EVALUATION OF MISSION PERFORMANCE AND SAFTY FOR FIRE-FIGHTING AMPHIBIAN

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Abstract

Fire-fighting with amphibians is very efficient because an amphibian can carry a large amount of water and easily take water by landing on the lake or sea and scooping. JAXA, ShinMaywa Industries, Ltd., and JADC have been conducting joint technical research to develop a fire-fighting amphibian. In this paper, evaluations of fire-fighting operation for the new amphibian by using flight simulator are presented through development of cockpit display system and application of support instruments by using Head-Down Display (HDD) and Helmet-Mounted Display (HMD). The characteristics and problems were clarified on each display method, especially HMD. The results are useful for future improvement of pilot-interface for fire-fighting missions.

1 Introduction

In case of a forest fire recently increasing by global-warming or massive fire caused by earthquake, it is difficult to extinguish or prevent fire spreading by the ground forces, whereas aerial fire-fighting is effective[1]. Especially, fire-fighting with amphibians is very efficient because an amphibian can carry a large amount of water and easily take water by landing on the lake or sea and scooping. [2]

Water-dropping operations with amphibians in fire-fighting missions are commonly conducted at about 100 feet of altitude to avoid dispersion and to complete efficient extinguishment. The altitude is relatively low, so that the some accidents such as collision with mountains, trees, and power lines were happened. In Japan, there is a plan of fire-fighting amphibian, which is now being designed by ShinMaywa Industries, Ltd., and this amphibian will be able to conduct much safer fire-fighting mission by using its capacity of large mass of water and ability of low speed flying. For example, the amphibian will have capacity of water of 15 ton and minimum air speed of 70 - 80 kt. However, in Japan there are very few experiences of the mission in actual flight, although it is very important to understand the mission profile of fire-fighting to complete this research and design. Therefore, evaluation research of fire-fighting mission such as defining the mission profile, cockpit management and pilot work load during water-dropping and scooping, and advanced system to enhance pilot awareness and operations, has to be conducted. For this purpose, JAXA, ShinMaywa Industries, Ltd., and JADC have been conducting joint technical research to develop a fire-fighting amphibian, as shown in Figure 1. In this paper, evaluations of fire-fighting operation for the new amphibian by using flight simulator are presented through development of cockpit display system and application of support instruments by using Head-Down Display (HDD) and Helmet-Mounted Display (HMD).

Fig. 1: Image of Fire-Fighting Amphibian.

2 Water spreading pattern for Aerial-Firefighting

To conduct fire-fighting simulation using flight simulator, water spreading pattern from aircraft is most important element to determine the evaluation criteria.[3-6] However, water-dropping phenomena in fire-fighting operation were very complicated and unknown. In our previous research,[7] the phenomena was investigated using wind tunnel tests when water is dropped from the airplane and a large amount of water splits up into fine particles and spreads in all directions. The model of spreading pattern by using CFD calculation was made and it was validated by the wind tunnel tests, as shown Fig. 2. Then, actual spreading patterns from full-scale airplane were able to be predicted with the CFD along some flight velocity and altitude. Some calculations were also carried out for cross wind conditions. These patterns are used to construct water-dropping model for fire-fighting flight in the flight simulator.

