Development of the Waveoff Decision Device

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One of the most exacting tasks required of naval pilots is the landing of high-performance airplanes aboard an aircraft carrier. This operation demands precise control and any gross excursion from the glide slope will require the pilot to execute a waveoff. An extensive series of analytical flight trajectory studies were conducted on several naval aircraft to determine the "point of no return" beyond which the pilot is unable to arrest sink rate and execute a waveoff. These studies defined the potential carrier ramp strike waveoff criteria for the airplanes studied. At the completion of the analytical studies, a hardware evaluation of the "waveoff decision device" was initiated. This device mechanized the results of the previous analysis and defined the waveoff limits in terms of airplane geometric position from the aircraft carrier ramp. Preliminary flight tests have indicated that the concept of predicting potential ramp strike is feasible.

Concept

ONE of the most critical and exacting tasks required of naval pilots is the landing of today's high-performance airplane aboard an aircraft carrier. This operation demands precise control of the airplane flight path and any gross excursion from the prescribed approach glide slope will require the pilot to execute a waveoff or "go around" for another landing attempt. With glide slope information continuously transmitted to the pilot and a qualified LSO (landing signal officer) observing each pass to provide additional flight-path correction information, as well as an immediate waveoff signal, some pilots still strike the ramp of the aircraft carrier.

As is commonly known, numerous carrier-landing accidents occur because of the inability of the pilot to execute a satisfactory waveoff subsequent to instructions from the LSO. It is apparent that many of these accidents could be avoided if the LSO could give the waveoff signal earlier. There is obviously a "point of no return" beyond which the pilot is unable to arrest airplane sink rate and climb away from the oncoming flight deck, regardless of his control manipulations.

In April 1963, the Bureau of Naval Weapons initiated an analytical flight trajectory study of the North American A-5A airplane at the NAVAIRDEVCEN (Naval Air Development Center). The purpose of this study[1] was to determine the point of no return for the A-5A airplane and to define the potential carrier ramp strike waveoff criteria for this airplane, with the ultimate goal of providing the LSO with information to assist him in the decision-making process.

In addition to considering power and stick inputs, parameters such as airplane speed, sink rate, and rotation, as well as carrier wake effects, were studied to determine their contribution to defining waveoff boundaries. The results of this analysis indicated that boundaries, such as those established by the study, should be mechanized into some type of device that would assist the LSO in his waveoff decision as he directs airplanes in landing aboard an aircraft carrier. This would involve the establishment of waveoff boundary criteria for the remaining Navy-operational and near-operational airplanes.

A further study[2] defined the point of no return or carrier waveoff outer limits for the A-3B, A-5A, A-6A, F-4B, and F-8A airplanes as a function of initial sink rate and landing speed. The parameters that establish the waveoff limits include horizontal and vertical distance from the carrier ramp.

Three limiting factors, listed in the following, were used in the initial analysis to identify the waveoff boundaries: 1) airplane hook-to-ramp clearance at the ramp shall be 10 ft, 2) allowable pilot response to a waveoff signal shall be 0.3 second, and 3) pilot waveoff technique shall include military power application with no longitudinal control input.

During a normal carrier landing, the desired airplane hook-to-carrier ramp clearance is approximately 10 ft. This distance was felt to be a satisfactory safety margin for an airplane executing a close to the ramp waveoff. It was assumed that this 10-ft tolerance would absorb aircraft rotation, analytical synthesis error, and potential system error. The second consideration made was to introduce a pilot response time that would represent an average value for all pilots. Human factors data[3] provided a value of 0.3 sec as a measure of time required for the pilot to respond to a waveoff signal. In reviewing all available data on the normal waveoff procedure as described in various pilot flight manuals,[4-7] it was concluded that when the aircraft is close in on the ramp the best response to a waveoff should be to apply power only. Modification of items 2 and 3 of these airplane waveoff boundary criteria as they were affected by flight-test results will be discussed later.

