A Study of the Flight Safety under IMC

Yuichi Kumamoto
Guidance Research Engineer

Hajime Fujimoto
Guidance Research Engineer

Takaki Amano
System Research Engineer

Keiji Kobayashi
Control Research Engineer

Advanced Technology Institute of Commuter helicopter LTD.
Kakamigahara City, Gifu-Pref. 504 Japan

1.ABSTRACT

Recently, accidents of small aircraft, especially that of helicopters, have been increased in Japan. The various reasons for that are supported. One of the most attractive and most important causes is an operation in bad weather (poor visibility). The cause can be divided into two cases, one is the loss of communications and his/her position during the unexpected rapid weather change, and the other one is the excessive workloads by the loss of visual cue (ex. Vertigo).

Under the above circumstances, the drastic improvement of the helicopter operations safety in bad weather has been researched and developed from 1994 to 2000 by ATIC (Advanced Technology Institute of Commuter helicopter Ltd.). Our goals are;

1. To improve the ability of instrument flight of helicopters.
2. To improve the ability of the IFR operations based on the future navigation systems with the Global Positioning System (GPS).

After introducing the outline of whole "Flight Safety study", this paper mainly describes the Automatic Flight Control System with DGPS helicopter precision terminal procedures to enable near zero-zero approaches to a hovering at heliports, including the recent result of flight simulation.

2.ABBREVIATIONS

ACAH	Attitude Command Attitude Hold
ACC	Actuator Control Computer
ADC	Air Data Computer
AEO	All Engine Operative
AI	Attitude Indicator
ATC	Air Traffic Control
ATIC	Advanced Technology Institute of Commuter helicopter
BLD	Balked Landing
CLD	Continued Landing
CNS	Communication, Navigation, and Surveillance
CP	Collective Pitch
DGPS	Differential GPS
DME	Distance Measuring Equipment
FBW	Fly By Wire
FCC	Flight Control Computer
FD	Flight Director
FMS	Flight Management System
GPS	Global Positioning System
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
ILS	Instrument Landing System
IRS	Inertial Reference System
LDP	Landing Decision Point
MFD	Multi-Function Display
ND	Navigation Display
OEI	One Engine Inoperative
PFD	Primary Flight Display
SID	Standard Instrument Departure
SPICE	Stick & Pedal Interface & Control Electronics
STAR	Standard Instrument Arrival Route
TA	Category A
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VOR	VHF Omnidirectional radio Range

3. INTRODUCTION

3.1 Technical problem for helicopter IFR operation

Recently, though safety and dispatch reliability of the helicopter are taken seriously, the operation by the instrument flight is required in order to realize safety and reliability in which the helicopter is equivalent to the fixed wing aircraft. However, there is a CNS problem in present helicopter IFR system and especially, the technical problem have been left for the safe operation in bad weather.

1. It is difficult to operate IFR using the ATC from the ground in low altitude

because communication and radar system does not work at this region.
2. Present IFR systems and standards are for fixed wing aircraft, so they're not suitable for the IFR operation of the helicopter.
3. The IFR operation to a low altitude at the heliport is very difficult in present IFR system.

From such circumstances, the accidents also occur frequently because of sudden weather change in VFR operation (14 times for 12 years from 1985). Not only foregoing problem but also other problems such as noise and low dispatch reliability have been left in technical problem to be solved.

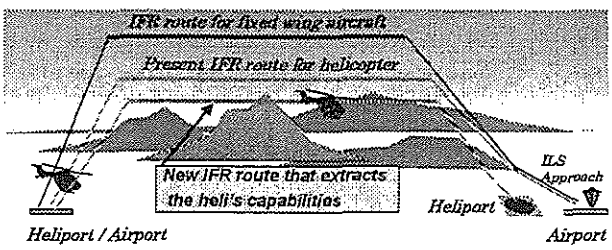

Fig. 1 Present helicopter IFR operation

3.2 Outline of ATIC

The Advanced Technology Institute of Commuter helicopter (ATIC) was established in March 1994 with investments from the Japan Key Technology Center (organization of the Ministry of International Trade and Industry and the Ministry of Posts and Telecommunications) to address these technical aspects of helicopter flight.

There are two research themes in the ATIC - noise reduction and flight safety improvement. ATIC Research Dept. No. 1 is undertaking research into external noise-reducing technology, while research into helicopter flight safety technology is being conducted by ATIC Research Dept. No. 2.

For flight safety, many researches have been executed and future air navigation system (FANS) using the GPS has been constructed in the world. The helicopter IFR operation using infrastructures such as GPS system has been also considered in Japan and it will be operated in early 21st centuries.

For the above circumstances, the ATIC research Dept. No.2 has studied the helicopter which can ensure safety and operation reliability under IMC by dividing the goal into two of "simplification of the navigation" and "simplification of the flight". In this paper, we describe mainly the simplification of the navigation.

We have studied the following technologies to reduce the pilot workload.

1. technology which accurately navigates the fixed flight path from the takeoff to the landing by manual operation and automatic operation.
2. technology that the pilot can intuitively recognize that the operation is rightly carried out.
3. technology which can display information effectively for pilot.

Research progress of the ATIC research Dept. No.2 is shown at table 1. The concept study was carried out in 1994, and the flight simulations were performed 8 times from 1995 to 1998. The ground test was carried out from 1998 to 1999 using hardware and software that will be actually used in flight test.