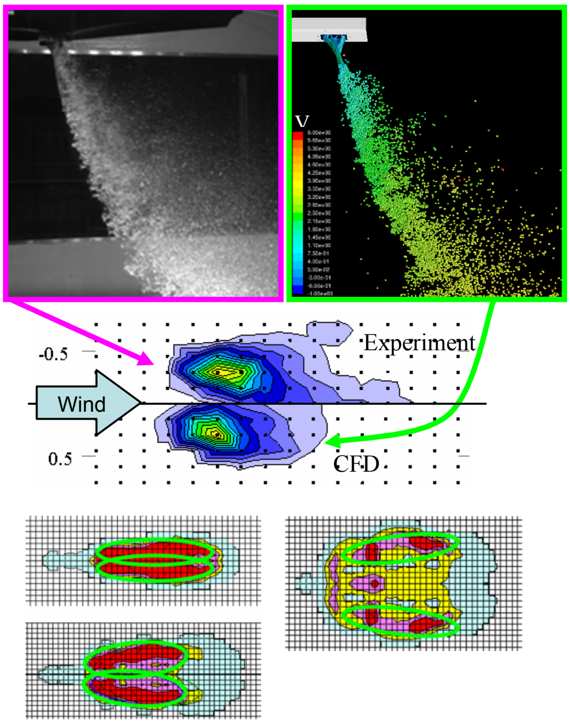

Fig. 2: Water dropping phenomena was investigated, and CFD Prediction was validated by Wind tunnel tests. And water dropping model was generated for Flight Simulator.

3 Flight simulation for fire-fighting of the amphibian with JAXA FSCAT-A

JAXA has some of flight simulators for R&D. FSCAT-A, which has fixed-wing airplane cockpit, is flexible, high-performance research simulator as shown in Fig. 3. It has simulated cockpit layout of wide body with two engines, and 120 degrees of viewing angle, 6-axis motion system. Using this simulator, various models of aircraft dynamics and cockpit instruments have been tested easily.

In this research, fire-fighting operations were demonstrated by using this simulator to investigate subjects of the missions, pilot interface, and so on. To conduct fire-fighting mission by the simulator, a water-dropping controller and water status display were equipped to the cockpit (Fig. 4). To support accurate water-dropping operation from higher altitude, display system was developed on the MAP display on HDD and integrated display on HMD.

Fig. 3: JAXA Flight Simulator FSCAT-A

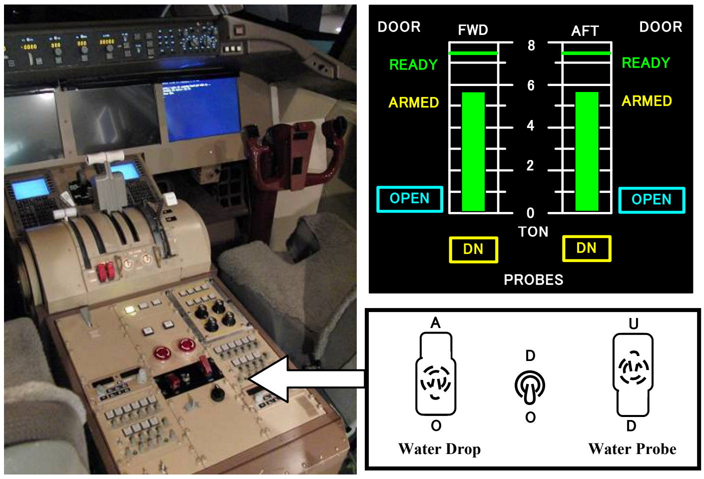

Fig. 4: water-dropping controller and water status display in the cockpit of simulator

4 Evaluation of flight profile of fire-fighting mission by amphibian

4.1 Flight profile of fire-fighting operation

The purpose of this research is to investigate of the adequate operation method for fire-fighting amphibian and to organize suitable pilot interface in order to drop water from higher altitude to achieve much safer and more efficient operation by utilizing capacity of large mass of water and ability of low speed flight.[8] Conducting flight simulation for aerial fire-fighting by amphibian, it is important to evaluate the mission concept and to search for problems by pilot comment. For this purpose, water-dropping operation and water-scooping operation have to be separately evaluated.

We chose mountain area near the lake to demonstrate the forest fire and scooped the water at the lake, as shown in Fig. 5. Mission scenarios of the fire-fighting operation were the scooping of water at the lake and the water-dropping to the fire on the gentle or steep slope.

In the water-dropping mission, mountain area was assigned as location of the mission and the task of each fire-fighting mission was defined and evaluated. Example of flight profile is shown in Fig. 6. Various flight conditions were investigated such as water-dropping altitude from 100 to 500 ft, velocity from 70 to 110 knts, and also some cross wind conditions.

