DIGITAL FLY-BY-WIRE SYSTEM FOR BK117 FBW RESEARCH HELICOPTER

Takeshi Tomio, Munenori Ishikawa, Shuji Nakamura, Naoki Sudo
Kawasaki Heavy Industries, LTD.
Gifu Pref., Japan

ABSTRACT

Fly-By-Wire(FBW) flight control technology is expected to provide reduced pilot workload, enhanced controllability and reduced life cycle cost for helicopters as well as fixed-wings.
BK117 FBW Research Helicopter, shown on Figure 1, is being assessed in flight tests to establish FBW technology applicable to helicopter. Its 4-axis full authority digital FBW is basically a triplex redundant system. The core control functions like the direct link which corresponds to the mechanical linkage has two-fail operational capability, and it is clearly separated from the other functions of the lower criticality. The system has other following features.

- Side-stick Controller.
- Software written in Ada.
- Direct Drive Valve(DDV)
- Digital servo loop

The Kawasaki/MBB BK117 is a twin engined helicopter with a rigid rotor system, and the FBW system is installed remaining the mechanical control linkage for the backup system. This paper describes the design concept, the system architecture, the redundancy management, and the system assessment conducted prior to the flight test.

I Introduction

Helicopters are widely used in both military and commercial fields for many kinds of operations, such as, fire-fighting, police patrol, outside-broadcast, emergency medical service, transportation, scout, attack, air-air combat, ship board and so on. Mission elements are also extended to extreme flight phase environment of day and night, atmospheric disturbances including icing condition, terrain following, closing obstacles and others. These require helicopters the following advanced technologies which will be accomplished and integrated in the future.

- Glass cockpit technology.
- Advanced flight control technology with high authority management.
- Technology for atmospheric environmental compatibility with critical atmospheric condition.

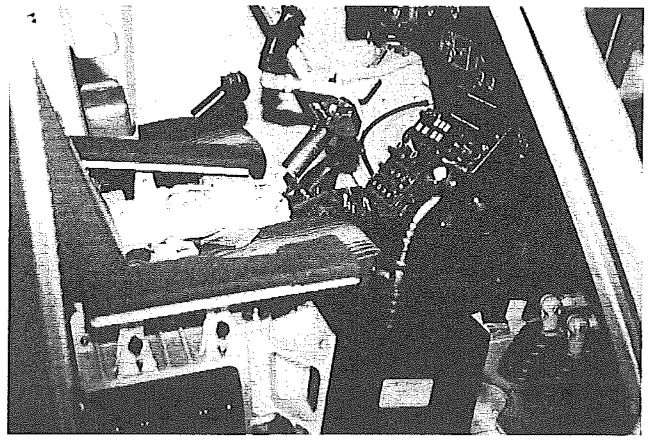


Figure 1. Cockpit of the BK117 FBW Research Helicopter

FBW flight control system is one of the most important key technologies, and will provide the following advantages;

- Reduced pilot workload by,
  - Decoupling of control axes.
  - Expert automatic flight path management.
  - Automatic flight envelope management.
- Effective mission fulfillment by improvements of the maneuverability/agility/handling quality.
- Reduction of operating and manufacturing cost.
- Improved survivability.

BK117 FBW Research Helicopter is programmed to establish a concept of FBW flight control system suited to helicopter in both technologies of hardware and software. The program was undertaken succeeding the technological experiences which had been obtained in the past programs in Kawasaki Heavy Industries(KHI) i.e. P-2V7 VSA with an analog single FBW, STOL Research Aircraft "ASKA" with a digital triplex flight control system[1], the investigations of DDV hydraulic servo control and the flight simulations to develop the helicopter control law with 4-axis side stick.

II FBW System Design Philosophy

FBW flight control systems are practically used on military and commercial fixed-wing aircraft, while practical use of the system on helicopters lags due to the following helicopter natures;

- ·Marginal space and weight provisions.
- ·Criticality of single point failure on the helicopter safety because of no redundant control surface which obstruct reconfiguration at a single failure on any one of the four axes of rotor control.

Due to these natures FBW concept for helicopter differs from that for fixed-wing aircraft.
FBW flight control system for helicopter should be as simple as practicable and as reliable as possible.

Figure 2 outlines the design philosophy of the FBW flight control system being evaluated on BK117 FBW Research Helicopter. The system consists of two parts clearly separated depending on the flight criticality of the function. One part is the Primary Flight Control System(PFCS) for the flight essential function, and the other is the Automatic Flight Control System(AFCS) for the flight phase essential function.

This configuration is concluded to ensure effectively the reliability required for each system with optimum weight and cost. As Figure 2 shows the comparison of these two systems with conventional mechanical flight control system, PFCS provides core function for flight safety and AFCS provides the improvements of flight control performance and functions.

The basic architecture of the system is shown on Figure 3. PFCS has two-fail operational capability, whose function is called the backup control function. On the otherhand, AFCS has only one-fail operational capability, whose function is called the normal mode control function. AFCS connects with PFCS only in the normal mode.

