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FUZZY INTELLIGENT PILOT SUPPORT SYSTEM FOR AN AUTOROTATIVE FLIGHT OF HELICOPTER

by

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1. Abstract

This paper describes a study on an application of fuzzy system to pilot support system for an emergency condition of single-engine helicopter after engine failure. Our system named FIPSS contains two fuzzy systems; one is a fuzzy system to control a helicopter in an unstable condition after engine failure, and the other is a fuzzy system to set a flight course for autorotative landing. We performed flight simulation tests of a breadboard model of FIPSS, and concluded that fuzzy system is useful for both aircraft control and decision making. The techniques used in FIPSS can be extended to pilot support system for normal flight condition, and a system like FIPSS is expected to be a pilot aid to enhance the helicopter operation.

2. Introduction

Fuzzy system is one of the expert system techniques to express the vagueness of words of natural language for utilizing human knowledge in a computer system. A fuzzy system has a set of if..then rules describing human knowledge or experiences in natural language and a set of membership functions describing vagueness of each word, and it can be applied to system control, decision making and so on by executing some operations like so called fuzzy inference. Utilization of human knowledge described in natural language allows a computer system to carry out some actions which could be done only by human expert, e.g. the control of a cement kiln and a glass plant. And in avionics field we can point a feasibility of a computer system which supports or takes the place of a pilot by utilizing skilled pilot knowledge described in a fuzzy system.

In our study, we designed, made and tested a breadboard model (BBM) of pilot support system which incorporates fuzzy system techniques to decrease the pilot workload in an autorotative flight after engine failure, where helicopter is more unstable than normal flight condition. After an engine failure a helicopter pilot has to do the following dual actions at the same time , so he must endure a high workload condition.

(i) Control action to keep the rotor speed, which is no longer regulated by the engine governor, and to recover the aircraft attitude.

(ii) Search of a safe landing point and decision making to create a flight course to reach the landing point.

Our pilot support system intends to support these actions by both increasing the time for decision making and displaying some landing informations, in order to improve the flight safety in an emergency condition.

Before the design of the BBM of FIPSS we made a research on how to support pilot effectively, and found that the following two items are useful.

(i) Automatization of flight control to increase time for decision making.

(ii) Supporting decision making directly by executing some parts of decision making process with a data base which includes skilled pilot knowledge.

So, in our system named FUZZY INTELLIGENT PILOT SUPPORT SYSTEM, FIPSS has two major functions corresponding to the above items.

(i) Control function to automatically establish a stable autorotative flight.

(ii) Decision making support function which advises a proper flight course to the pilot.

The BBM of FIPSS has also an automatic flight function after engine failure by coupling above two functions. The overview of FIPSS operation is shown in figure 1.

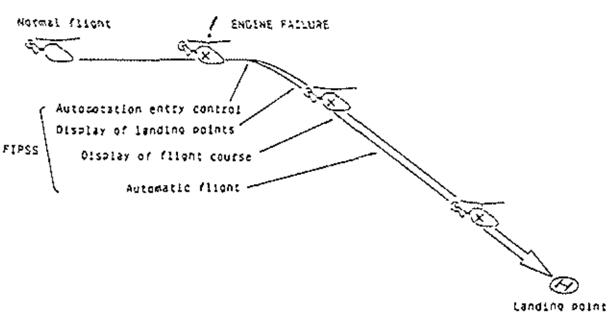

Figure 1 Operation of FIPSS

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RULE 1;
    if   PITCH_ANGLE      is POSITIVE_SMALL
    and  PITCH_RATE       is POSITIVE_SMALL
    then CONTROL_COMMAND  is NEGATIVE_MIDDLE

    ( If the nose is rising up gradually
      and the pitch rate is upward and
      small,
      then the cyclic stick should be put
      forward moderately. )

RULE 2;
    if   PITCH_ANGLE      is NEGATIVE_MIDDLE
    and  PITCH_RATE       is ALMOST_ZERO
    then CONTROL_COMMAND  is POSITIVE_SMALL

RULE 3;
    if   PITCH_ANGLE      is NEGATIVE_BIG
    and  PITCH_RATE       is NEGATIVE_BIG
    then CONTROL_COMMAND  is POSITIVE_BIG