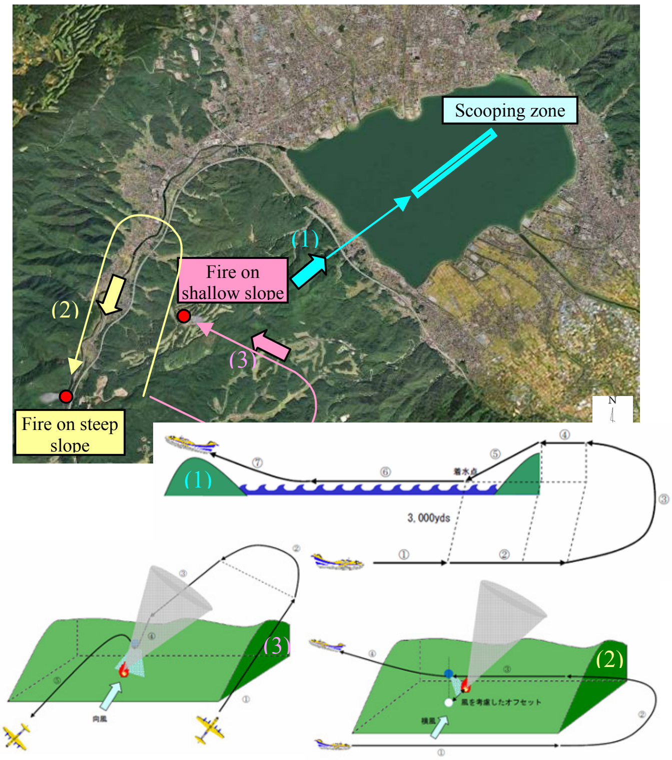

Fig. 5: Demonstrated area for fire-fighting

For the water-scooping mission, large lake in the mountain area was assigned. Approach and landing on the water in the limited length of water landing strip, scooping in the strip, and take off avoiding mountain area, were evaluated. Efficient water-dropping and scooping methods were evaluated through the simulation of those missions and conditions.

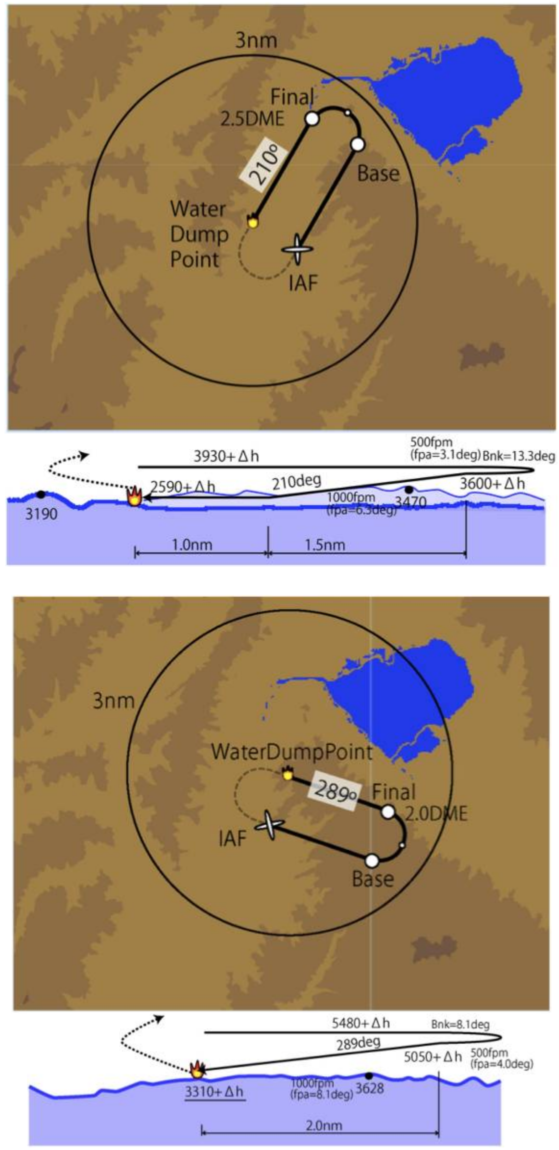

Fig. 6: Mission profile at mountain area for water dropping

4.2 Flight environment for Simulation

Here, there are some descriptions of simulation environment of flight simulator for mission demonstration. Those are defined to be able to obtain the pilot comments, to evaluate the effective method of mission completion, and to

