Visual Perception of Pilots in Carrier Landing

Theodore Gold*
Sperry Gyroscope, Great Neck, N.Y.

Experimental investigations were performed in a visual carrier landing simulator to determine the accuracy and consistency with which Navy pilots can judge position on the glide slope and flight path during final approach. These studies covered conditions involving a quiet sea state in which there was no angular deck motion present, as well as a moving deck. The effects of dusk and night landings and the presence of the Fresnel Lens Optical Landing System (FLOLS) were included. The results indicate that pilots' mean estimates of position when on-course are within a small fraction of a degree of being correct under dusk and night conditions, with a static or moving carrier, with and without the FLOLS. However, variability in judgment is high. Sensitivity to changes in position is reduced with a moving carrier, and falls to a low value of about 40% at night, without the FLOLS. Mean estimates of flight path are within 4 min of arc of being correct when the aircraft is flying toward the desired aim point under all ambient and ship conditions. Again, variability in judgment is high. Sensitivity to changes in aim point is low, falling to about 10% at night.

Introduction

THE approach and landing on a conventional airfield is a demanding task for the pilot in all branches of civil and military aviation. Special circumstances make landing on the deck of an aircraft carrier even more difficult. The limited size of the touch-down region on the deck, the pitch, roll, and heave motion of the deck, and the absence of visual aids in the approach zone behind the stern of the carrier, are aggravating factors.

The importance of visual perception in the manual control and monitoring of carrier landings led to this program to evaluate the effects of some of the key visual factors on the pilot's ability to make critical judgements. The study was concerned with the accuracy with which a pilot can estimate his position on the glide slope and his flight path or aimpoint, during dusk and night carrier landings. The ability to perceive vertical position and flight path are primary factors in the visual control of the aircraft in the vertical plane. Base line levels of performance were established with the pilots using only natural cues in the visual environment for landings during a relatively quiet sea state. The effects of heavier sea states and of visual aids such as the optical landing system are two key factors that were evaluated in this study.

Visual Simulator

General

Since the primary effort in this research was directed to the role of the pilot's visual perception of the external world, the simulator was designed to provide the pilot with the highest degree of visual fidelity obtainable. The constraints imposed on the design of the simulator were size and freedom to program a wide selection of approach trajectories. It was decided to eliminate control inputs to the simulator by the pilot because only constrained aircraft trajectories would provide duplicated known visual stimuli at all times. Therefore, the data obtained in such controlled experiments would be more amenable to direct analysis.

The simulator consists of a three-dimensional scale rendition of the carrier at sea which the pilot views dynamically through an optical system throughout the approach to the carrier. The pilot sits in a moving cab and views the scale model of a carrier on an ocean extending from the approach zone to a visual horizon. The scale of the model with respect to the real world is 1:600. A periscope with unit magnification is used by the pilot to provide him with his correct viewing point in model space. The cab moves longitudinally and laterally to simulate the corresponding motions of the aircraft in relation to the carrier and the ocean bed and carrier move vertically to simulate altitude changes of the aircraft. Rotating optical elements in the periscope simulate aircraft pitch, bank, and heading changes at any point in the approach zone. Approaches from 7000 ft from the carrier to passage over the stern were simulated by this apparatus.

Fresnel Lens Optical Landing System

The Fresnel Lens Optical Landing System (FLOLS) is located on the port side of the landing deck on carriers, and provides the pilot with a direct visual indication of his position on the glide slope during the approach. This indication is in the vertical position of a single yellow light (FLOLS index light) in relation to a horizontal bar of green lights (Fig. 1). The yellow light is always horizontally centered on the green bar. It will be oriented above the bar when the aircraft is high, aligned with the bar when the aircraft is on the glide slope, and positioned below the bar when the aircraft is low. At any given range from the aim point on the deck, the magnitude of the visual angular displacement of the light from the bar is proportional to the displacement of the aircraft from the glide slope on-course. The optical implementation of the

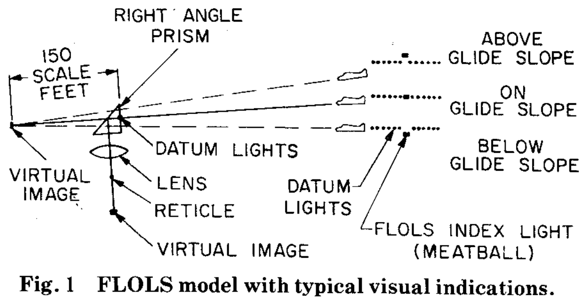

Fig. 1 FLOLS model with typical visual indications.

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* Manager, Human Factors.

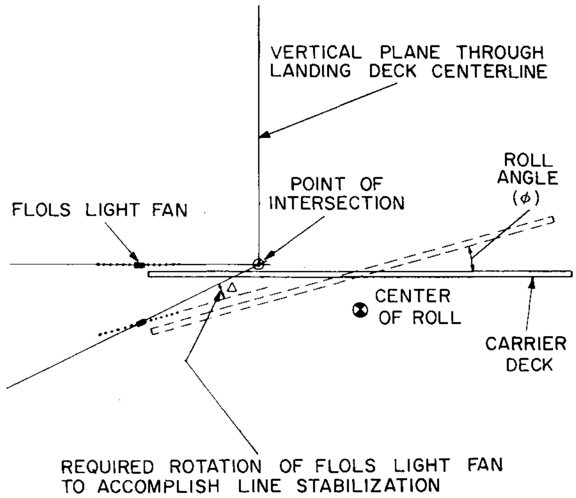

Fig. 2 Scheme for providing roll compensation in the line-stablized FLOLS.