Table 1 ATIC schedule

94	95 96 97	98	99 2000
Concept Study	Design and Development	Ground Test	Flight Test

We briefly introduce the flight verification system, then describe the development of flight management system for civil helicopters, which reduce the pilot workload, including the results of the evaluations obtained using the latest flight simulations.

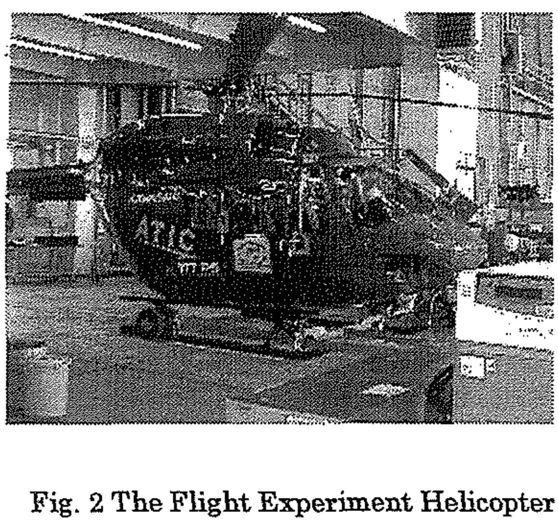

Fig. 2 The Flight Experiment Helicopter

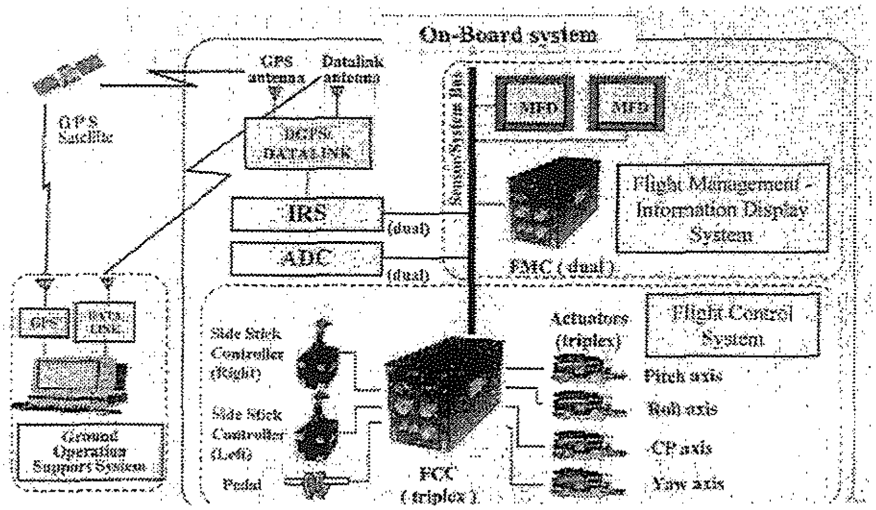

Fig. 3 Configuration of the On-board System

4. CONFIGURATION OF THE ON-BOARD SYSTEM

An overall configuration diagram for the on-board system is shown in Fig.3. The on-board system consists of a flight control system and a flight management - information display system. The flight control system is used to improve the flying qualities and simplify the control operation. This system utilizes a full-authority Fly-By-Wire (FBW) control system to achieve both the response required in Visual Meteorological Conditions (VMC) and high stability required for instrument flights under Instrument Meteorological Conditions (IMC). We can thus adopt sophisticated flight control laws, which enable great improvements in flying qualities. The flight management - information display system guides the helicopter and helps the pilot's judgments. The flight management computer guides the helicopter using positional information obtained from the Global Positioning System (GPS) receiver. In addition, during take-off and landing, the Differential GPS (DGPS) offers more accurate positional information by using compensation information obtained through a data link. With this information helicopter can track an accurate flight path that extracts the helicopter's capabilities, such as a curved approach and landing path. The automatic flight is carried out by linking the FMC and FCC. There are three flight control laws in FCC, RCAH (Rate Command Attitude Hold), ACAH (Attitude Command Attitude Hold), ACVH (Attitude Command Velocity Hold), and ACAH is used in automatic flight because it is the most stable control law in these laws. The navigation commands that calculated in FMC are transmitted to FCC and are transformed to the control commands. They're also transferred to SPICE for backdrive, the side stick moves under automatic flight as well as the case in which the pilot operates. So, the pilot can intuitively understand the condition of the control visually. And pilot can always do override under automatic flight when the pilot applies the force to the ASSC. The information display function helps the pilot make decisions by displaying information required during flight in an integrated and optimized form using two Multi-Function Display (MFD) units. Thus, the flight control system and the flight management - information display system together reduce the pilot workload in piloting and other non-piloting operations.

5. DEVELOPMENT OF FMS

5.1 Flight Management System

In the ATIC research Dept. No.2, the research has been studied on the problem of the navigation within the CNS problem. Concretely, the flight management system based on GPS or DGPS has been studied by changing system such as VOR/DME or ILS used at present. Especially, we have studied automatic flight to hovering and FD flight to LDP. The automatic flight is defined as a system for flying the designed flight path automatically by navigation command calculated in guidance function. In the meantime, the FD flight is defined as a system for flying manually, while the pilot uses FD as a reference. The minimum height of FD flight is defined as a height of LDP considering the failures such as an engine failure under IMC. The minimum height of the automatic flight is defined as a height of hovering considering CAT Ⅲ (near zero-zero approach) of fixed wing aircraft.

And we have researched not only flight management system, but also approach profile that extracts the helicopter's capabilities when the GPS is sanctioned as primary navigation mean.

