, can be selected separately and may be operated on a single-axis basis under VFR if the pilot desires. The hardware is configured such that the pitch/roll CSAS and the yaw CSAS can be installed as two separate and independent units.

The pitch and roll CSAS is manufactured by Sperry Flight Systems, Phoenix, Arizona USA, to a design specification and concept developed by MBB. The yaw CSAS was both designed and is manufactured in part by MBB. During the development and certification phases of the programme, MBB was responsible for all flight testing with Sperry providing technical support for the pitch and roll CSAS. In the event, this marriage between the two companies proved to be most successful.

The CSAS improves the dynamic stability and flight control characteristics about the respective helicopter axis. This improvement brings about complete dynamic stability under the most unfavourable conditions in the flight envelope. The pilot's workload and time spent on the flying task are thus reduced so that he is able to cope with the increased demands caused by navigation, air traffic control and communications, experienced when operating under IFR.

Each axis of the CSAS consists of a simplex, i.e. non-redundant, limited authority system, optimised for adequate stabilisation and, at the same time, designed to minimise the effects of failure conditions.

In contrast to simple stability augmentation systems, transparent flying qualities are ensured owing to the true control augmentation loop, which measures the pilot control inputs and provides the corresponding compensatory signal to the stabilisation system. The design concept for each axis also includes a washout fuction to guarantee that the actuators automatically return to their mid position, without the pilot having to use a re-trim switch. Thus, as far as possible, the entire actuator authority is retained for the stabilisation function. The resulting helicopter handling qualities are such that the higher frequency disturbances caused by external gusts are compensated for by the CSAS; long-term flight path correction and course correction, which are less strenuous, are left to the pilot. In operation, good attitude retention is obtained while, at the same time, ensuring rapid recentring in the event of larger manoeuvres more akin to the VFR envelope.

Pitch and Roll CSAS

The hardware set-up for the pitch and roll axes is shown in Fig. 2. Attitude reference is provided by the panel mounted pilot's artificial horizon. A remote Control Unit is installed in the lower centre of the instrument panel to facilitate engagement of each axis. In addition, a system cut-off switch is provided on the pilot's cyclic grip to simultaneously disengage all axes. Position pick-offs are attached to the base of the cyclic stick to measure the pilot's control inputs relative to the airframe.

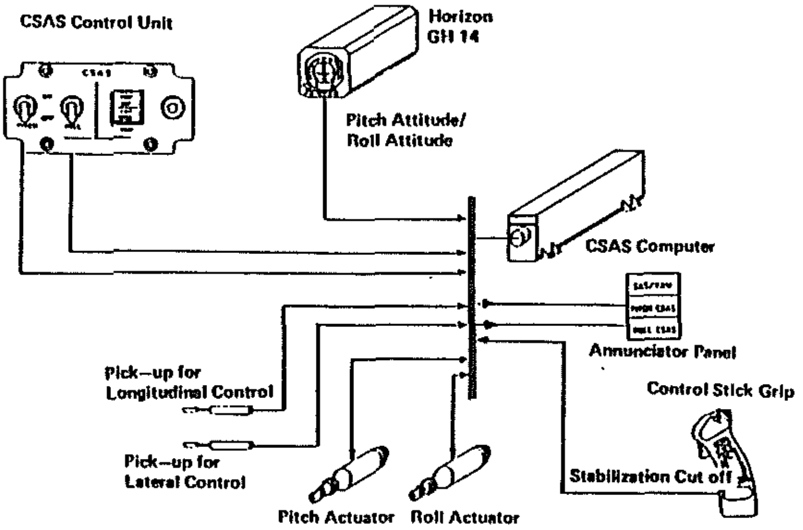


Figure 2 System Set-up of Pitch and Roll CSAS

The CSAS Computer performs all the signal processing, implementation of the control laws, logic functions, filtering and actuator power amplification.

