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Jet-Induced Aerodynamics of V/STOL Aircraft over a Moving Deck

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The jet-induced aerodynamics of a representative V/STOL aircraft was assessed over a three degree-of-freedom ship deck motion simulator by McDonnell Aircraft Company under contract to the Naval Air Development Center. The objective was to determine the effects of deck motion on the induced aerodynamics during landing and takeoff operations from seaborne platforms. Comparisons with predictions based upon steady-state data obtained with fixed deck positions indicate that deck motion can often produce higher lift loss and variations in moments, particularly for complex combined deck motions. This is attributed primarily to modified fountain impingement forces and increased turbulent mixing due to deck motion. Several configuration variations were also evaluated, including the effects of model contouring and lift improvement devices. These results indicate that accurate simulation of the fuselage lower surfaces can be very important and that lift in ground effect can be improved significantly by simple fences, even at high deck roll angles.

Nomenclature

b = wing span, in. or cm
c = mean aerodynamic chord length, in. or cm
CFNS = nondimensionalized induced lift coefficient based upon static gross thrust, $=\Delta L/F_G$
CPMS = nondimensionalized induced pitching moment coefficient based upon static gross thrust, $=\Delta PM/F_G c$
CRMS = nondimensionalized induced rolling moment coefficient based on static gross thrust, $=\Delta RM/F_G b$
D_{j_e} = equivalent nozzle exit diameter based upon the total area of all nozzles, in. or cm
f = frequency, Hz
F_G = total static gross thrust of the nozzle exhaust flow, lbf or kg
H = model nozzle height above the deck, or the distance of the nozzle exit plane above the neutral point of the moving deck, in. or cm
h = heaving amplitude, in. or cm
LID = lift improvement device
ΔL = induced lift force acting on the airframe
NPR = nozzle pressure ratio, P_{t_j}/P_0
P_0 = ambient pressure, psi or kg/m^2
ΔPM = induced pitching moment, in.-lbf or m-kg
P_{t_j} = nozzle exhaust total pressure, lbf/in.^{2} or kg/m^2
ΔRM = induced rolling moment, in.-lbf or m-kg
t = time, s
α = deck pitch angle, deg
γ = deck roll angle, deg
ϕ = phase angle between pitch and roll or other combined deck motions, deg

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Introduction

OPERATION of V/STOL aircraft from ships, particularly from small ships such as the DD 963 class destroyer, can present problems due to the ship motion and the flowfield conditions in the landing area. Near the deck, the jet-induced aerodynamics can degrade V/STOL aircraft lift capability as well as the stability and control. In addition, the motion of the ship in heave, pitch, and roll, the location of the aircraft relative to the landing platform, and the wind conditions may alter these induced forces and moments.

Under contract to the Naval Air Development Center, a parametric evaluation of the jet-induced aerodynamics of typical advanced V/STOL aircraft configurations was conducted above both a fixed and a moving platform. The results are documented in Ref. 1.

Tests were performed over a range of deck motion amplitudes and frequencies representing ship responses to moderate to rough sea conditions (sea states 3-5). Simple sinusoidal deck motions were used. Configuration variables included fuselage contouring, wing height, nozzle arrangement, and the use of lift improvement devices (LIDs).

Deck Motion Simulation

The amplitude and frequency range requirements for the deck motion were derived by scaling typical ship responses to selected sea state conditions using ship motion data from Ref. 2. To establish flow similarity between model and full-scale conditions, the subscale deck motions were defined to match the ratio of the jet to deck velocities at full scale. Thus, the amplitudes were scaled by the model scale (about 5%), while the frequencies were scaled by the inverse of both the model scale and the ratio of full-scale to model jet velocity to account for temperature differences. For example, for the configuration tested, a full-scale deck motion frequency of 1/8 Hz (typical of ship rolling motions) requires a model-scale frequency of approximately 2.2 Hz.

To facilitate data analysis, the deck motions were simulated with sine waves. As can be seen from typical results of the computer program based upon Ref. 2 in Fig. 1, the response of a DD 963 destroyer can be represented adequately by a sine wave for certain periods.

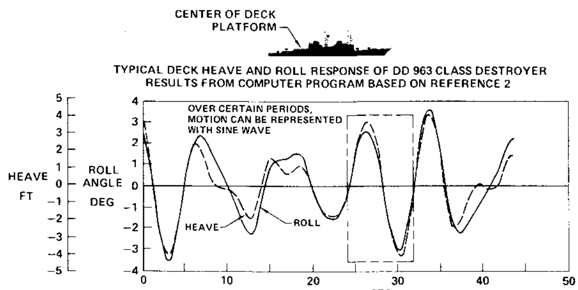

Fig. 1 Ship motion predictions based upon Ref. 2.