RULE 4;
    ............
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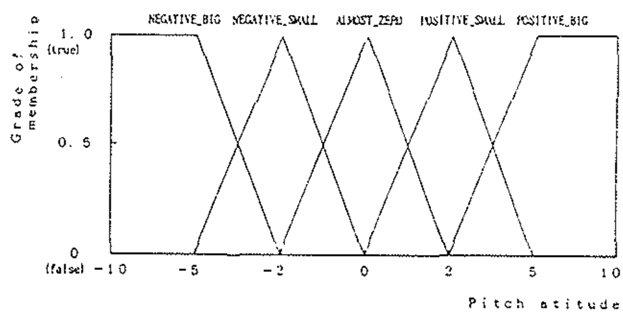
(a) Example of fuzzy control rule



(b) Example of membership function

Figure 2 Fuzzy rule and membership function

3. Outline of fuzzy system

Fuzzy system is one of the expert system based on a theory to process the vagueness of natural language. In the followings, a flight control system of helicopter is taken for example to explain fuzzy system briefly.

In fuzzy control system, control laws are described with linguistic rules that include vague expressions. And the rules are based on knowledge and experiences of experts. For instance, the rules shown in fig. 2(a) are part of the rules for a helicopter control system. These if-then rules describe know-how of pilots to control a helicopter.

In these rules the expression such as 'small' or 'big' should be noted.

These expressions are easy to understand for mankind, but to process them in computer system the vagueness of the words 'small' or 'big' must be numerically defined. Conventionally, binary definition based on true or false has been used, e.g. "A number less than 5 is small". However there comes the unnaturalness that "4.99 is small but 5.01 is not small". In fuzzy theory, the degree of 'small' can be defined so that it gets a value between zero and one where zero shows no degree of 'small'. A chart shown in fig. 2(b) is used for processing vagueness of the words 'small', 'big', 'middle', and so on in close form to human feeling. This chart is called "membership function" and it expresses the relationship between words of natural language and numerical value. With membership function a computer system can generate control command by processing linguistic rules. This process is called fuzzy inference, and there are many methods of fuzzy inference proposed now, but details of these methods are not described in this paper.

Up to this point fuzzy control system has been taken to explain fuzzy system, but a fuzzy system can be also applied to a system of decision making.

In a fuzzy control system, the direction and quantity of steering command are decided from present attitude and rate of the helicopter.

On the other hand in case of decision making system, a fuzzy system infers the best selection of flight course from the aircraft situation.

Knowledge and experiences of experts are neither based on a mathematical expression nor a numerical value. The conventional method of control system sometimes does not work well because the poor precision of mathematical plant models. But fuzzy system can be made not depending much on mathematical technique because it is described with the rules in natural linguistic expression. And the rules of fuzzy system are easy to understand and design.

4. System description of FIPSS

Figure 3 shows the block diagram of FIPSS. Roughly speaking FIPSS consists of two subsystems i.e. the control subsystem which is a fuzzy controller and the display subsystem which is the higher subsystem of the control subsystem.

The display subsystem has a map generator and a CRT display with a touch-panel sensor, which displays flight informations to pilot and also gets pilot's input. It infers some flight courses to support pilot's decision making after an engine failure. Flight course data generated by the display subsystem can be linked to the control subsystem.

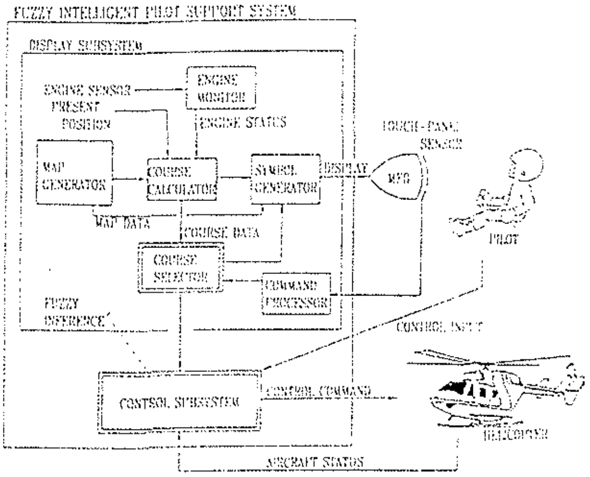


Figure 3. FIPSS overview

The control subsystem having some functions including the autorotation entry function and the attitude hold function, detects pilot's control and aircraft state through the sensors, and controls the aircraft corresponding to the selected control mode.

