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SUPERIMPOSED PERSPECTIVE VISUAL CUES FOR HELICOPTER HOVERING ABOVE A MOVING SHIP DECK

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ABSTRACT

The subject of the investigation is the manual low altitude hovering task, above a small moving ship-deck, using visual field cues supplemented by superimposed display symbology. In this task, rather than tracking the ship deck motion, the pilot should keep the helicopter inertially stable at a desired inertial position above the ship deck. This hovering stage lasts until the touch-down can be performed during some period of quiescent ship motion. This hovering task is very demanding, in particular in adverse atmospheric and sea conditions. The main difficulties during this task arise from the lack of inertially stable visual references, necessary to keep the helicopter inertially stable above the ship-deck. The scope of this research is to investigate, both experimentally and analytically, the effectiveness of the superimposed visual field information, on the hovering performance. This additional information can be realized by inertial visual references generated on the ship deck, and/or by a helicopter-based head-up display. For the ship deck references, inertially stable 3-D visual structures such as line drawn cube or box are investigated. For the head-up display information, only the artificial horizon is investigated. The results of the investigation clearly show that the hovering performance is improved by the inclusion of inertially stable visual cues. Moreover, it is shown, that the performance is almost independent of the size of the 3-D structure. Thus, it is possible to realize the ship-based visual references within practical physical dimensions, i.e. a cube size of 1 meter.

1. Introduction

The manual landing of a helicopter on a small moving ship deck, is a very demanding task, in particular in adverse weather and sea conditions. It imposes a high workload on the pilot and frequently is not performed satisfactorily. The requirements for both civilian and military helicopter operations from small ships, have increased significantly during the recent years. As a result, a large number of improvements have been introduced into helicopters, necessary to meet the marine operations requirements. In spite of the improvements and the addition of various sophisticated systems, the landing on a ship deck is still performed manually [1]-[5]. The entire landing procedure can be divided into four main stages:

1. Approach-to-landing.
2. Hovering above the landing deck.
3. Touch-down.
4. Securing of the helicopter on the deck.

A number of references [6]-[9] investigated the control and information systems for VTOL and helicopter approach-to-landing (stage 1). The present work concentrates on the second stage, i.e. the hovering above the deck, prior to the touch down. The required hovering location is referred to as the Station Keeping Point (SKP). Hovering above a moving deck is a much more demanding task than hovering above a fixed location on the ground. It is known that if a pilot attempts to track the ship motion, the ship-to-helicopter distance might become dangerously small, as a result of phase lags between the helicopter and the ship motions. In this case, the pilot must abort the attempt for touch down and initiate the whole procedure. This dangerous and undesired situation can be avoided by hovering at an inertially stable location (SKP), above the moving deck, until some moment of quiescent ship motion arrives, during which the touch down can be performed [1]. During hovering, the pilots main source of information originates from the visual field. Since the Human Operator's (HO) visual references are relative to the moving ship deck rather than to inertial space, his spatial orientation with respect to the inertial space is impaired. Moreover, the helicopter is subjected to atmospheric disturbances which constitute a high frequency forcing function, responsible for the main part of the pilot's activity. This difficulty is enhanced by the fact that the landing area of small ships is also small, and the hovering above the deck has to be carried out with great precision.

In a preliminary study of the present subject [10], it has been shown that by providing the pilot with explicit inertial position and rate information, by means of display augmentation, his workload can be reduced and the hovering performance can be improved. These results demonstrated the importance of displaying inertial position information, but the questions of how to realize this information and how to present the additional cues, were not yet addressed.

Display augmentation can be realized on the helicopter by means of head-up display or at the ship by a 3-D visual structure. With the existing measurement equipment on board of the helicopter, it is very difficult to obtain accurate inertial position estimates in the cockpit. On the other hand, it is possible to estimate quite accurately, the ship deck motion [8], [9] and to use these estimations to generate ship based visual inertial references. Then the pilot, instead of deriving visual orientation cues from the moving ship deck, can derive cues from the inertially stable references, which are line drawn geometrical shapes. It was shown in [11]-[13] that the HO is able to derive his spatial orientation more accurately by viewing 3-D geometrical shapes than by 2-D images. Moreover, it was found [13] that viewing statically a line drawn cube, the spatial orientation errors made by the HO are independent of the view point angular orientation. Therefore, a line-drawn inertially stable cube structure was chosen as the ship-based visual reference and it became of prime interest to investigate the inherent errors made by the pilot during the hovering task. The line drawn cube can be created by a matrix of signal lights and can be stabilized using an electromechanical motion platform like the one described in [13]. In spite of errors in the estimation of the inertial position, in order to simplify the investigation it was assumed that the cube can be ideally stabilized.

There is a basic difference between the visual information presented to the pilot in the preliminary study [10], and in the present investigation. In the study of reference [10] position errors and their rates were presented explicitly. In constrast, in the present study with the use of the line drawn cube, the HO has to estimate his position errors by mentally processing the perspective shape of the cube. Moreover, additional difficulties in the hovering task originate from the lack of coupling between the helicopter pitch and heave motions. In the case of fixed-wing aircraft, a pitch motion is directly linked to be a vertical motion. Namely, vertical velocity information can be derived from the vertical shift of the image as a result of the pitch motion. On the other hand, in helicopter hovering this coupling does not exist. Thus, the pitch motion appears to the pilot as a vertical shift of the viewed image, but the shift does not include information about the vertical position of the helicopter. Such information can be extracted from changes in the perspective cube shape. The pitch motion in hovering is coupled to the surge motion, so that the image vertical shifting includes information about the surge rate and acceleration.

The research includes experimental and analytical work. The analytical model of the hovering task is necessary for a better understanding of the effect of the various parameters on the task performance. Moreover, analytical and experimental results are mutually supporting in validating the hovering results on one hand, and providing insight into the control mechanism on the other hand.

Analytical models of man-machine systems are classified in the literature in two groups. The classical control engineering approach (McRuer et al. [14]-[15]) indicates the state variables which are required from a control theoretical point of view, without studying how these variables are perceived. The modern optimal control engineering approach (Kleinman et al. [16]-[21]), states that the well-trained, well-motivated HO behaves almost like an optimal controller, subject to his inherent limitations and to the control task. In this model the sources of HO remnant are specified as observation and motor noises. Observation noise accounts for uncertainty in the perception of parameters, while motor noise accounts for the random errors in executing the intended control movements. The Optimal Control Model (OCM) is used both for instrument display control tasks [21]-[27] and for visual field control tasks [28]-[31].

In the present paper the analytical and experimental results of the hovering task are presented. The visual field is augmented with a ship based reference being a line drawn cube, in combination with artificial horizon realized on the helicopter HUD. The cube is inertially stabilized above the ship and does not move with the ship. A simplified hovering task is considered, in which helicopter motions exist in the longitudinal plane, and the ship deck is subjected to heave motions only, without pitch or roll.

2. The Analytical Model

The longitudinal hovering situation is described in Fig. 1. A general description of the display viewed by the pilot is given in Fig. 2. The pilot's task is to keep the helicopter at a desired inertial height, such that a sudden collision between the ship and the helicopter will not occur. The task is performed in the presence of vertical atmospheric disturbances and vertical motions of the ship deck. The desired hovering altitude is presented to the pilot by means of a line drawn cube. A horizontal bar which is attached to the ship's mast serves the pilot as a mean to observe the motion of the helicopter, relative to the ship deck.

In the investigation the surge motion is assumed to be controlled by an autopilot. The helicopter pitch control is executed automatically by the automatic surge control system, without intervention of the pilot. Thus the pilot has to control the heave motion only, using the collective lever. The atmospheric disturbances are assumed to influence only the helicopter vertical motion.

2.1 The Dynamic Model

The dynamic model of the system consists of the helcopter's linearized equations of motion, the equations representing the ship deck motion and the atmospheric disturbances. The equations of motion of the helicopter represent the motion in the vertical axis in response to the collective control input commands and to the atmospheric disturbances. The atmospheric disturbances are described by a first-order Markov process. The ship deck motion is described by a second-order Markov process. Summarizing the above mentioned assumptions, the dynamic model can be described by the following state equation:

$$\dot{\underline{x}} = A\underline{x} + \underline{B}\delta_c + \underline{w}_d \qquad (1)$$

Equation (1) is elaborated upon in the Appendix (see Eq. (A.1)). The state vector is defined as $\underline{x}=col(h,w,w_g,h_s,w_s)$, where:

h - helicopter vertical displacement.
w - helicopter vertical velocity.
w_g - atmospheric disturbances.
h_s - ship vertical displacement.
w_s - ship vertical velocity.
$\underline{x}$ - state vector.
$\underline{A}$ - state matrix.
$\underline{B}$ - control vector.