The pitch and roll actuators are to be found in series with the primary flying controls and are installed immediately in front of the input mechanism of the hydraulic power servos. The pitch actuator authority is limited to approximately ± 4,5 % of the full control range and the roll actuator to ± 8 %. Since the BK 117 is equipped with hydraulic boost, the CSAS actuators do not have to operate against high loads and thus are able to obtain a high frequency response. The actuators are earthed by means of the break-out forces of the pretensioned spring box in the "beep" trim system. A functional block diagram is shown in Fig. 3.

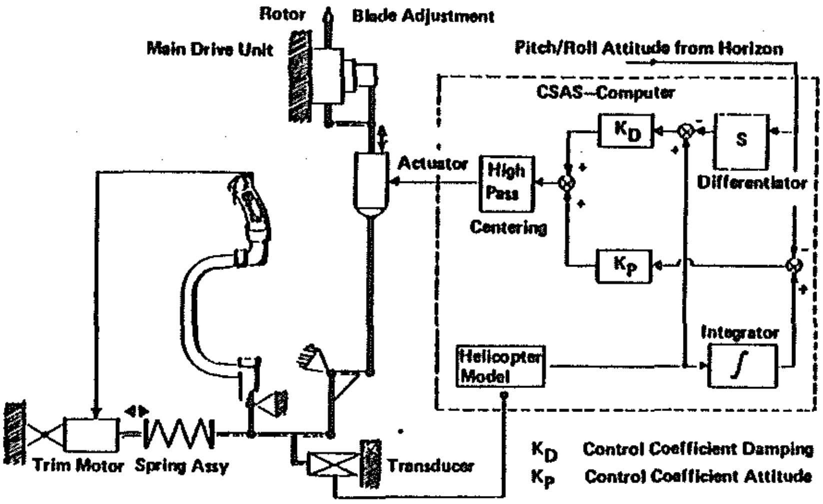


Figure 3 Block Diagram of Pitch/Roll CSAS

The nominal dynamic helicopter response is obtained from the mathematical model and the pilot's control inputs. The commanded attitude and rate are compared with the measured attitude and differentiated attitude value to produce an error signal, which is used to control the series actuator. The high pass filter directly in front of the actuator eliminates long-term drift and ensures self-centring of the actuator. Both the pitch and roll axes are based on the same concept with minor changes owing to differences in the helicopter model, filters and gains.

Yaw CSAS

The hardware set-up for the yaw axis is shown in Fig. 4. A rate gyro is used for sensing the helicopter motion about the yaw axis. Experience on previous flight control systems has demonstrated that a rate gyro and integration of the signal to provide a quasi-heading reference were preferable to an HSI and differentiation. The rate gyro is installed in a neutral position at the rear of the cabin and forward of the tail boom to eliminate the possibility of aeroelastic feedback.

An attitude gyro signal is also used in the yaw axis, not for stabilisation purposes, but to provide a simple speed reference for use in computing the yaw trim value. A common Control Panel is shared with the pitch and roll CSAS.