The features of the system are,

- ·4-axis full authority digital FBW system.
- ·Consists of two separated systems of PFCS and AFCS
- ·Multi-axis Side-Stick-Controller.
- ·Fault tolerant System Architecture offering high reliability,

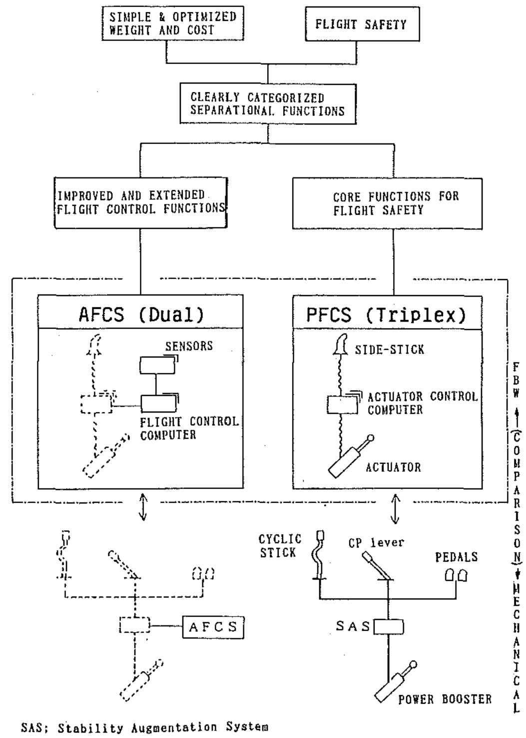


Figure 2. Functional Separation of the FBW System

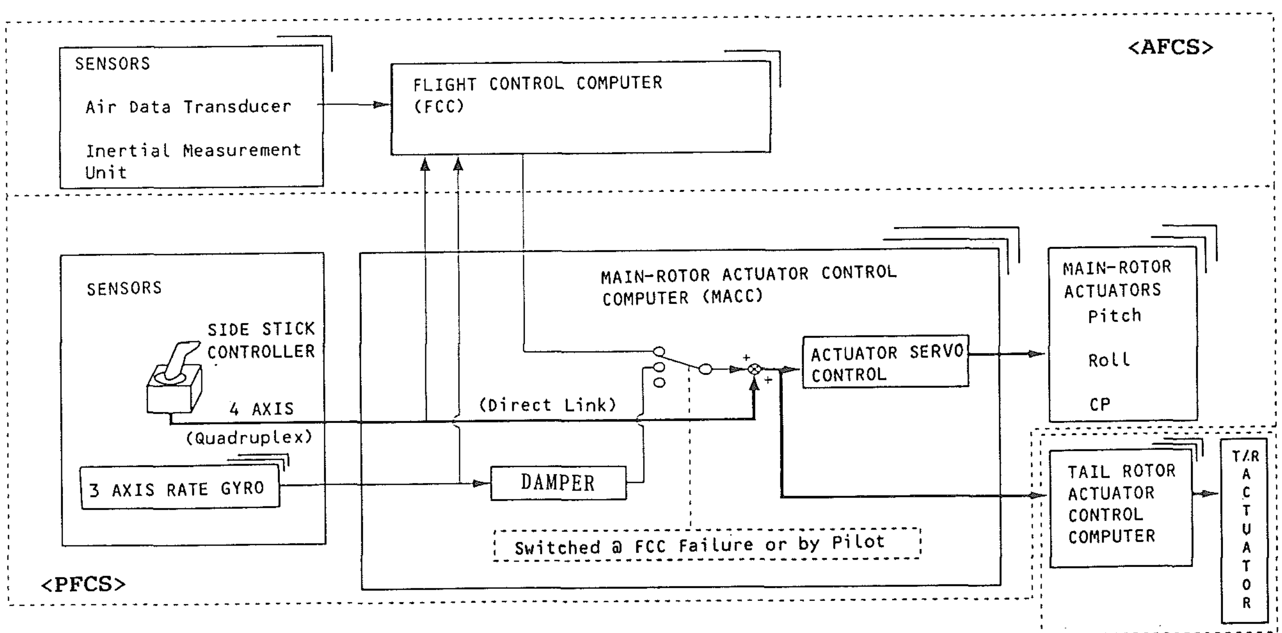


Figure 3. Basic Architecture of the System

··Triplex Redundant/Two-Fail Operational(PFCS).
··Dual Redundant/One-Fail Operational(AFCS).
·Flight control software, written in Ada.
·Communication using MIL-STD-1553B data bus.
·Advanced hydraulic Actuators, controlled by the Direct Drive Valve(DDV).

It is noted that the tail-rotor control system is separated only for technical investigation of the different types of DDV actuation system, and it will not appear in the production type system.

III System Design

Flight control functions

Backup control function

The backup control function is flight essential function replacing conventional control system and rate damper. This function has two sub-modes i.e. the direct link mode and the damper mode. In the direct link mode, aircraft is controlled only with the side stick inputs to obtain minimum controllability. In the damper mode rate damping function is added to the direct link function to improve aircraft stability so that fairly high-level flight task can be performed.