δ_c - collective input command.

$\underline{w}_d$ - disturbance vector with covariance matrix W_d.

The helicopter model used in the investigation represents a Bell UH-1H. The coefficients representing the helicopter in hover flight, at sea level, were taken from [32].

2.2 The Observation Model

The HO observations are relative to the inertial space and to the moving ship deck. Therefore, according to the experimental conditions (that will be described hereafter), the observation vector will include the absolute position and velocity, and/or the position and velocity relative to the deck. The observation vector can be described as a linear combination of the state vector, by the following equation:

$$\underline{y}(t) = C\underline{x}(t) + \underline{v}_y(t) \qquad (2)$$

where:

$\underline{y}(t)$ - vector of observed variables

C - observation matrix

$\underline{v}_y(t)$ - vector of observation noise components, which are assumed to be zero-mean Gaussian white noise processes with covariance matrix V.

The observation vector, including the absolute and the relative position and velocity, is given by:

$$\underline{y}(t) = \mathrm{col}(h, w, h-h_s, w-w_s)$$

It is assumed [16], that the HO perceives observations which are delayed by τ seconds. Thus the noisy and delayed observation vector perceived by the HO, $\underline{y}_p(t)$, is given by:

$$\underline{y}_p(t) = C\underline{x}(t-\tau) + \underline{v}_y(t-\tau) \qquad (3)$$

2.3 The Optimal Control Model

A block diagram of the Optimal Control Model (OCM) is shown in Fig. 3. The basic assumption of the OCM is that the HO has perfect knowledge of the vehicle and the measurement models. The HO action is accomplished in two stages:

a. Optimal reconstruction of the state variables from the noisy delayed vector of the observed variables. This is done by means of Kalman filtering and optimal prediction.

b. Determination of the control function δ_c^*, such that in the steady state the following cost function is minimized:

$$J(\delta_c) = \lim_{t_f \to \infty} E\{\frac{1}{t_f} \int_0^{t_f} [\underline{x}^T Q \underline{x} + r\delta_c^2 + g\dot{\delta}_c^2]dt\} \qquad (4)$$

Q is the weighting matrix of $\underline{x}$, while r and g are the weighting coefficients of δ_c and $\dot{\delta}_c$, respectively.

Since the Kalman filter has a perfect knowledge of the optimal control δ_c, a perfect estimate of the state is obtained by simply integrating the state equations. On the other hand, it is clear that in reality the HO's estimates are not perfect. Therefore, in order to prevent Kalman filter from perfectly knowing the control, a HO *motor noise* is added to the control force u_c, imparted to the neuromuscular system (see Fig. 3). This motor noise accounts for the fact that the HO does not know his control action precisely.

The inclusion of the control rate in the cost function is mathematically equivalent to the *first order neuromuscular* dynamics in the transfer function of the HO [16].

The solution of the reconstruction and control problem is derived from Kleinman et al. [16,18,21].

Several parameters of the analytical model are not known a-priori. The unknown parameters can be determined by a model matching procedure. This is a post experimental procedure, in which the unknown parameters are adjusted such that the analytical model outputs, i.e. the covariances of state and control variables, match with their corresponding experimental values. The unknown parameters are:

a. The weighting coefficients Q, r, g. Nevertheless, the elements of the diagonal matrix Q, which weight the uncontrollable but asymptotically stable state variables of the atmospheric disturbances and ship motion, can be a a-priori set to zero. Therefore, the unknown elements of Q are only the elements which weight the helicopter position and velocity, i.e. $Q=\text{diag}(q_h, q_w, 0,0,0)$.

b. The time delay τ and the neuromuscular time constant τ_N.

c. The covariances of the observation noises $\underline{V}_y$ and motor noise V_m, which have been shown by Levinson et al [20] to be proportional to the covariances of $\underline{y}$ and u_c, respectively. The noise levels at the observation and motor noises are defined as follows:

$V_{y_i}[\text{db}] = 10 \log[V_{y_i} / \pi E\{y_i^2\}]$; i is the number of measurements

$$V_m[db] = 10 \log[V_m/\pi E\{u_c^2\}] \; .$$

3. Fixed Base Simulation Program

3.1 Experimental Set-Up

A block diagram of the fixed base simulation set-up is shown in Fig. 4. The HO's control commands translated into analog voltages, are converted to digital signals and are imparted to a Data General Eclipse Mini Computer. The computer is programed to solve the vehicle equations of motion and to perform the necessary graphics calculations to create, in real-time, the perspective image. This image displayed on a cathode-ray tube (CRT) display, is received by a TV camera and finally projected on a screen of 2.40x2.40 meters, placed 4.5 meters in front of the subject. The projected image viewed by the subject is used to create the control commands which close the control loop.

3.2 The Experimental Program

The experimental program started after a training period of four weeks. The four subjects who participated in the experimental program were undergraduate students of the Faculty of Aeronautical Engineering and have participated as subjects in other aeronautical experimental programs in the past. The training period is especially important in light of the absence of acceleration cues, requiring the subjects to be familiarized with the image and with the motions of the ship and the helicopter. The subjects were instructed, using the collective lever, to keep the helicopter at a constant inertial height above the ship deck. The required height corresponded to the center of the cube and was not shown explicitly. The range of the SKP from the cube center was fixed at R=70 [ft] and was kept constant throughout the experimental program. The effect of the cube size, d, was investigated. Three values of the ratio σ which equals R/d were investigated: σ=4, 8 and 16.

The scope of the experimental program was:

a. Investigation of how and to what extent the HO utilizes the various displayed visual cues. The question was whether "explicit" cues, such as the deviation of the horizon from the cube center, or "implicit" cues, such as the cues included in the perspective cube structure, are utilized.

b. Determination of the most effective display configuration for the given task.

c. Determination of the hovering accuracy in terms of the observed position errors, for each display configuration.

During the investigation nine experiments were conducted which are divided into five series. For each experiment, each of the four subjects performed 5 runs, each of 168 seconds duration.

During each run the time histories of the state and control variables were recorded by the computer.

3.2.1 Description of the Experiments

Series A: Perspective visual cues only (Fig. 5)

Experiments 1, 2 and 3 were conducted in order to determine the ability of the HO to perform the control task, by deriving the position information, from the perspective shape of the cube only. Therefore, in this series the visual scene included only the line drawn cube. In order to assure that the perspective cube shape is the only visual cue, the helicopter longitudinal body axis x^b was pointed at all times at the center of the cube. Thus the cube appeared always at the center of the screen. Experiments 1, 2, 3 referred to values of σ=4,8 and 16, respectively.

Series B: Perspective cues in the presence of pitch motion (Fig. 6)

In Exp. 4, which was conducted at σ=8, the ship image was displayed together with the perspective cube. The ship which was subjected to heave motion, presented the pilot with references relative to the ship deck. The horizon line was not displayed and was assumed to be hidden by the ship's structure. Apart from the heave motion, the helicopter executed also a pitch motion, which was a result of the surge autopilot activity, and was not under the control of the pilot. Therefore, the pilot had to control only the helicopter heave motion. The helicopter pitch motion was simulated by a second order Gaussian process, created by a white noise passed through a second order filter with ζ=0.1 and w=0.5 [rad/sec]. This pitch motion caused the displayed image (ship and cube) to move vertically on the screen, but the perspective shape of the image didn't change. As a result the pilot had to derive the positional information, like in Series A, from the perspective shape of the cube. The uncorrelated vertical motions of the image on the screen as a result of the pitch activity, acted like a "visual disturbance".

Series C: Combination of perspective and explicit visual cues in the presence of pitch motion (Fig. 7)

Experiment 5 is similar to Exp. 4, but in addition to the display of Exp. 4, in Exp. 5 the horizon line was also displayed. In this situation the HO has two sources from which the position error can be perceived. The first source is the perspective cube shape, like in the previous experiments. The second cue is the explicit heave error, perceived from the angular distance between the horizon line and the cube center. It should be noticed that the cube center, C, was not displayed explicitly. The purpose of this experiment was to investigate if, and to what extent, the HO utilizes the explicit displacement information (in addition to the implicit information perceived from the cube shape).