5.1.1 Efficiency of FD flight and automatic flight

The effectiveness of these flights is divided into two cases whether the GPS is approved as primary navigation means or not.

The FD flight using the GPS is used as supplementary navigation means, when the GPS is not approved as primary navigation means, and the conventional route is used. The pilot workload is reduced, because a control is easier than usual method in this case. The flight safety is also improved by using the FD, because it is possible to move safely to the position where helicopter can be controlled from ground when weather changes rapidly from VMC to IMC. When the GPS is approved as primary navigation means in the FD flight, it is possible to reduce the pilot workload more and more in comparison with the case as mentioned by flying the GPS route and using DGPS on approach of which the high precision is required. Furthermore, it is possible to set the flexible flight route, because it is not necessary to use the ground navigation aids in the route setting. Operation reliability is also improved, because the navigation becomes possible to near LDP even in IMC. In addition, there is the possibility of the application by the low cost in comparison with the installation of the automatic flight, because there is no improvement of the flight control system such as the case of the automatic flight.

The advantage of the automatic flight in not approving the GPS as primary navigation means is equal to the application of the FD flight except that the navigational accuracy is improved.

Though it is also almost equal to the case of the FD flight in which the GPS is approved as primary navigation means, the operation reliability is improved more and more in comparison with the FD flight, because a helicopter is navigated to the hover in the automatic flight.

5.1.2 Details of the Flight Management System

Fig. 4 shows the block diagram of the flight management system. The guidance function is the most important in the flight management

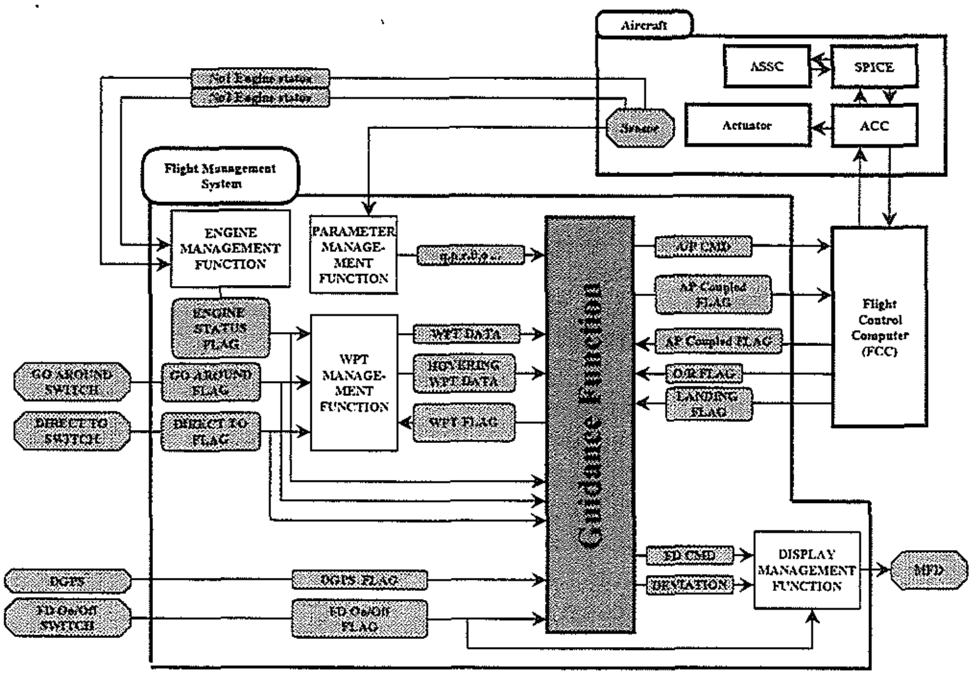

Fig. 4 Block Diagram of Flight Management System

system. And it is coupled to the flight control system, then FD flight and automatic flight are accomplished. There are four functions as other functions in flight management system. Engine failure control function watches the engine condition. Parameters control function watches the sensor conditions. Waypoint control function controls the waypoint used by the guidance function, and display control function controls outputs for display.

The guidance function judges the condition of the helicopter from the state flag (ex. Go Around flag) and waypoint data. And the guidance function adjusts the command gain necessary for calculating the navigation command. And the errors from the preset course are also calculated, and it is multiplied by command gain adjusted in advance, then the navigation command is created. The calculated errors are used for not only a calculation of the navigation command but also a decision of disengagement for automatic flight and changing the waypoint.

The guidance function is based on the traditional PID control to calculate the four axes navigation commands which are pitch attitude command (θ command), roll attitude command (ϕ command), yaw rate command(r command), and vertical speed command (H dot command) which are supplied to FCC (table 2). Those navigation commands are fed to actuators for automatic flight and to MFD for pilot FD manual flight.

Table 2 Navigation Command

Axis	Response Type	Reference		
		En-route Approach CLD	Hovering	BLD
Pitch	Attitude Command	Velocity Error	X Error	Velocity Error
Roll	Attitude Command	Lateral Deviation	Y Error	Lateral Deviation
Yaw	Rate Command	Heading Error		
CP	Rate Command	Height Error		Torque Error

5.1.3 Design of the approach profile

It is necessary to develop IFR operation ability by utilizing capabilities of the helicopter in order to improve the flight safety and dispatch reliability under IMC, and there are some problems to be solved for the IFR operation in approach and landing. These elements are concretely required.

