EFFECT OF WIND OVER DECK CONDITIONS ON AIRCRAFT APPROACH SPEEDS FOR CARRIER LANDINGS

Air Vehicle And Crew Systems Technology Department (Code 6042)
NAVAL AIR DEVELOPMENT CENTER
Richard P. Micklos Warminster, PA 18974-5000

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The NAVAL AIR DEVELOPMENT CENTER performs photographic surveys of operational carrier landings to determine aircraft landing parameters and structural loads. Recent landing loads surveys have reported aircraft approach speeds in excess of those expected. This increase is a cause of concern, since higher approach speeds increase the loads on the aircraft's arresting hook, landing gear and associated support structure. These higher loads shorten the fatigue life and increase maintenance costs for the aircraft. Table (1) lists the mean values of principle landing parameters from recent carrier surveys. The column of table (1) labeled NATOPS Approach Speed is the recommended approach speed for an aircraft landing at the mean landing weight.

This report identifies the source of this approach speed increase, and shows that it is real and statistically significant. It identifies excess wind over deck, a wind over deck condition higher than the minimum recovery head wind, as the source of the increase in approach speed.

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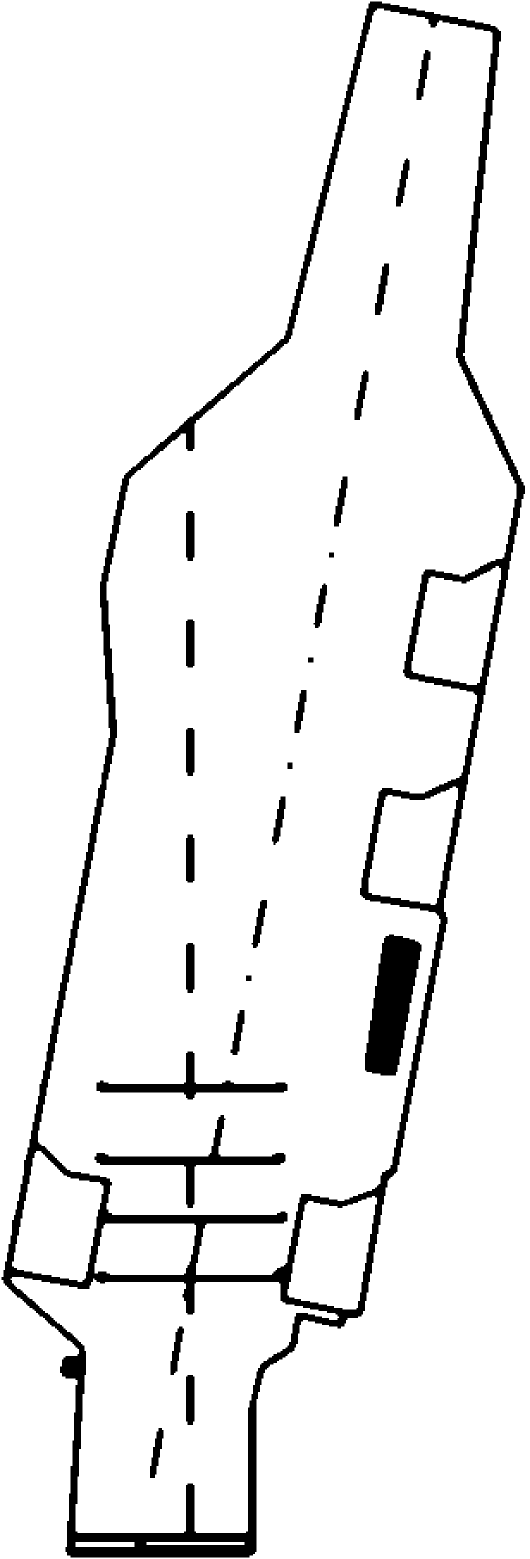
Conclusions

The analysis of carrier landing loads data shows that increasing the amount of wind over deck causes a proportional increase in the aircraft's approach speed measured at touchdown. This argues against the traditional assumption that increased wind over deck does not increase approach speed but results in a decrease in aircraft engaging speed. The additional constraint of holding the aircraft on a prescribed glideslope causes this incremental increase in approach speed.