Series D: Combination of perspective and explicit visual cues without pitch motions (Fig. 8)

In Exps. 6, 7 and 8 the displayed scene included the ship, the cube and the horizon. But in this series the helicopter didn't execute pitch motion. Therefore the horizon line appeared as a stationary horizontal line through the center of the screen. The purpose of these experiments was to investigate the mechanism of the explicit information perception, in the absence of the disturbing vertical shift of the displayed image, caused by the pitch motions. Experiments 6, 7 and 8 performed for σ=4, 8 and 16 respectively.

Series E: The baseline configuration (Fig. 9)

In Exp. 9, the pilot's visual field was not augmented. In this baseline experiment, where the helicopter didn't execute pitch motion, only the ship and the horizon were displayed. The experiment was performed for σ=8. The pilot didn't perceive implicit nor explicit inertial position information. This experiment represents a highly simplified replica of the actual task, as presently executed. In this experiment the subjects were instructed to maintain, as good as possible, the height given by the average position of the horizontal bar attached to the ship's mast. The purpose of this experiment was to investigate whether and how accurately, the HO is able to perform the control task.

Table 1:Experimental Conditions

	Display Configuration				
Exp.	Ship	Horizon	Cube	σ = R/d	Comments
1	-	-	+	4	-
2	-	-	+	8	-
3	-	-	+	16	-
4	+	-	+	8	Pitch Motion
5	+	+	+	8	Pitch Motion
6	+	+	+	4	-
7	+	+	+	8	-
8	+	+	+	16	-
9	+	+	-	8	-

The various experimental conditions are described in Table 1. The atmospheric disturbance was simulated by first order Markov process with $cov(w_g)=20\ [ft/sec]^2$. The ship heave motion was simulated by a second order Markov process with $cov(h_s)=6\ [ft^2]$, approximating sea state five.

3.2.2 Experimental Results

Post experimental processing included the computation of the means and the covariances of the time histories of the state and control variables, for each run and for each subject. The results presented in Table 2. are the averaged covariances, over all subjects and all trial runs. They represent the mean and the standard deviation of the covariances of the helicopter position and velocity, and the control activity. The averaged means of the time histories were very close to zero. Besides the results presented in Table 2, Figs. 10-18 depict the time histories of the altitude and the control activity of a typical run, for each one of the 9 experiments. Table 2 also presents the results of the analytical model after they had been matched to the experimental data. In this procedure the model's unknown parameters, i.e. q_h, q_w, r, g, V_{y_i}, V_m, τ and τ_N were adjusted such that the covariances of h, w and δ_c were matched with their corresponding experimental values. The parameters yielding the "best match" are listed in Table 3. In general the following can be concluded:

a. A very good match is established between the analytical and the experimental results.

b. In all the experiments the following "best match" values have been obtained: time constant $\tau=0.1$ [sec], neuromuscular time constant $\tau_N=0.2$ [sec], motor noise levels about -20 [db].

   These values are typical for manual control tasks (see [10], [21]-[24], [27]-[31]).

<u>Results of Series A</u>

In Figs. 10, 11 and 12 the effect of σ, the cube size-to-range ratio, is demonstrated. It can be seen, that for $\sigma=4$, due to the large cube image (Fig. 10), the height errors are relatively small. The stick activity shows the existence of high frequency components, resulting from an increased HO gain in the feedback loop. For $\sigma=8$, the cube image becomes smaller and consequently it becomes more difficult for the HO to estimate his height. Therefore, Fig. 11 shows the existence of periods during which the HO does not change the control input. Such a period lasts until the HO succeeds in estimating his height. As a result, the height errors are higher for $\sigma=8$ than for $\sigma=4$. The same behavior, but enhanced, can be seen in Fig. 12, depicting the results of Exp. 3 in which $\sigma=16$.

Table 2: Comparison between the model and experimental results.

Exp.	cov(h) [ft^2]		cov(w) [ft^2/sec^2]		cov(δ_c) [$inch^2$]	
	Exp.	Model	Exp.	Model	Exp.	Model
1	2.09 ± 0.26	2.29	3.92 ± 0.66	2.75	0.155 ± 0.038	0.127
2	6.08 ± 1.71	6.96	5.31 ± 1.35	4.14	0.113 ± 0.041	0.123
3	14.90 ± 2.83	12.40	8.49 ± 2.34	6.08	0.136 ± 0.066	0.191
4	4.73 ± 1.08	4.59	3.91 ± 0.68	3.46	0.101 ± 0.052	0.134
5	1.29 ± 0.42	1.17	2.27 ± 0.55	1.85	0.123 ± 0.041	0.101
6	0.80 ± 0.23	1.04	2.06 ± 0.39	1.72	0.138 ± 0.025	0.096
7	1.10 ± 0.32	1.04	2.06 ± 0.67	1.72	0.104 ± 0.029	0.096
8	1.11 ± 0.24	1.04	2.16 ± 0.55	1.72	0.110 ± 0.030	0.096
9	9.67 ± 2.71	-	7.01 ± 1.88	-	0.133 ± 0.033	-

The analytical model included observations of the helicopter's inertial position and velocity. It can be seen in Table 3 that the position observation noise level increases with σ. In Exp. 1 the observation noise covariance V_h=0.102 [ft^2], is about 5% of the covariance of the measured variable, cov(h)=2.29 [ft^2]. In Exp. 3 V_h and cov(h) are almost equal. Therefore, it can be concluded that satisfactory estimation is obtained only for relatively large cube sizes or alternatively if the cube is viewed from a short range. Both of these situations are not practical because of the small ship dimensions and the required rotor clearance.

Table 3 : Matched Parameters of the Analytical Mode

Exp.	Measure. Model	V_y [db]	cov y	V_y	q_h/g	q_w/g	r/g	V_m [db]
1	$y_1=h$	-18	2.29	0.102	1.22	0.51	3.1	-18
	$y_2=w$	-6	2.17	0.013		g=9.76		
2	$y_1=h$	-7	6.96	3.83	1.22	0.51	3.1	-24
	$y_2=w$	-5	4.14	1.08		g=9.76		
3	$y_1=h$	-5	1 2.4	1 2.3	1.22	0.51	3.1	-22
	$y_2=w$	-5	6.08	6.01		g=9.76		
4	$y_1=h$	-6	4.59	3.62	1.22	0.51	3.1	-20
	$y_2=w$	-4	3.46	4.33				
	$y_3=h-h_s$	-11	8.87	2.21		g=9.76		
	$y_4=w-w_s$	-11	6.28	1.56				
5	$y_1=h$	-13	1.17	0.18	2.11	0.07	3.5	-20
	$y_2=w$	-12	1.85	0.36				
	$y_3=h-h_s$	-11	7.24	1.81		g=7.09		
	$y_4=w-w_s$	-11	5.74	1.43				
6,7,8	$y_1=h$	-14	1.04	0.13	2.11	0.07	3.5	-20
	$y_2=w$	-12	1.72	0.34				
	$y_3=h-h_s$	-11	7.30	1.82		g=7.09		
	$y_4=w-w_s$	-11	5.10	1.27				

Results of Series B and C

In Fig. 13 the results of Exp. 4 are presented. These results are quite similar to the results of Exp. 2 which was conducted with σ=8 as well. The covariances of h, w and δ_c are also very similar (Table 2) in both experiments. This similarity was expected, because in both experiments the visual cues used during the HO's spatial orientation process, were derived from the perspective shape of the cube only. It was also expected that the disturbing vertical shifts caused by the pitch motions, would somewhat deteriorate the performance. Nevertheless, it can be seen in Table 2 that the covariances of h, w and δ_c in Exp. 4 are about the same (and even smaller) than the cues in Exp. 2. Comparison between Fig. 10 and Fig. 12 shows quite similar behavior in both experiments. This means that the pitch motion did not affect the ability of the subjects to derive implicit positional information from the cube structure.

The results of Exp. 5 are depicted in Fig. 14. Comparison between the results of Exps. 4 and 5 shows that the additional explicit information presented in Exp. 5, markedly improves the hovering performances. This improvement includes approximately 75% reduction of the height error covariance, 50% reduction of the velocity covariance and 20% reduction of the control activity (see Table 2).

The observation vector of the analytical model, for both the B and C series, included inertial and relative to the deck observations. The noise levels for the absolute position and velocity were found to be -6[db] and -4[db] in Exp. 4, and -13[db] and -12[db] in Exp. 5. This indicates that the inertial observations are much more accurate when the explicit information is presented. The noise levels of the relative to the deck observations were found to be -11[db] in both experiments.