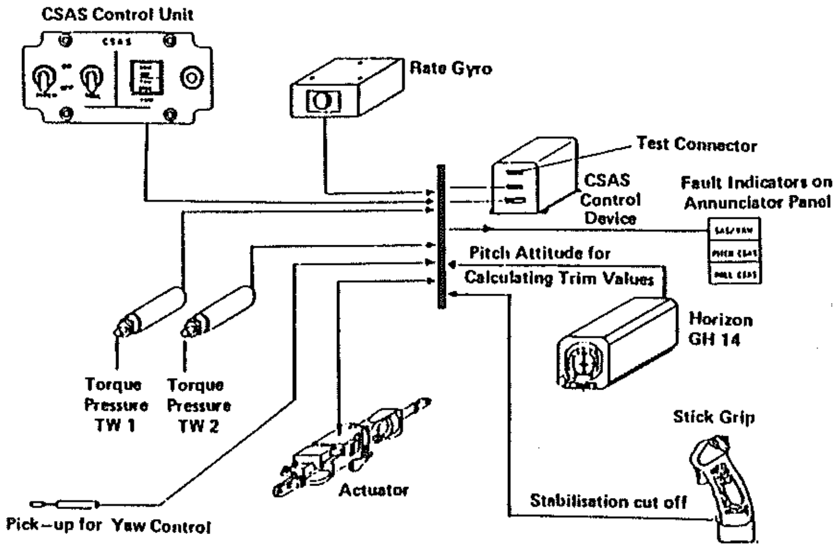


Figure 4 System Set-up of Yaw CSAS

A pedal position pick-off is used to monitor the pilot's inputs, which are required for the dynamic model. In addition, the engine torque is determined from two pressure sensors and is used as a further input to the yaw trim calculation.

Since the tail rotor controls do not have power actuation in the basic version, an integrated mechanical hydraulic boost (MHS) and electrohydraulic actuator (EHS) unit has been developed. These two actuators are arranged in the tail boom fin assembly. The MHS is designed with overtravel to ensure 100% authority in the event of an EHS failure. The EHS is permitted ± 10% of full range which has been found to be adequate for stability augmentation. "Beep" trim is not provided in the yaw axis.

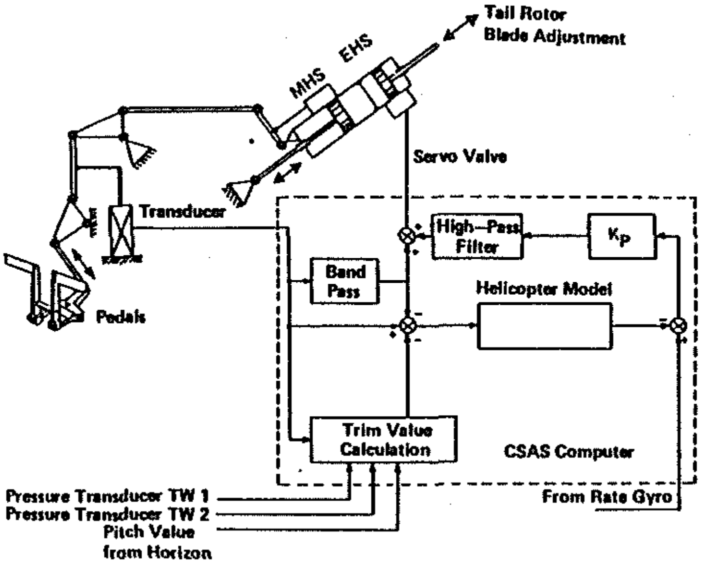


Figure 5 Block Diagram of Yaw CSAS

The yaw CSAS shown in Fig. 5 is functionally very similar to the pitch and roll axes. However, an additional notch filter is included to eliminate the possibility of the pilot exciting the yaw axis at the tail rotor drive natural frequency. Furthermore, a comprehensive yaw trim calculation is included to aid self-centring, and to maintain control response characteristics, with respect to engine power changes, similar to those without stability augmentation.

Trim and Force Feel System (FFS)

Since hydraulic power controls are installed in all control axes, artificial force feel is included in both longitudinal and lateral cyclic in the form of bidirectional preloaded spring boxes and electric trim motors. A friction system with no trim facility is installed in collective and yaw. For the IFR configuration, the basic longitudinal cyclic trim system has been modified to enhance piloting qualities (Fig. 6).