1. It shouldn't interfere with the operation of fixed wing commercial aircraft around the airport, and it should be operated simultaneously.
2. The operation in the pinnacle heliport should be enabled.
3. Noise problem in the building roof operation in urban area or heliport operation should be overcome.

In this study, the course which combined an steep angle profile of 12 degrees considering low noise with the TA vertical take-off and landing approach profile was designed (Fig. 5).

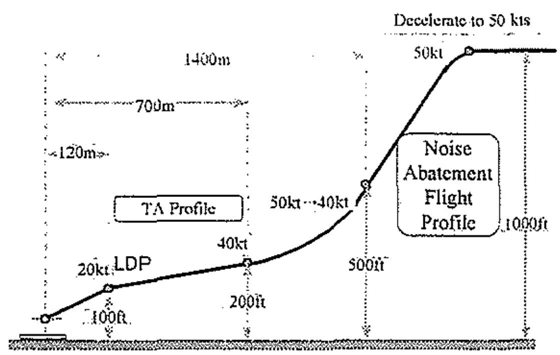

Fig. 5 Approach Profile

By flying at 50kt and -1000fpm, the region that is easy to generate slap noise is avoided under low-noise profile approach. The transition segment for connecting with the conventional TA profile is set after the low-noise profile end, and the speed is decelerated from 50kt to 40kt, and the height is also descended from 500ft to 200ft. It is similar to the TA profile after the transition segment end. This profile has been confirmed that it is available for the practical use by using actual helicopter (BK117).

Fig. 6 shows the comparison the above-mentioned flight path with the course in the ILS approach used in the conventional helicopter IFR operation. We see from fig. 6 that it is not necessary to operate in low altitude for long time if we use the new course, then it's possible to solve the noise problem very easily. And, it is also possible to prevent the interference of the fixed wing aircraft because the conventional ILS approach course can be avoided by flying this course. In addition, it is also possible to land on heliport and building roof in urban area where ILS has not been provided.

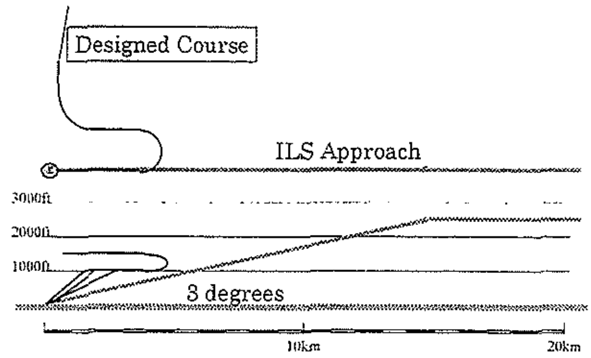

Fig. 6 Comparison with New App. and ILS

5.1.4 Design requirement of the guidance function

The design requirement of the guidance function for automatic flight is shown in table 3. These values are designed, as the error for automatic flights, without including the error of GPS and the accuracy of hardware. The flight path for the automatic flight is divided into three of en-route, approach and hovering. And requirements for height error, lateral deviation, speed error are set for each segment. En-route is defined as the segment from SID to STAR and approach as the segment to the hovering after the STAR.

Table 3 The Design Requirements for Automatic Flight

	En-route	Approach	Hovering
Herr[ft]	±30.0	±30.0	±5.0
Dev[ft]	±50.0	±50.0	±20.0
Verr[kt]	±10.0	±10.0	—

5.1.5 Override function

Fig. 7 shows the re-engage region for automatic flight. It has been designed in order to return automatically to the route when the pilot finished override if the helicopter is in the region.

