FLIGHT TEST OF BK117 FLY-BY-WIRE RESEARCH HELICOPTER

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Abstract

BK117 fly-by-wire research helicopter program was initiated in 1989 to study fly-by-wire technology applicable to a small helicopter. The system features full authority actuation, digital computing, triplex redundancy, four-axis side-stick controller and DDV(Direct Drive Valve) actuator.

Flight control law has two control modes; normal mode and back-up mode. Normal mode gives improved flying qualities and back-up mode takes over when normal mode becomes unavailable due to system failures.

Flight test was carried out as a final phase of the program. Fly-by-wire technology suitable to a small helicopter was established through flight test. The improvement of flying qualities due to flight control law was confirmed. Several findings for further improvement about flight control law and side-stick controller were also obtained.

Introduction

There are now 10,000 commercial helicopters operating throughout the world. In Japan,about 1,100 helicopters are under operation, and this number is the third largest next to the United States and Canada. In recent years, helicopter missions are expanding more and more, and requirements of operation are getting higher. Easy-to-control helicopter with high maneuverability and good stability is desired for flight safety. "Fly-By-Wire" is key technology to answer these requirements.

Fig.1 BK117 Fly-By-Wire Research Helicopter

BK117 fly-by-wire research helicopter program was initiated in 1989 to study fly-by-wire technology applicable to a small helicopter and flight test was completed in March 1993. Fig.1 shows BK117 fly-by-wire research helicopter which became the first fly-by-wire helicopter in Japan. BK117 is a light twin-engine helicopter developed by KHI (Kawasaki Heavy Industries Ltd.) and MBB (Messerschmitt Boelkow Blohm currently Eurocopter Deutschland).[1] Table 1 shows the schedule of this program.

Major objectives of this program are as follows.

(1) Establishment of redundancy management technology
(2) Establishment of compact and reliable actuator technology
(3) Development of four-axis side-stick controller

(4) Development of flight control law

This paper mainly discusses flying qualities aspect of this program.

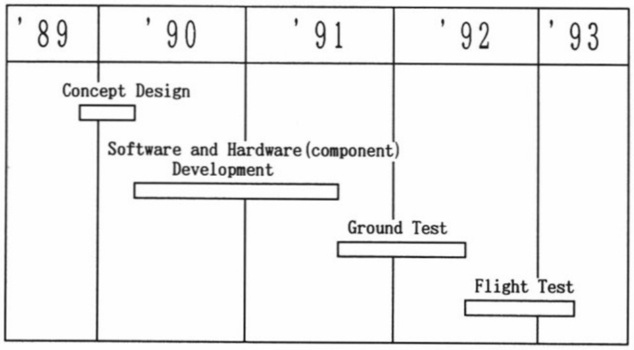


Table 1 Schedule of BK117 Fly-By-Wire Research Helicopter Program

Fly-By-Wire System

Fig.2 shows the configuration of the fly-by-wire flight control system. Conventional mechanical control system was retained for safety pilot to keep airworthiness. Two side-stick controllers were installed on both sides of evaluation pilot seat. One is a four-axis force controller (Fig.3), and the other is a one-axis controller for collective pitch control. Pilot can control helicopter with only one four-axis controller, but the configuration with two controllers was selected for flight test. The signals from side-stick controllers and motion sensors are processed by the digital computers and the output signals drive DDV (Direct Drive Valve) type fly-by-wire actuators. The actuators were connected to mechanical control system in parallel by hydraulic driven clutches. Safety pilot can disconnect fly-by-wire actuators at any time to override evaluation pilot.