In the development of waveoff boundaries, there is one unique flight path an airplane can travel for a given set of initial conditions when a waveoff is initiated by the pilot. An example of a military power waveoff trajectory resulting from an initial approach speed (V_0) of 134 knots and a sink rate (R/S_0) of 20 ft/sec for the F-8A is illustrated in Fig. 1. By applying the previously noted airplane waveoff boundary

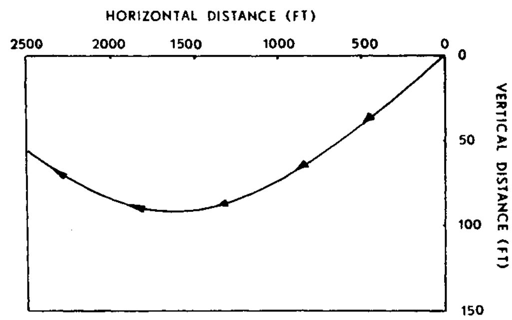

Fig. 1 Waveoff flight trajectory using military power for F-8A at V_0 = 134 knots and R/S_0 = 20 ft/sec.

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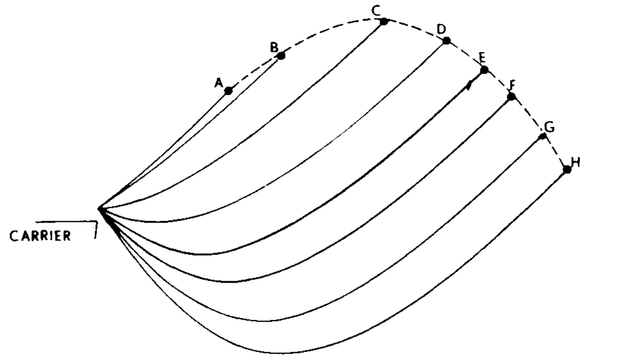

Fig. 2 F-8 Waveoff flight trajectories within carrier environment, 10-ft ramp clearance.

criteria as constants to the airplane waveoff trajectory within the carrier environment, an envelope is described. Figure 2 illustrates how the envelope evolves as the waveoff is initiated at different positions (A–H) relative to the carrier ramp. This results in the airplane either climbing or sinking as it passes over the ramp at the 10-ft ramp clearance point. Figure 3 presents a sample of the resulting waveoff envelope determined from the flight-path data given in Fig. 2.

Development

At the completion of the analytical studies, it was decided to initiate a research and development hardware evaluation of a WODD (waveoff decision device). This device was to be based upon mechanization of the waveoff limits in terms of horizontal and vertical distance from the carrier ramp.

There are several parameters about which knowledge is required when an evaluation of the airplane's flight path is to be compared with a fixed position in space. These parameters include sink rate, forward speed, and horizontal and vertical position relative to the aircraft carrier. If one is able to constantly monitor these parameters and compare them with predetermined limits, a definition of potential ramp strike conditions can be ascertained for each landing airplane. The demanding problem here is not the determination of the waveoff limits but rather how to properly monitor the approaching aircraft. This can be accomplished effectively by using the Navy AWCLS (all-weather carrier landing system). This system, the AN/SPN-42 (Fig. 4), includes a precision tracking radar that automatically acquires and tracks the approaching airplane.

The instantaneous position coordinates of the airplane are supplied by the radar to the data stabilization unit where the position coordinates are corrected for deck attitude and then fed into the flight-path computer. The desired flight path, selected for the particular type of aircraft, is compared in the computer with the measured flight path. During the latter part of the approach and landing, the flight path is compensated for deck motion. For the automatic landing mode,

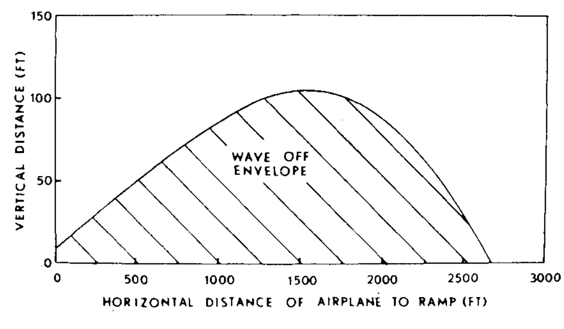

Fig. 3 Sample waveoff flight envelope for F-8A at V_0 = 134 knots and R/S_0 = 20 ft/sec.