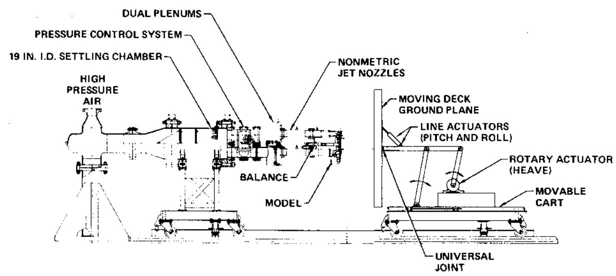

Fig. 2 V/STOL jet interaction test apparatus.

Test Facility

The test apparatus (Fig. 2) consisted primarily of two independent nozzle plenum chambers from which the model nozzle pipes are mounted.

A six-component force balance was attached to a support beam, centrally mounted off the settling chamber. The test models were attached to the force balance in the vertical plane about one wing span from the plenums. The nozzles were nonmetric, to maximize the accuracy of the jet-induced force measurements. The thrust characteristics of each nozzle were calibrated on a separate nozzle thrust stand rig.

The deck motion simulator consisted of a scale deck, a hydraulic actuation system, a movable support cart, an electronic control system, and electronic/mechanical safety devices. The hydraulic actuation system consisted of a rotary actuator for the heaving motion and two linear actuators, located at right angles to one another, for pitch and roll.

The deck motion was controlled by an electronic system consisting of a function generator for command inputs, servovalves for flow control, amplifier circuit boards, and potentiometers for position indication to a closed-loop system. The maximum ranges for the deck motions were: heave, ±6 in. (15.2 cm); pitch, ±10 deg; and roll, ±15 deg each at frequencies up to 3 Hz.

Model Descriptions

Two models of a representative three-jet subsonic V/STOL aircraft configuration were utilized in the investigation: one a fully contoured model and the other a flat-plate planform model, as shown in Fig. 3. These models, at about 5% scale, had identical planforms, simulating the vehicle illustrated in Fig. 4. This vehicle has a lift fan in the forward fuselage and two lift/cruise fans mounted above the wings. Both contoured and planform models were tested to investigate the degree of airframe simulation required for accurate jet-induced aerodynamic testing. The simple flat-plate model provides an inexpensive approach to such tests. Model dimensions are given in Fig. 5.

The upper fuselage and aft section of the fully contoured model were removable, allowing the model to be configured as a planform model with a contoured lower fuselage and wings, an intermediate approach to airframe simulation. A planform extension and a raised tail were added to simulate the aft fuselage. Lift improvement devices (LIDs), consisting of two longitudinal strakes and a forward lateral fence, were available for mounting on the lower fuselage.

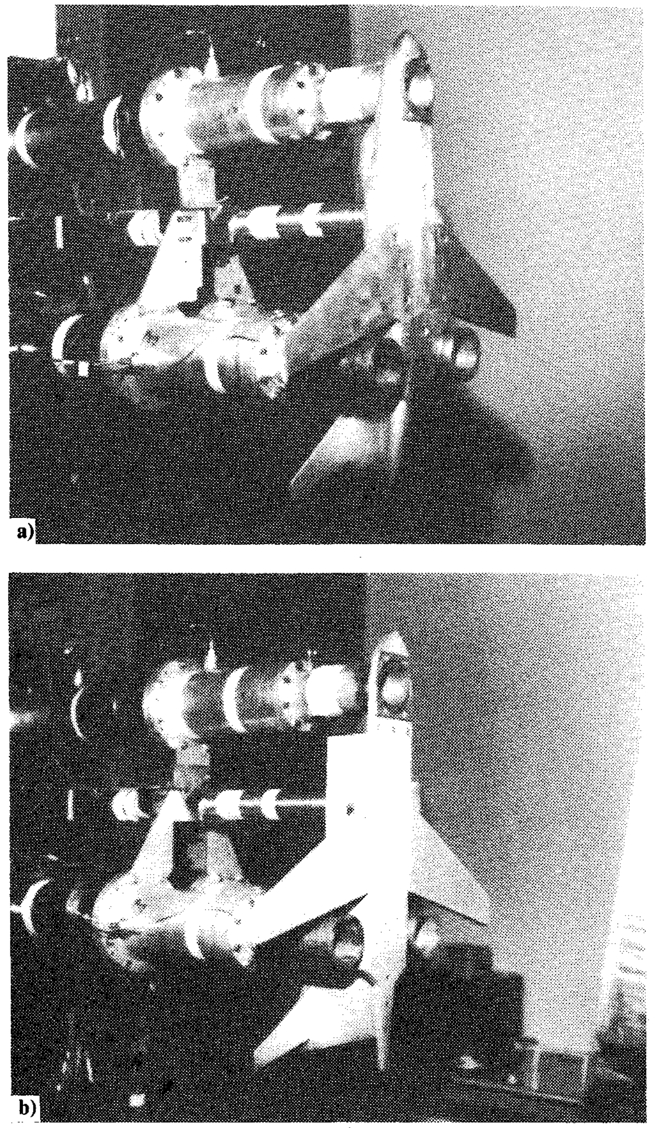

Fig. 3 Subsonic V/STOL models. a) Subsonic V/STOL fully contoured model; b) subsonic V/STOL 2-D planform model.