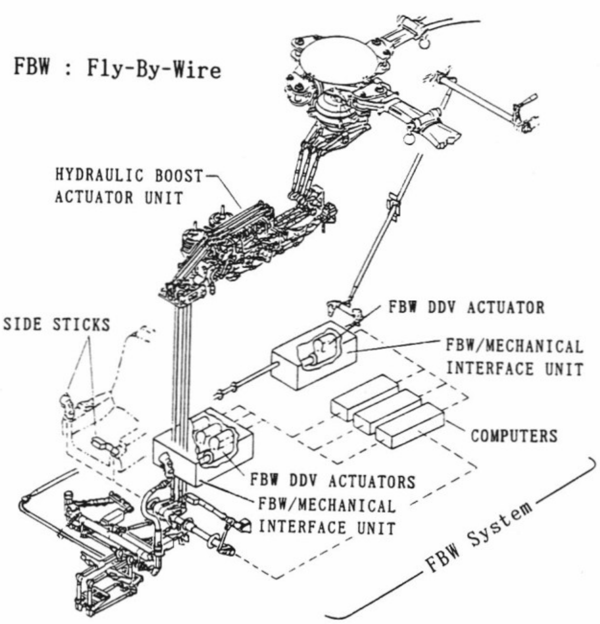


Fig.2 Configuration of the Fly-By-Wire Control System

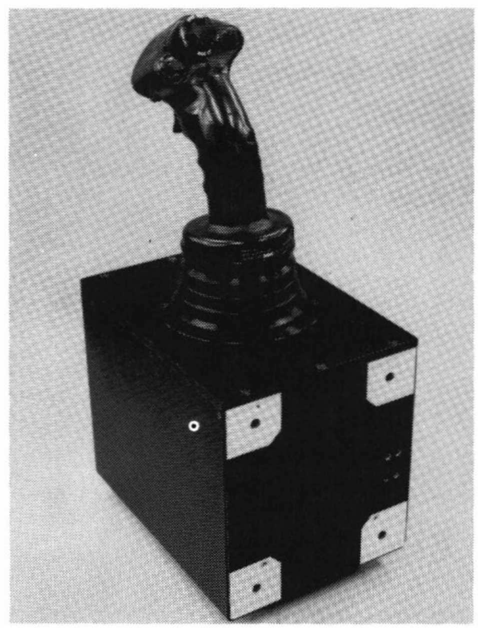


Fig.3 Four-axis Side-stick Controller

Fig.4 shows the architecture of the fly-by-wire control system. Fly-by-wire system consists of two parts; PFCS (Primary Flight Control System) and AFCS (Automatic Flight Control System). PFCS is an essential part for flight safety and has triple redundancy. It can continue operation even with dual failures. AFCS gives sophisticated flight control function and has dual redundancy. It can continue operation with a single failure. That is,