The higher than anticipated approach speeds reported by NADC carrier landing loads surveys are caused by the increment of approach speed resulting from higher wind over deck conditions.

The NATOPS Recommended Approach Speed Curves are correct for a minimum recovery head wind landings. An additional correction factor must be included in evaluating aircraft approach speeds to account for the variation in wind over deck conditions.

The structural loads on the aircraft during carrier landings are higher than those calculated when those calculations are based on the assumptions in MIL-A-8863A. Higher approach speeds, resulting in higher aircraft engaging speeds, increase the resulting hook and landing gear loads on the aircraft.



However there is an ideal WOD which should especially not be exceeded due to adverse effects

4.2.7 Effective Glideslope Due to Wind and Deck Motion. The glideslope angle, referred to as the basic angle aboard ship, is the fixed pitch angle around which the lens assembly stabilizes. A basic angle setting of 3.5° is most commonly used, with 4° used for higher wind-over-deck conditions (35+ knots) or on the small decks when hook-to-ramp clearance is near the 10-foot minimum. In moderate wind-over-deck conditions (30 to 35 knots), a 3.75° basic angle may be desirable. In Figure 4-7, note that decreased closure rate of aircraft to ship caused by wind-over-deck reduces the actual glideslope flown (effective glideslope).

WIND OVER DECK (KNOTS)	BASIC ANGLE (DEGREES)	EFFECTIVE GLIDESLOPE*
35	4	3.2
30	3.5	2.8

*Based on a 130-knot approach speed

Approach Speed vs Wind Over Deck Analysis

The Angle of Attack Indexer, as well as the Angle of Attack (AOA) indicator on the heads up display, is the primary flight instrument used while flying an approach to a carrier landing. The AOA for an "on speed" approach is indicated on the instrument and is independent of aircraft weight. By holding the proper AOA, and maintaining the aircraft on the glideslope established by the carrier's Fresnel lens, a pilot will perform a successful carrier landing.

The NATOPS recommended approach speed curves are derived from flight test data for each individual aircraft model. For a fixed value of glideslope angle and fixed angle of attack, these curves result in a linear relationship between aircraft approach speed and landing weight.

The NAVAL AIR DEVELOPMENT CENTER (NADC) calculates approach speed for actual carrier landings from the sum of engaging speed (closing speed with the ship) derived from our film records and the "Wind over Deck" recorded on the aircraft carrier.

Attempts to verify the accuracy of NADC approach speeds with the recommended NATOPS curves have consistently shown that the measured approach speeds are higher than those recommended in the NATOPS manuals. Higher approach speeds have been measured during carrier surveys for all models of carrier aircraft. Figure (1) is a plot of measured approach speed versus landing weight for our entire F-14 data base. This data base includes F-14 landing data from Survey 33, performed aboard the USS ENTERPRISE in 1974, thru Survey 47, performed on the USS DWIGHT D EISENHOWER, in September of 1989. Figure (1) also shows the recommended NATOPS Approach Speed Curves for both the F-14A and F-14A PLUS aircraft.

For a carrier conducting flight operations, the aircraft recovery bulletins prescribe a minimum value of "wind over deck" required to land aircraft. The values are different for each aircraft type. "Wind over Deck" is the sum of two components, first the prevailing natural wind and second, the wind created by the forward motion of the ship. The carrier normally sails into the prevailing wind to maximize the value of "wind over deck". The actual "wind over deck" provided is determined by the requirements of the various types of aircraft in the landing pattern, the amount of natural wind, the sea state and other ship operating constraints (such as restrictions on operating areas, weather, other maritime traffic, speed capability or fuel state of escorting vessels). To reduce the carrier's fuel consumption, minimum ship speed is often used consistent with operational requirements.