Normal mode control function

The FBW system controls aircraft with a high-level control law designed to improve controllability in the normal mode. The normal mode control function has two types of sub-modes called the Attitude-Command-Attitude-Hold mode and the Rate-Command-Attitude-Hold mode.

System architecture

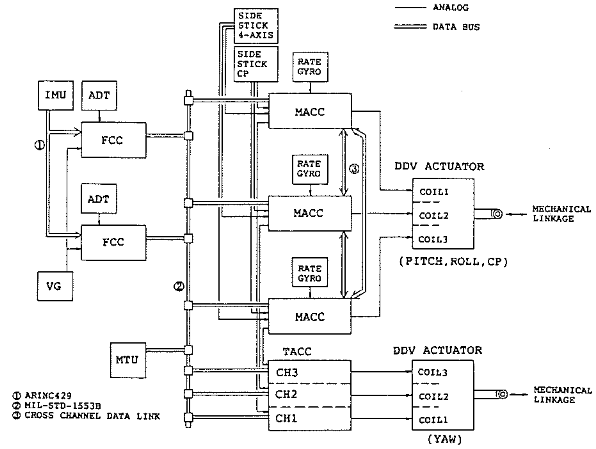
Figure 4 shows the system architecture of BK117 FBW system. As shown in the figure, a MIL-STD-1553B data bus separates AFCS from PFCS clearly, and AFCS is connected to PFCS by only this data bus.

PFCS

The core of PFCS is triplex Main-rotor Actuator Control Computers (MACC) which perform the following functions.

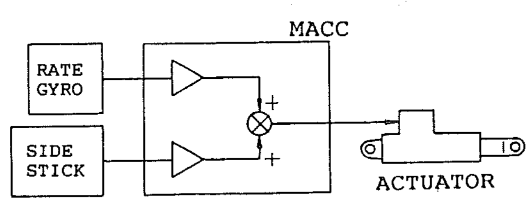
- ·Redundancy management for the flight essential sensors
- ·Redundncy management for the servo drives
- ·Control law processing for the backup control function
- ·DDV servo drive for pitch, roll and collective pitch (CP) axes
- ·AFCS connect/disconnect managment

A 4-axis side stick controller, a CP-axis side stick controller and three 3-axis rate gyros are the flight essential sensors providing analog signals to PFCS. For pitch, roll and CP axes, DDV servo drives are integrated in MACCs,

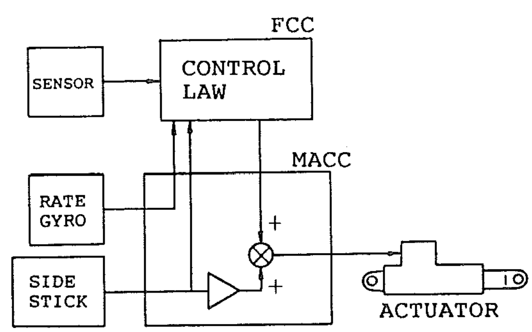


ADT	AIR DATA TRANSDUCER
CCDL	CROSS CHANNEL DATA LINK
FCC	FLIGHT CONTROL COMPUTER
IMU	INERTIAL MESUREMENT UNIT
MACC	MAIN ROTOR ACTUATOR CONTROL COMPUTER
MTU	MONITOR TEST UNIT
TACC	TAIL ROTOR ACTUATOR CONTROL COMPUTER
VG	VERTICAL GYRO

Figure 4. FBW System Architecture



(a) Backup mode



(b) Normal mode

Figure 5. System Data Flow

and are digitally closed. Yaw servo drive is separated from MACC, and Tail-rotor Actuator Control Computer (TACC) drives the yaw actuator along the analog command from MACC. Data for redundancy management, mode logic and so on are exchanged among MACCs via Cross Channel Data Links (CCDL). Three MACCs also exchange discrete signals to synchronize the software frame. MACC processes the backup control function in 6.5msec cycle, and performs servo control in 1msec cycle. The control law for the backup control function combining some gains and limiters is quite simple so that software bug is prevented and CPU load is reduced. While a backup control mode is performed, the data flow in the system is as shown in Figure 5(a).

AFCS

AFCS is a dual redundant system whose key component is Flight Control Computer (FCC). The functions of FCC is as follows.