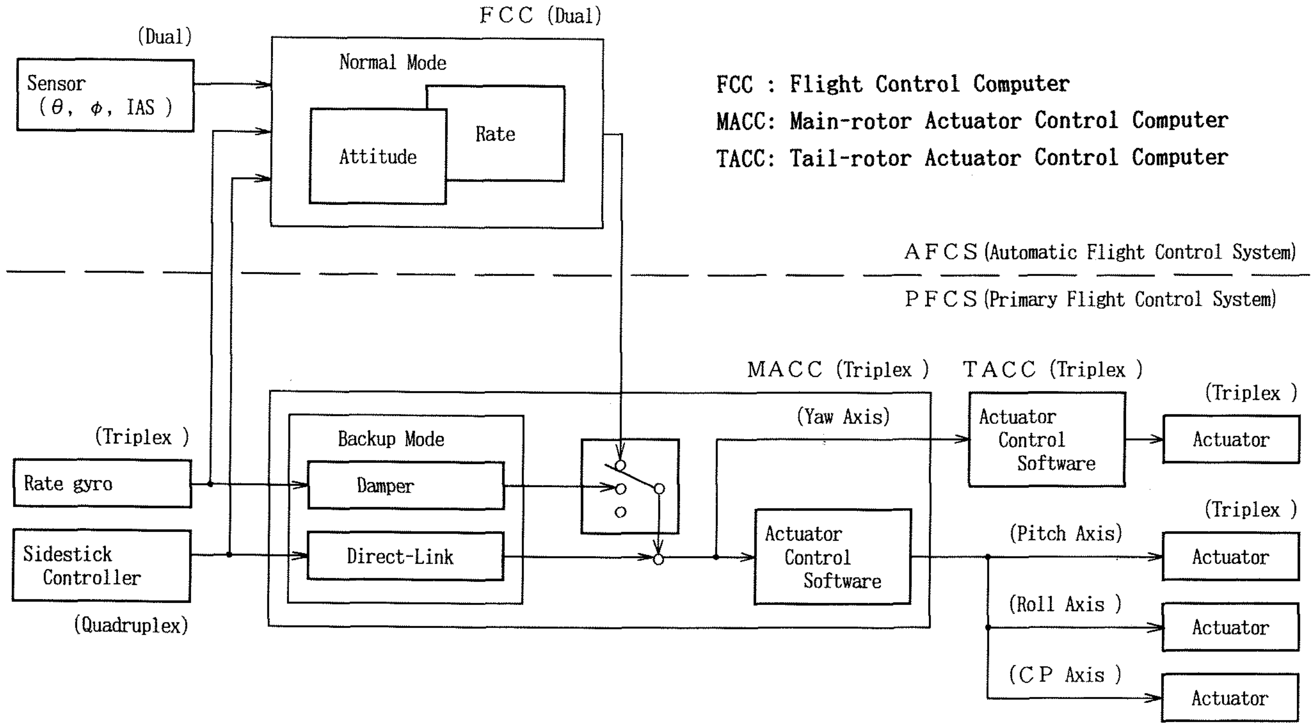


Fig.4 Architecture of the Fly-By-Wire Control System

high reliability is attained by PFCS, and compactness(including light-weight and low cost) is attained by keeping AFCS redundancy minimum. MACCs(Main-rotor Actuator Control Computers) have servo loop control function in addition to flight control law calculation and redundancy management. For yaw control,TACCs(Tail-rotor Actuator Control Computers) have servo loop control function separately and three types of actuation system were evaluated.

Flight Control Law

Table 2 shows the control modes of the flight control law. They are divided into normal mode and back-up mode.

Normal mode is intended to give improved flying qualities and reduce pilot work load at normal operating condition.Two submodes of different response types were studied. Attitude mode has ACAH (Attitude Command Attitude Hold) response type and rate mode has RCAH (Rate Command Attitude Hold) response type for pitch and roll control axes.
Both modes have rate response for yaw axis and direct response for CP (collective pitch) axis. Response characteristics mentioned above and reduction of cross-coupling are realized by explicit model following method. Coordinated turn function at cruise speed is also incorporated in normal mode.

Back-up mode is provided for flight safety. It is used when AFCS can not continue its operation due to more than two AFCS failures. This mode is intended to be as simple as possible to keep software reliable. Back-up mode also has two submodes; direct-link mode and damper mode. Direct-link mode connects side-stick controllers and swashplates directly just like mechanical control system except adding CP-to-yaw cross coupling reduction. Damper mode was studied as an alternative of direct-link mode. Multi-axis side-stick controller might affect flying qualities largely although BK117 with conventional stick has good flying qualities.

These modes can be selected in flight through fly-by-wire control panel installed in the cockpit.

Modes		Features
Normal mode	Attitude mode	·ACAH response type ·Reduction of cross-coupling ·Turn coordination
	Rate mode	·RCAH response type ·Reduction of cross-coupling ·Turn coordination
Backup mode	Damper mode	·Stability augmentation
	Direct-link mode	·Replacement of the mechanical link with the electrical link.

Table 2 Modes of Flight Control Law

Pilot Simulation

Five series of pilot simulation were carried out at KHI's flight simulation facility mainly for flight control law design. Study of hardware specification and scheme for flight safety was also conducted.

It took the longest time to survey the suitable control sensitivity. As a result, second order non-linear control sensitivity was selected as shown in Fig.5. It enables precise control around trim condition and rapid large control within moderate control force.