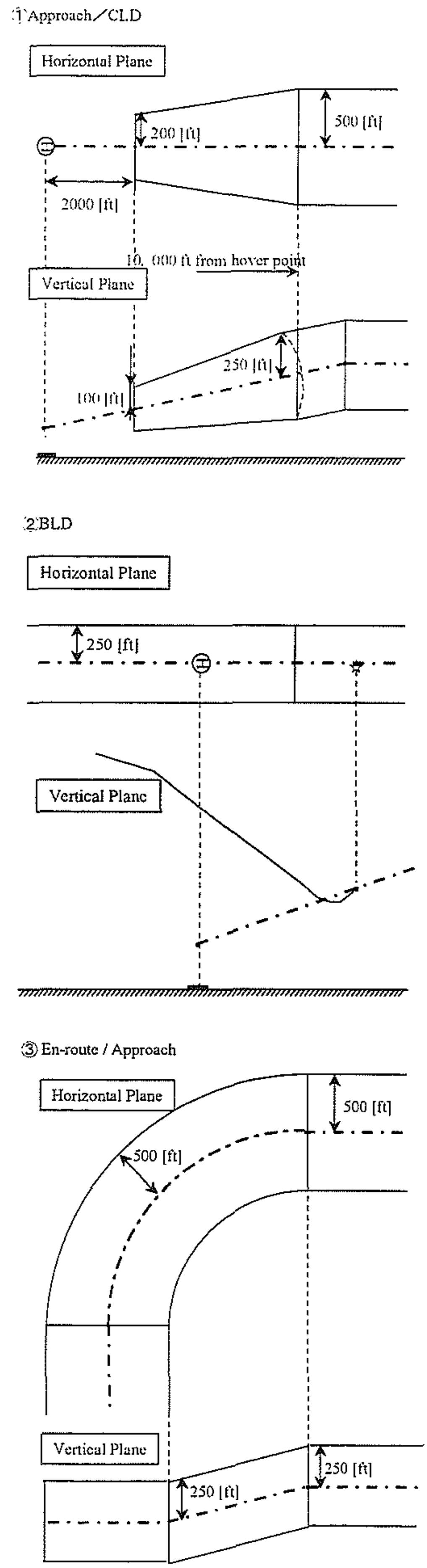

Fig. 7 Re-engage Region for Automatic Flight

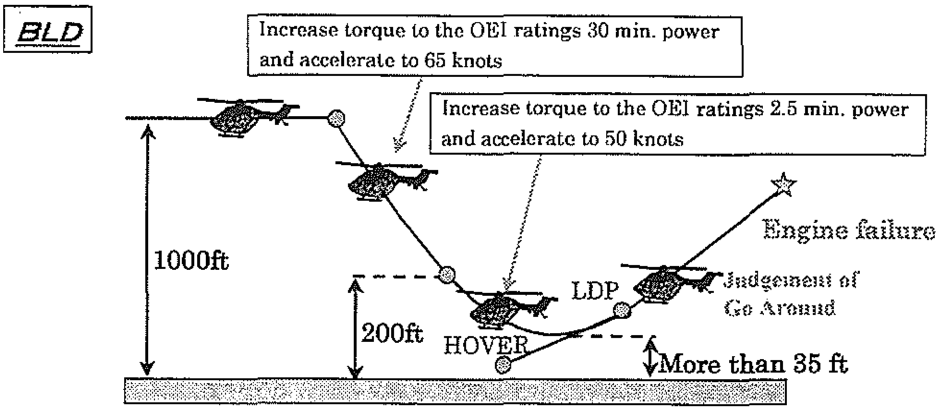

Fig.8 BLD Profile

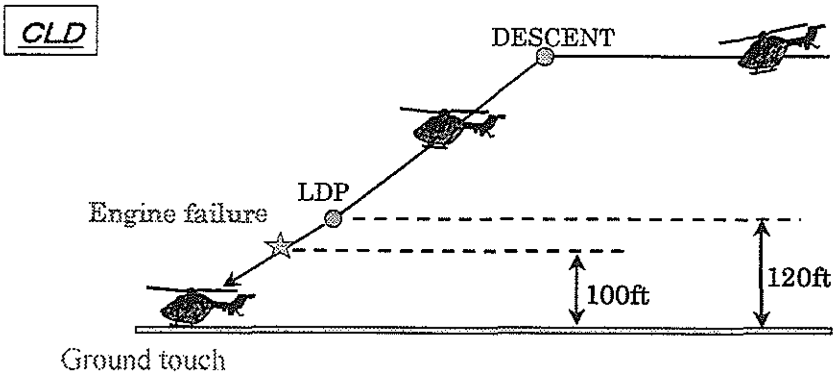

Fig.9 CLD Profile

5.1.6 One engine failure mode

We have also studied the guidance function for BLD and CLD in order to operate even one engine failure (fig. 8, 9). The BLD is executed by pushing the button as a pilot judgment.

5.2 Information – display system

Since visual cue is insufficient under IMC, the manual operation becomes very difficult. We have studied the presentation method, especially the display of the PFD for information display system that the pilot can easily acquire the attitude of the helicopter even in IMC.

The PFD that we designed for flight test is shown in fig. 10. The AI display changed at the MFD full size to recognize the attitude of helicopter with ease. And, the meter confirmation of the pilot was simplified by switching airspeed indicator to hover meter (horizontal velocity indicator) by airspeed.

Fig. 11 shows the ND that we designed for flight test. We see from fig. 11 that a pilot can intuitively recognize the circumstances around a helicopter because the ND shows an airway that is combined with topographic map. The conventional display of ND usually shows only a horizontal plane, but this ND also shows a vertical plane under the display of a horizontal plane, so a pilot can recognize the relation with a helicopter and the ground.