The functions and operations of each subsystem are as follows.

(i) Display subsystem

After a detection of engine failure the display subsystem displays some points suitable for landing, overlapped on a geographic map. When the pilot selects and touches a point where he wants to land on the CRT display, the subsystem recognizes the point through the touch-panel sensor. Then the subsystem generates some courses to fly to the selected landing point avoiding geographical obstacles. The subsystem performs fuzzy inference for each course to decide whether the course is good or bad for safe landing. Some significant items which must be considered by pilot to decide the flight course are described in if..then rules for this inference, and the conclusion of this inference is an nondimensional parameter which shows the degree of excellence of a flight course. Three courses which marked the best inference conclusions are displayed on the CRT. Now, the pilot can select a flight course touching the CRT display, then the courses not selected by the pilot fade away. When the control subsystem and the display subsystem are coupled, the data of the selected course will be linked to the control subsystem to guide the aircraft automatically toward the landing point.

(ii) Control subsystem

The control subsystem have some functions i.e. an autopilot function including SAS and attitude hold for normal condition, an autorotation entry function for flight just after engine failure and an automatic flight function after deciding the landing point and the flight course to reach there. The latter two functions are engaged automatically depending on the engine condition or the flight phase. The autorotation entry function allows automatic recovery just after an engine failure. When an engine failure is detected, this function keeps the rotor speed, stabilizes the aircraft attitude and adjusts the airspeed to get the minimum descending rate. When the display subsystem and the control subsystem are coupled, the automatic flight function will be engaged automatically after a steady autorotation is established, and it carries out a flight along the selected flight course taking the place of the pilot.

5. Control subsystem of FIPSS

In this section, the control subsystem ,which gives the pilot the time for the decision making by means of releasing the pilot from the recovery action after engine failure, is discussed.

This control subsystem provides the following functions.

(i) Stability augmentation function not disturbing pilot control.

(ii) Autopilot function to hold altitude,attitude and the airspeed in normal flight.

(iii)Autorotation entry function with yaw control and rotor RPM keeping after engine failure.

(iv) Speed hold function , Rotor RPM keeping function and Attitude hold function in autorotation.

(v) Turn coordination function.

(vi) Navigation function for automatic flight along the course which is generated by the display subsystem.

This subsystem has the following four pilot-selectable modes to vary the share of this subsystem in the cockpit load.

(i) Direct(DRT) mode in which control subsystem does not take part at all.

(ii) Stability Augmentation System(SAS) mode in which only stability augmentation function is engaged. This mode does not have an autorotation entry function.

(iii)Fuzzy Autopilot(FAP) mode which has altitude hold, attitude hold and speed hold functions. And this mode has the autorotation entry function which enables the helicopter to enter an autorotative flight automatically.The pilot can control the airspeed and the angle of bank with the cyclic stick.

(iv) Fuzzy Navigation(FNV) mode in which the function to trace the course advised by the display subsystem is added to the functions of FAP mode after steady autorotation is established.

This subsystem performs most of these functions using fuzzy control.

Fuzzy control system is one of the expert systems for system control. The feature of fuzzy control system is the description of the control law with some if-then rules and membership functions. As an example of fuzzy control system, the "Rate Control" block of this subsystem is shown in figure 4.

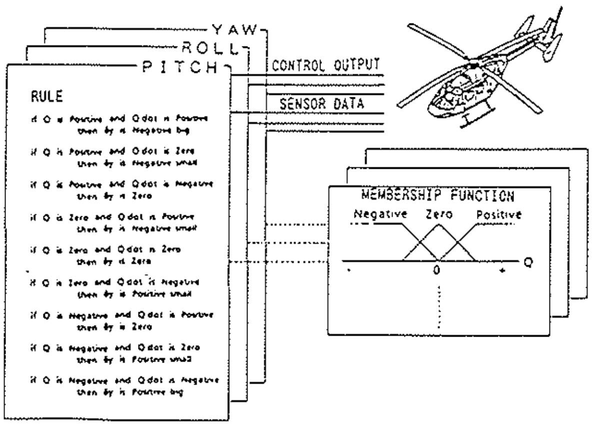


Figure 4 Rate control block

It is easy to make a simple rule set as shown in figure 4. However, in order to control the attitude or the airspeed of a helicopter, many variables are required for the antecedent(input side) of the rule base, so that the number of combination of antecedent variables, which directly means the number of rules, increases explosively. Then the design of a fuzzy control system becomes very difficult or almost impossible.