<u>Results of Series D</u>

In Figs. 15, 16 and 17 the results of Exp. 6, 7 and 8 are depicted. It can be seen both in these figures and in Table 2, that the results of the three experiments are very similar, in spite of the fact that the cube image becomes smaller, with *increasing* σ. It has been found earlier, in the results of series A, that for the smallest apparent cube size (σ=16) the ability to derive positional information from the cube shape is highly impaired. But in Exp. 8, the hovering performance is almost similar to the performance shown in Exps. 6 and 7. Therefore, it can be concluded that the HO uses the explicit information for his inertial measurements, rather than the cues perceived from the perspective cube shape. Comparison between the results of the experiments of Series D, with the results of Series C, indicates *that the disturbing pitch motions do not affect the performance.* The reason is that the vertical shift of the image, in Series C, does not affect the angular distance between the horizon and the cube center and thus does not affect the explicit positional cues.

Since the experimental results of the three experiments in series D yielded similar covariances, only one set of parameters was sought in the model matching procedure. Similarly to Exp. 5 the observation vector in Exps. 6÷8 included inertial and relative to the deck observations. The analytical results in this case were found to be similar to the analytical results of the C series.

Results of Series E

The results of Exp. 9, in which the pilot's visual field was not augmented, are shown in Fig. 18. It can be seen that there exist periods of time in which the HO didn't change the control until he managed to estimate his height. Following these periods of inactivity, large control commands were applied, which resulted in large height errors. Moreover, in this experiment, a strong tendency of the subjects to track the deck motion was noticed (although they were instructed to avoid tracking it). Therefore all the three covariances in this experiment are amongst the highest of all the experiments.

For this experiment it is not possible to match an analytical model, in the Optimal Control Model framework. The reason is that the analytical model requires full observability of the state vector. In Exp. 9 the observations are relative to the ship deck only. Therefore, the inertial height and velocity, necessary to close the control loop, are unobservable. Nevertheless, the subjects succeeded in performing the hovering task, to some extent, because the ship motion forcing function was bounded.

4. Conclusions

The display of inertial position information can be effectively utilized by the pilot. Consequently, the performance of the helicopter hovering task above a moving ship deck is markedly improved.

Implicit inertial position information of the helicopter, can be realized by creating a line drawn inertially stable cube, above the ship deck. This information is effective only for relatively large cube sizes, or alternatively for a cube viewed from a short range. Both situations are impractical for helicopter landing on a small ship deck, due to the ship dimensions and the required rotor clearance.

Explicit inertial position information of the helicopter can be created by combining the line drawn cube realized above the ship deck, with a horizon bar display on the helicopter HUD.

The human operator uses the explicit positional information rather than the implicit information perceived from the perspective shape of the line drawn cube. The Head-Up-Display displayed horizon, in combination with a ship based cube structure of relatively small dimensions, is therefore a successful combination for providing the inertial position information in the hovering task.

The Optimal Control Model is used as a mathematical framework for studying the hovering task. Using the analytical model, the observation and motor noises, the inherent human limitations and the system performance are modeled. Comparison of the analytical results with experimental results provides a useful framework for studying these human characteristics.

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Appendix: <u>State Equation and Observation Matrices of the Analytical Model</u>

The state equations representing the various experimental conditions are:

For Exps. 1-3

$$\underline{\dot{x}} = \begin{bmatrix} \dot{h} \\ \dot{w} \\ \dot{w}_g \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & z_w & z_w \\ 0 & 0 & -a \end{bmatrix} \begin{bmatrix} h \\ w \\ w_g \end{bmatrix} + \begin{bmatrix} 0 \\ z_{\delta_c} \\ 0 \end{bmatrix} \delta_c + \begin{bmatrix} 0 \\ 0 \\ a \end{bmatrix} w_g \qquad \text{(A-1)}$$

For Exps. 4-9

$$\underline{\dot{x}} = \begin{bmatrix} \dot{h} \\ w \\ w_g \\ h_s \\ w_s \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & z_w & z_w & 0 & 0 \\ 0 & 0 & -a & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -\omega_s^2 & -2\xi_s\omega_s \end{bmatrix} \begin{bmatrix} h \\ w \\ w_g \\ h_s \\ w_s \end{bmatrix} + \begin{bmatrix} 0 \\ z_{\delta_c} \\ 0 \\ 0 \\ 0 \end{bmatrix} \delta_c + \begin{bmatrix} 0 & 0 \\ a & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \omega_s^2 \end{bmatrix} \begin{bmatrix} w_g \\ w_s \end{bmatrix} \tag{A-2}$$

$z_w = 0.385$; $z_{\delta_c} = -9.77$; $a = 2$; $\omega_s = 0.8 \left[\frac{\text{rad}}{\text{sec}}\right]$; $\xi = 0.05$.

The observation matrices are:

For Exps. 1-3:

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{A-3}$$

For Exps. 4-8:

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 & -1 \end{bmatrix} \tag{A-4}$$

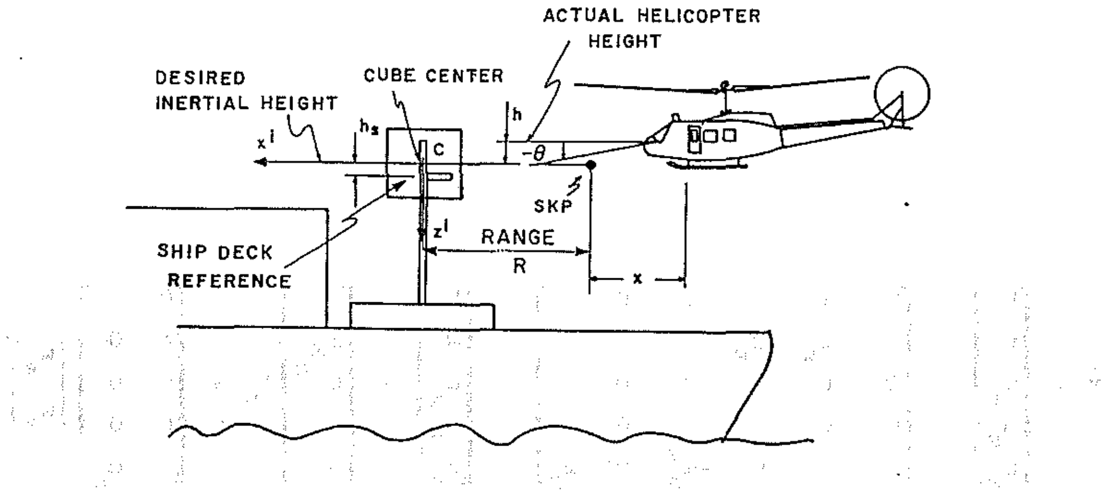


Fig. 1 - Hovering Task in the Longitudinal Plane.

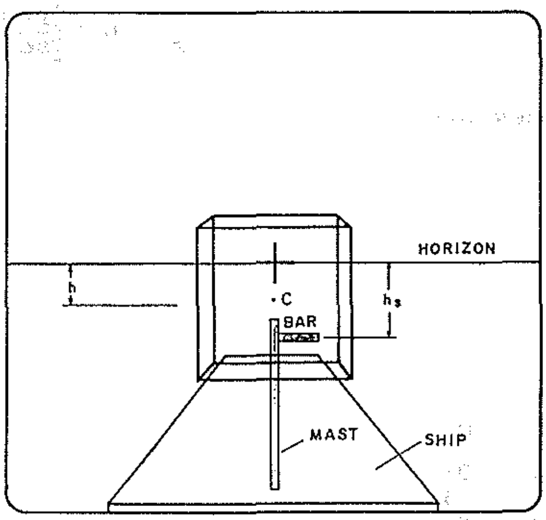


Fig. 2 - Display Configuration.