- Redundancy management for air data and attitude sensors
- Redundancy management for the MIL-STD-1553B data bus
- Control law processing for normal mode control function

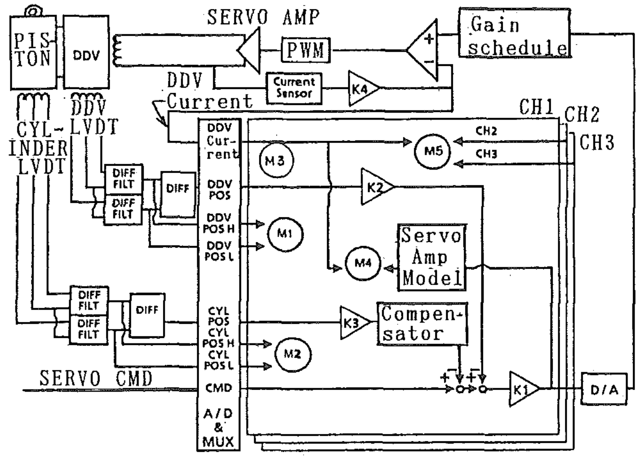
FCC obtains the flight essential sensor data from MACCs via the MIL-STD-1553B data bus. Additionally the air data and the attitude sensors also provide aircraft data to FCC, to process the normal mode control law. Control commands provided by FCCs are sent to MACCs via the MIL-STD-1553B data bus. And the control commands from FCCs are added on the direct link commands generated all the time by MACC. The data flow in the normal mode is as shown in Figure 5(b), and PFCS disconnects AFCS whenever AFCS is abnormal to ensure safe flight. Two FCCs are synchronizing the software frame, while AFCS and PFCS are not synchronized. The redundancy management for the MIL-STD-1553B data bus is performed by FCCs. One FCC is the bus controller and the other FCC is the backup bus controller.

Maintenance aid

The MIL-STD-1553B data bus is also utilized to monitor the system. Monitor Test Unit (MTU) on the bus displays FCC, MACC and TACC parameters, and initiates pre-flight test. Also by using MTU the side stick controller configuration is selectable i.e. the 4-axis control by the right hand side stick only or the 3-axis control by the right hand stick with CP-axis control by the left hand stick.

Redundancy management

BK117 FBW system performs redundancy management to obtain fault torelant capability of two-fail operational for the backup control function and one-fail operational for the normal mode control function. To simplify the software, complex technique like analytic redundancy technique is not applied. MACC performs redundancy management for the flight essential sensors, the servo drives and MACCs. Sensor signal selection and fault detection for the side stick controllers and the rate gyros are carried out by means of voting for triplex system. Each MACC and TACC detects failure of its own servo system, thus servo operation by only a single channel is possible. FCC performs signal selection by voting for the flight essential sensors without sensor valid signals so that only one-fail operational is possible. For the air data and the attitude sensors, which are dual system, fault detection is carried out by means of signal comparison.



M1 DDV LVDT MONITOR
M2 CYLINDER LVDT MONITOR
M3 DDV COIL SHORT MONITOR
M4 SERVO MODEL MONITOR
M5 DDV CURRENT CROSS-CHANNEL MONITOR

Figure 6. FDIR for the Servo System

Software

Software is one of the most important techniques which determines the reliability of a fight control system. For small scale aircraft, FBW system should have a small size software with simple structure and deterministic action. And fault avoidance concept should be adapted to eliminate software error inherently. In the BK117 FBW system Ada language has been adapted to obtain higher fault avoidance. Ada has severe rules for type of variable, structure of subprogram and so on, and errors caused by compilation or link is very rare. Generally software written in Ada has disadvantage of large size of executable module and low processing speed. But simplifying software and applying a high speed hardware, this issue is not significant.

Servo system

The servo system consists of Actuator Control Computers (ACC) and electro-hydraulic actuators incorporating Direct Drive Valve (DDV).

The ACCs control the DDV actuators with digital closed servo-loops executed at 1kHz(1msec). ACCs also execute fault detection, isolation and reconfiguration (FDIR) at 154Hz (6.5msec), monitoring the below items about servo system, as shown on Figure 6.

- LVDT self-monitor
- DDV coil short self-monitor
- Servo model self-monitor
- DDV coil current cross-channel monitor

The DDV actuators are installed in the FBW/mechanical interface units on the cabin floor. The DDV actuators drive the power boost actuators of BK117 helicopter via the basic mechanical control linkage, with mechanical feedback to the controls for the safety pilot. The DDV actuators are powered by the stand-by hydraulic system (103bar) of basic BK117 Helicopter.

In order to restrict the DDV actuator power level below the allowable limit load of the basic mechanical linkage, the actuators have relatively small power. Due to the low power level, the actuators incur a large ammount of non-linear elements, such as friction or hysteresis. At the design phase of the DDV actuators, minimization of the non-linear elements was carefully aimed.

The specifications of the servo system are written as follows;

- Single hydraulic and triple electrical inputs
- Two-fail operational redundancy
- Direct drive valve(DDV)
- Dynamic response
  @9.5Hz above -3dB and -90degree (for pitch/roll/CP)
  @12Hz above -3dB and-90degree (for yaw)
- Stroke ±23.8mm (for pitch/roll)
  ±28.5mm (for CP)
  ±20.3mm (for yaw)

Two types of DDV, linear-type and rotary-type, are evaluated. To achieve jam-proof capability required for rotorcraft control actuators, special designs are incorporated i.e. dual spool control valve and chip-shear capability (above 80LBS) for the linear-type DDV and the rotary-type DDV, respectively.