In order to solve this problem, we have used the method of the multistep inference combining some blocks of rule set which describes only a simple function, as shown in figure 5.

Figure 5 shows the block diagram of the control subsystem. The cores of this subsystem is the path of "Speed control Block"-"Attitude hold block"-"Rate control block" and the block of "Collective pitch control block".

"Speed control block" infers the reference value of the attitude angle to hold the present speed in normal flight. Moreover, to obtain the airspeed for the minimum descending rate , the reference value of the attitude angle is inferred after the engine failure.

"Attitude hold block" infers the reference value of attitude rate to follow the attitude reference generated by "Speed control block".

"Rate Control block" generates the control command to follow the reference attitude rate.

The function of the stability augmentation , the control of the speed and the attitude and an bank angle hold can be achieved through this path.

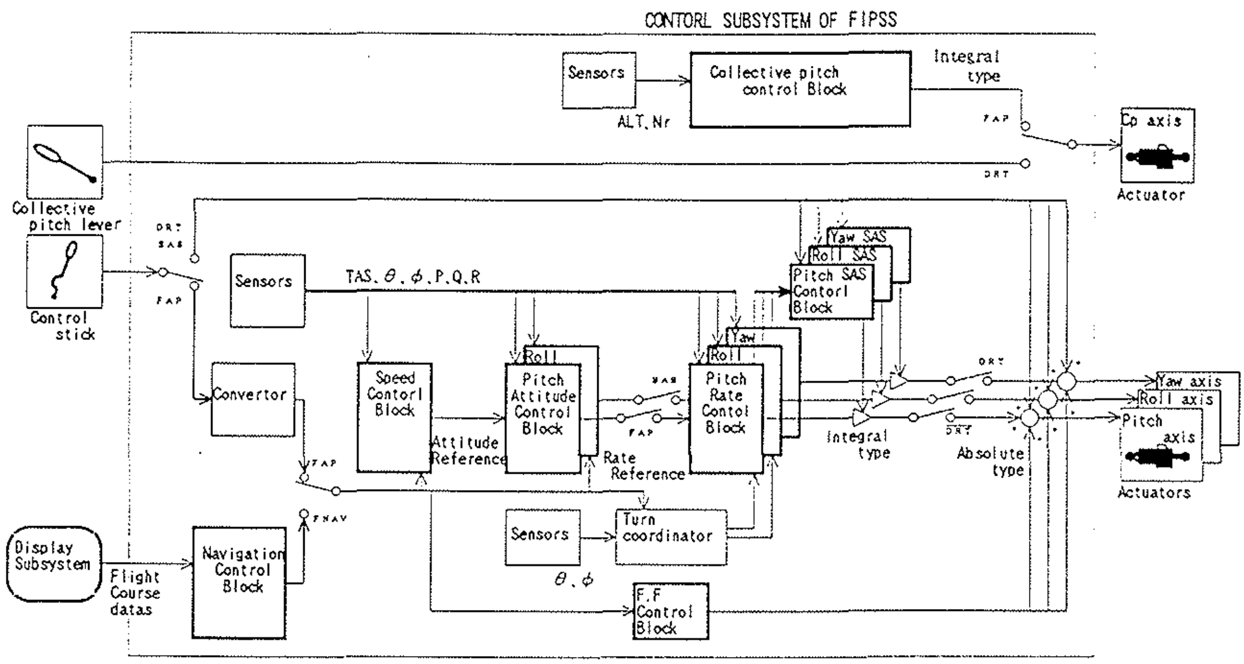


Figure 5 Block diagram of control subsystem

On the other hand, "Collective Pitch Control block" infers the quantity of the collective pitch command to maintain altitude in normal flight. Moreover, after engine failure, this block generates the command so that the rotor RPM is maintained within limitations.

The subsystem has the following blocks for other functions.

• "Navigation control block" which generates the guidance command to fly along the course generated by the display subsystem.

• "Feedforward(FF) control block" which improves the response of the helicopter to the pilot input when the FAP functions are working.

• "Stability augmentation system(SAS) control block" which adjusts the output of fuzzy SAS control not to spoil the pilot control in SAS mode.