It was decided to apply two schemes for flight safety as a result of pilot simulation. One is implementation of hardware that watches fly-by-wire actuator and the other is authority limitation of fly-by-wire actuators at the first phase of fly-by-wire flight. Pilot simulation was also useful for feel characteristics study of side-stick controllers.

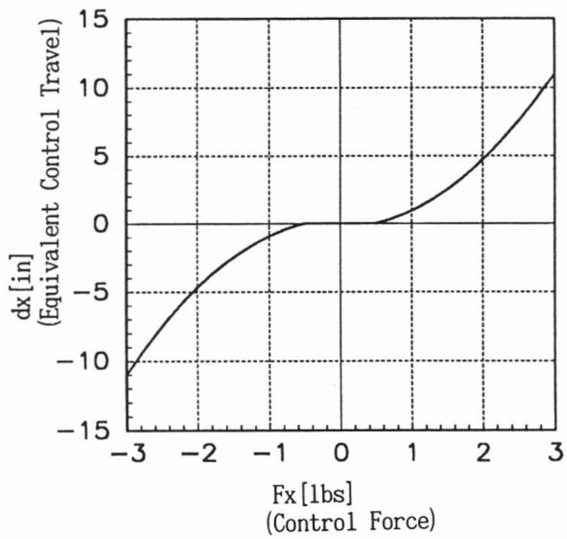


Fig.5 Non-linear Control Sensitivity

Fig.6 shows the whole simulation facility and Fig.7 shows the configuration of the pilot simulation. Major elements of the facility are as follows.

- ·Fixed base single seat cockpit
- ·Four-axis and one-axis side-stick controllers (Variable feel characteristics)
- ·Two CRT type multi-function cockpit displays
- ·Symbol generators(IRIS computers) for cockpit displays
- ·GE Compu-Scene IV computer image generator
- ·Three channel infinity optics and one channel projection type visual display
- ·Data General MV20000 digital computer(host computer)

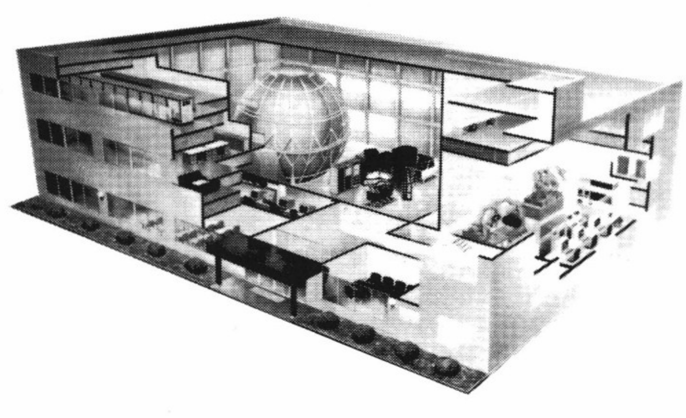


Fig.6 Flight Simulation Facility

Non-linear real time helicopter model was used for pilot simulation. This model features rigid blade element main rotor model, which includes flapping, lagging and RPM change degree of freedom. The model was verified by comparison with flight data.