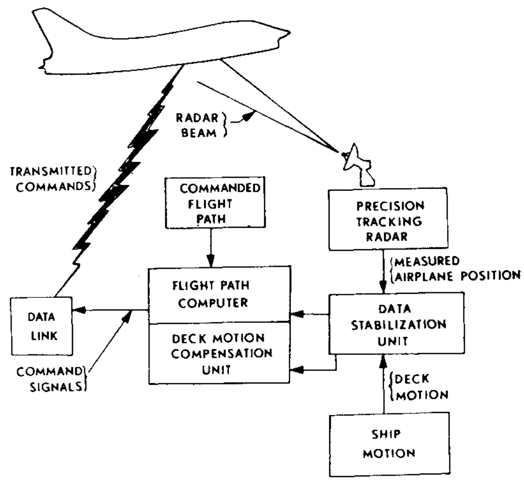

Fig. 4 AN/SPN-42 system operation.

control signals are transmitted over a data link and are used to maintain the airplane on the desired flight path to the touchdown point on the carrier deck.

The modification to the SPN-42 system necessitates additional computer capacity to accommodate the WODD requirements. By using SPN-42 information and comparing it with predetermined limits, the WODD can identify potential airplane ramp strikes. If the airplane exceeds the programed limits, a signal must be given to the LSO. Techniques for displaying this signal and related data are being considered. The WODD obtains the airplane flight-path characteristics from the SPN-42 and utilizes only part of the system, as shown in Fig. 5.

In addition to identifying a potential ramp strike, a preramp strike warning signal has been incorporated into the system. It appeared desirable that some warning be included in the WODD for pilots making gross landing approach errors. Thus, the warning area described in Fig. 6 for the F-8A was added to the WODD system. Operational experience with the SPN-42 landing system indicates that the WODD system should be operating during the last 15 sec of the landing. During the last 2 to 3 sec prior to touchdown, the pilot is committed to whatever situation the airplane is in; thus, monitoring of the flight path from this time interval to touchdown is meaningless.

In lieu of the time variable, an aircraft range of 600 to 3200 ft from the ramp will define the WODD system monitoring zone. This could, of course, be modified depending on

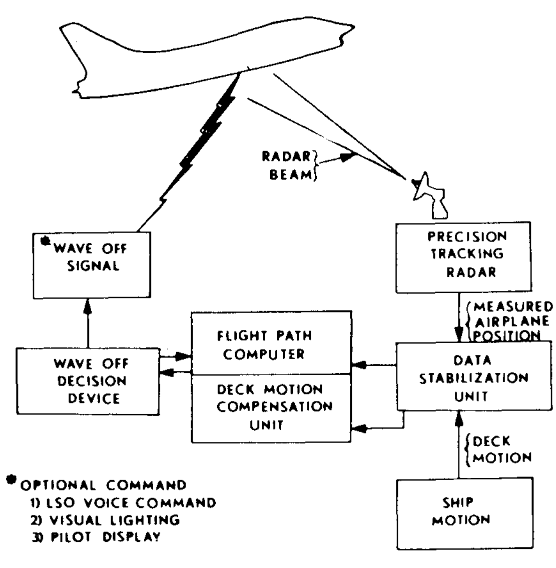

Fig. 5 Waveoff decision device system operation.