The operating conditions during the tests to establish the NATOPS Recommended Approach Speed Curves may not be the same as those existing during an operational survey. The NATOPS tests are constrained by the low speed handling qualities of the particular aircraft, which determines the minimum flying speeds for the aircraft. The glideslope followed during the test, which is defined by the fresnel lens, establishes the aircraft's sink rate. The minimum recovery head wind is determined by the difference between the minimum flying speed and the maximum engaging speed capability of the carrier's arresting gear.

If the "wind over deck conditions" or the combination of ship speed and natural wind is not identical to that existing during the NATOPS test program, the value of approach speed, glideslope angle or angle of attack maintained during an carrier landing will vary from the NATOPS test conditions.

During the final stages of a carrier landing, the pilot's principle guidance shifts from the AOA indexer to the glideslope indicator i.e. the "ball" seen on the Fresnel Lens. The pilot must maintain the ball centered in the mirror to land safely on the carrier deck. It is the corrections that the pilot makes to keep the ball centered that account for the approach speed variations we observe. This can be demonstrated by examining the following scenarios. Each of these cases start with an aircraft of identical landing weight flying the NATOPS recommended approach speed for that landing weight.

CASE 1

Assume the pilot is landing in still air onto a carrier which is not moving through the water. In this case, the aircraft's approach speed and engaging speed are identical. Further, assume that the pilot is maintaining the prescribed approach angle of attack, and flying down the prescribed glideslope, this establishes his sink rate. In this case, the aircraft's glideslope angle (BETA) as seen from the flight deck is defined by the equation

TAN (BETA) = sink rate/engaging speed
(engaging speed is equal to approach speed in this case)

CASE 2

Now, the pilot is performing the same carrier landing, at the same landing weight, but in this case a natural head wind of X knots exists. Again the carrier is not moving. The approach speed, AOA, and glideslope angle do not change. In this case, the engaging speed is the aircraft approach speed minus the head wind. The equation defining the aircraft's glideslope angle as seen from the flight deck is

TAN (BETA) = sink rate/engaging speed
= sink rate/(approach speed - X)

Next, the pilot performs the same carrier landing under identical conditions of weight, natural head wind, approach speed, etc, except that the ship has a forward velocity of Y knots. In this case, the aircraft's engaging speed with the carrier deck is the aircraft's approach speed minus the sum of natural head wind and ships forward velocity, (this sum is the value of "wind over deck", W). W = X + Y. The equation defining glideslope angle as seen from the flight deck is

TAN (BETA) = sink rate / engaging speed
= sink rate/(approach speed - wind over deck)
= sink rate/(approach speed - W)

CASE 4

Finally , the pilot performs the same carrier landing under identical conditions of weight, approach speed, etc, except that natural head wind and the ship forward velocity have both changed. In this case, the aircraft's engaging speed with the carrier deck is the aircraft's approach speed minus the sum of new natural head wind and new ships forward velocity, resulting in a new value of "wind over deck", W'. The equation defining glideslope angle as seen from the flight deck is

TAN (BETA) = sink rate / engaging speed
= sink rate/(approach speed - wind over deck)
= sink rate/(approach speed - W')

Clearly, each of these four cases is different. If the approach speed is identical, then the sink rate or glideslope angle must change. The pilot must adjust the parameters within his control, e.g. AOA and engine thrust, to maintain his aircraft on glideslope, since this controls his touchdown point. This forces the pilot to change his approach speed and AOA to land.

To test this assumption on the effect of wind over deck with respect to aircraft approach speed, the NADC data base of carrier landing parameters was used. We currently have landing parameters from a total of over 1100 F-14 carrier landings from a variety of carrier surveys. This data was sorted by landing weight and wind over deck. Landings with weights within a range of one thousand pounds were analyzed. This was to determine if a relationship could be established between approach speed and wind over deck. The NATOPS Recommended Approach Speed versus Landing Weight curve indicates that a one thousand pound weight variation in landing weight results in a two knot variation in approach speed. The queue size of 1000 lbs was selected since the standard error of estimate for engaging speed for the 70mm film system is 2.077 knots for an individual landing, the same uncertainty associated with a one thousand pound weight variation.