IV BK117 FBW Research Helicopter

The excellent characteristics, especially safety and flying quality, of the testbed helicopter are the most important to evaluate effectively the FBW flight control system.
The BK117 Helicopter shown on Figure 7, developed by the international co-operation of KHI and ECD (MBB), has full compatibility for the testbed due to her following excellent features. [2]

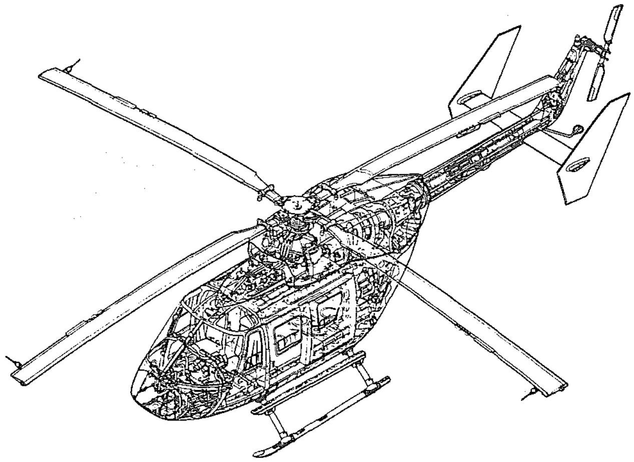


Figure 7. Kawasaki/MBB BK117 Helicopter

- High maneuverability and controllability provided by the hingeless rotor.
- Highly safe characteristics served by the dual redundant concept of the major provisions of the helicopter that are the twin-engined powerplant, the dual hydraulic systems, the dual electrical systems and others.
- Dual pilots seating in parallel
- Large cabin and cargo volume in which much equipment can be installed without adverse affections on the airworthiness of the helicopter.

The BK117 FBW Research Helicopter is constructed to utilize fully these advantages.

Outlines of the research helicopter

The FBW flight control system and the instrumentation system for data aquisition are added to the testbed, BK117 of serial number of P5, in the manner that the adverse affections on the airworthiness of the testbed is minimized.

The configuration of the flight control system is shown on Figure 8. The existing mechanical flight control system is remained as a back-up system, and the FBW flight control system is connected in parallel with the backup system by using the FBW/Mechanical interface unit.
Modifications of the existing mechanical flight control system is minimized so that the system remains as is when the FBW system is disengaged.
A FBW evaluation pilot occupies on the right hand seat and a safety polot who controls the helicopter by the existing mechanical backup system occupies on the left hand seat. The safety pilot can disconnect the FBW system by activating an Emergency FBW Disconnect Switch which is provided on his CP lever.

In addition to aboves, several safety provisions are incorporated in the BK117 FBW Research helicopter as listed below.

- Synchronization of both systems of FBW and Mechanical;
  Before the FBW system is engaged and connected

to the mechanical back-up system、the DDV actuators move to match with the mechanical linkage position、and after then both systems are connected each other.

·Bypass mode provided on the DDV actuators;
The DDV actuators go to the bypass-mode when the FBW system shuts down due to a catastrophic failure.

·Emergency manual FBW disconnection;
The FBW system can be disconnected by pulling of the mechanical handle which releases the pressure supply to the hydraulic clutch.

·Actuator hardover monitoring provision to protect the DDV actuator against over travel beyond the allowable limit.

·On board monitoring of the system operating data and helicopter flight parameters.

Fly-By-Wire flight control system

The FBW flight control system、whose architecture is presented in previous paragraphs Ⅱ and Ⅲ、is completely installed on the BK117 FBW Research Helicopter. All of the major components i.e. MACC、FCC、TACC、the DDV actuator、the 3-axis rate gyro etc. were developed by domestic manufacturers、and have been qualified as on-board equipment.

FBW/Mechanical Interface Unit

Two interface units are installed on the FBW research helicopter. One of them、shown on Figure 9 is for 3 axes(pitch、roll、CP) and the other is for yaw axis. The units have a linkage mechanism whose operating modes、FBW MODE or MECHANICAL MODE、are managed by the FBW system engage-disengage command.

Instrumentation System for Data Aquisition

Flight parameter data and FBW System operation data are aquired by an on-board instrumentation system. The system consists of two sub-parts of the PCM Data recording system and the telemetering system for monitoring the condition of the research helicopter on the ground control center. More than 100 parameters are monitored during the flight test.

V System Assessment

The FBW Research Helicopter is being assessed on both of the functions and the performance.
The remarkable item of the assessment configuration is the flight simulation tests conducted at the ground test phase prior to the flight test.
The flight simulation tests have been conducted with the actual FBW Research Helicopter mounted in the Flight Simulation Facility as shown on Figure 10 and Figure 11. This test configuration offers the following advantages.