FLOLS provides a "fan" of light in azimuth, so that the pilot will receive an indication of vertical position even though he may be displaced laterally from the centerline of the unit.

If the FLOLS were fixed to the carrier, ship motion would cause the glide slope to waver in space in accordance with the random movement of the ship, particularly in roll and pitch. The technique used to counteract these effects and provide a more stable indication to the pilot is called line stabilization. The line of intersection between the plane of the glide slope on-course provided by the FLOLS fan, and a vertical plane through the centerline of the landing deck is maintained fixed in space, irrespective of roll and pitch of the carrier. Pitch compensation is provided by pitching the FLOLS unit in opposition to the pitch motion of the ship on a 1:1 basis. The technique for accomplishing roll compensation is shown in Fig. 2. The vertical displacement of the FLOLS produced by the roll of the ship causes a translation of the guidance system. The FLOLS fan is rolled through an angle Δ which is proportional to the roll of the ship ϕ, to maintain the stable line of intersection with the vertical center plane through the deck. Note that the stabilizing roll angle Δ is in the same direction as the ship roll angle ϕ. Therefore, the amplitude of the roll of the FLOLS fan in space exceeds the roll of the ship. Figure 2 shows the geometry associated with stabilization for a roll to the port side. The same principles apply to stabilization for a starboard roll, in which the FLOLS unit will be elevated above its mean vertical position.

The implementation of the simulated FLOLS to the small scale of 1:600 for the carrier was accomplished by placing the equipment below the carrier deck and using a prism to direct the images to the pilot (Fig. 1).

Experimental Design and Test Procedures

Basic Experimental Design

The program was designed to assess the effects of ambient illumination, ship motion, and the presence of the FLOLS on the visual performance of pilots in carrier landing. Three different ship situations were selected as test conditions. One condition involved the static carrier representing a relatively quiet sea state, and was designated (S). This was a repeat of a previous study,[1] and its presence was dictated by the use of a new group of three pilots as test subjects. Differences in performance between test conditions could then be attributed to the change in test condition, eliminating any differences between the groups of pilots in the two studies. The second test condition (D) involved a dynamic carrier moving in pitch, roll, and yaw, while the third condition (DF) included the presence of an operating FLOLS on a dynamic carrier. The time available with each subject precluded the use of a fourth test condision (SF), a static carrier with FLOLS. This would have permitted isolating possible interaction between the effects of carrier motion and the FLOLS. However, the line-stabilized FLOLS presents the same direct readout of position to the pilot under both static and dynamic ship conditions. The measurement of its effect under dynamic conditions, including effects due to interaction with ship motion, was therefore considered sufficient for the purposes of this study. The attempt to isolate interaction effects did not warrant the 33% increase in time required for the tests.

Two ambient illumination levels, dusk and night, were investigated for each of the ship conditions, yielding a total of six test situations. The dusk condition included the presence of a visual horizon (DH) while the night condition did not include the horizon (NH′).The previous study indicated that visual performance was not measurably influenced by the presence of the horizon. The conditions DH and NH′ were selected because they represent the extremes from the standpoint of visual cues available to the pilot.

Three carrier pilots were made available by the US Navy for these tests, each for a two-week period. One pilot was from a VF (fighter) squadron, one from a VA (attack) squadron, and one from a VS (antisubmarine warfare) squadron. Each of the pilots had experience as a Landing Signal Officer (LSO) on a carrier.

Glide Slope Tests

The aircraft trajectories simulated in the glide slope tests are shown in Fig. 3. The six flight paths are linear, and they all terminate on the correct aim point on the carrier deck. This aim point permits the arresting hook to engage the center arresting cable when the aircraft is on the correct glide slope (on-course). The six flight paths are symmetrically placed above and below the ideal glide slope, which is at an elevation angle of $3^1/_2°$. The test paths are displaced $\pm^1/_8°$, $\pm^1/_4°$, and $\pm^1/_2°$ from the glide slope. Positions on these test paths above the glide slope were given the designations H1, H2, and H3, while those below the glide slope were designated L1, L2, and L3.

Pilots were required to make judgments of position in two categories, high and low. The glide slope itself was not used as one of the stimuli, to avoid a forced choice situation when the aircraft was actually on course. In addition to the high/low judgments, the pilots were also required to judge the degree of departure from the glide slope in terms of the three categories, 1, 2, and 3. Therefore, responses were in the form such as H-3 for an extreme high or L-2 for an intermediate low position. This psychophysical technique is a variation of the classical method of constant stimuli.[2] Judgments of position were made at five ranges from the aim point, with initial values

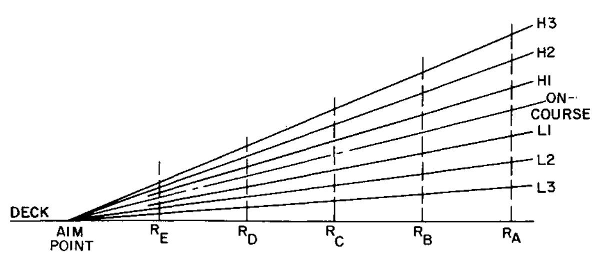

Fig. 3 Aircraft trajectories used in glide slope tests.