Linear regression curves were fitted to the "constant weight" landings. The equation fitted was

Approach Speed = A + B * (Wind over Deck)

The results are as follows:

WEIGHT	No. of Landings	"A"	"B"	Std Error
44-45K	15	114.4	0.785	3.8
46-47K	99	114.9	0.720	6.4
48-49K	192	114.7	0.804	5.4
49-50K	196	112.0	0.965	6.4
50-51K	204	118.6	0.748	6.9
51-52K	175	119.0	0.777	7.2

Clearly, all the data for the F-14 shows an increase in measured approach speed with increasing wind over deck which is independent of increasing landing weight. These curves indicate that 80% of the increase in wind over deck is translated into an increase in approach speed. A series of approach speed versus landing weight curves, plotted for specific values of wind over deck, also shows higher approach speeds as a function of wind over deck. These curves are presented as figure (2) for the F-14, figure (3) for the F-18 and figure (4) for the A-6E.

The regression analysis performed on our F-14 data base was repeated using our EA-6B Aircraft data base . The relationship between approach speed and wind over deck for the EA-6B is similar to that for the F-14. The EA-6B was chosen since this data base does not include any landings from Survey 47, which experience unusually high gusts, wind over deck, and rough seas. The results for EA-6B Aircraft are as follows:

WEIGHT	No. of Landings	"A"	"B"	Std Error
37-38K	23	106.5	0.894	6.2
38-39K	36	118.0	0.522	6.0
40-41K	50	113.6	0.798	5.1

These data samples show the same variation of approach speed with wind over identified for the F-14.

To further pursue the effect of wind over deck and landing weight on approach speed, a multiple regression on our landing data base was performed. This solves for the coefficients "A", "B" and "C" in the equation

Approach Speed = A + B * (WIND OVER DECK) + C * (LANDING WEIGHT)

MODEL	No. of Landings	"A"	"B"	"C"
F-14	1130	112.0	0.780	0.000094
EA-6B	191	108.5	0.812	0.000081
A-6E	267	68.6	0.755	0.001175
F-18	608	90.7	0.270	0.001497

For these equations, the value of approach speed and wind over deck are in knots and landing weight is in pounds. The effect of a one knot increase in wind over deck causes a larger increase in approach speed than a 1000 lb increase in landing weight for all aircraft except the F-18. The typical increase in approach speed with landing weight on a NATOPS approach speed vesus weight curve is two(2) knots per thousand pounds. Only the regression curve for the F-18 shows this typical NATOPS variation.

If the NATOPS tests to determine Minimum Recommended Approach Speed are all performed at the value of Minimum Recovery Head wind, essentially at constant "wind over deck", the effect of increasing "wind over deck" would not be apparent.

This analysis indicates that values of wind over deck in excess of that used while establishing the NATOPS approach speed curves forces the pilot to increase his approach speed to maintain his aircraft on the glideslope. Because changes in approach speed cause a change in lift for a fixed angle of attack, a corresponding change in sink rate will result. The excess wind over deck does not cause a one for one increase in approach speed. This is supported by the magnitude of the "B" coefficient of the regression analysis. The increase in approach speed coupled with the decrease in sink rate, reduces the glideslope angle. This variation in glideslope angle has also been observed in the surveys.

Table 1 of Military Specification MIL-A-8863A, Airplane Strength and Rigidity Ground Loads for NAVY Procured Airplanes, provides a design relationship between Aircraft Sinking Speed and Aircraft Engaging Speed.

This relationship is

Average Sink Speed = 0.128 * Mean Engaging Speed

where Sink Speed is in Feet per Second and Engaging Speed in Knots

and that the standard deviation of sink speed is given by

STD DEV (sink speed) = (0.015 * Mean Engaging Speed) + 1.667

with a minimum value of 3.0 using the same units.