investigate the pilot interface. As stated above, simulation was carried out in the mountain area. Moreover, detailed condition suitable to conduct the evaluation of water-dropping and scooping has to be examined.
For the water-dropping test, both fire on the slant slope and steep slope are demonstrated on the mountain. By using those conditions and considering descent performance to the fire and maneuver performance to avoid mountains after water-dropping, the mission profiles were determined under almost maximum performance of this amphibian.
Landing on the water, scooping, take-off and ascent was evaluated on the lake in the mountain area by also utilizing almost maximum performance of this amphibian, especially at landing and take-off over the mountain.
Indication of fire and smoke were applied to inform the position of the fire and to help awareness to the pilot. In the smoke, decreasing the visibility was also demonstrated, as shown in Fig. 7.

Fig. 7: Simulation of fire and smoke for environmental demonstration

Water-dropping model was derived from wind tunnel testing and CFD analysis, as shown above. The model includes dependency on flight speed and flight height as data base spreading pattern, which were obtained by parametric calculation of CFD that has been verified by wind tunnel testing results.

4.3 Basic concept of cockpit display

In the actual fire-fighting mission, amphibian descends from high altitude to very low altitude of about 100ft with nose-down attitude, and the pilot carries out the water-dropping with the fire in sight. In this operation, it is sometimes difficult to keep safety due to depending on the terrain such as steep slope or valley. Therefore, water-dropping is conducted at higher altitude of about 300ft with level-flight with larger amphibian with STOL capability to achieve the higher safety and performance in our operation, as mentioned above.
However, it is difficult to find the fire in sight at water-dropping point because the angle of looking down from cockpit to the fire is very large, just below the amphibian. Therefore, navigation display to the aiming point of water-dropping is needed to support the pilot operation, and the display system is shown here.
Basic cockpit display systems for pilot assistance to support the water-dropping operation were shown in Fig. 8. Purpose of the system is to display the navigation to the fire or aiming point and the indication of the timing of water-dropping. Location of fire, which had been determined by other pointing instruments, was shown on MAP display in HDD, as well as the other guidance information of air-data sensor, INS, GPS, and so on. Moreover, the favorable approach path to the fire and the predicted water-spreading pattern with real-time prediction were indicated. This real-time spreading pattern is essential display for the fire-fighting which is calculated by considering

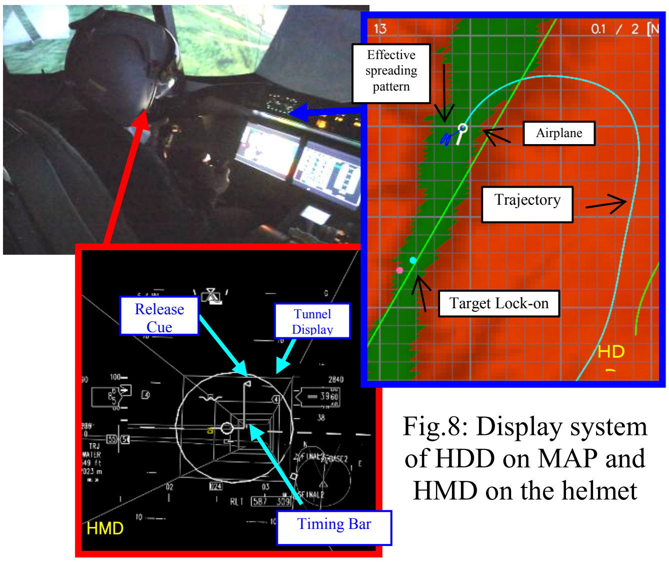

Fig.8: Display system of HDD on MAP and HMD on the helmet

air-speed, altitude, attitude, wind, and so on, to predict on the ground when the amphibian drops water at the time. The aiming point is also displayed as optimized condition which can obtain the maximum area of water-spreading pattern under the assumption that location of the fire is able to determine by means of optical device or else, such as HMD. Pilot needs to follow the navigation and to drop water at the aiming point.