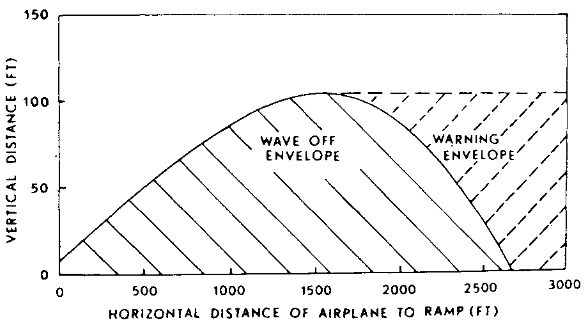

Fig. 6 Sample waveoff and warning flight envelope for F-8A at V_0 = 134 knots and R/S_0 = 20 ft/sec.

flight-test results. Figure 7 presents the waveoff boundaries for the F-8A at an initial approach speed of 134 knots for various initial sink rates.

Each aircraft included in the WODD has three approach speed curves, with a ±10 knots speed spectrum containing sink rate variation as shown in Fig. 7. This results in a parametric matrix that provides waveoff boundaries in terms of horizontal and vertical distance from the ramp for the aircraft for any variation of speed and sink rate.[8] The computer can interpolate between input waveoff data.

Bell Aerosystems Co., Buffalo, N.Y., under contract to NAVAIRDEVCEN, has been assigned the task of developing and designing hardware for the system. For the initial prototype evaluation, the modification to the AN/SPN-42 system requires the removal of some Mode I program digital computer instructions and the insertion of waveoff and warning limits into the system's computer.

Application

The operational procedure involving the use of the WODD is shown in Fig. 8. The flight-path history for an F-8A at an initial landing speed of 134 knots is presented to illustrate the application of the WODD. It is assumed that the airplane has developed an excessive sink rate and has a gross glide slope and altitude error. Looking at Fig. 8, position A: the airplane is low on the glide slope at a sink rate of 25 ft/sec (normal landing sink rate is 12–15 ft/sec); position B: the pilot receives a warning and arrests his sink rate to 20 ft/sec and the LSO warning light goes out; position C: the pilot receives a warning again at the 20 ft/sec warning limit; position D: a waveoff signal is given because the pilot has not corrected for the 20 ft/sec rate of sink warning at position C; position E: the pilot initiates a waveoff by applying military power after a 0.3-sec delay; and position F: the clearance at the ramp is 10 ft and the aircraft is climbing. Although Fig. 8 represents an extreme case of pilot error in the landing mode, it does clearly illustrate the sequence of operations and how the WODD system is to function.

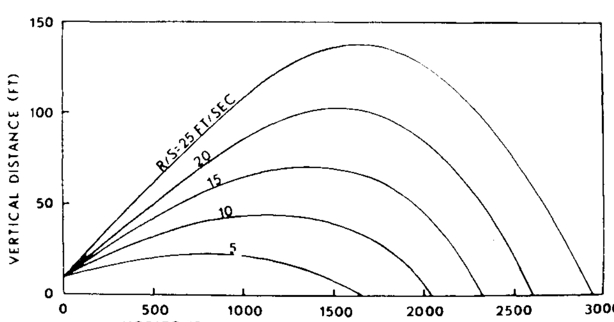

Fig. 7 Vertical vs horizontal distance, waveoff boundaries for F-8A at V_0 = 134 knots.

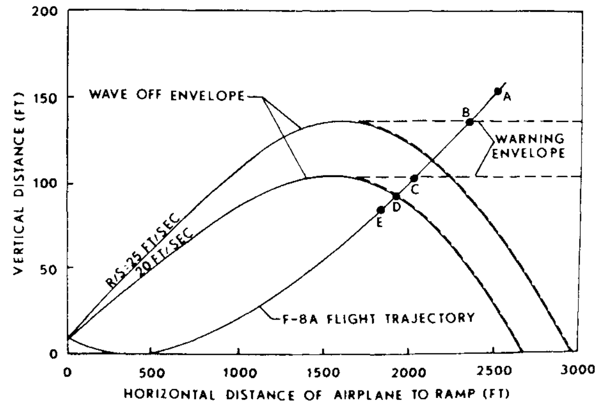

Fig. 8 Sample operational procedures of the waveoff decision device for the F-8A at V_0 = 134 knots.