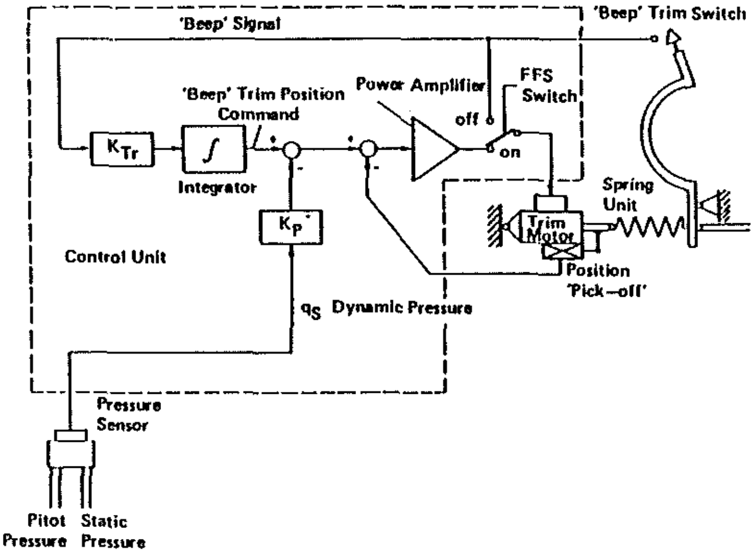


Figure 6 Force Feel System

The conventional "beep" trim function operates in the classical way except that, owing to the modification of the trim motor into a servo actuator, the "beep" switch is used to change the content of a digital store instead of switching the power directly to the trim motor. Pitot-static pressure is measured in parallel with the conventional trim function, and is used to modify the trim motor position and hence the stick forces. The concept permits any desired control force against airspeed characteristics. In the case of the BK 117, the optimisation has been performed for desirability of handling characteristics and to improve the IFR control force stability.

3. Flight Test Evaluation and Results

3.1. Flight Testing Concept

Two aircraft were used during the flight test evaluation. One machine was dedicated to the flight control system development and optimisation, while a second aircraft was fitted with a complete flight instrument and navigation system to evaluate IFR performance. piloting techniques and procedures.

For the CSAS optimisation and certification a comprehensive test instrumentation was installed, following the normal practice, monitoring more than 40 parameters including structural loads, engine performance, control positions, vibrations and aircraft attitude and dynamic response. Flight critical parameters were transmitted directly to the ground via a telemetry link for on line monitoring and evaluation by technical personnel. This procedure proved particularly useful during the parameter optimisation phases. In addition, a PCM system with a limit frequency of up to 150 Hz was employed to record all channels on an in-flight magnetic tape recorder for off line analysis and evaluation.

A total of more than 55 flying hours was invested to prove the flight control system covering, as far as possible, the loading condition limits and altitude/temperature speed envelope.

3.2. Design Optimisation of Stabilisation Parameters

During the design stage of the CSAS, a comprehensive theoretical analysis was performed to establish the most suitable gain values for each axis. Linearised derivative models were used for this purpose, including the 6-degree-of-freedom rigid body equation and rotor dynamics with blade flapping, lagging and torsional degrees-of-freedom.

In the basic configuration, without stabilisation, the short period and spiral modes and the coupled roll/yaw Dutch roll modes are all stable. The phugoid mode, however, is usually unstable throughout some part of the flight envelope but can easily be rendered stable with good damping characteristics by including pitch attitude and rate feedback. Fig. 7 shows the effect of the two gain factors for a typical 130 KIAS cruise condition at max. take-off weight.