In t[illegible] subsystem, the time when the engine torque is los[illegible] regarded as the occurrence of the engine failur[illegible]

Thus, in this subsystem each inference block is designed as a function unit to perform only a simple function, and the subsystem performs various functions cascading them and/or connecting them inner/outer-loops.

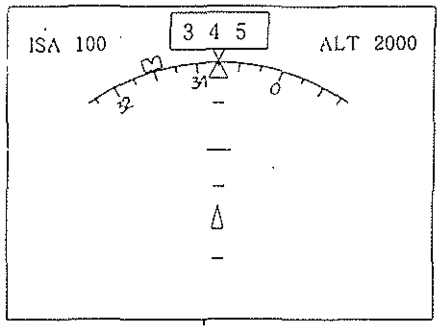
In this method, each inference block is so small that adjustment of rules and membership functions become easy. And the system design combining some functional units has a benefit of facilitating addition and deletion of system functions.

6 Display Subsystem of FIPSS

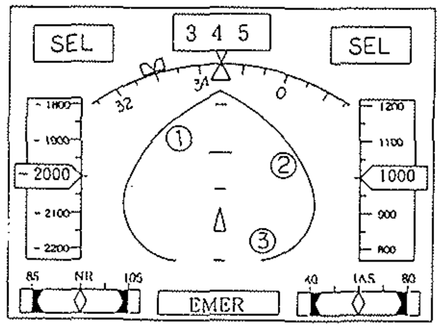
Display subsystem is an expert system which provides the pilot with flight informations about landing points and flight courses in autorotation.

One of the analyses of pilot action on decision making about the landing points and the flight courses is as follows;

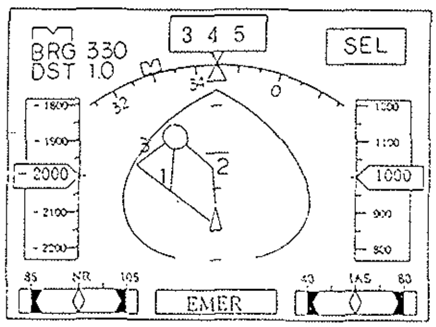
(i) Just after an engine failure a pilot looks for a possible landing place.



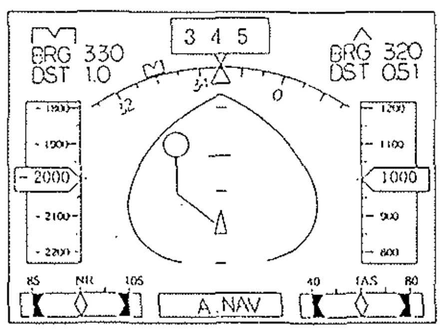
(a) Normal cruise;
map and HSI



(b) Engine failure 1;
reachable range and landing points



(c) Engine failure 2;
recommended flight courses



(d) Engine failure 3;
selected flight course

figure 6 Format and sequence of display

(ii) Then he images a flight course to reach there. and judges whether he can reach there or not with some parameters including the distance to the point. wind direction and wind speed.

(iii)If the judgement is "reachable". he memorizes it as one of alternatives of the flight courses for emergency landing.

(iv) He also looks for another landing point. images a course to reach there and judges whether reachable or not.

(v) After repeating such operations in a little while. the time limit forces him to compromise. At last he decides a landing point and a course to reach there.

The display subsystem models after some parts of such mental actions which can be processed systematically. i.e. above mentioned (ii). (iii) and (iv).

The algorithm of the display subsystem is as follows.

(i) Just after an engine failure the reachable range is calculated from the present altitude. the descend rate. the wind direction and the wind speed.

(ii) The points suitable for landing in the reachable range are selected from the data base in the map generator.

(iii)Flight courses to reach the selected points are generated geometrically. and altitude margin for each flight course at the landing point is calculated taking account of altitude loss caused by turns. And the minimum distance between obstacles and the course is calculated from the digital data of geographic map. A course which has a negative value of altitude margin and/or minimum distance is eliminated because it means impossibility of reaching and/or a collision with obstacle.

(iv) The remaining courses are evaluated with fuzzy inference as follows.

(a)Mean value of distance from obstacles to the course.

This is calculated from the calculated altitude on the course and the elevation of the surface. The larger this value is. the better score of evaluation is.

(b)Length of the course.