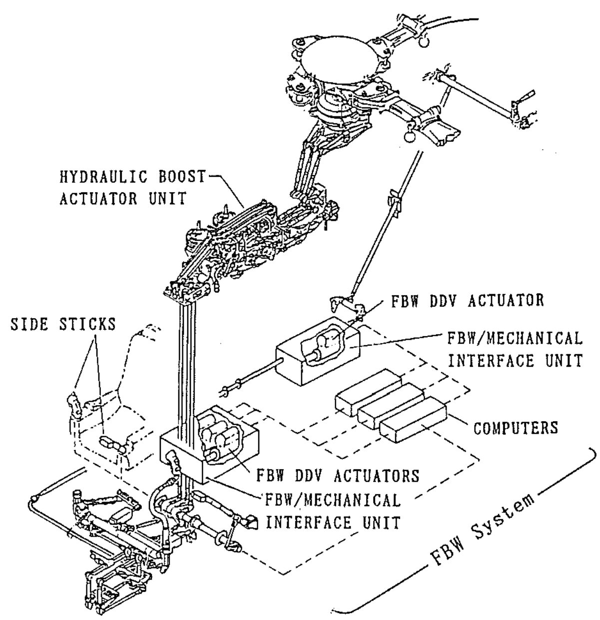


Figure 8. Configuration of the Flight Control System

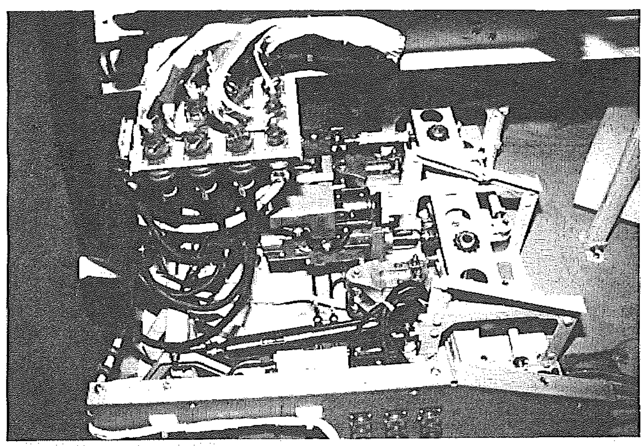


Figure 9. FBW/Mechanical Interface Unit

·Accurate evaluation of the flight control law because of、
 ··Perfect introduction of the static and dynamic characteristics of both flight control systems of the FBW and the mechanical backup into the flight simulation.
 ··Pilot interface completely the same with the flight test condition.

·Verification for the software/hardware integration with maximum effectiveness by utilizing the whole aircraft system.

·Precise evaluation of flight safety by、
 ··Training of pilots on the FBW configuration helicopter.
 ··Effective emergency procedure established on the actual cockpit environments.

The evaluation of the two pilots' coordination at a catastrophic FBW system failure is the most interesting and important. The emergency procedure has been evaluated and established during the flight simulation tests.
A typical example was the evaluation of the actuator hardover as follows; When the actuator hardover was put into the FBW system, the monitoring provision detected the hardover and shut down the DDV system. Then the DDV actuators immediately went to the bypass-mode operation. The safety pilot successfully overrided and continued the control of helicopter within the flight envelope limits.

The overall test flow from the components development to the flight test is shown on Figure12. Some topics on system assessments are shown below.