These equations were plotted on curves of sink rate versus engaging speed. These curves are presented as figure (5) for the F-14, figure (6) for the F-18, figure (7) for the A-6E and figure (8) for the EA-6B. These curves show that the data from the landing loads surveys,with very few exceptions, does not exceed the structural design criteria of specification MIL-A-8863A. Curves of average sink speed plus one standard deviation of sink speed versus engaging speed are also provided. In addition, curves showing the expected values of sink speed as a function of engaging speed for a 3.5 degree glideslope and a regression curve of the measured values of sink speed versus engaging speed are also included. Figure (5) identifies a total of twenty three landings whose combination of sink speed and engaging speed exceeeds the one sigma level of Mil-A-8863A. This is from a total of 1130 observations. Only two of these landings occurred during Survey 47 on the USS DWIGHT D. EISENHOWER (CVN-69). Thirteen of these landings were recorded aboard the USS ENTERPRISE (CVN-65) during Survey 33 which occurred in 1974. Four of the remaining landings occurred on the USS KITTY HAWK (CV-63) during Survey 38 in 1980. One night landing on the USS JOHN F KENNEDY (CV-67), during Survey 43 in 1984. Three landings, one day and two night, were recorded during Survey 45 aboard USS ENTERPRISE in 1985.

A significant portion of the increase in Aircraft Approach Speed observed during our carrier surveys can be accounted for by the increase in wind over deck above the required minimum recovery head wind. A calculated value of expected approach speed based on the NATOPS approach speed and excess wind over deck is listed in table 2 below for each F-14 Carrier Survey. The value of "B" used was 0.8. Excess wind over deck is the survey value minus 20 knots. The value of twenty knots was taken from table 1 of the structural design specification MIL-A-8863A. This is a representative value, since minimum recovery head wind varies with different aircraft carrier arresting gear type.

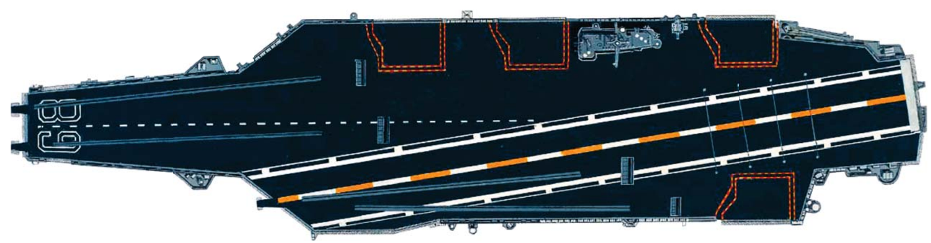


TABLE 2: MODIFIED F-14 APPROACH SPEEDS

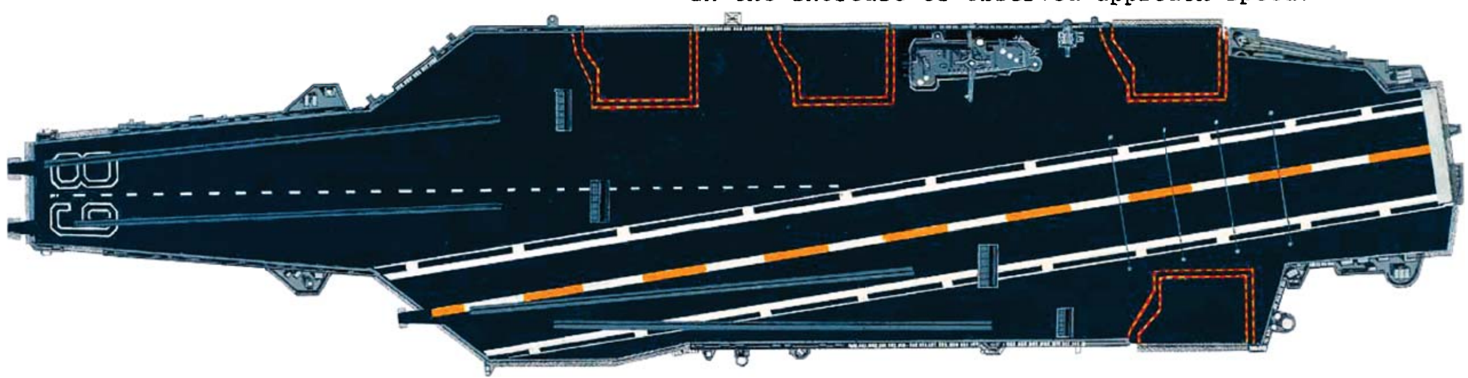
SURVEY	NATOPS VPA	SURVEY VPA	EXCESS WOD	EXPECTED VPA
47 (3.5)	134	148	8	140
47 (4.0)	134	147	14	145
45 DAY	127	140	8	133
45 NIGHT	127	140	11	136
43 DAY	129	135	4	132
43 NIGHT	129	134	4	132
42	129	135	6	134
38	128	129	7	134
35	126	131	7	132