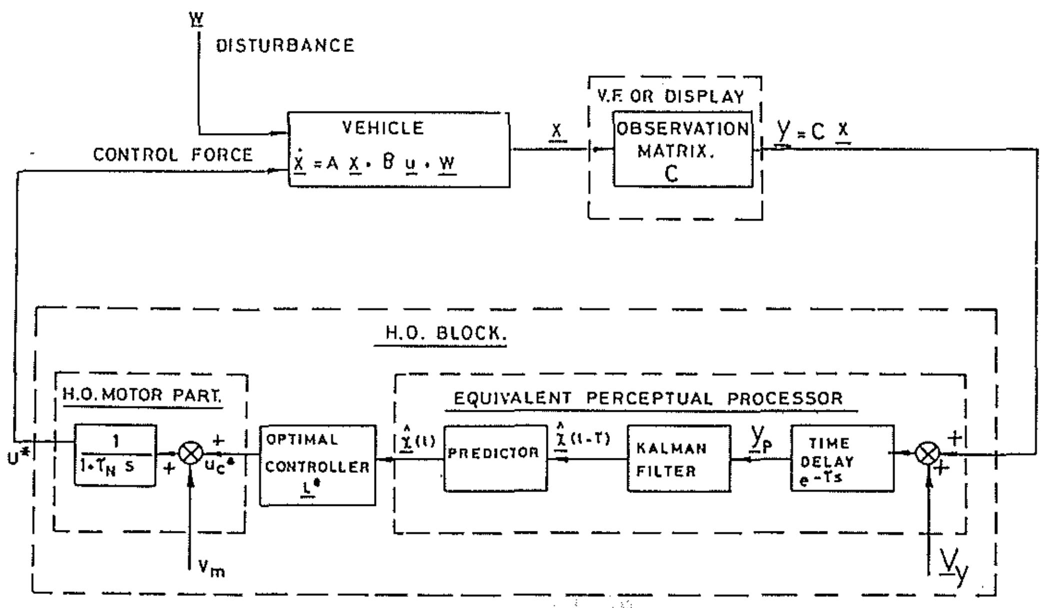


Fig. 3 - The Optimal Control Model.

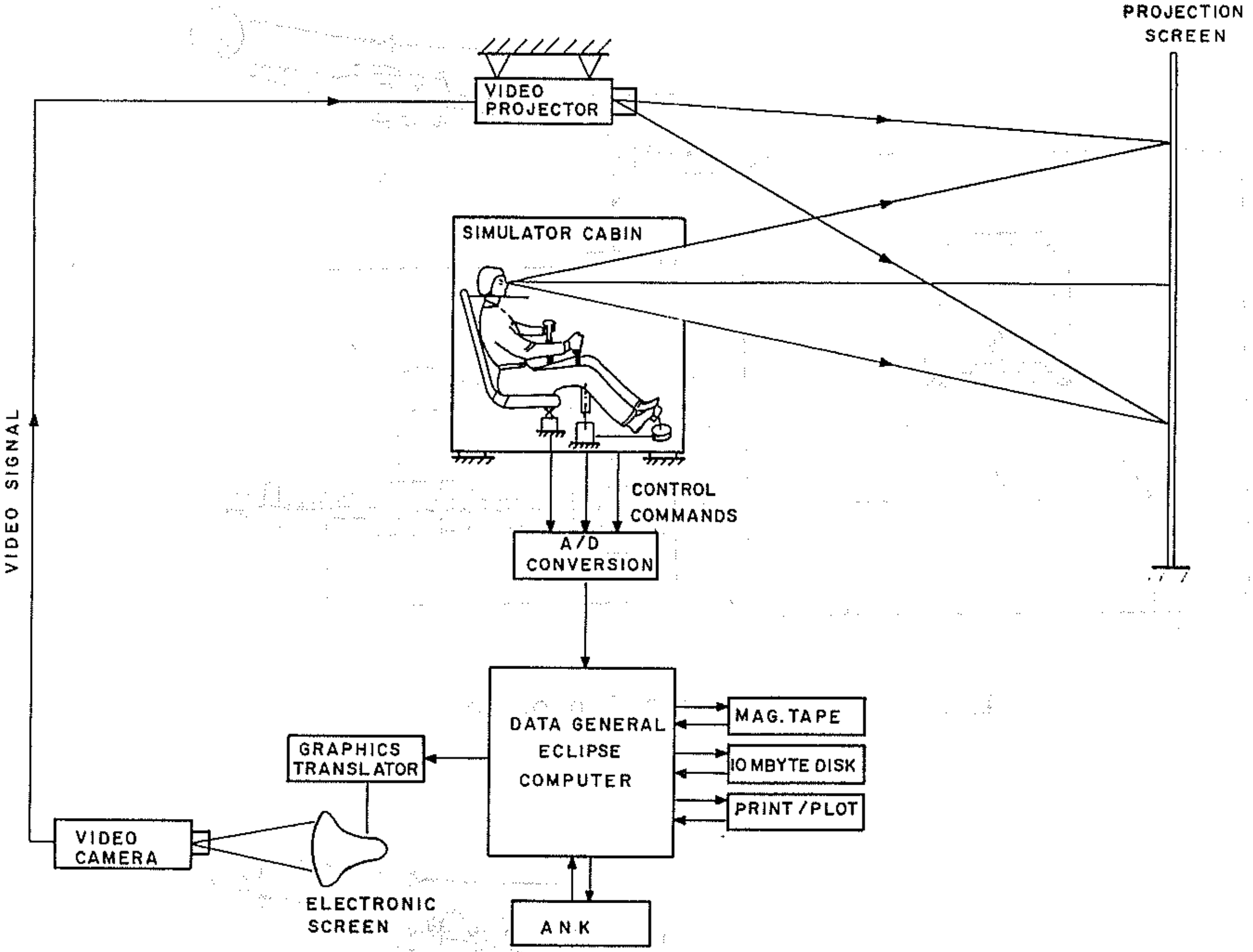


Fig. 4 - The Experimental Set-Up.

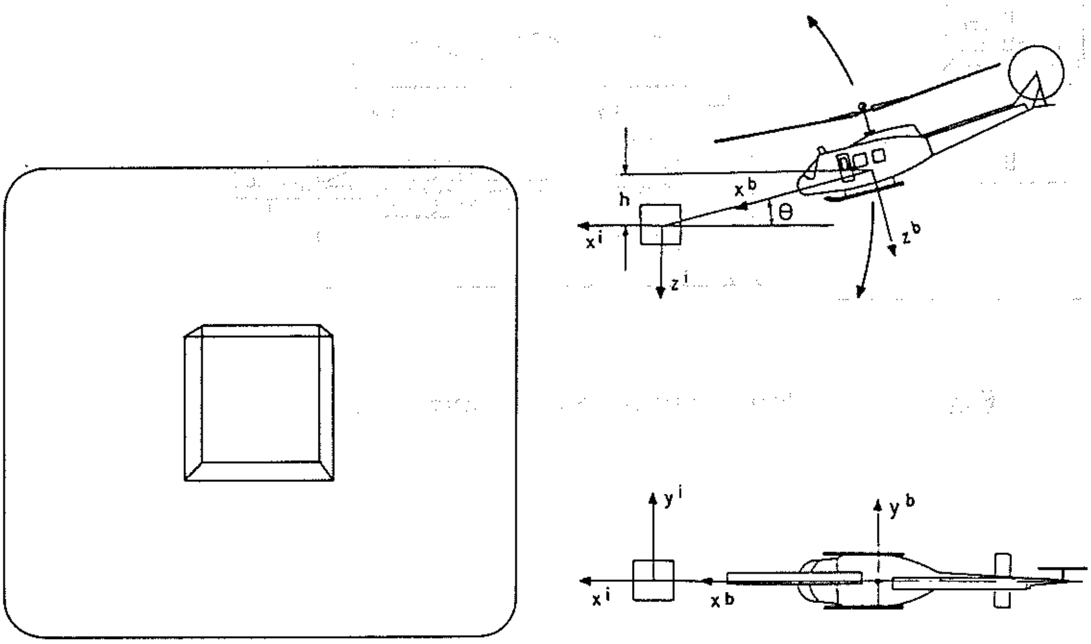


Fig. 5 - Configuration of Exps. 1, 2 and 3.