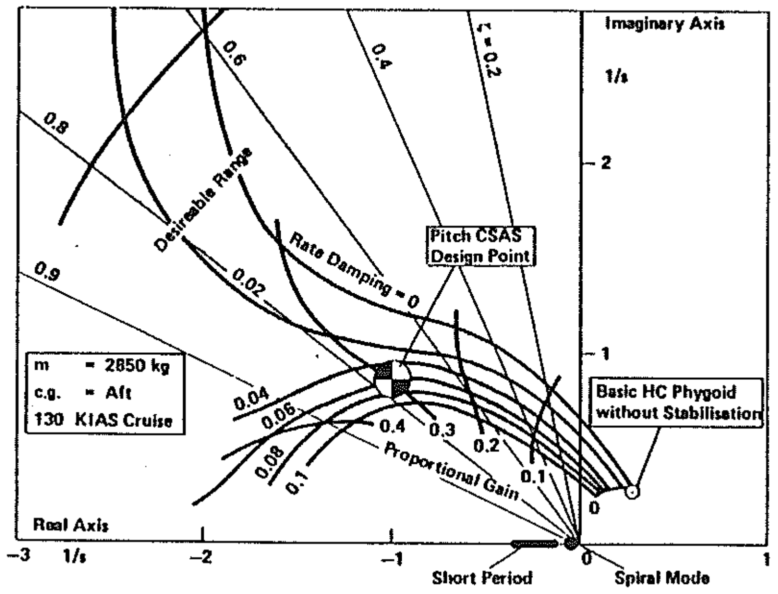


Figure 7 Influence of Pitch CSAS Gain Values on the Phugoid Mode

It can be seen that relatively small amounts of attitude feedback are required to stabilise the phugoid mode. Rate damping alone, however, is not sufficient for complete stabilisation. Optimum placing of the closed-loop eigenvalues has been the subject of a number of studies including [1], [2], [3], [4] and, in general, rapid response with short time constants is desirable. However, the gains cannot be increased indefinitely since eventually non-linear control characteristics, such as backlash and hysteresis, no matter how small, and non-linear aerodynamics will lead to limit cycling. A desirable range of damping and natural frequency is shown in Fig. 7, with the BK 117 pitch axis design point. Similar design concepts were employed for the roll and yaw axes. These values were found to be acceptable during the development flight trials and no significant modifications were undertaken during the system development.

Typical test results from the certification testing are presented in the following sections.

3.3. Dynamic Stability

The longitudinal dynamic stability was evaluated by disturbing the helicopter from its initial trimmed flight state with a pulse input into the collective control. A typical time history is shown in Fig. 8 for a 132 KIAS cruise condition at 2850 kg max. take-off weight and aft centre of gravity. Generally, dynamic longitudinal stability decreases with airspeed, increasing aircraft weight and increasing aft centre of gravity. It can be seen that the 10 to 15% collective input suitably simulates a vertical gust resulting in an initial disturbance of approx. 10°/s. The subsequent pitch damping is well within the minimum transport category airworthiness criteria for frequencies below 5 seconds period of a half amplitude decay rate in one cycle.

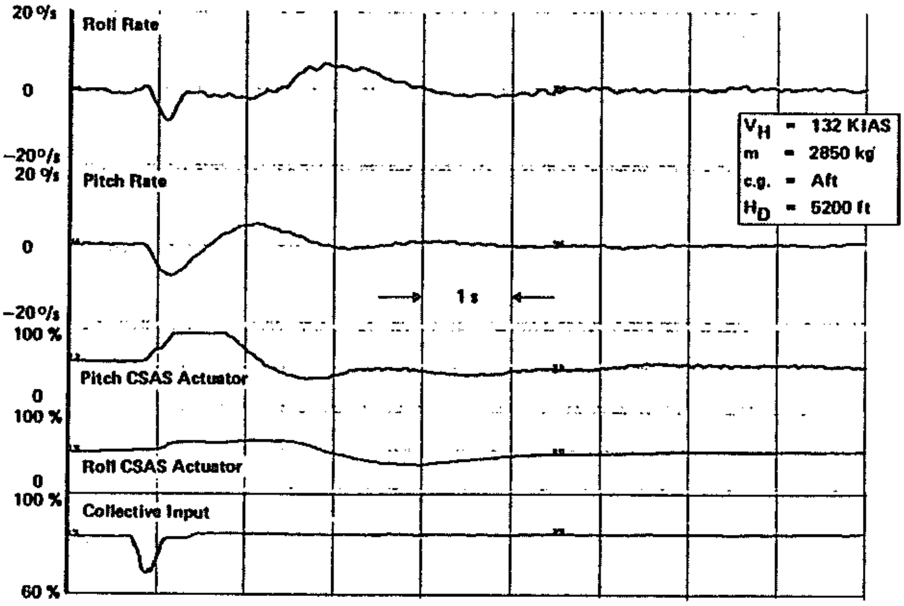


Figure 8 Helicopter Response to Collective Input

Pedal inputs of about 15 to 20% were used to excite the coupled roll/yaw mode (Dutch roll) as shown in Fig. 9. Once again, the damping is well within the minimum requirements.