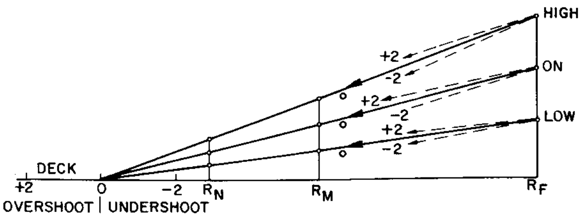

Fig. 4 Aircraft trajectories used in aim point tests.

of 7000, 5600, 4200, 2800, and 1400 ft from the aim point. The pilots were exposed to the visual situation for 800 ft of travel to the carrier from each of the initial ranges. A single aircraft-to-carrier closure rate of 100 knots was used in the glide slope tests.

A test run provided five data points, one at each of the five ranges. A test session consisted of 30 runs, which included five replications of each of the six test positions at each of the five ranges. Therefore, a test session yielded 150 data points (6 positions × 5 ranges × 5 replications). Each test session was repeated for every test condition to produce a total of 300 points per test condition. The sequences of three ship conditions (S, D, and DF) and ambient condition (DH and NH′) were counterbalanced among the three pilots and in time. The six glide slope test conditions generated a total of 1800 data points for each of the three pilots, or 5400 data points in total.

AIM Point Tests

From a stimulus standpoint, the perception of the flight path vector or aim point is interrelated with position. Therefore, test conditions incorporating glide slope variations were designed for the aim point tests (Fig. 4). The same three positions on the glide slope (high, on, low), were used as starting points at each of three ranges. The high and low positions were at $^3/_8°$ above and below the on-course. The test ranges were 5000 ft (R_F, far), 2500 ft (R_M, medium) and 1250 ft (R_N, near) from the ideal aim point.

There were therefore nine possible starting points available, combinations of any of three ranges and any of three positions on the glide slope. Five possible aim points were simulated from each of the nine starting points in the approach zone. These aim points comprised the correct aim point on the deck, (the 0 position), two levels of overshoot, (the +1 and +2 positions), and two levels of undershoot (the −1 and −2 positions). The overshoot and undershoot aim points were varied in position on the deck as a function of range, to provide approximately the same angular deviation from the correct aim point at the three ranges. Angular subtense was considered more appropriate than linear extent as an independent perception variable.

The nine starting points and five aim points produced 45 stimulus combinations, which constituted a test session. Ten orders of presentation of these stimuli were developed, and these were combined with counterbalanced orders of ambient conditions and ship conditions, as in the glide slope tests. This design produced a total of 1350 data points per pilot, or 4050 data points for all three pilots.

Test Procedures

Each pilot was given an indoctrination covering the purpose of the program, the use of the simulator, and the test procedures. Practice sessions were conducted in which the pilots were exposed to all test conditions and stimuli, for both glide slope and aim point studies. Preliminary data were collected until stable levels of performance were achieved.

For the glide slope tests, the cockpit cab was started at a distance of 7000 ft from the reference point on the landing deck of the carrier, with the periscope open. The periscope remained open as the cab advanced 800 ft, at which point the shutter was closed, the cab stopped, and the pilot made his judgment of glide slope position. The glide slope adjustment was then made by raising or lowering the ocean bed by a change in potentiometer setting. The cab advanced toward the carrier at a fixed rate simulating 100 knots for about 600 ft of travel, at which point the shutter on the periscope was again opened for a duration of 800 ft of travel. The shutter was then closed and the pilot made his next judgment of glide slope position. The same procedure was repeated for the three remaining runs in the approach. The exposure intervals for each approach were 7000–6200 ft, 5600–4800 ft, 4200–3400 ft, 2800–2000 ft, and 1400–600 ft. Each approach required above five minutes, consisting of one-minute intervals at each of the five ranges. The subjects were given five-minute rest periods after every sixth approach.

The aim point tests were conducted with a procedure similar to the one used in the glide slope studies. Each test condition involved an adjustment for both initial glide slope position and flight path of the aircraft. The duration of the exposure interval for which time the periscope remained opened was determined by a programmed value of exposure time for the particular test condition. The pilots made judgments regarding both glide slope position and aim point for each trial.

Analysis of Test Data

Classical Psychophysics Analysis

The classical procedure with the method of constant stimuli is to have a subject judge a stimulus as greater or less than a designated criterion. In the present study, the pilots were asked to judge their positions on the glide slope in one of the six categories on which they were trained. Three of these were high (+) and three were low (−). Collapsing the response data into two categories, high and low, produces the classical psychophysical data. When the relative frequency or probability that a response will be in one category, say high, is plotted as a function of the magnitude of the stimulus, the functional relation obtained is called the psychometric function. This function will be a straight line when plotted on probit paper, if there is a normal probability density distribution of responses of the pilot for each stimulus, as shown in Fig. 5. The displacement of the median response (ΔS) is a measure of the bias of the subject, while the slope of the line is a direct measure of the sensitivity of the subject to change in position.