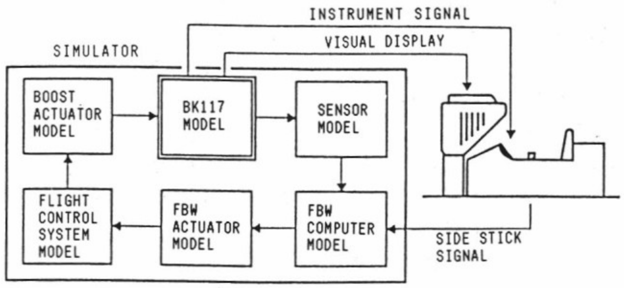
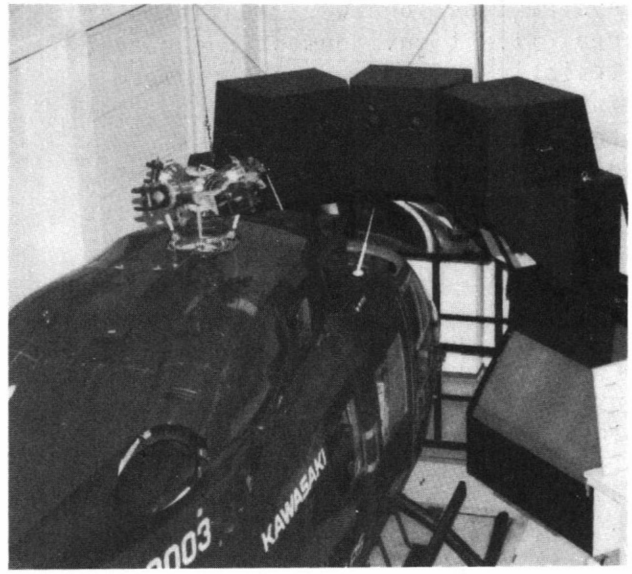


Fig.7 Configuration of Pilot Simulation

Hardware-In-The-Loop Simulation

After completing the check of the fly-by-wire avionics system, total system was implemented into the flight test vehicle for further ground test. At the final phase of this test, test vehicle was carried into the flight simulation facility and hardware-in-the-loop simulation was conducted. Fig.8 shows the configuration of this test.



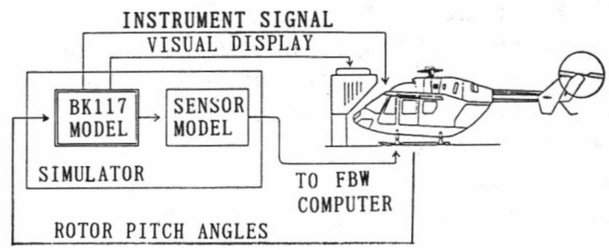


Fig.8 Configuration of Hardware-In-The-Loop Simulation

In this configuration, all the control system was in operation except motion sensors, and only helicopter and motion sensors' dynamics were modeled in the simulation host computer. Flight instrument information was displayed in liquid crystal flat panel MFDs (Multi Function Displays) instead of conventional flight instruments. This was a good method to confirm all the function of the system including on-board software not only technically but also economically. Final tuning of the flight control law and the flying qualities evaluation were conducted in succession.

Other big objective of the hardware-in-the-loop simulation was to confirm flight safety. It was confirmed that safety pilot could recover control after system failures. Also for this objective, this configuration was a good one because real cockpit was used and pilot interface was almost same as real flight.

All the emergency procedures including pilot coordination were established through this test and pilots got great confidence to start flight test.

Flight Test

Table 3 shows the schedule of flight test. Flight test was divided into three phases to ensure flight safety.

In the first phase, fly-by-wire system was in operation but not connected to the mechanical control system. In this phase, all the system functions were confirmed in real flight environment and characteristics of motion sensors were investigated to determine the threshold level for failure detection.

In the second phase, fly-by-wire system was connected to the mechanical control system, but the authority of fly-by-wire actuators was limited so as that safety pilot could recover control even when fly-by-wire actuators should run away. In this phase, closed loop characteristics and transient motion were evaluated. It was found that stability of normal mode was a little weak and control sensitivity of roll axis was a little high. They were improved by adjustment of flight control law. Transient motion of fly-by-wire system engagement and that of system reconfiguration due to system failures were found to be small enough.