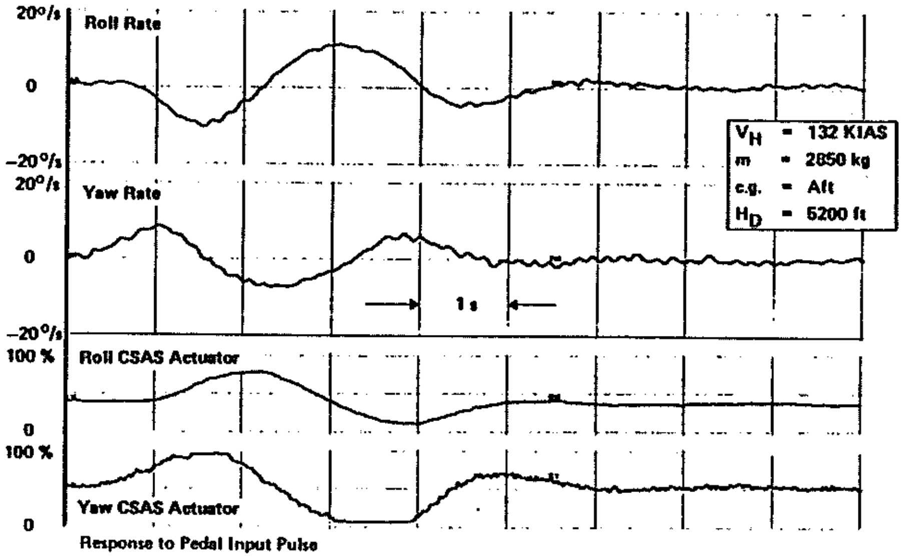


Figure 9 **Helicopter Response to Pedal Input**

One common aperiodic motion is the spiral characteristic when the aircraft roll attitude is displaced. This mode can be investigated by disturbing the roll attitude with the lateral control and returning it to its orginal trim position. Investigations showed, however, that on the BK 117 the roll rate immediately stops and returns to the trim value as soon as the stick input is removed (Fig. 10).

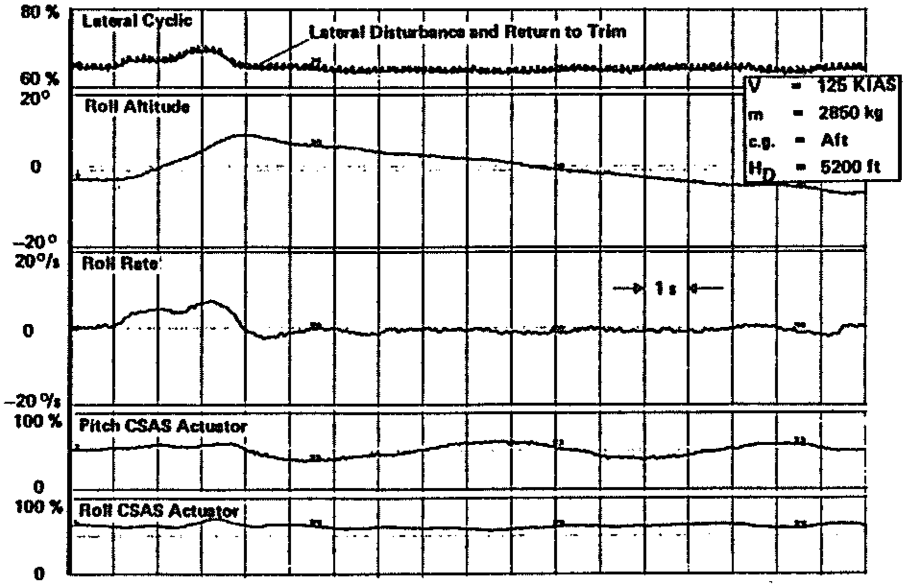


Figure 10 **Spiral Mode**

Static Stability

The supplementary IFR airworthiness regulations require a clearly perceptible cyclic control force increase as the airspeed is changed, in addition to static longitudinal stability required for the VFR operation.