Evaluation

The next step in the development of the carrier waveoff concept was to evaluate the WODD by flight testing the system. The NAVAIRTESTCEN (Naval Air Test Center), Patuxent River, Md., was requested to determine the operational feasibility of WODD. The specific tests that were assigned NAVAIRTESTCEN were divided into two phases and included the following.

Phase I

1) Waveoff technique: Determination of an optimum waveoff technique for the F-8E and A-7A airplanes. The waveoff technique will consider aircraft rotation, as well as the application of power to effect the waveoff. (As the development of the WODD has progressed, it has become obvious that the pilot uses longitudinal control to rotate the aircraft under some close-to-the-ramp situations; thus, the need has arisen to evaluate the effect of both power and longitudinal control in a waveoff condition.)

2) Maneuvering effects: Determination of range, vertical speed, and of velocity fluctuation limits due to normal maneuvering on the glide slope. The purpose of these tests is to determine if a limit should be included in the WODD to preclude unnecessary waveoffs due to exceeding the waveoff boundaries under normal conditions.

Upon completion of phase I of the flight tests, the results from this phase will be incorporated in the waveoff and warning boundaries of the WODD which will be used in phase II of the tests.

Phase II

1) Waveoff boundaries: Determination of the validity of the waveoff boundaries of the WODD. The waveoff technique and maneuvering on the glide slope tested in phase I will be considered in the evaluation.

2) Waveoff signal display: Determination of the optimum waveoff signal display to the LSO. Consideration will be given to visual and aural signals, as well as a combination of both.

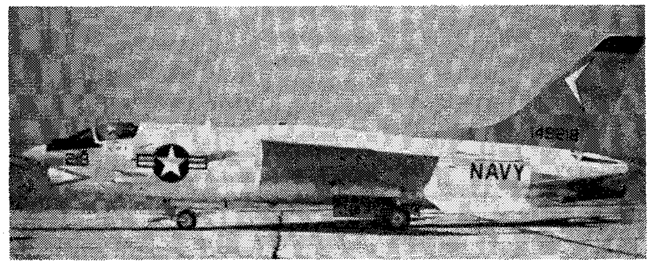

Fig. 9 F-8E WODD test aircraft.

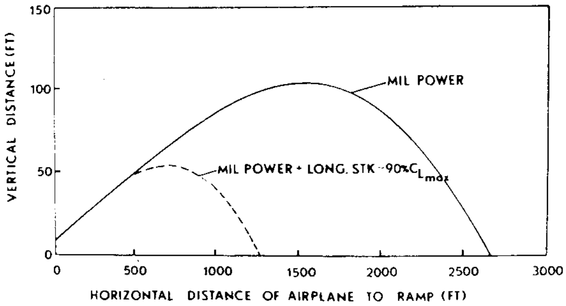

Fig. 10 Comparison of waveoff envelopes for F-8A at V_0 = 134 knots and R/S_0 = 20 ft/sec, military power and longitudinal stick, 90% $C_{L_{max}}$.

The first flight tests were flown during the fall of 1967 utilizing an F-8E (see Fig. 9). The first phase of the test consisted of five flights: two at NAVAIRTESTCEN and three aboard the USS ENTERPRISE. The initial flights were directed toward obtaining what the pilot felt would be the optimum waveoff capability of the F-8. The pilot indicated qualitatively that by adding military power and rotating the aircraft to 15 units angle of attack (15 units = 17.3 deg), he could maximize his waveoff capability.