The limitation in this procedure is that it dichotomizes the response data into "high" and "low" categories, there-

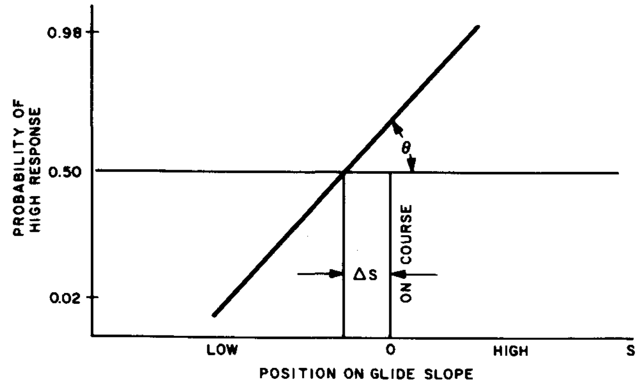

Fig. 5 Classical psychometric function for glide slope data plotted on probit paper.

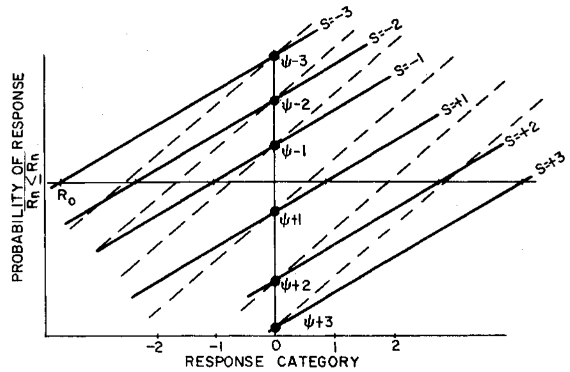

Fig. 6 Response distribution functions which yield the same psychometric function.

by neglecting the important measures of variability in response to a specific stimulus, which is inherent in the raw data. Furthermore, it is possible to obtain the same psychometric function for two subjects whose probability density distributions of response as determined from S-R matrix data are different. This is shown in the Fig. 6, where hypothetical sets of cumulative response distributions are plotted for each of the six stimuli in the glide slope study. The probability of a response being equal to or less than any value R_n, i.e. $P(R \leq R_n)$, is plotted for each stimulus as a function of R_n on probit paper. The intercepts ψ_s are the complements of the probabilities involved in the psychometric function, since

$$P(\text{high}) = 1 - P(\text{low}) = 1 - \psi_s$$

The two sets of response distributions (solid and dotted lines), representing different response variabilities, will generate the same classical psychometric function.