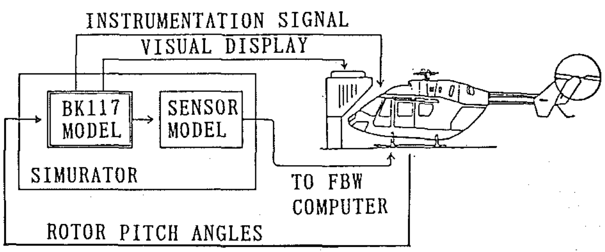


Figure 10. Flight Simulation Set-Up with the BK117 FBW Research Helicopter

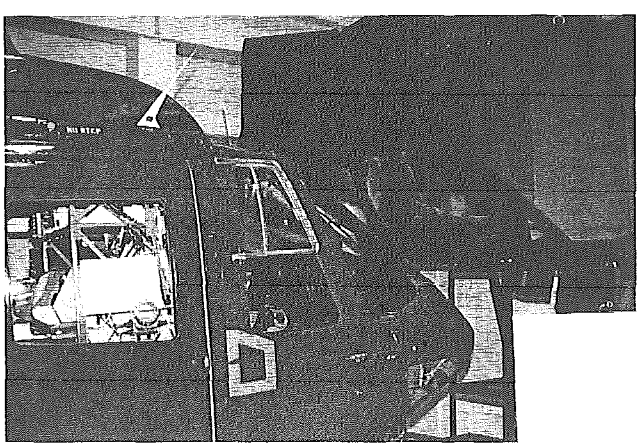


Figure 11. The Bk117 FBW Research Helicopter in the Flight Simulation Facility

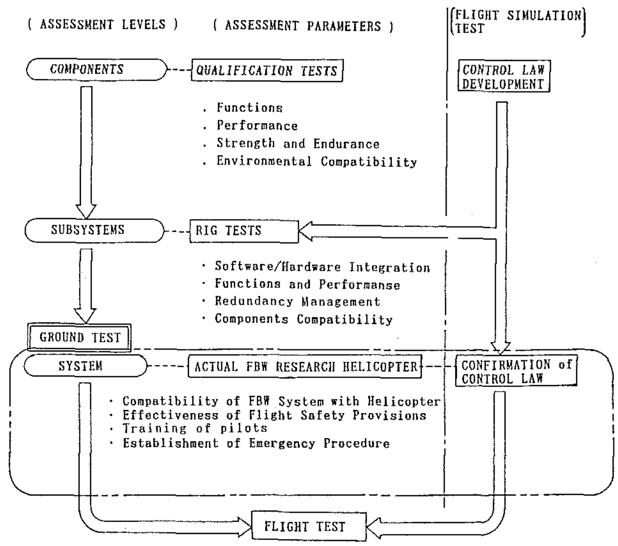


Figure 12. Flow of the System Assessment

Software/hardware integration test

The software/hardware integration test of servo system was conducted to determine the servo loop gain, the FDIR parameters including the threshold level,the time delay,etc.

For the dynamic response test, the DDV actuators were installed in the rig which simulated the stiffness, the load (friction and spring) and the mass of the FBW/mechanical interface linkage and the basic mechanical linkage. Concerning BK117 FBW Research Helicopter, there were gain peaks originated from the relatively small stiffness of the DDV actuator load. The phenomenon was due to the relatively small actuator power and the installation position of the actuators which are in the middle of the basic mechanical linkage. The compensation element was introduced in the servo loop to prevent the gain peak and the dynamic response requirements were satisfied. To make an additional statement, concerning a production type FBW helicopter, the abovementioned phenomenon will not occur because the FBW actuators will be installed near the swashplate assemblies and have large power.

To determine the FDIR parameters, the target of actuator trangent was set, with which BK117 Research Helicopter could keep good handling quality. This target value was defined with the preliminary pilot-in-the-loop simulation test. And to achieve the target, the FDIR parameters were predetermined with the computer simulation of the failure of the servo system. And the FDIR parameters were tuned in the software/hardware integration test.

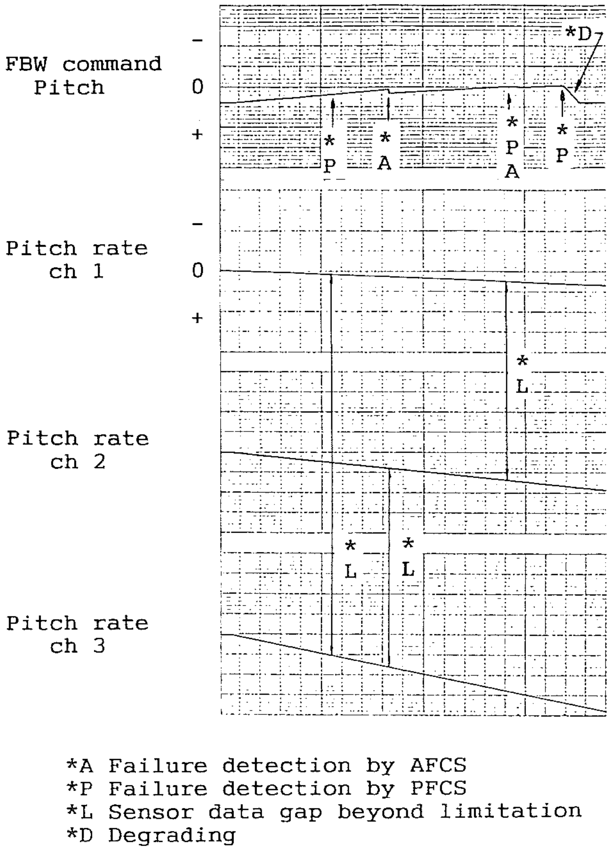


Figure 13. A Result of Failure Simulation

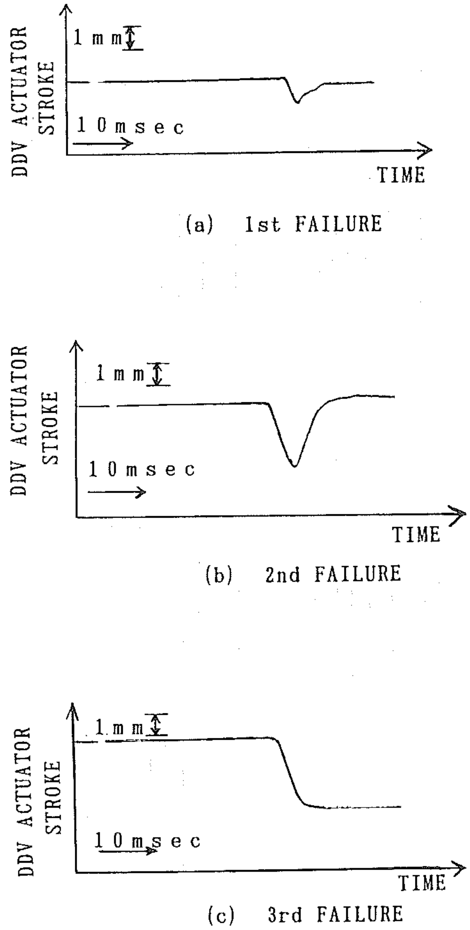


Figure 14. DDV Actuator Trangent

Ground test

One of the most important items in the ground test phase is the failure simulation test. In this test, the system is evaluated both in the open loop configuration and in the pilot-in-the-loop configuration. FIGURE 13 shows a result of the open loop failure simulation to verify the logical action of the system after occurrence of sensor failures. Detections of failure and also degradation of control mode are shown in this figure. An example of the actuator trangent in case of the servo system failure is shown on Figure 14. It was substantiated that the actuator trangents shown on Figure 14 have few influence on the handling quality of the helicopter.