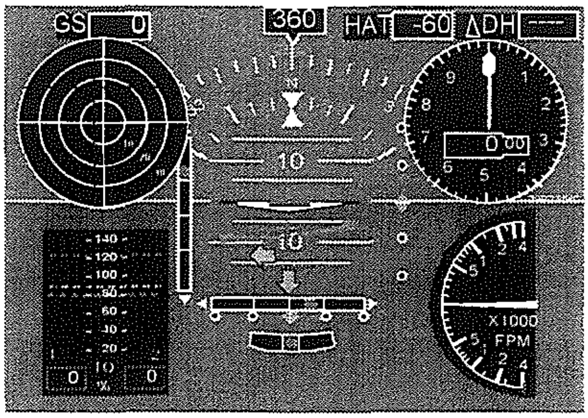

Fig. 10 Primary Flight Display

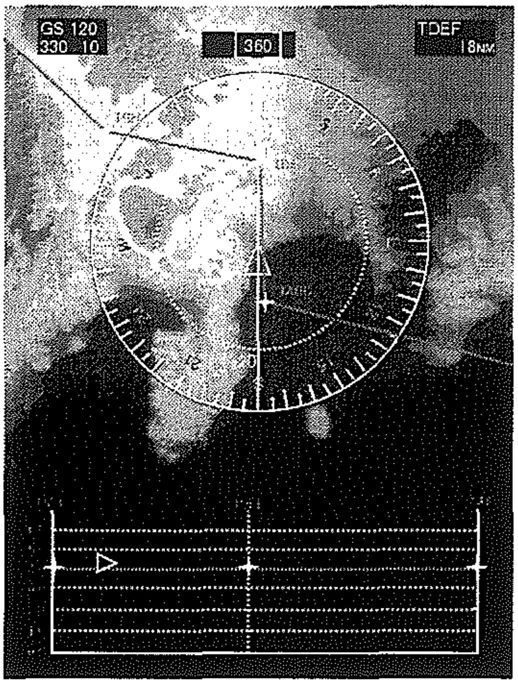

Fig. 11 Navigation Display

6. RESULTS OF THE FLIGHT SIMULATION

The flight simulations have been performed four times for this study, and the various data required to design the guidance function were obtained from the results of those tests. A simulated cockpit for the simulation was prepared and used in this study connected to a dome-type flight simulator of Kawasaki Heavy Industries, Ltd. (KHI)(Fig.12, 13).
Our primary evaluation results thus far are described below, based on the latest simulation.

Fig. 12 Simulated cockpit for simulation

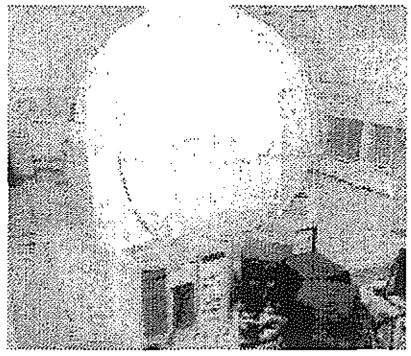

Fig. 13 KHI dome-type flight simulator

Fig. 14 shows the waypiont for flight simulation. The wind conditions were checked around the Gifu Air Base used by flight test carried out from the middle in 1999, we set wind direction 315°, steady wind of 20kt and gust.
The automatic flights were carried out from en-route to hovering in AEO and BLD/CLD in OEI. By performing sufficient flight simulations prior to a flight demonstration, satisfactory performance, reliability, and safety can be established before starting the flight tests.

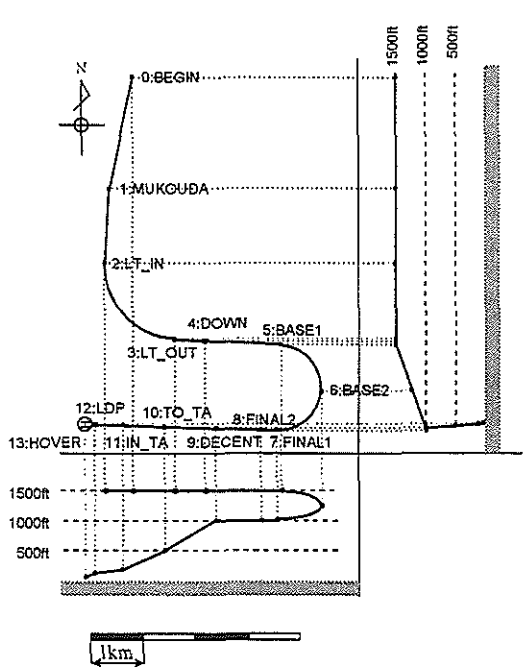

Fig. 14 Waypoint for flight Simulation

6.1 Results of the evaluation on en-route

Fig. 15 shows the time histories of the velocity error on en-route. We see from the graph (a) of fig. 15 that velocity error was within ±3 knots in no wind condition. It is satisfied with the design requirement for automatic flight that we established. On the other hand, the graph (b) of the velocity error in wind condition is not smoother than the result of the above. It is considered that it is based on the effect of the gust. There is a part that exceeds the design requirement in wind condition. But the design requirement has been established under no wind condition and the helicopter is controllable in this case, of course there is no tendency to diverge by gust.

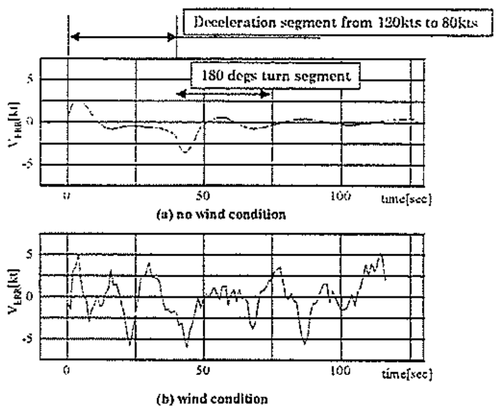

Fig. 15 V error (En-route)

Fig. 16 shows the graph of the deviation and height error on en-route. The frame in bold line in the graph shows the design requirement of the automatic flight set in ATIC.

In case of there being no wind, there is a part in which the height error deviates from the design requirement a little. It is occurred in the leg that decelerates from 120kt to 80kt. This cause is because the rate-of-climb arises in order to do the pitch-up in the deceleration. And, it is equal on the height error in case of the no wind condition and wind condition. On lateral deviation, there is a part that deviates from the design requirement. It is occurred near the changeover from the turning descent leg to the level straight-line leg.