The BK 117 basic configuration is fitted with a conventional spring box and trim motor and, additionally for IFR, the force feel system previously described. In this way, the IFR cyclic stick force requirements are also covered in flight states where no static stability requirements exist for VFR.

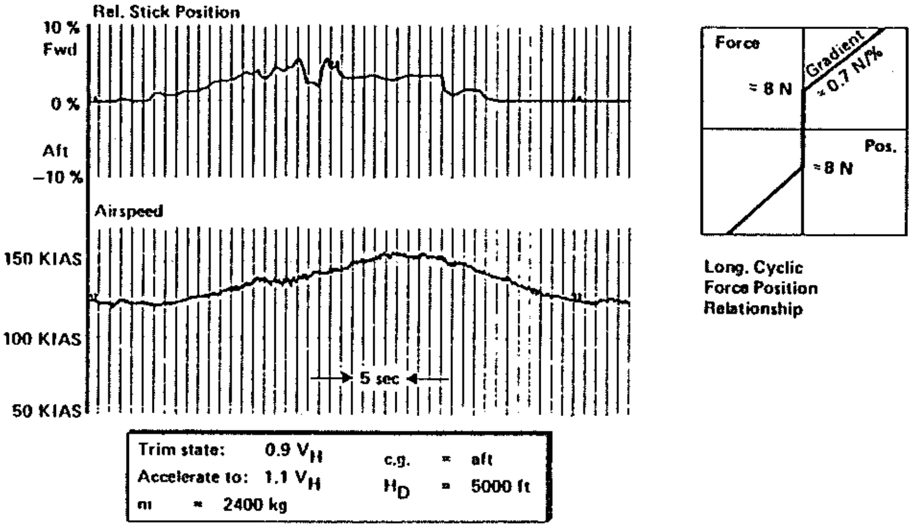


Figure 11 Longitudinal Acceleration and Return to Trim

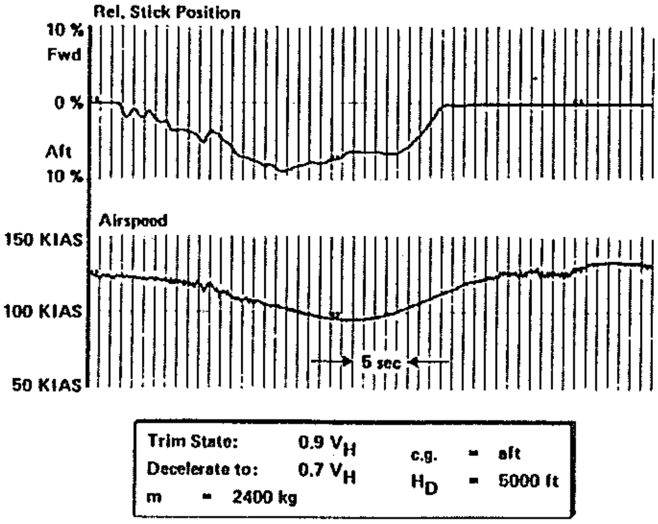


Figure 12 Longitudinal Deceleration and Return to Trim

However, in the longitudinal axis an additional return to trim characteristic has to be demonstrated. The intention of this requirement is to ensure that the aircraft will always re-establish the trimmed speed condition, should disorientation occur or the control be unintentionally disturbed.