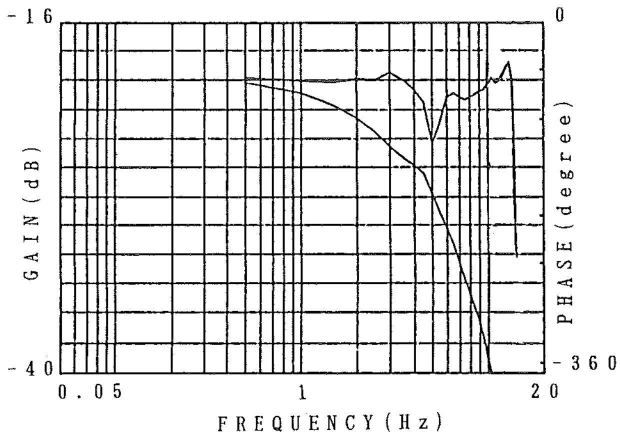
In the ground test phase, also the dynamic response of the FBW flight control system was measured on BK117 FBW Research Helicopter. A result of the dynamic response is shown on Figure 15. It is notified that the mechanical linkage have the gain peak near 10 Hz, but the system is not unstable.

Concluding Remarks

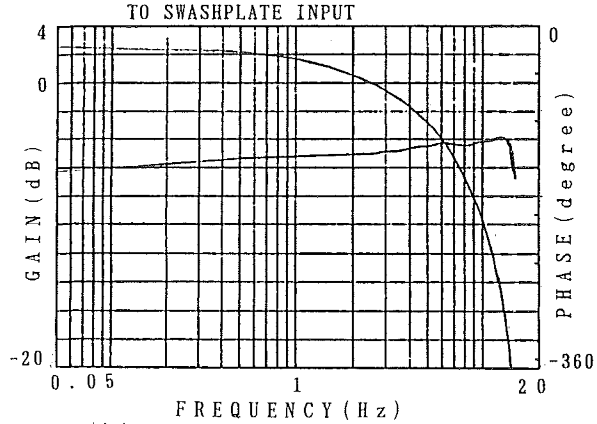
BK117 FBW Research Helicopter is programmed as the first trial in Japan to establish the technological basis of the FBW system for helicopter. This program is now undergoing and the assessments in the flight tests are continued. Future helicopters will demand reliable and sophisticated FBW system providing higher controllability and maneuvarability with less pilot workload. The experiences with this FBW system and the results of the assessment tests are expected to give many fruits for the development of the next generation helicopter.

Acknowledgments

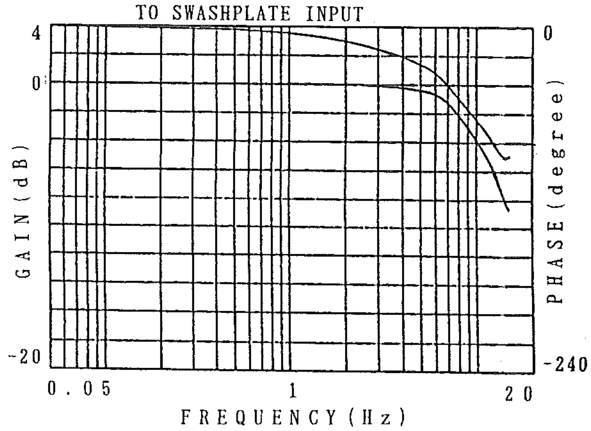
The authors appreciate the members of associated manufacturers who have exerted great effort to develop the equipment of the FBW system.



(a) FROM SIDE STICK CONTROLLER OUTPUT
TO SWASHPLATE INPUT



(b) FROM SERVO SYSTEM INPUT
TO SWASHPLATE INPUT



(c) FROM SERVO SYSTEM INPUT
TO DDV ACTUATOR OUTPUT

Figure 15. Yaw Servo System Dynamic Response

References

(1) T. Uchida, Y. Shimizu et al. "TRIPLEX DIGITAL FLIGHT CONTROL SYSTEM FOR THE STOL RESEARCH AIRCRAFT "ASKA"", AIAA/IEEE 8th Digital Avionics Systems Conference, 1988.

(2) B. Gmelin, G. Kissel, G. Mansfeld "KEY TECHNOLOGIES FOR A NEW FLYING HELICOPTER SIMULATOR", International Symposium, In-flight Simulation For The 90's, 1991.