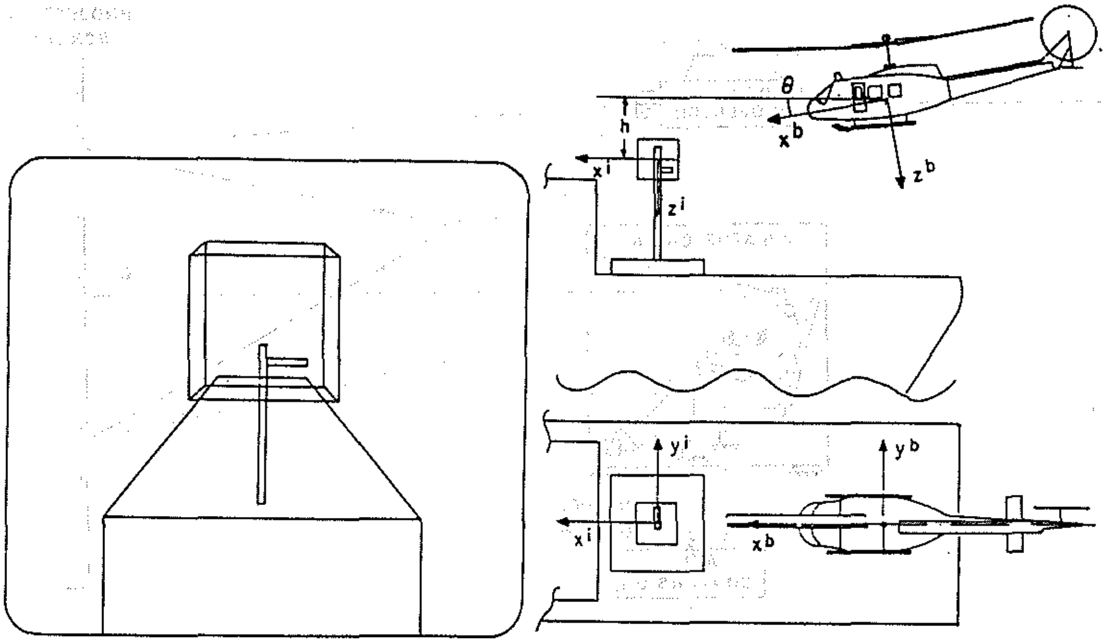


Fig. 6 - Configuration of Exp. 4.

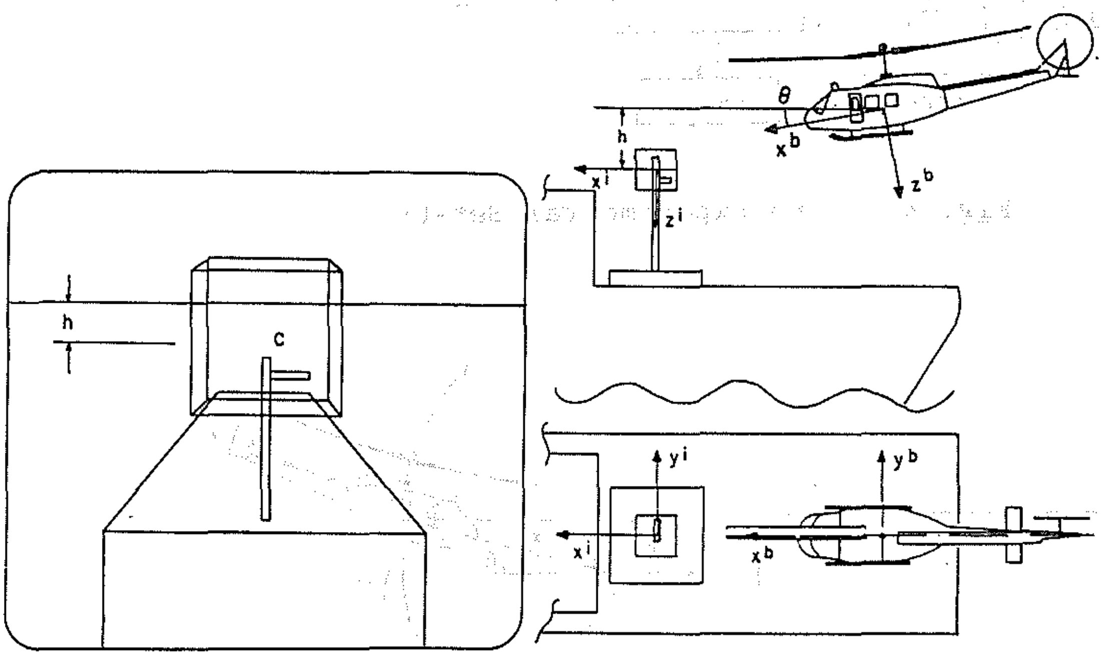
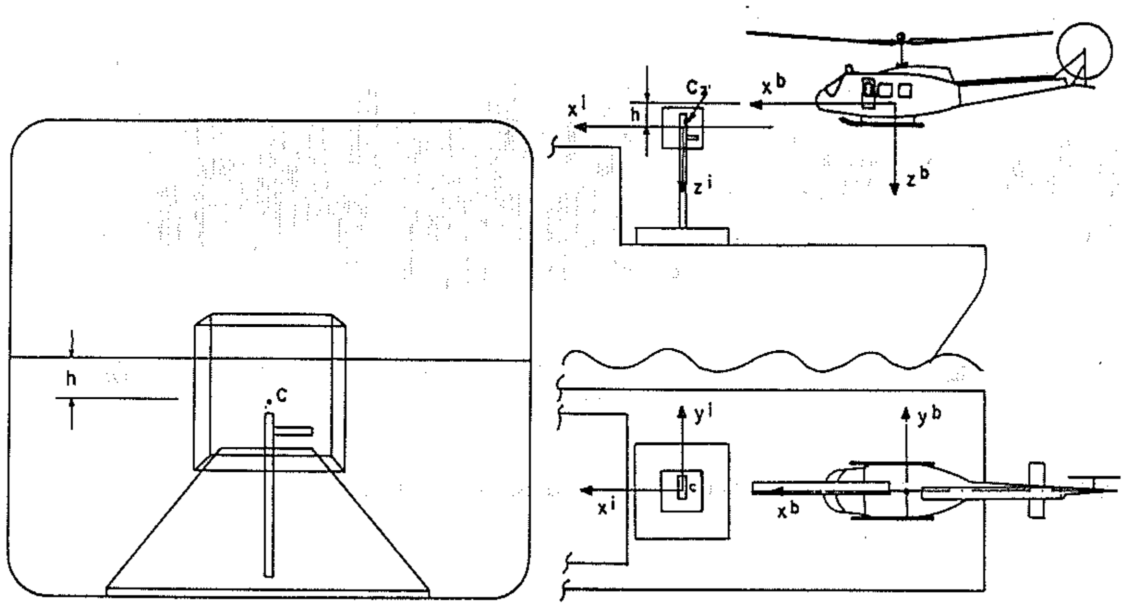
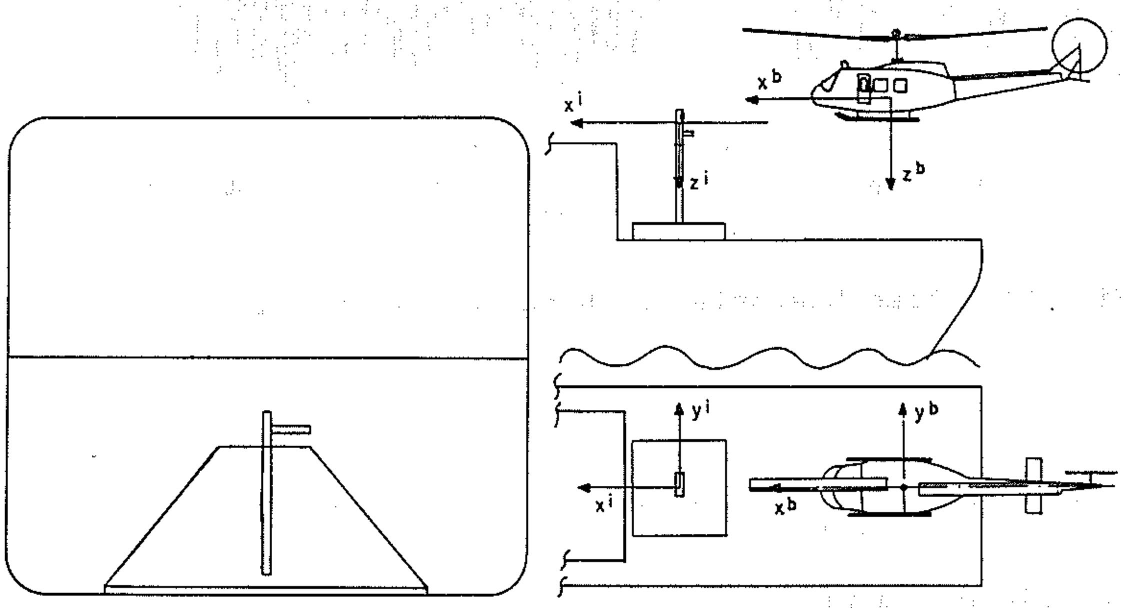