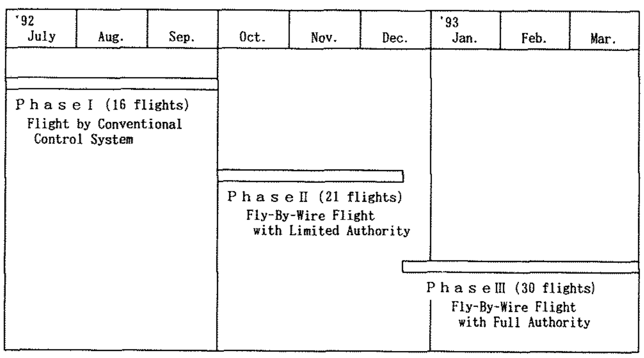


Table 3 Schedule of Flight Test

Category	Task	Description
Normal Flight Maneuver	Climb	climb at 1,000fpm. maintain speed and direction.
	Turn	turn at 30 degree bank angle. maintain altitude and speed.
	Speed change	speed up to 80kts and down to 40kts. maintain altitude and direction.
	Descent	descend at 1,000fpm. maintain speed and direction.
	Hovering	decelerate to hovering. maintain altitude and direction.
Aggressive Maneuver	Roll reversal	achieve ±40 degree bank angle. maintain altitude and speed.
	Acceleration and deceleration	accelerate from 30kts to 80kts and decelerate to 30kts within 35s. maintain altitude and direction.
	Pull-up and push-over	achieve 1.6g and 0.4g. maintain direction and roll attitude

All tasks are started from 60kts straight level flight except Acceleration and deceleration.

Table 4 Tasks for Pilot Evaluation

Pilots could conduct these flight tests without fear owing to the authority limitation. They commented that this configuration was very useful.

In the final phase, authority limitation was removed and flying qualities were evaluated. Two kinds of test were carried out for this purpose. One is control response data acquisition to identify flying quality element such as stability, bandwidth and so on. The other is overall assessment of flying qualities using Cooper-Harper pilot rating scale. Flying qualities of each flight control mode were evaluated for eight kinds of tasks including aggressive ones. Evaluation tasks are summarized in Table 4.

Test Results

Test results of flying qualities evaluation are presented in this section.

Fig.9 shows the results of longitudinal dynamic stability obtained from pulse response data. Direct-link mode which has no feedback loop

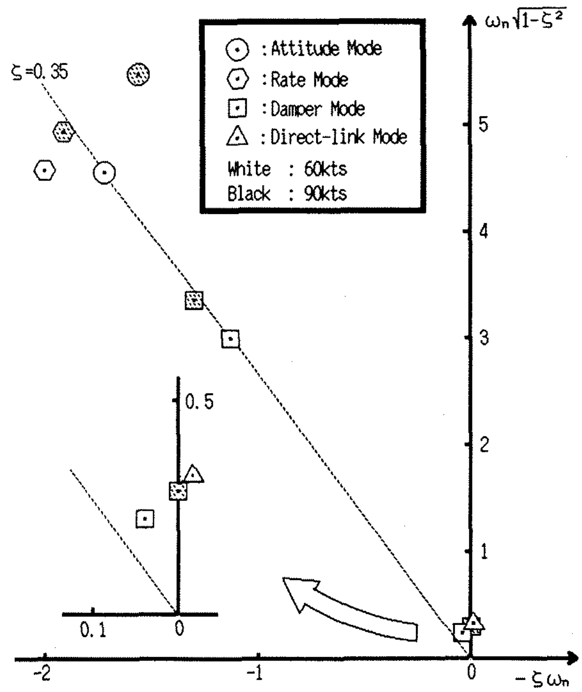


Fig.9 Results of Longitudinal Dynamic Stability

shows bare helicopter characteristics. Unstable long period mode is observed even at the cruise speed due to rigid rotor system. Stability was improved by feedback control for other modes, especially for normal modes. Pilot work load was greatly reduced by this improvement.

Fig.10 shows the results of cross-coupling characteristics. Pitch and roll attitudes after CP input are compared between attitude mode and direct-link mode. Attitude change is kept small for attitude mode owing to decoupling function with the help of attitude hold function.
Total flying qualities of normal mode were greatly improved by this function in addition to good stability.