If the course is too long. the uncertainty of reaching the landing point increases. And if the course is too short. the excessive altitude margin must be disposed. Therefore the course with the moderate distance gets the best score of evaluation.

(c)Altitude margin at the landing point.

If the altitude margin is too small. the course is dangerous and the score of evaluation gets worse remarkably. If the altitude margin is too large. the excessive altitude margin must be disposed the same as (b). and the score of evaluation gets worse a little.

(d)The complexity of course shape.

The simpler the shape of the course is. the better score of evaluation is.

(e)Wind direction at the landing point.

In an autorotative landing headwind is desirable. So the smaller angle between wind and the course at the landing point is. the better score of evaluation is.

(v)The overall result of the evaluation by fuzzy inference is expressed with a value between zero and one. The rank of course and landing point is decided according to the value.

(vi)Then the display subsystem displays the reachable range and the landing points with their ranks overlapped on a geographic map. The pilot can select one of them through the touch-panel sensor on the CRT display.

(vii)After the pilot selects a landing point. three courses to the landing point which have higher ranks than the others are displayed with their ranks. If the pilot selects one of the courses. the courses not selected fade away.

As mentioned above, the display subsystem supports pilot's decision making by displaying emergency landing points and flight courses with their ranks evaluated by fuzzy inference. If the display subsystem and the control subsystem are coupled, the flight course data generated by the display subsystem is sent to the control subsystem and the aircraft is automatically guided toward the landing point.

The formats for the display subsystem are shown in fig.6.

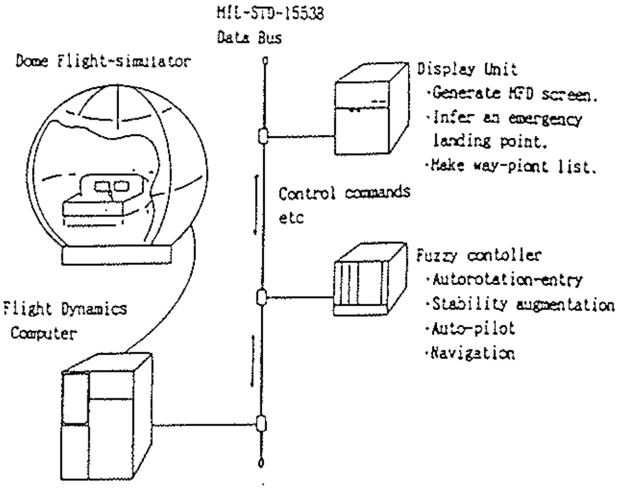


Figure 7. Test setup

7. Evaluation of the BBM of FIPSS in flight simulation tests.

Some pilot-in-the-loop flight simulation tests were performed to evaluate the effectiveness of FIPSS. The BBM of FIPSS is connected to flight simulator, and sudden engine failure conditions were simulated.

(1) Test setup.

A dome type simulator which provides a wide field of view was used for the simulation tests, because in a steep descending flight after engine failure a wide downward view is required to provide the pilot with realistic visual cues.

The helicopter cockpit equipped with the MFD for FIPSS was installed into this simulator. And, the BBM of FIPSS and the simulator were connected with a MIL-STD-1553B data bus.(figure.7) The pilot controls are the conventional type, i.e. a cyclic stick, a collective pitch lever and rudder pedals.

The helicopter model used in this simulation is a single engine and single rotor helicopter of 3000-kg.

(2) Test procedure.

The flight simulation tests were performed according to the following procedure.

(i) Normal cruise flight at 3000ft over Gifu area.

(ii) Sudden engine failure is applied with no cues to the pilot.

In order to compare the effect on the pilot workload reduction by the control subsystem, all the four operation modes of FIPSS mentioned formerly were tested in the same test condition,and pilot comments and time histories of aircraft motion were recorded.

And pilot comments on the following points were collected for the qualitative evaluations of the display subsystem.

(i) Pilot workload on the decision making for autorotative flight course both in case of flight with FIPSS informations and without FIPSS informations.

(ii) Suitableness of the display including the contents of information and the display format, for the various environmental conditions.

In addition to the pilot comments, the pilot operations were recorded to analyze the pilot judgment.

(3) Test result.

Analyzing the time histories of the aircraft motion and pilot control, and pilot comments, the performance of the BBM of FIPSS was evaluated.

The items to be evaluated are as follows.