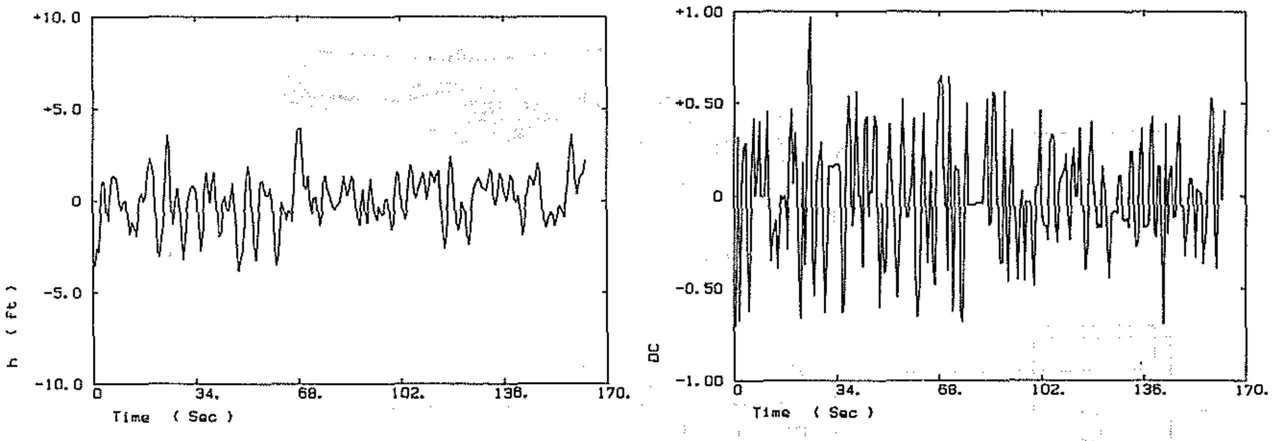
Fig. 7 - Configuration of Exp. 5.



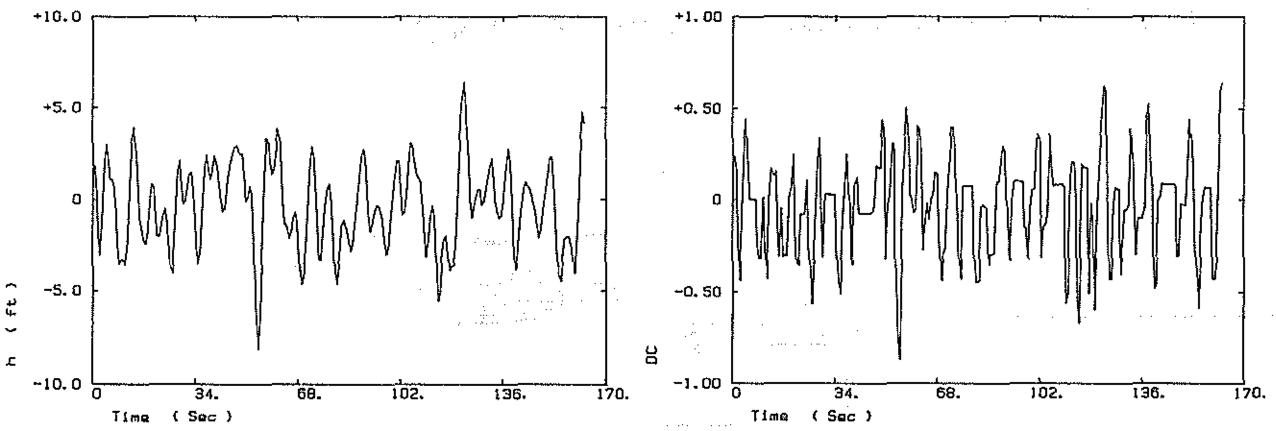
<u>Fig. 8</u> - Configuration of Exps. 6, 7 and 8.



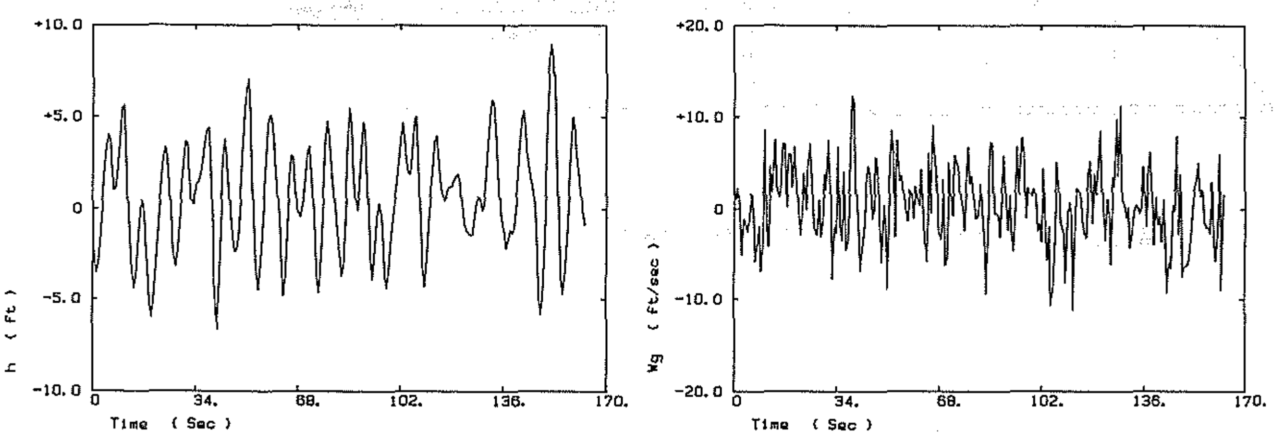
<u>Fig. 9</u> - Configuration of Exp. 9.



<u>Fig. 10</u> - Time histories of h and δ_c of Exp. 1.



<u>Fig. 11</u> - Time histories of h and δ_c of Exp. 2.



<u>Fig. 12</u> - Time histories of h and δ_c of Exp. 3.

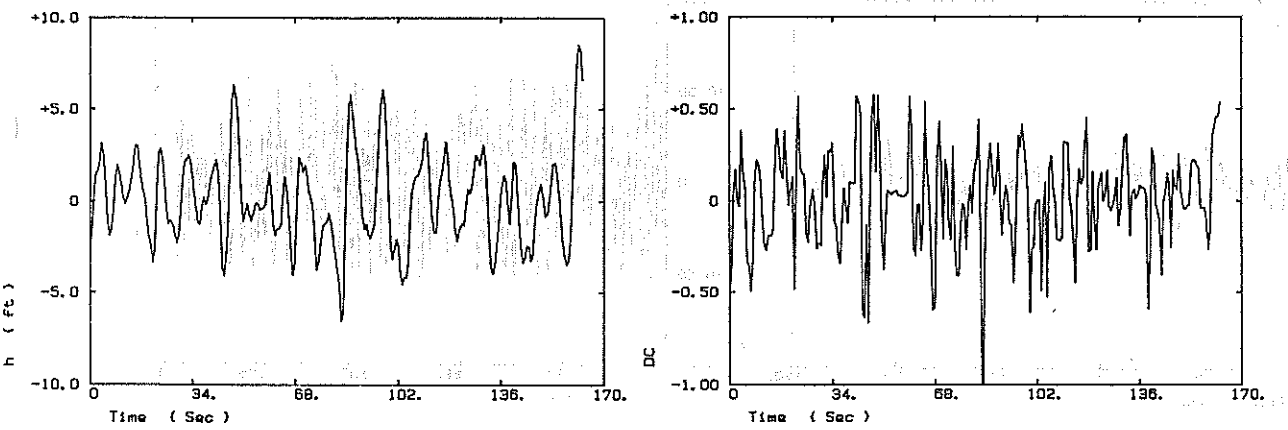


Fig. 13 - Time histories of h and δ_c of Exp. 4.

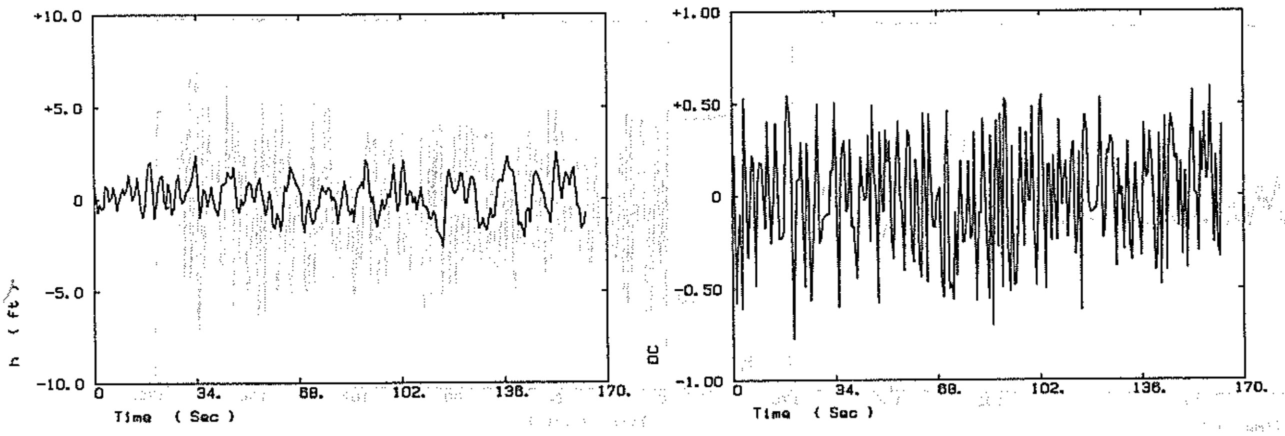


Fig. 14 - Time histories of h and δ_c of Exp. 5.