Earlier analytical results[9] indicated the potential improvement that could be gained from utilizing longitudinal control as well as military power at waveoff. Figure 10 presents a comparison, in terms of waveoff boundaries, between the use of military power only and the use of military power plus longitudinal control equivalent to 90% $C_{L_{max}}$. Note that the vertical distance for initial sink rate of 20 ft/sec decreased from 104 to 54 ft as maximum available longitudinal control was added to the waveoff criteria.

Although both pilot comments and analytical results indicated that the airplane should be rotated by using longitudinal control at waveoff, it was difficult to identify how much control was used by the pilot from the instrumentation data. Since these results were inconclusive, the next step was to try to match flight-test results to analytical predictions. The data were divided into three initial approach speeds of 130, 150, and 160 knots. Each mean speed allowed for ±5 knots variation. Figures 11–13 present the flight-test results for each of the speeds, respectively. Each point represents the vertical and horizontal distance from the carrier ramp at which the pilot initiated the waveoff. The trajectories are so defined relative to the carrier that the airplane will have a 10-ft clearance and zero sink rate at the ramp.

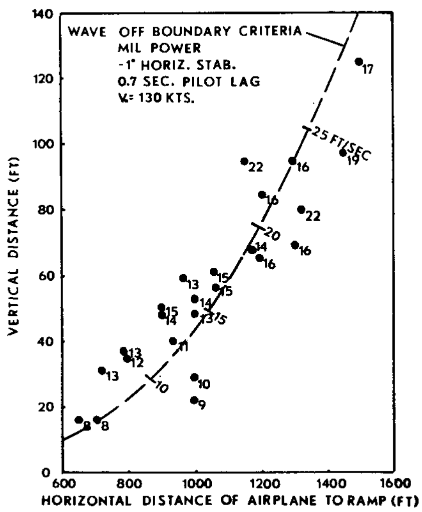

Fig. 11 Vertical vs horizontal distance of airplane to ramp, flight-test data, enterprise, F-8 initial speed at waveoff, V_0 = 130 ± 5 knots.

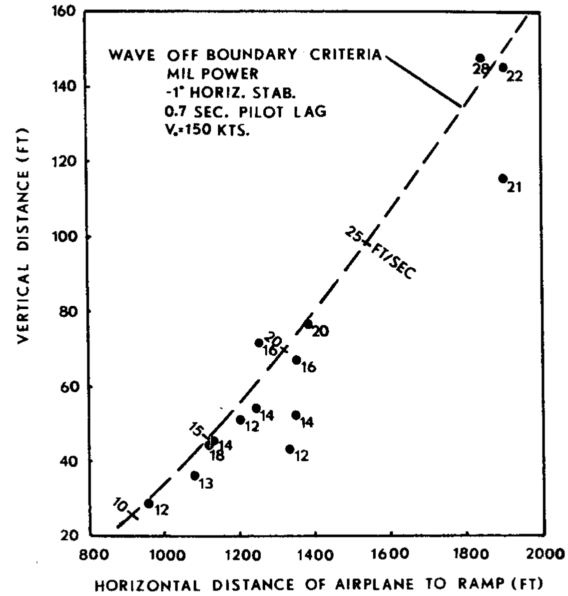

Fig. 12 Vertical vs horizontal distance of airplane to ramp, flight-test data, NAVAIRTESTCEN, F-8 initial speed at waveoff, V_0 = 150 ± 5 knots.