4.4 Overview of results of basic navigation

Flight simulations of water-dropping at steep slope and shallow slope with various flight conditions were conducted, and obtained flight data and pilot comments to evaluate the mission and equipment.
In this flight, lower air speed of 90kt and higher altitude of 300ft is favorable condition for our amphibian to maximize the water-spreading pattern and maintain safety. The water-dropping condition is much safer because of the high altitude, as we expected.
Water scooping operation is easy to carry out because the amphibian has much power. Some other amphibian needs to scoop water at higher air-speed, but lower air-speed scooping is also possible for this amphibian. Approaches and landing on water and take-off have sometimes problems because of the terrain. These will be discussed at following section.
Pilot interface for fire-fighting worked very well and was able to complete the mission. Accuracy of dropping and spreading on the water must be sufficient by using the navigation and support system.

5 Evaluation of water-dropping mission with enhanced system of HMD

5.1 HMD system for water- dropping

In the fire-fighting mission, pilot has to observe outside of the window continuously, especially, at emergency mission such as fire-fighting. HDD is not suitable for the mission because pilot is required to look down from the window. On the other hand HDD (Head Up Display) and HMD (Helmet Mounted Display) are favorable to indicate navigation information. Moreover, HMD system can include advanced technique of pointing device to determine the coordination of the fire location by looking through the HMD.[9-10] HMD in the cockpit of the simulator is shown in Fig. 9.

Fig.9: Helmet Mounted display (HMD)

Even by utilizing these types of devices such as HUD and HMD which can display navigation symbols on the scenery outside of window, the display might force to look at the symbols than the scenery outside, and lead to danger situation. So it is necessary to pay attention about the design of the symbol and also to evaluate the display systems. For the evaluation of performance of navigation display, there are some indexes such as slave of the target, situation awareness, and easiness of understanding. Here, the target value of the index was not determined because the actual fire-fighting mission, environment, and required performance had not been defined yet as the target of design. But comparisons between some methods are shown as evaluation of navigation display on HMD. For this purpose, three type of display methods were demonstrated as navigation display on the HMD as shown in following sections.

5.1.1 ccIp (continuously computed Impact point) display method

The ccIp display method shows water-spreading pattern on the HMD as impact point which is continuously computed, and the pilot maneuvers to make the oval marks in HMD of water-spreading area coincide with the fire outside of window. Altitude navigation is also integrated and indicated as the water-dropping symbol, and the pilot controls the symbol to coincide with the center of the oval marks. Example of display is shown in Fig. 10, and concept of the display in Fig. 11.

The ccIp does not need the position of fire prior to the fire-fighting, but only the scenery with fire. It allows more flexibility, and pilot only needs to find the fire and decide the approach direction, altitude, flight path, and so on.