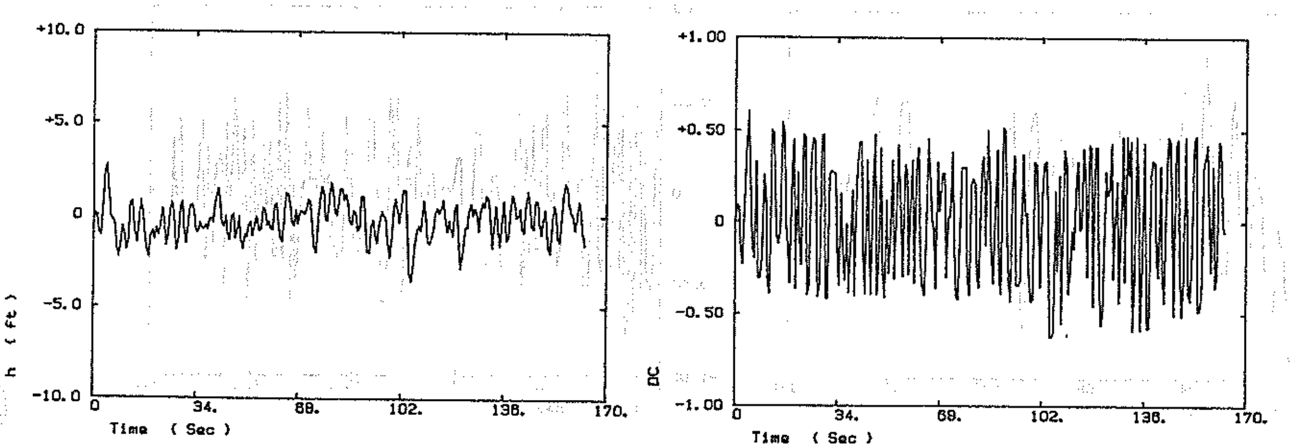


Fig. 15 - Time histories of h and δ_c of Exp. 6.

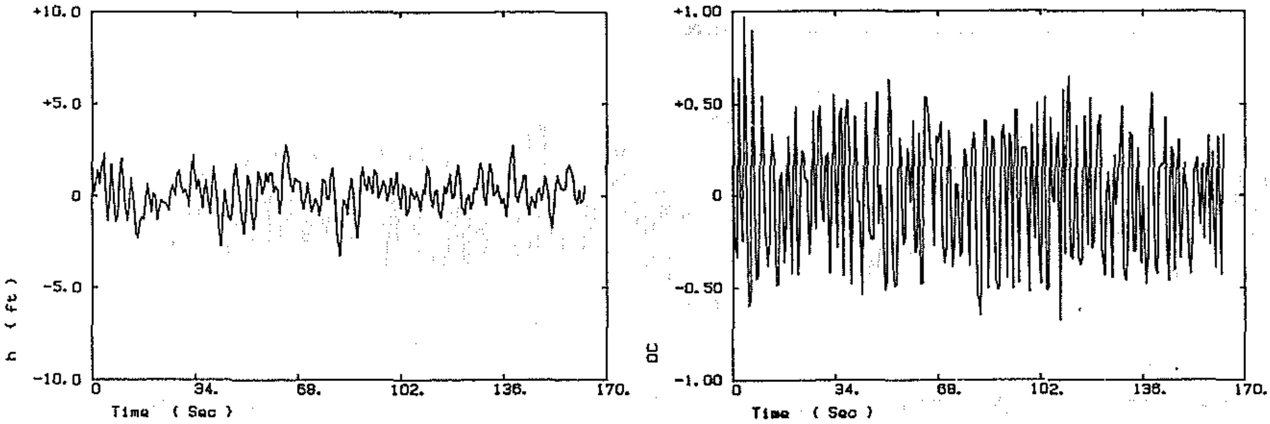


Fig. 16 - Time histories of h and δ_c of Exp. 7.

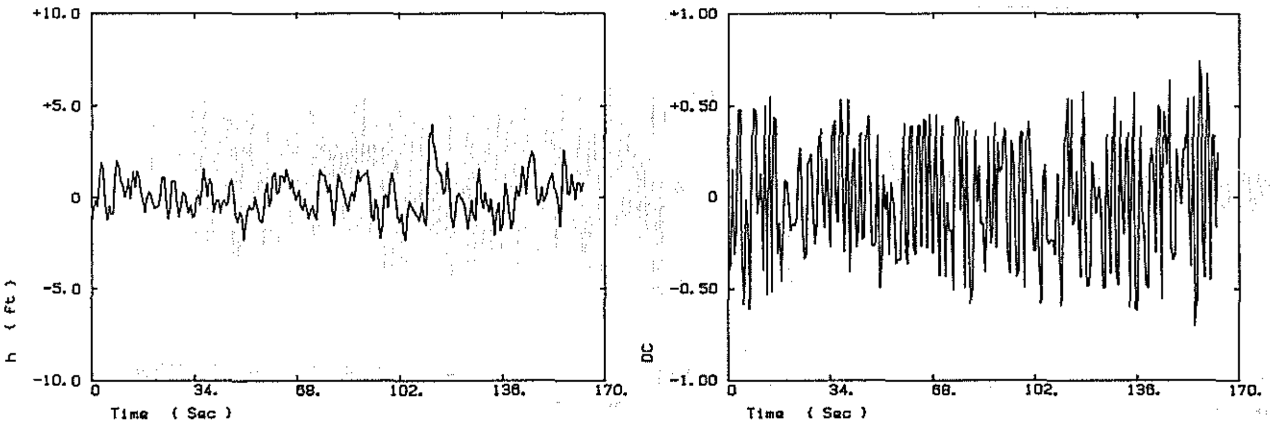


Fig. 17 - Time histories of h and δ_c of Exp. 8.

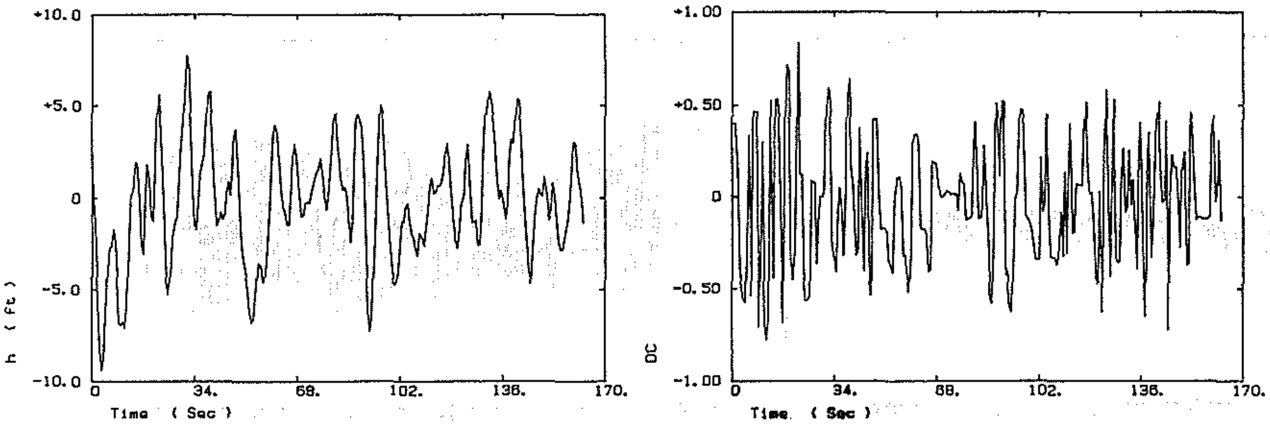


Fig. 18 - Time histories of h and δ_c of Exp. 9.