(i) Performance of the control subsystem.

(ii) Performance of the display subsystem.

(iii)Effect on the pilot workload reduction.

Figure 8 shows a scene of the simulation test and an example display of MFD.

Figure 8 Flight simulation test

First of all. The aircraft control by a pilot and the aircraft control by fuzzy controller are compared. Figure 9 shows the helicopter control by fuzzy controller in case of engine failure at the airspeed of 100kt in 10kt crosswind.

As shown in figure 9. the rotor RPM. which decreases due to the engine failure. is recovered well by the downward collective pitch lever operation. and the yawing is suppressed by rudder pedals. Then the airspeed of helicopter is decreased to get a minimum rate of descend. As the result. the helicopter establishes a steady autorotation smoothly. A comparison of fuzzy control and the pilot control are shown in table 1.

Fuzzy control spends as twice as longer time than the pilot control to stabilize the rotor RPM. However. the average fluctuation of the rotor RPM by fuzzy controller is 3% smaller than that by the pilot operation. It took about 16 seconds for fuzzy control to stabilize the airspeed of the helicopter. and it is 6 seconds shorter than the pilot operation.

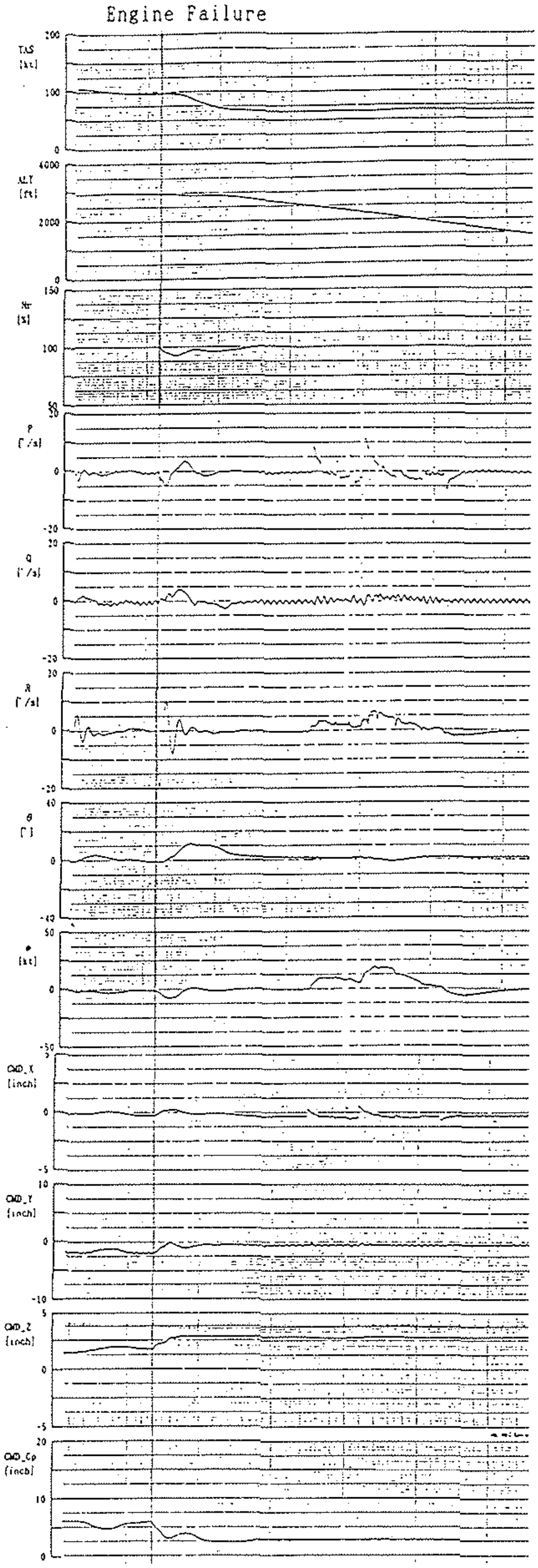


Figure 9 Time history of an autorotation

Moreover. The attitude of the helicopter is stabilized in about 9 seconds which is about half of the time by the pilot operation.

Thus. the control subsystem of FIPSS can control a helicopter equivalently to or better than a skilled pilot.