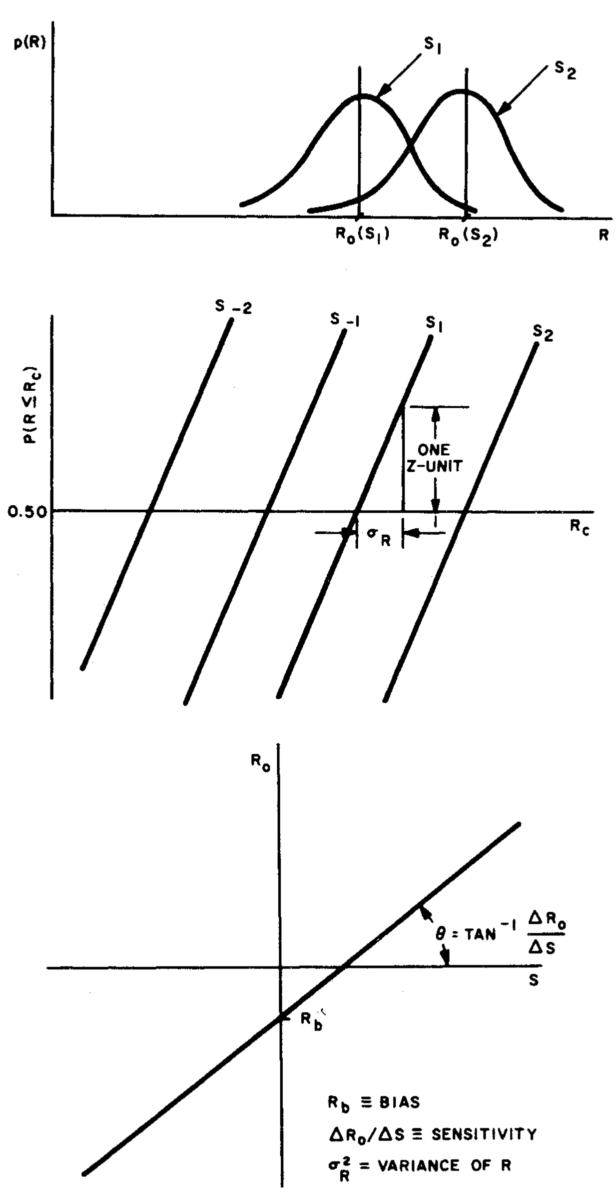

Fig. 7 Performance parameters obtained for typical response analysis

Modified Response Analysis

The modified technique used in analyzing the response data for both glide slope and aim point studies provides three independent measures of visual performance by the pilots. The meaning of these performance parameters is defined in Fig. 7. If there is a normal probability density distribution of response $p(R)$ for each of the stimuli presented (S), the cumulative probability distributions of response $P(R \leq Rc)$ for each stimulus will be a straight line when plotted on probit paper. The slope of this straight line is inversely proportional to the standard deviation of the responses (σ_R) for the particular stimulus. Therefore, the slope of the cumulative response distribution is a measure of variability in response. The mean value of σ_R for all the stimuli was taken as the variability index for the pilots' responses under a given set of test conditions.

The median response for a given stimulus $R(S)$ is the value of the response R at a probability level of 0.50. When the median response is plotted as a function of stimulus, and a best fit straight line is generated for these data based on the method of least squares, two additional performance parameters are produced. The bias R_b is the median response when the stimulus is zero. A negative value of R_b, as shown in Fig. 7, is an indication that a pilot is underestimating the stimulus. With a negative bias, the stimulus must be distinctly positive before the pilot will produce a median response of zero. The second parameter is the sensitivity of the pilot to a change in stimulus, and this is given by the rate of change of median response with respect to the stimulus $(\Delta R_o/\Delta S)$. Therefore, the sensitivity is measured by the slope of the line representing the linear correlation between median response (R_o) and stimulus (S). The three measures of performance, the bias R_b, the sensitivity $(\Delta R_o/\Delta S)$, and the variability index σ_R are generated independently from the stimulus-response matrix data obtained in the experiments. There is no relationship among these variables, and each measures a different facet of the pilots' visual performance.

Computer programs were developed to perform all the calculations required for this analysis. The analysis was implemented for 158 different combinations of variables for the glide slope tests and 252 combinations for the aim point tests. The salient results involving sensitivity and variability are presented in the plots in Figs. 8 and 9.

Results and Implications

Glide Slope Analysis

In all quantitative results, the values for bias (R_b) and variability (σ_R) were expressed in terms of glide slope units of measurement. One unit has a value of $^1/_8°$ displacement from the reference on-course. The response sensitivity $(\Delta R_o/\Delta S)$ is a dimensionless ratio.

The mean response bias R_b for all three pilots under all test conditions were within the maximum value of 0.94 units (0.12°) from the on-course. (These bias data are not shown.) Therefore, the pilots' mean estimates of position when on-course are within a small fraction of a degree of

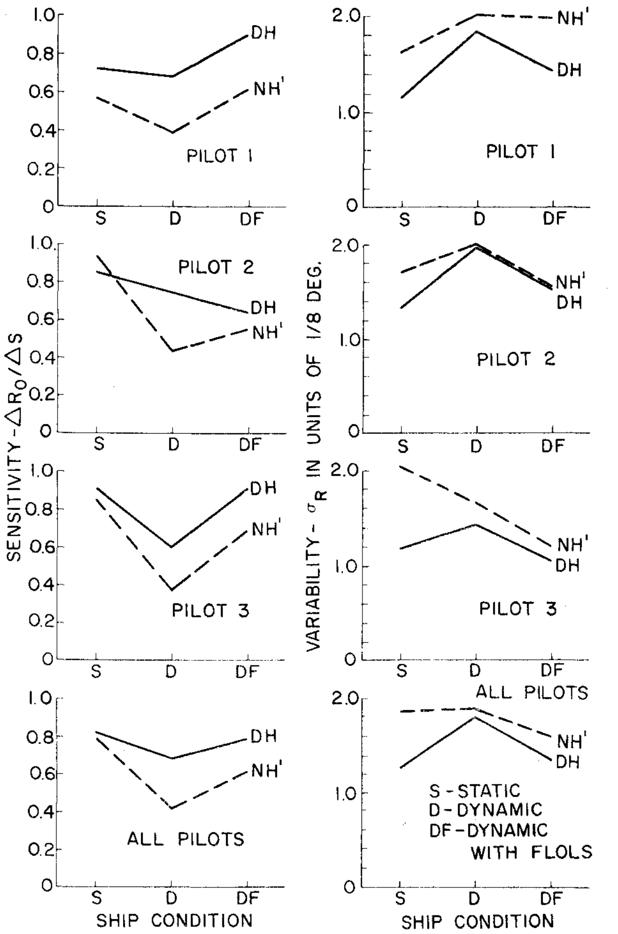

Fig. 8 Sensitivity and variability for glide slope shown as functions of ship and ambient conditions.