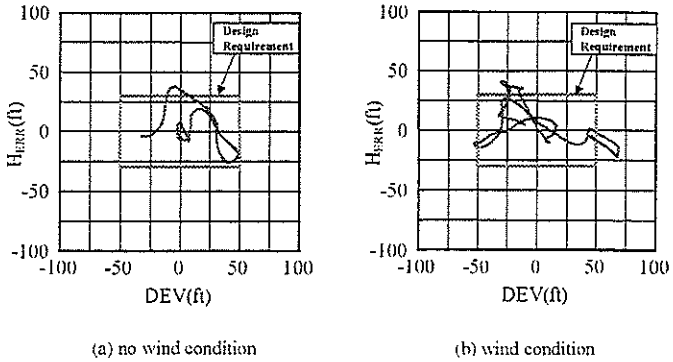

Fig.16 Results of Evaluation (En-route)

6.2 Results of the evaluation on approach

Fig. 17 shows the time histories of the velocity error on approach. We see from the graph (a) of fig. 17 that the velocity error was within ±3 knots in no wind condition and it was satisfied with the designed requirement. Attitudes of the helicopter were changed so frequently by deceleration and descent that the velocity error fluctuated frequently in comparison with the case of en-route. The graph (b) of fig. 17 shows the velocity error in the case of wind condition. We see from the graph (b) of fig. 17 that the motion of the velocity error calmed down from about 120 seconds. The wind condition causes this result. At the beginning of the evaluation, though the helicopter was under the influence of gust because airspeed was used for reference speed, reference speed was changed to the ground speed by height of helicopter (about 500 ft), then the helicopter was out of influence of gust. It is clear that the velocity error was satisfied with the design requirement because it was within ± 5 knots in both cases.

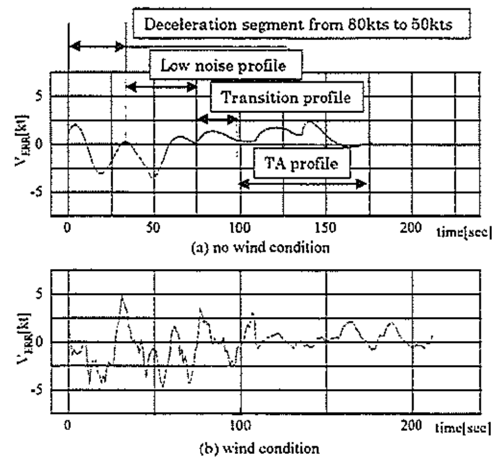

Fig. 17 V error (Approach)

Fig. 18 shows the graph of the deviation and height error on approach. We can see from fig. 18 that both deviation and height error were satisfied with the design requirements. The accuracy on the approach is better than that on en-route, because by using the gain scheduling by the airspeed, it becomes higher gain as lower speed.

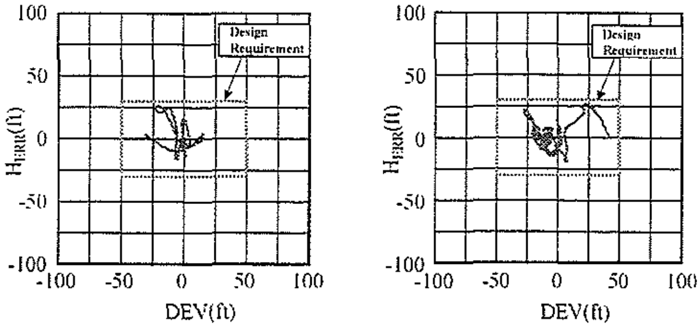

Fig.18 Results of Evaluation (Approach)

6.3 Results of the evaluation for BLD

The results of the evaluation for BLD were satisfied with requirements of torque and velocity that were designed by the flight manual. In this paper, we show the most important factor, height loss. Fig. 19 shows the graph of height loss at BLD. The height loss was 60 ft in the case of no wind condition, and it was 7 ft in the case of wind condition. This is because the wind direction becomes head wind at 315 degrees. We see from fig. 19 that BLD is safely realizable.

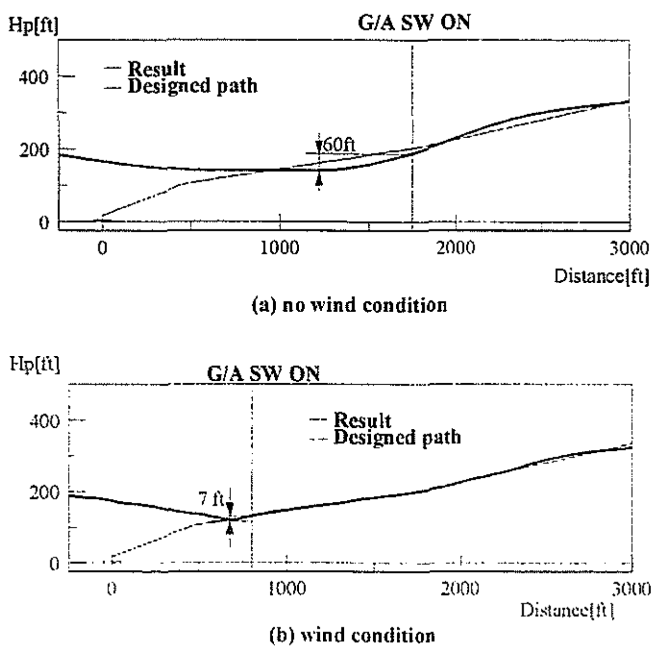

Fig. 19 Height Loss at BLD

6.4 Results of the evaluation for CLD

Fig. 20 and fig. 21 show the results of evaluation at CLD. The rectangle near the 0ft of the Hp graph shows the skid height. We defined landing time that the time when the helicopter touched this rectangle. And, ±100ft Square that shown near the 0ft of the deviation graph shows the size of the landing area of the roof top heliport.