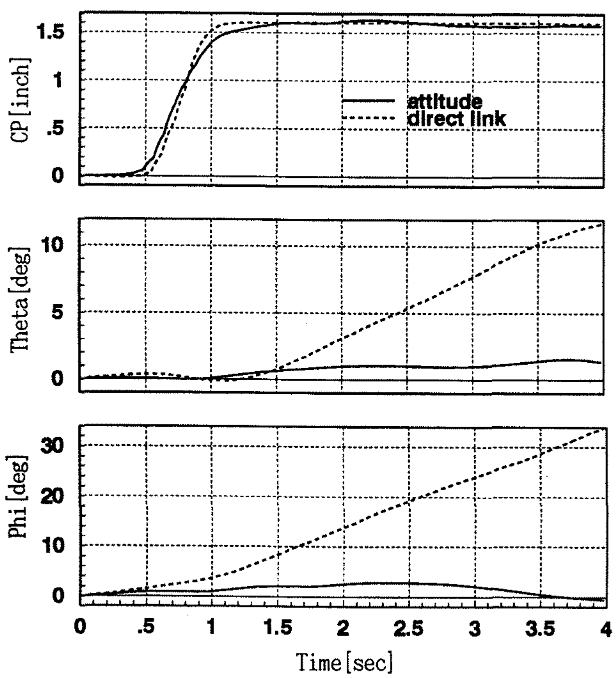


Fig.10 Results of Cross-Coupling Characteristics

Overall assessment of the flying qualities was conducted by two pilots. Fig.11 shows the results of "Right Turn" task and "Speed Change" task. Task description is as follows.

·Right Turn : Start with 60kts straight level flight condition. Turn right with 30±5 deg bank angle for 15 seconds and return to initial flight condition. Keep initial altitude (± 100ft) and speed (± 10kts) all through the task.
Speed Change: Start with 60kts straight level flight condition. Accelerate to 80kts and keep the speed (± 8kts) for 10 seconds, decelerate to 40kts and keep the speed (± 8kts) for 10 seconds, and return to initial flight condition. Keep initial altitude (± 100ft) and heading (± 20deg) all through the task.

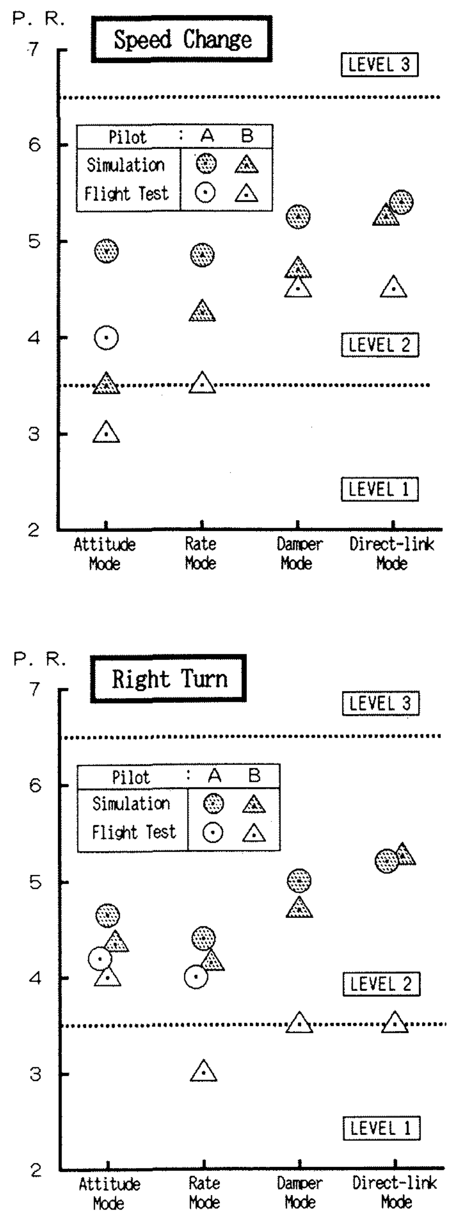


Fig.11 Results of Pilot Evaluation

Flight evaluation result was generally better than that of ground simulation. Main reason of the difference seems to be the difference of the visual cues and air turbulence condition between real flight and ground simulation. Visual cue of real flight is generally better than that of ground simulation and light turbulence based on MIL-handbook was incorporated for ground simulation.