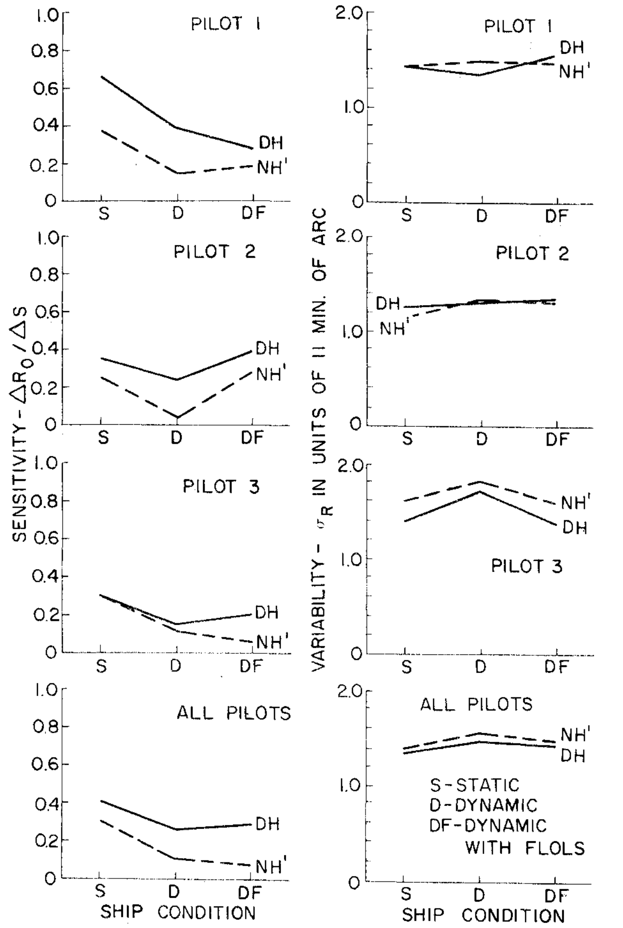

Fig. 9 Sensitivity and variability for aim point shown as a function of ship and ambient conditions.

the correct position. There was no consistent variation in bias with ambient condition or ship condition, save for one pilot, who had higher positive biases under static ship conditions, for both dusk and night situations. This pilot overestimated his position by about 0.76 unit (0.09°) when on the glide slope, under static ship conditions *(S)*. Biases were considerably smaller as pilots and test conditions were combined. These results are in agreement with those obtained in the earlier study.[1]

Changes in sensitivity and variability with ship condition and ambient condition, for each of the three pilots, are shown plotted in Fig. 8. The same data for all pilots combined is also presented in these plots, which reveal the trends in the results. Sensitivity is higher under dusk conditions (DH) compared with night (NH′), indicating higher levels of visual performance under daylight conditions. The differences are considerably larger with a moving carrier with and without the FLOLS (DF and D), when compared to differences with a static carrier *(S)*.

The small differences in sensitivity between dusk and night conditions with the static carrier (0.82 and 0.79) agree with the previous results in Ref. 1. Comparable sensitivities from Ref. 1 are 0.88 for dusk and 0.86 for the night condition, from the data for all six pilots combined. The absolute levels of sensitivity for the two studies are close also, being within about 7% of one another. The base levels for glide slope sensitivity established for the six pilots in the first study are therefore in agreement with the levels obtained for the three pilots in this study.

Returning to the sensitivity data plotted in Fig. 8, the reduction in sensitivity in going from a static (S) to a moving carrier (D) is considerably larger at night (0.79 to 0.42) compared with dusk (0.82 to 0.68). These results are reasonable when the differences in the perceptual situations are considered. Under dusk conditions the pilots have many visual cues to position. These include the three-dimensional perspective of the carrier as a whole, the ocean surface texture with the waves and the wake of the carrier, and the trapezoidal shape of the landing deck. At night only the outline of the landing area, delineated by the pattern of landing lights on the deck, is available to the pilot. However, this perspective pattern is a strong cue, since it enables the pilot to attain almost the same level of sensitivity in the impoverished night landing situation compared with dusk, provided the carrier does not change its attitude; i.e., the static ship condition. Carrier motion limits the effectiveness of the deck perspective. A pitching deck will constantly change the perspective of the landing area. In fact, a change in pitch attitude of one degree is equivalent to a change in position on the glide slope of one degree, which is twice the maximum displacement used in the glide slope tests. The maximum amplitude of the carrier motion in pitch under the dynamic conditions simulated in this study is 1.3°. Consequently, the pilot who uses the perspective of the landing deck as a cue has the difficult task of integrating the changes in carrier perspective to obtain some mean shape, from which he may judge his position on the glide slope. Carrier roll and yaw add confounding unsymmetrical effects to the shape of the landing area. At night the unstable perspective cue is the only one from which the pilot can judge his position on the glide slope. Therefore, the change from a static (S) to a dynamic (D) carrier condition should lead to a larger degradation in visual performance at night (NH′) compared with dush (DH). The percentage reduction in sensitivity from the static to the dynamic conditions are 47% at night and 17% for the dusk situation.