Table 1 Comparison of the pilot control and FIPSS

Items	contoller mode	Pilot A	Pilot B	Average (4pilots)	Fuzzy contorller
Time delay to start recovery (sec)	DRT	1.4	2.0	1.6	0.0
	SAS	1.1	1.3	1.3	
Rotor RPM recovery time (sec)	DRT	7.8	11.1	8.5	18.0
	SAS	6.5	14.3	9.0	
Change of rotor RPM (Max. Min) (%)	DRT	103. 91	103. 90	103. 90	102. 92
	SAS	102. 90	99. 90	101. 90	
Settling time to reference speed (sec)	DRT	25.7	17.5	22.1	15.6
	SAS	20.4	15.4	20.4	
Error of speed from minimum-desent-speed (kt)	DRT	+5	+10	+6.1	+3.5
	SAS	+10	+5	+5.0	
Yawing recovery time (sec)	DRT	10.7	25	18.2	6.6
	SAS	9.3	24.3	13.2	
Change of Yaw-rate (p-p) (deg/sec)	DRT	38.0	36.0	36.5	31.1
	SAS	37.0	40.0	38.0	
Side-slip recovery time (sec)	DRT	6.6	11.1	10.1	6.4
	SAS	5.4	9.3	9.1	
Maximum side-slip angle (deg)	DRT	15.0	16.0	16.0	10.0
	SAS	12.0	14.0	13.8	

As for display subsystem. three highly ranked of landing points inferred by fuzzy inference were indicated and identified on the MFD.

Table 2 shows the distribution of the pilot selection of the landing point advised by the display subsystem. In most cases. the pilot selects the point of the first rank or the second rank.

Thus. it has been shown that the display subsystem can perform equally adequate judgements to those of a skilled pilot.

Some notable remarks in the pilot comments are as follows.

(i) The effectiveness of the display subsystem.

The analysis of the pilot comments shows that all the pilots preferred an autorotative flight with the display subsystem more than that without the display function. Thus. it is shown that the display subsystem is very useful as an aid for pilot's decision making in emergency autorotation flight.

Table 2. Distribution of pilot selection

		The 1st-ranking landing piont	The 2nd-ranking landing piont	Below the 3rd-ranking points	Total
With Display Unit	DRT	4(40%)	5(50%)	1(19%)	10
	SAS	6(40%)	6(40%)	3(20%)	15
	FAP	1(14%)	6(86%)	0(0%)	7
	FMV	2(50%)	2(50%)	0(0%)	4
	Total	13(36%)	19(53%)	4(11%)	36
Without Display		3(43%)	3(43%)	1(14%)	7

Especially. the display of the reachable range and the display of the landing points have a good reputation. because these give the pilot strong confidence in his judgment. In this simulation tests. the best configuration of FIPSS estimated by the pilots is the combination of the display subsystem and the control subsystem which is working in FAP modes. because the autorotation entry function provides the pilot with enough time to look the display .

(ii) The contents of display.

No pilot feels the lack of displayed informations. The items to be improved requested by the pilot for the display subsystem are as follows.

(a) The course should be indicated with a smooth and not cranked curve.

(b) There is a tendency that too much altitude remains at the landing point.

(c) In mot cases. the displayed courses do not much differ so that a pilot may be puzzled to select one.

The total evaluation result for the BBM of FIPSS was generally excellent while some items to be improved for the display remain as mentioned above.

8. Concluding Remarks

In this study the effectiveness of a pilot support system utilizing fuzzy system techniques has been demonstrated, as follows.

(i) A fuzzy control system can control a helicopter automatically in an emergency condition after engine failure, which is one of the most critical flight condition and requires a quick and precise pilot control. The control performance of a fuzzy controller is equivalent to or in some cases better than that of a skilled pilot.

(ii) In a pilot support system fuzzy system can be applied not only to aircraft control but also to a part of decision making process; in the BBM of FIPSS, a fuzzy system estimated flight courses whether they were good or bad for safe landing, and proper conclusions were got in most cases of the flight simulation tests.

Fuzzy inference, which is the most important operation in a fuzzy system, is relatively simple technique, besides, it can be utilized for many purposes including aircraft control and support of decision making. Fuzzy system enables a computer system design which utilizes human experiences or way of thinking, so that the capability of a computer system will be enhanced into some fields where conventional techniques have no solution. We found a feasibility of application of fuzzy system to avionics field through this study.

Acknowledgement

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