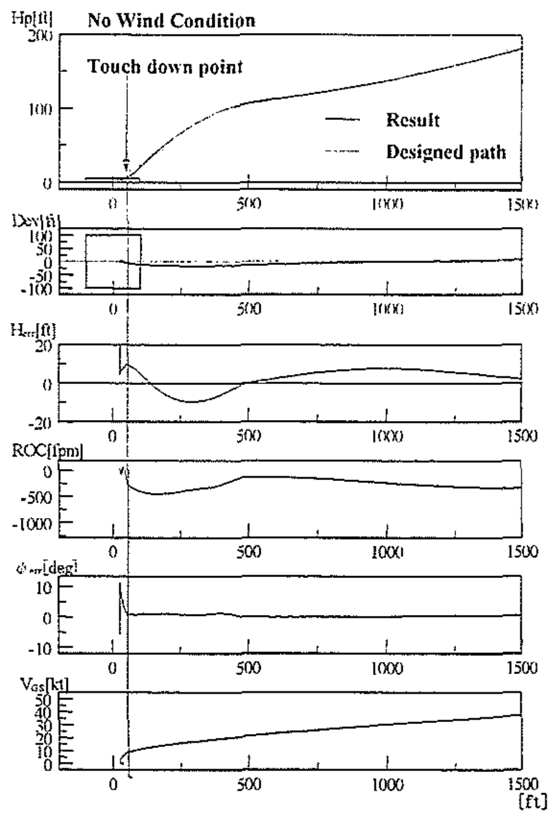

Fig. 20 Results of CLD (no wind)

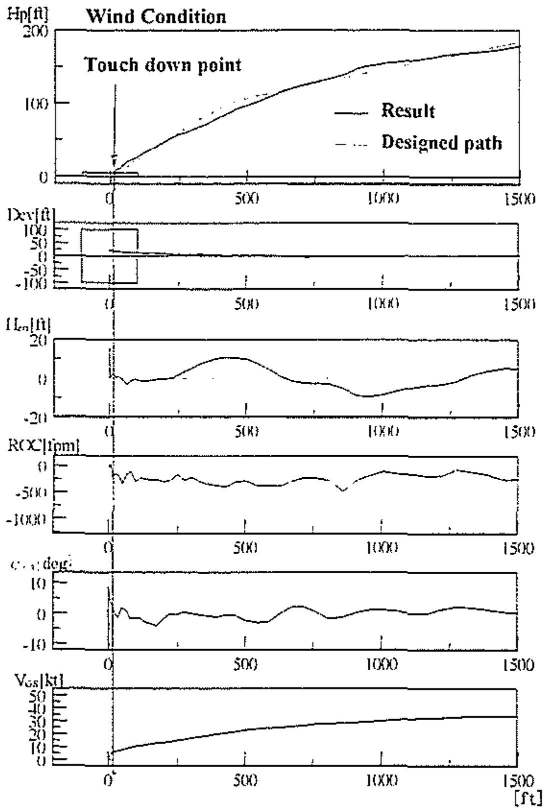

Fig. 21 Results of CLD (wind)

We see from fig. 20 that;

1. It can be grounded without going out from the heliport.
2. The deviation was within ± 20 ft after LDP.
3. The height error was within ± 15 ft after LDP.
4. Rate-of-descent at the ground touching was about 300 fpm, so it was satisfied with the requirement of the rate-of-descent (480 fpm) of the skid (BK117).
5. The direction error was within ±1 degree at the ground touching.
6. The ground speed was under 10 knots at the ground touching.

We see from the above results that automatic flight of CLD is possible in both conditions.

7. CONCLUSIONS

In this paper, the development of a flight management system especially automatic flight for civil helicopters being undertaken by ATIC to reduce pilot workloads has been described. The design requirements are established, considering the operation of civil helicopters, designed a guidance function based on those requirements, and evaluated the results of our design through flight simulations. The following results were obtained:

1. We designed the approach profile that could solve both of "noise problems at heliport or building roof in urban area" and "interference with the fixed wing aircraft operation in the airport" and we examined the profile for automatic flight.
2. The guidance function in the engine failure was examined. And two logic of go around mode and continued landing mode were established.
3. Then, we confirmed through the flight simulation that the guidance function was satisfied with our design requirements.

The results of override function were omitted by circumstances of the space this time,

4. We also examined the override function by flight simulation, and we confirmed that the function was very useful to the automatic flight.

We established the automatic flight, the flight simulation test for FD flight will be carried out at least 3 times in future, and pursue to establish the logic for FD flight.

The flight test is also started from July 1999, and about 100 flights have been scheduled including the evaluation of the automatic flight and FD flight.

9. REFERENCES

1. S.Tanase, H.Nagamori and T.Taira, Flight Test of BK117 Fly-By-Wire Research Helicopter of the 19th Congress of the International Council of the Aeronautical Science Sep. 1994.
2. T.Amano, A.Fujiwara and T.Akita, A Study on Pilot Support Display System for Helicopters of the 35th Aircraft symposium Oct. 1997.(in Japanese)
3. N.Kuraya, Current and Future Application of GPS on Civil Helicopters of the 35th Aircraft symposium Oct. 1997.(in Japanese)
4. H.Fujimoto, M.Takasaki, T.Amano, K.Kimura, Automatic Flight Control and Flight Director Systems of the Heli Japan 98 Paper n. T7-2 Apr. 1998.
5. Y.Kumamoto, H.Fujimoto, M.Takasaki, K,*Kobayashi, A Study of the Guidance* function for Commuter Helicopter of the 36th Aircraft symposium Oct. 1998.(in Japanese)