Comparison of the mean values of approach speed from our surveys with the calculated values of NATOPS Approach Speed plus the quantity "B * excess wind over deck" shows excellent agreement with our older survey data (prior to survey 45). Survey 45 night landings also match the prediction within 4 knots. The landings from Survey 47 using a 4.0 degree lens settings also agree with the prediction. The excess approach speeds for the day landings of Survey 45 and the 3.5 degree landings of Survey 47 are not completely accounted for. However the agreement with other F-14 data from the same surveys does indicate that the difference was not caused by an error in the survey procedures or data analysis.

Field Data Verification

In an attempt to verify the analysis of the effect of wind over deck on aircraft approach speed, the data from F-14 Field Carrier Practice Landings was reviewed. This data was collected during Survey 37 at NALF FENTRISS. These landings were performed with very little wind, typically two to four knots. The approach speed versus landing weight for a total of one hundred and eight F-14 landings were plotted on figure (9). When compared with the NATOPS approach speed curves the data shows approach speeds higher than recommended. However, to control sink rates for field landings, the glideslope is set at 3.25 degrees, not the 3.5 degree setting used for most carrier landings. When the measured values of approach speed are normalized to the 3.5 degree setting, the results change significantly, as shown on figure (10). This suggests that the increase in approach speed over the NATOPS recommendation seen in this data is caused by the lower lens angle.

This is another situation that supports the assertion that the corrections the pilot makes to hold in aircraft on glideslope result in the increase of observed approach speed.



Engaging Speed Analysis

The F-14 data base was examined to determine the number of carrier landings which exceeded the hook load or arresting gear load limits. Figure (11) shows the engaging speed and landing weights for over 1130 F-14 landings as well as the hook load and arresting gear limit curves. This plot shows that very few of the aircraft landings exceeded the static structural design criteria.

From this data base, only twenty nine landings exceeded the limit curves. Twenty six of these landings are for F-14A (PLUS) landings from Survey 47 on the USS DWIGHT D. EISENHOWER. As for the other events, one occured on Survey 43 on the USS JOHN F. KENNEDY, one occurred during Survey 42 on the USS CARL VINSON, and one was an F-14 night landing during Survey 45 on USS ENTERPISE. Twelve landings were touch and go landings which do not involve hook or arresting gear loads. Four of the arrested landings exceeded the hook limit by less than 0.3 knots. We consider our camera system to be accurate to $\pm$ two knots.

Two of the landings from Survey 47 exceeded the arresting gear limit for a MK7 MOD 3 arresting gear, the type of unit installed on three of these aircraft carriers. Landing 160 was a 52043 lb F-14A (PLUS) whose engaging speed was 0.9 knots faster than the arresting gear limit and caused a 182 " ram travel of the arresting gear. Landing 880 was a 50697 lb F-14A (PLUS) whose engaging speed exceeded the arresting gear limit by 4.4 knots and caused a 183 " ram travel. The MK 7 MOD 3 arresting gear should stop a 54000 lb F-14A at the arresting gear limit engaging speed in 183" of ram travel. These values of ram travel supports the argument that the approach speeds for these two aircraft were too high.

The one landing from Survey 43 which exceeded the hook load limit, landing 185, produced an arresting gear ram travel of 184". This was a 51450 lb F-14A whose engaging speed was 0.8 knots below the arresting gear limit.

The one landing recorded on the USS ENTERPRISE (landing 9342) was a 50100 lb F-14 which had an engaging speed of 134 knots. This ship is equipped with a MK 7, Mod 2 arresting gear, whose normal ram travel is 171". This landing was one of three night landings which produced 172" of ram travel.