Each point has a small digit next to the symbol which identifies the initial airplane sink rate. Although there is some scatter, there appears to be a definite trend in the flight-test results. The data are defining a definite boundary for the lower sink rates for each initial speed. There are some areas of inconsistency, however. In addition to a greater scatter in the data at the higher sink rate, the sink rates are not in a progressively increasing pattern as would be expected. A preliminary matching of the analytical prediction to flight-test results was attempted by the addition to the flight-test curves of the waveoff boundary envelope. The criteria for this boundary were: 1) military power, 2) −1° horizontal stabilizer, and 3) 0.7-sec pilot lag. It should be noted at this point that the pilot's ability to recognize and respond to a waveoff signal was found to require approximately 0.7 sec. This is contrary to the previously assumed value of 0.3 sec used in the analysis. A preliminary evaluation of the data indicated the pilot reaction time is on the order of 0.7 sec. A statistical study of the data verified this conclusion. A frequency curve was established in order to define the mean pilot lag time. Figure 14 presents the results of this study and shows that a value of 0.7 sec is the approximate value.

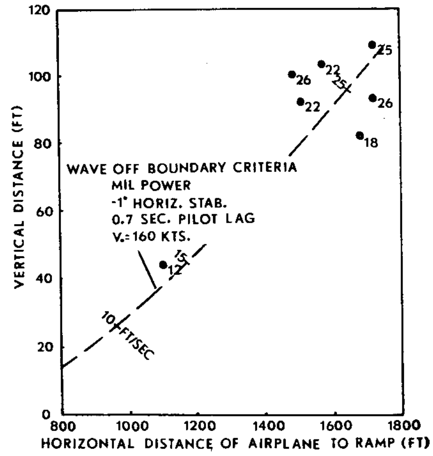

Fig. 13 Vertical vs horizontal distance of airplane to ramp, flight-test data, NAVAIRTESTCEN, F-8 initial speed at waveoff, V_0 = 160 ± 5 knots.

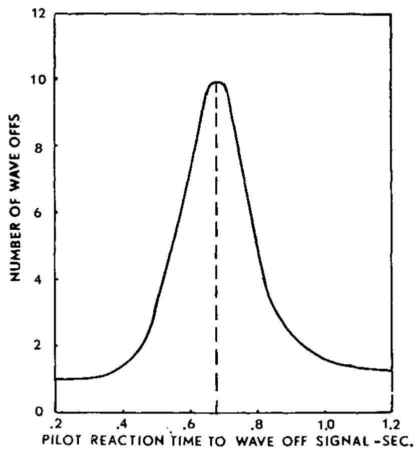

Fig. 14 Pilot reaction time frequency curve for waveoff signal.

The calculated sink rates are noted on the analytically determined curves.

In general, it was felt that the initial comparison of preliminary flight-test and analytical data matching was encouraging. Additional flight tests will be required to verify the WODD predicted boundaries. Such problems as nonsteady state condition before waveoff must be evaluated. The pilot felt that the lack of correlation between the data was due, for the most part, to vertical deceleration of the aircraft just prior to waveoff. This deceleration was an intentional maneuver on the part of the pilot since he felt that this represents the classic cause of a potential ramp strike. Unfortunately, no deceleration terms had been introduced into the WODD boundaries.

Future

The ultimate objective of this project is to provide a device that will perform the necessary computations to predict conditions under which a safe waveoff can be accomplished, and which will provide sufficient lead time to the pilot and LSO to effect a safe waveoff. If the flight-test program of the prototype establishes the feasibility of such a device, it is highly probable that WODD will be incorporated into the Navy carrier landing aid systems. Since precision radar tracking and a digital computer are integral parts of the WODD system, it would seem logical to incorporate this device as part of the AWCLS. The SPN-42 system contains both of these primary subsystems.

ACLS operates in three basic modes: talk down, semiautomatic, and automatic. In the talkdown and semiautomatic modes, the pilot is in control of the airplane and responds to either visual and/or aural corrective cues to land the aircraft. Present waveoff criteria for the SPN-42 in these two modes are restrictive and utilize the same limits for all aircraft. No consideration has been made for the variation in airplane waveoff capabilities. The WODD, however, does discriminate between each aircraft and accounts for its individual aerodynamic characteristics. Thus, WODD becomes a natural supplement follow-on to the existing system and provides an optimization of the present waveoff criteria in the ACLS.

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