However, result of normal mode especially attitude mode was not so good as expected. Several factors which affected the result will be discussed next.

Bio-mechanical roll oscillation

Unintentional roll oscillation around 1.4Hz occurred in turn maneuvers with attitude mode. Fig.12 shows the time history of this phenomenon. Same tendency was observed also for rate mode but with less degree. It was found that pilot's oscillatory control force due to helicopter motion through side-stick controller was the reason of this phenomenon after close examination and analysis. Digital notch filter was implemented for side-stick controller signals to cut this particular frequency. Close care is necessary for bio-mechanical coupling in side-stick controller design.

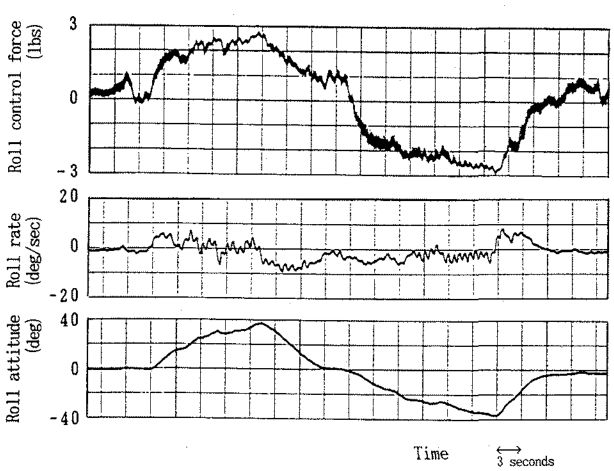


Fig.12 Roll Oscillation Phenomenon

Characteristics of side-stick controller

Control travel of a side-stick controller is smaller than that of a conventional controller for ergonomic reason of human arm. Our design was to make the travel even smaller to keep the sensor mechanism compact. This means high control sensitivity in respect to displacement. Pilot found it very difficult to operate switches without changing control force. It is necessary to enlarge control travel and reduce control sensitivity. It is also necessary to develop small, light-force switches and to implement them into the grip properly.

Non-linear control sensitivity was not favored by pilots. It was difficult to anticipate control response because of non-linearity and high control sensitivity for large control force region.

Cross-coupling characteristics

Cross-coupling characteristics are generally very complex. For example, roll motion due to CP increase is right roll at first, but becomes left in accordance with the increase of climb rate. Pilots expressed their opinion that thorough elimination of cross-coupling would reduce their work load more. It is necessary to incorporate dynamic elements and gain scheduling.

Concluding Remarks

BK117 fly-by-wire research helicopter program gave us many instructions for further improvement. With these experiences, KHI started new research program to obtain higher level technology required in 21st century.

Acknowledgment

The authors would like to thank to the cooperation of program members and hardware manufacturers in fly-

by-wire control system development and in conducting test.

Reference

(1) H.Huber and T.Masue, Flight Characteristics Design and Development of the MBB/KHI BK117 Helicopter, presented to the 7th European Rotorcraft and Powered Lift Aircraft Forum, 1981.

(2) T.Tomio,M.Ishikawa,S.Nakamura and N.Sudo,Digital Fly-By-Wire System for BK117 FBW Research Helicopter, presented to 18th Congress of the International Council of the Aeronautical Sciences,September 1992.

(3) T.Tomio,M.Ishikawa,M.Watari, S.Nakamura and T.Taira,Testing for Design Validation of the BK117 FBW Experimental Helicopter, presented to AIAA/AHS/ASEE Aerospace Design Conference,February 1993.

(4) T.Tomio,M.Ishikawa and N.Sudo, The Development of FBW System for BK117 FBW Experimental Helicopter, presented to Pacific International Conference on Aerospace Science and Technology,December 1993.