The addition of the FLOLS to the moving carrier increases the sensitivity of the pilots on the glide slope during both dusk and night conditions. The mean increase at night (0.42 to 0.61, for D to DF) is larger than for dusk (0.68 to 0.79). The improvement for the dusk condition leads to a level approaching the static condition, while the change does not lead to a level approximating performance with a static carrier at night. On this basis, the FLOLS does enhance performance on the glide slope, but its effect is not as large as if it provided a read-out of position which pilots can easily perceive. The reason for the low effectiveness of the FLOLS in generating a visual glide slope is its low angular sensitivity as a function of range. The ratio of the angular displacement of the yellow light (meatball) from the green datum bar, to the angular error in position of the aircraft on the glide slope, is $(L/(R-L))$ where R is the range of the aircraft and L is a fixed FLOLS dimension (150 ft). Therefore, this ratio is almost inversely proportional to range, and varies from 0.022 at 7000 ft from the aim point to 0.120 at 1400 ft. For a rather large glide slope displacement of $^1/_2°$ (30 min), the FLOLS readout will vary from 0.67 minute to 3.6 min at the far and near ranges used in this study. These values are between subthreshold and liminal levels for the type of visual discrimination involved in observing the FLOLS. Therefore, the pilots cannot be expected to make precise, consistent readouts with this form of display.

Variability in performance, as measured by the mean standard deviation (σ_R) for the distribution of responses for any specific position on the glide slope, is high under all test conditions for all pilots (Fig. 8). The range of values of σR is between 1.06 and 2.04 units (about $^1/_8$ to $^1/_4°$). This range is in close agreement with the results obtained in Ref. 1, which are from 0.98 to 2.10 units. Based on these values of σ_R, pilots responses vary a maximum of $\pm\frac{1}{2}°$ $(\pm 2\sigma_R)$ from their mean estimates of position on the glide slope 95% of the time. Even these high visual misjudgments are exceeded 5% of the time on a statistical basis. Thus, lack of consistency in visual judgment with the cues available to the pilot is a significant limitation from the standpoint of achieving very high levels of safety in carrier landing operations.

From Fig. 8, it can be seen that variability is consistently lower under dusk conditions compared to night. This difference can be attributed to the multiple visual cues available to the pilot under daylight conditions. The value of σ_R for all pilots combined increases from 1.27 to 1.81 units when the static carrier (S) is replaced with a moving carrier (D) at dusk. The addition of the FLOLS, (DF), reduces σ_R to 1.36 units, which approaches the level of the situation with static carrier. At night, the performance patterns for the three carrier situations differ among the three pilots. Only pilot 2 exhibits the typical performance pattern of degradation from S to D, with subsequent improvement when the FLOLS is added. For pilot 1, the addition of the FLOLS does not reduce variability, while pilot 3 has higher variability under static conditions compared with a dynamic carrier.

Considering the effect of range on glide slope performance, sensitivity is reduced as the aircraft approaches middle ranges and then increases at closer ranges. There are no appreciable changes in variability with range.

Aim Point Analysis

The results of this analysis, in which bias (R_b) and variability (σ_R) are expressed, are in terms of units of flight path error. One unit is equivalent to 11 min of arc.

The values of bias for all pilots under all test conditions vary from zero to a maximum of 0.38 unit (4 min). When the data for the pilots are combined, the maximum bias is reduced to 0.16 unit (approximately 2 min). Therefore, pilots' mean estimates of flight path when actually approaching the aim point are within a few minutes of the currect path. Under static carrier conditions, the mean bias consistently shifts in the positive direction when conditions are changed from dusk (DH) to night NH′). This is in agreement with the results obtained under comparable conditions in Ref. 1.

Sensitivity and variability are plotted in Fig. 9. Sensitivity is generally low, varying from 0.04 to a singular high of 0.65 for pilot 1 under dusk conditions with a static carrier. These sensitivities are considerably lower than those achieved by the pilots in the glide slope tests. This indicates that the pilots do not easily recognize changes in flight path. A sensitivity of 1.0 indicates a veridical mean judgment of change in flight path; i.e., recognition of the actual magnitude of the change. The sensitivities for all pilots combined, with a static carrier, are 0.41 for dusk and 0.30 at night. This compares favorably with the values of 0.39 and 0.27 under the same conditions in Ref. 1. Therefore, the pilots judgments of departures in flight path from a reference value are only about 40% of their true values at dusk and only about 30% at night.

Referring to Figure 9, the sensitivities of all pilots under al ship conditions are lower at night compared with dusk. The combined data for all pilots indicate the pattern of change with different ship conditions. For both dusk and night, the sensitivities are appreciably reduced when going from the static (S) to the moving carrier (D). The addition of the FLOLS to the moving carrier (DF) leads to some recovery in sensitivity for dusk conditions, but not at night. However, this recovery is not sufficient to reach the level obtained with the static carrier. The sensitivity remains low with a moving carrier, notwithstanding the addition of the FLOLS.