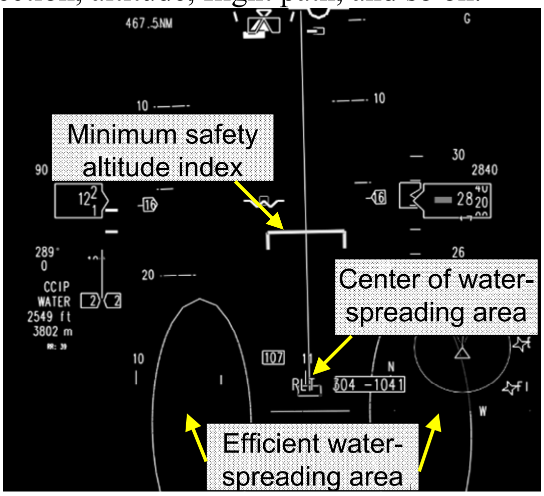

Fig.12: Example of display of ccIp

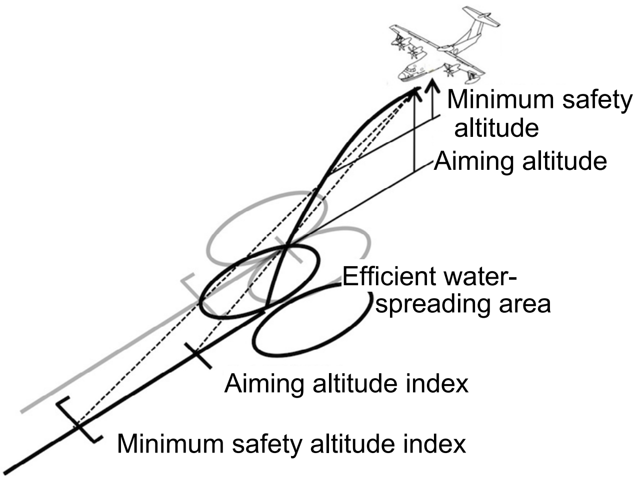

Fig.11: Display concept of ccIp

5.1.2 ccRp (continuously computed Release point) display method

The ccRp method shows release point of the water to hit the center of water-spreading pattern to the fire. Direction to the fire is also indicated by steering line on the HMD, and flight path angle by the altitude symbol. Pilot needs to make flight path symbol coincide with the steering line and altitude symbol. Flight path symbol include prediction with role rate of direction, so the difference between flight path angle and steering line means the bank command. Altitude symbol is calculated to be able to reach the aiming altitude for water-dropping in +/-3 degree of flight path angle. Distance to the point of water-dropping is shown as release cue, and water is automatically dropped at optimized position. Example of display is shown in Fig. 12, and concept of the display in Fig. 13.

This ccRp needs information of fire position prior to the water-dropping operation, and lock-on operation with HMD or else must be carried out, and locked-on target can be indicated as shown in Fig. 12. Error of direction to the fire in the steering cue increases as approaches to the target, and it reverses at the position. Pilot also needs to set the flight path and profile of altitude to the aiming point.