Typically, it has to be demonstrated in the cruise condition that, after a 20 KIAS speed deviation and return of the cyclic stick to the trim position, the airspeed must return to within 10% of the trim speed. This could easily be achieved with the BK 117 configuration as demonstrated in Figs. 11 and 12. The return to trim is often a limiting factor in the establishing of the minimum operating cruise, where demonstration of compliance must be shown at 1.1 V_{mini}. However,this did not present any difficulties on the BK 117, where a V_{mini} of 45 KIAS was established to harmonise with the Cat.A take-off safety speed of 50 KIAS.

Lateral-directional static stability does not form part of the basic airworthiness criteria and additional testing is required at suitable points in the flight envelope for IFR certification. Fig. 13 shows some typical lateral cyclic and pedal trim positions against sideslip angle, demonstrating clear static stability characteristics.

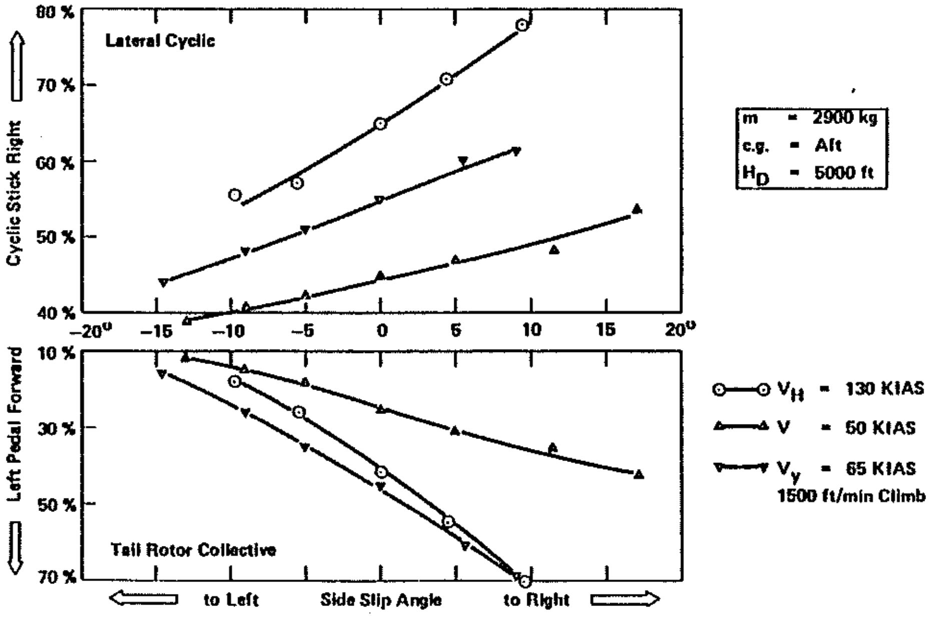


Figure 13 Lateral–Directional Static Stability

4. Conclusions and Future Development

Testing and certification has now been completed to provide the BK 117 with a dual pilot IFR capability. Flight testing has demonstrated a flexible flight envelope with a 45 KIAS V_{min}, 1500 ft/min climb and descent and a 9^{o} steep approach.

To suit mission requirements supplementary avionic aids such as integrated displays, Radio Altimeter, and Weather Radar are available.

Future development is planned for a Flight Director/Coupler and single pilot IFR operation.

5. References

1) F. O'Hara, Handling Criteria, Journal of the Royal Aeronautical Society, April 1967

2) K. Steininger, Funktionen des Piloten in Komplexen Systemen der Flugführung, Z. Flugwiss. 13 Heft 6, 1965

3) W. Just, Vergleichende Stabilitäts- und Steuerungsbetrachtungen bei Flächenflugzeugen und Drehflügelflugzeugen, Z. Flugwiss. 14 Heft 11/12, 1966

4) H. König, et al., Optimization of Automatic Flight Control Concepts for Light Helicopters with All-Weather Capability, Paper presented at 12th Meeting of the Guidance and Control Panel of AGARD, June 1971