The pilot's task of estimating his aim point is a difficult one because it involves judgment of a velocity vector from visual rates of motion which are low in vicinity of the true aim point.[3] The motion cues in this region are below the sensory thresholds of the pilot. The motion cues which are perceptible to the pilot are in his peripheral field, and these must be extrapolated in space to their origin, which is the true aim point, if they are to be useful in judging flight path. However, the pilot also has the option of differentiating his position on the glide slope over a finite period of time, from which visual information he may infer the direction of motion of the aircraft. All three pilots in this study used this technique, as determined in post experiment interviews. However, the pilot must have stable positional references to make this derivative type of judgment. This condition is realized much more closely with a static (S) carrier as compared with a moving carrier (D). The pilots also realized that carrier motion confounds the judgment of aim point. The reductions in mean sensitivity between the S and D conditions, 37% at dusk and 67% at night (Fig. 9), substantiate these inferences. In fact, under most dynamic conditions, Fig. 9 indicates that the sensitivity of some pilots to changes in aim point is less than 0.20, i.e., less than 20% of the actual changes in flight path. This is highly significant for flight control, since changes in position on the glide slope and establishing a correct path when actually on course are both dependent on the control of changes in the flight path of the aircraft.

Variability in judgment of aim point is high, varying between 1.15 units (13 min of arc) and 1.82 units (20 min), for all pilots and test conditions. Under static conditions, the variability index for all pilots is 1.36 for dusk and 1.39 at night. This is in reasonable agreement with the values of 1.29 for DH and 1.22 for NH′ obtained in Ref. 1. Differences in variability are small among either ambient conditions or ship conditions. With a mean variability index of 1.45 units (σ_R = 16 min), 95% of the pilots' judgments of flight path will vary between limits ±32 min ($\pm 2\sigma_R$) from their mean judgments.

Regarding the effects of range on performance, the average sensitivity for all pilots under all conditions increases as range from the aim point becomes shorter. Considering ship condition, the pattern of reduced sensitivity with a moving carrier, and recovery of some of this loss with the addition of the FLOLS is repeated for all conditions and ranges except the extreme range (5000 ft) at dusk. All the pilots tend to overestimate their mean aim point when on target at the far range, and this becomes an undershoot judgment at the near range. This pattern holds for all combinations of ambient and ship conditions and these results are in agreement with those obtained with the static carrier in Ref. 1.

Position on the glide slope as a factor affecting the judgment of flight path was also investigated. The bias R_b in the mean judgment of flight path is correlated with position on the glide slope. The pilots tend to underestimate their aim point when low on the glide slope (L), and this is reduced when on the glide slope (O), until it finally becomes an overshoot judgment when high on the glide slope (H). When the data for all pilots and conditions are combined, the values of R_b for the L, O, and H positions are −0.23, −0.02, and +0.21 aim point units. Sensitivity and variability in the judgment of aim point, however, do not vary systematically with position on the glide slope. These results regarding the effect of glide slope position are consonant with the results from the earlier studies in Ref. 1.

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Considerations for the Design of a Second Generation Induction Driven Transonic Wind Tunnel

J. Braha,* M. Salomon,* A. Seginer,† and J. Rom‡
Technion-Israel Institute of Technology, Haifa, Israel

The considerations for the design of a high Reynolds number 1.5m × 1.5m transonic wind tunnel to be operated up to 5 atm abs stagnation pressure are discussed. The wind tunnel has a closed return circuit, driven by high pressure air injector system. This design results in low initial costs and significant reduction in the operating costs. The experimental data obtained from the 60cm × 80cm induction driven wind tunnel is used as the basis for the present design. The injector design is based on an empirical relation between the test section Mach number and the injector pressure. The effects of circuit characteristics on the injector efficiency, the injector location, test section turbulence and noise levels as well as the flow quality are discussed. The measurements in the 60cm × 80cm wind tunnel indicate that the mass efficiency of the induction driven tunnel (IDT) will be 2 to 7 times better than that of an equivalent blow down (BDT) one. The measured noise level in the present IDT is less than 1% $\Delta C_{p_{rms}}$ and the turbulence level is between 0.5% to 1%. These levels are comparable to those realized in various continuous compressor driven transonic wind tunnels and are well below the corresponding values measured in various BDT ones.

Nomenclature

A_T = test section area
A_s/A_T = ratio of the area of the exit from the test section plenum chamber to the test section area
A_T/A_j = ratio of test section area to the injector area
C_p = pressure coefficient $(p - p_\infty)/(1/2)\rho U_\infty^2$
E = energy for compression of unit mass of air to storage pressure, Kw-sec/Kq
F = frequency
H = test section height
L = test section length
$\dot{m}$ = mass flow rate
M = Mach number
p = pressure
p_0 = stagnation pressure
t_f = duration of air discharge for test
t_t = useful test duration
U = velocity
w^0 = angle of divergence of test section walls
X = test section lengthwise coordinate
Y = test section height coordinate
γ = specific heat ratio
η_e = energy efficiency
η_m = mass efficiency
ρ = density

Subscripts

i = induced flow conditions
j = injector flow conditions
3 = condition at the end of the injector mixing section
∞ = test section condition

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*Research Engineer, Aeronautical Research Center. Member AIAA.
†Senior Lecturer, Department of Aeronautical Engineering. Member AIAA.
‡Professor, Lady Davies Chair of Experimental Aerodynamics. Associate Fellow AIAA.

Introduction

THE increasing importance of Reynolds number simulation in wind tunnels, especially in the transonic regime, is emphasized[1] by the experience with the new generation of aircraft. The correct evaluation of the airplane drag by wind-tunnel tests, particularly at high subsonic and transonic speeds, depends critically on high Reynolds number