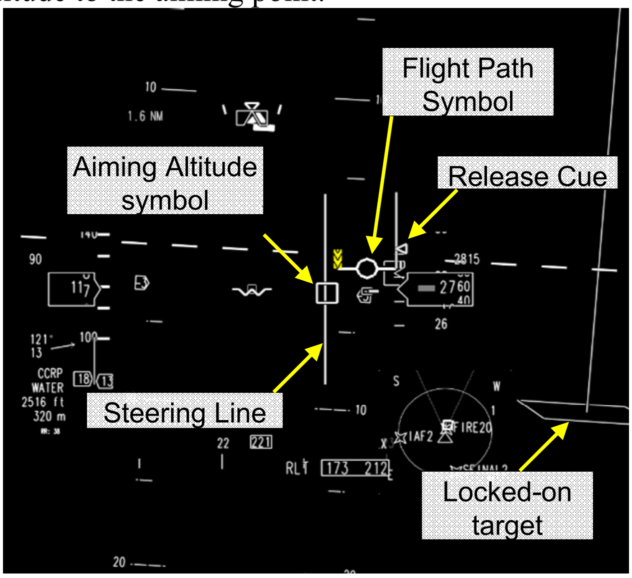

Fig.12: Example of display of ccRp

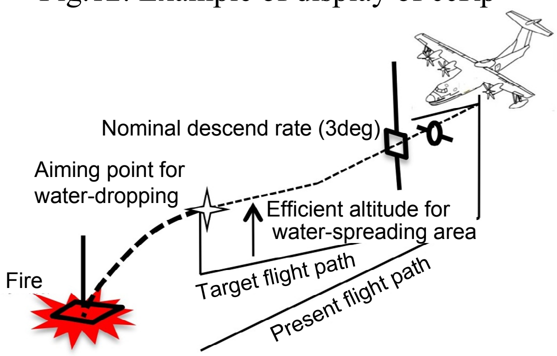

Fig.13: Display concept of ccRp

5.1.3 TRJ (TRaJectory) display method

Tunnel display on the HMD as trajectory (TRJ) display method was shown to help accurate flight path to the fire.[11] Those display methods were evaluated by pilots in the flight simulator. In this method, flight direction or continuous path to the calculated aiming point is shown as tunnel shape, and pilot needs to fly in the tunnel display. The aiming point is calculated at beginning of the flight and cannot refresh because the tunnel display might be changed dramatically and confuse pilot. Distance to the point of water-dropping is shown as release cue, but water has to be manually dropped at optimized position. Example of display is shown in Fig. 14. In this method, the tunnel is set as a flight path explicitly and the cue to keep the path is shown. Therefore, pilot doesn't need to care of the flight path and profile of altitude. Gain of the control is constant regardless of the distance to the aiming point. The cue is indicated to minimize the error of the direction and flight path, so the control of the amphibian is more severe than ccRp.

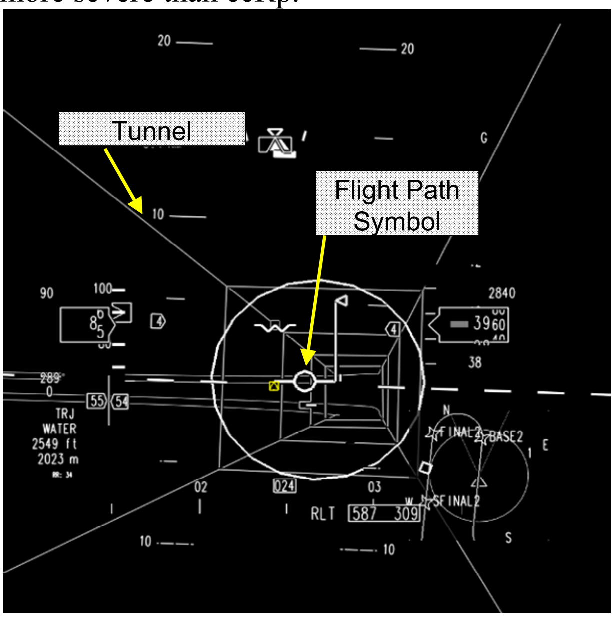

Fig.14: Example of display of TRJ

5.2 HMD results in FSCAT-A

Evaluations of simulated flight were conducted by five pilots, in which two pilots had experience of amphibian flight. All pilots did not have any experience of fire-fighting operations. Some pilots were able to conduct effective and safe operation for fire-fighting using HMD system. Results of evaluation were shown in Fig.15.