The landing parameters for the twenty nine high engaging speed landings are included in table (3). All of these had adequate values of wind over deck. If the conventional assumption that engaging speed is reduced by increased wind over deck is applied, then these landings are difficult to explain. The reaction of the aircraft carriers arresting gear to these landings confirms the accuracy of the reported approach speeds.

To place these assumptions of the effect of Wind over deck on Approach Speed on a scientific footing, Rank Correlation Coefficients were calculated from survey data. These coefficients were selected since the distributions for Approach Speed, Engaging Speed and Wind over Deck were not normal. This lack of normality prevents the use of the correlation coefficients associated with the regression curves.

The values of the Rank Correlation Coefficient vary from +1.0 to -1.0. Each event to be compared consists of a variable pair (X,Y). The variables to be ranked are assigned a values 1 to N were N is the number of items in the list. The values of N are assigned to X in the sequence of increasing values of the variable. The values of N are then assigned to Y also in its sequential order. A value of 1.0 for the Rank Correlation Coefficient indicates a perfect correlation between the two variables involved (Rank(y) = Rank(x)). A value of -1.0 indicates a perfect inverse relationship between the the variables involved (Rank(y) = Rank(-x)). A value of 0.0 for the coefficient indicates that no correlation exists between the variables (X,Y).

Rank Correlation Coefficients were calculated for the F-14 aircraft for the combinations of Approach Speed and Wind over Deck as well as Engaging Speed and Wind over Deck. These coefficients were calculated for the entire 1130 landing data base as well as for the date base divide into 1000 lb weight classes. The results are summarized in table (4). The values of Rank Correlation Coefficients for Approach Speed vs Wind over deck are inconclusive. A degree of correlation appears to exist, but the correlation is not statistically significant.

The values of the Rank Correlation Coefficient between Engaging Speed and Wind over Deck for the F-14 show convincingly that there is no relationship between these variables. This is a significant observation, it indicates that the amount of wind over deck does not effect the engaging speed of the aircraft. This supports the theory from our regression analysis that increases in Wind over Deck result in an increase in approach speed not a decrease in Engaging Speed.

To extend this observation to other model aircraft, Ranked Correlation Coefficients were calculated for Engaging Speed and Wind over Deck for the A-6E, EA-6B and F-18 Aircraft. The Coefficents calculated for the 271 A-6E landings was -0.0645, and for the 194 EA-6B landings was -0.0327. These values indicate that no relationship exists between Engaging Speed and Wind over Deck for the observed landings of these aircraft. The value calculated for the F-18 was -0.3988, which is considered to be inconclusive. Further evaluation of 598 F-18 landings by dividing the data base into 1000 lb weight groups was also inconclusive. These results are listed in table (5).

Analysis of F-18 aircraft landing was then extended to calculate the Rank Correlation Coefficient between Approach Speed and Wind over deck. These values, which also are included in table (5), are inconclusive. This indicates that the landing performance of the F-18 is different than that observed for the F-14.

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Conclusions

The analysis of carrier landing loads data shows that increasing the amount of wind over deck causes a proportional increase in the aircraft's approach speed measured at touchdown. This argues against the traditional assumption that increased wind over deck does not increase approach speed but results in a decrease in aircraft engaging speed. The additional constraint of holding the aircraft on a prescribed glideslope causes this incremental increase in approach speed.

The higher than anticipated approach speeds reported by NADC carrier landing loads surveys are caused by the increment of approach speed resulting from higher wind over deck conditions.

The NATOPS Recommended Approach Speed Curves are correct for a minimum recovery head wind landings. An additional correction factor must be included in evaluating aircraft approach speeds to account for the variation in wind over deck conditions.

The structural loads on the aircraft during carrier landings are higher than those calculated when those calculations are based on the assumptions in MIL-A-8863A. Higher approach speeds, resulting in higher aircraft engaging speeds, increase the resulting hook and landing gear loads on the aircraft.

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