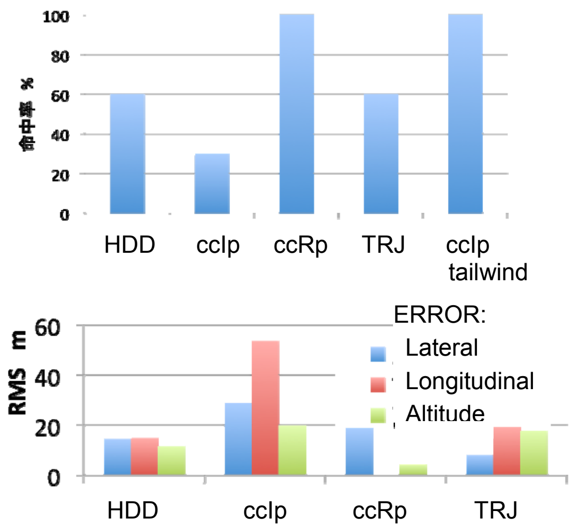

Fig.15: Results of evaluation of hit rate, error of the water-dropping

5.2.1 ccIp display results

The hit rate, error and pilot rating of ccIp showed low scores. The reason is because the oval area of ccIp display was shown at the very low position, just under the cockpit, and pilot cannot see the fire directly even though the area was indicated on the HMD. Moreover, head-down operation was required for the pilot to watch the oval area. It is danger because pilot cannot look around the scenery outside of the window. However, this ccIp method shows higher score of hit rate under the tailwind condition because the calculated water-spreading area move to forward and pilot can look at it directly. Even under this condition, error of the water-dropping was still larger than other method because pilot has to recognize the relationship between fire and target area as perspective projection technique through slant angle, comparing with the other method which has a cue of linear indicator or horizontal plain view. The ccIp has some difficulties for pilot to recognize the position and timing of the water-dropping. This problem is essential for the high-altitude level flight although it is better under the tailwind condition. To apply this method for the fire-fighting flight, limited conditions, such as tail wind and shallow dive flight, are required, or some other improvements have to be considered.

5.2.2 ccRp display results

The ccRp shows good results in hit rate, pilot rating, and error. Especially, hit rate was very high because of the automatic water-dropping. On the other hand, lateral accuracy was worse than TRJ method and HDD, and vertical accuracy was also worse than HDD. Higher hit rate was considered to be caused by the automatic operation, but might not be by the ccRp's characteristics. However, comparing with TRJ in the following section, ccRp requires the moderate pilot task and in total thinking ccRp seems to be better solution after decision of the course and altitude of approach to the target. In the pilot comment, the gain of the symbol on HMD became higher as approach to the aiming point, and it should be improved.

5.2.3 TRJ display results

Using the TRJ method, Hit rate was same level as HDD, but pilot rating shows worse. This pilot rating result was essential subject for the TRJ, that is, this method required pilot to force concentration for a very long time. Moreover, the display is not intuitive to understand. Lower hit rate than HDD and ccRp was caused by the error of the altitude. Especially, case (b) forced the pilot to control along the TRJ display of constant descent rate to the aiming point, and many tasks in the flare maneuver and water-dropping operation were needed at the aiming point. It is difficult to control altitude under the higher task condition. On the other hand, pilot under the other method can control altitude and establish level flight before the aiming point along his decision with flexibility, so the error of altitude was very small. This method will be used under the very tough condition such as very low altitude operation in narrow valley under which the precise flight plan is required prior to the mission. But if limitation of the flight is not severe and pilot decision during flight is allowed, this TRJ is not suitable.

5.2.4 Characteristics of HMD

It is expected for pilot to have better visibility of outside of window by using HMD. In many pilot comments, it was found that pilot can watch both symbol of HMD and view of outside simultaneously. On the other hand, there were too many detailed symbols in TRJ so that it was difficult to see the view of outside. Moreover, pilot tended to focus on the symbols and could not care of the view of outside. It is difficult to evaluate the actual visibility of view of outside in the simulator. Although attention for the view of outside on pilot awareness can be improved by learning and training, it might be difficult to solve essentially and special attention has to be paid in actual mission on safety view point.

6 Concluding Remarks

To realize fire-fighting mission with amphibian, the mission profile was determined and system performance to accomplish the mission was evaluated. Not only water-dropping performance but also safety water-scooping operation on the water was investigated, and provability of mission completion was confirmed.

The detailed information shown in above was useful for efficient development of the aid system. Three type of HMD system was organized and evaluated on the flight simulator to conduct safer and more efficient fire-fighting operation. As results, characteristics and problems were clarified on each display method. Adequate awareness level for outside view, determination of position of fire, and flight path to the fire would be needed to be examined through the improvements of experimental environments. It was sometimes difficult for un-experienced land-plane pilots to scoop the water. It is necessary to improve this support system, operation limit, and training syllabus, for this problem. These data and pilot comments must be very important for future improvement of the system and research of pilot-interface for the fire-fighting missions.

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