Jet-Induced Aerodynamic Data at Fixed Deck Positions

The jet-induced aerodynamic lift for the fully contoured, subsonic configuration is shown for fixed deck positions in Fig. 6. Close to the deck, near the gear height, ground jet-induced entrainment causes a lift loss of approximately 3% of the gross thrust. Further away, at a height of two equivalent nozzle diameters, the induced lift peaks at about 1.5% lift gain, due to the fountain upwash formed between the jets. Out of ground effect, no fountain forms and only a minimal lift loss of 0.5% results, due to free-jet flow entrainment.

The induced lift and pitching moment are significantly affected by deck pitch angle as shown in Fig. 7. Near the deck, induced lift and pitching moment vary significantly with deck pitch. Induced lift losses are apparent, primarily at the positive pitch angles where the nose is farther away from the deck. This is attributed to increased suckdown near the two rear nozzles. Slightly above gear height, at $H/D_{je} = 0.8$, this suckdown on the aft end decreases the negative or nose-down pitching moment.

At $H/D_{je} = 2$, the height for near maximum fountain strength, negative pitch results in a reversal of the induced pitching moment from positive to negative. This is probably

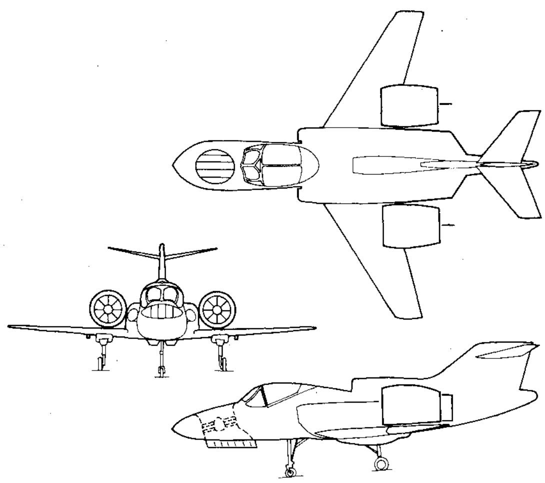

Fig. 4 Subsonic V/STOL configuration.

Parameter	Subsonic V/STOL
Reference Diameter, D_{je}	4.024 in. (10.22 cm)
Wing Planform Area, S_W	84.5 in.^{2} (545.16 cm^2)
Wing Span, b	21.66 in. (55.02 cm)
Wing Mean Aerodynamic Chord, c	4.13 in. (10.48 cm)
Tail Area, S_T	17.0 in.^{2} (109.68 cm^2)
Aircraft Planform Area, Sp	159.9 in.^{2} (1031.61 cm^2)
C.G. Location, Measured from Nose Along Fuselage Centerline	12.89 in. (32.74 cm)
Overall Aircraft Length, L	25.52 in. (64.82 cm)

Note: Dimensions given in model scale

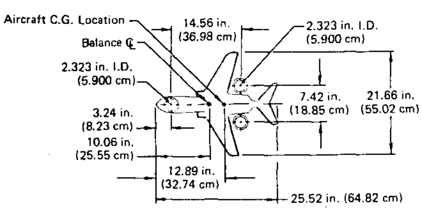

Fig. 5 Subsonic V/STOL model detail dimensions.

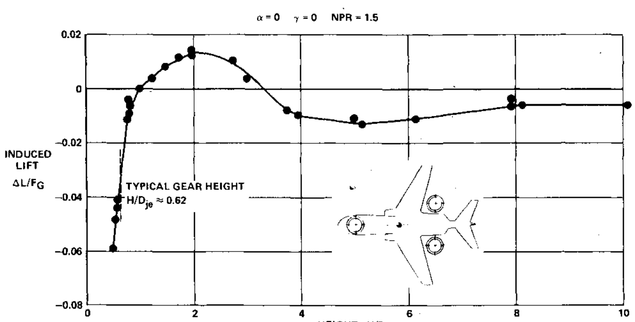

Fig. 6 Subsonic V/STOL height effects.

due to an increase in the suckdown on the forebody and movement of the fountain impingement point aft. At an H/D_{je} of 5 and above, there is little sensitivity to deck pitch angle.

Similarly, close to the deck, induced lift and rolling moment vary significantly with deck roll angle, as shown in Fig. 8. A significant lift loss occurs at roll angles greater than ±2 deg. This is attributed to a loss in fountain lift as the impingement point moves off the centerline toward the side farther away from the deck, as well as increased suckdown on the wing close to the deck. The lift loss is accompanied by a destabilizing rolling moment for the same reasons. As with pitch angle, there is little effect at a height of five diameters and above.

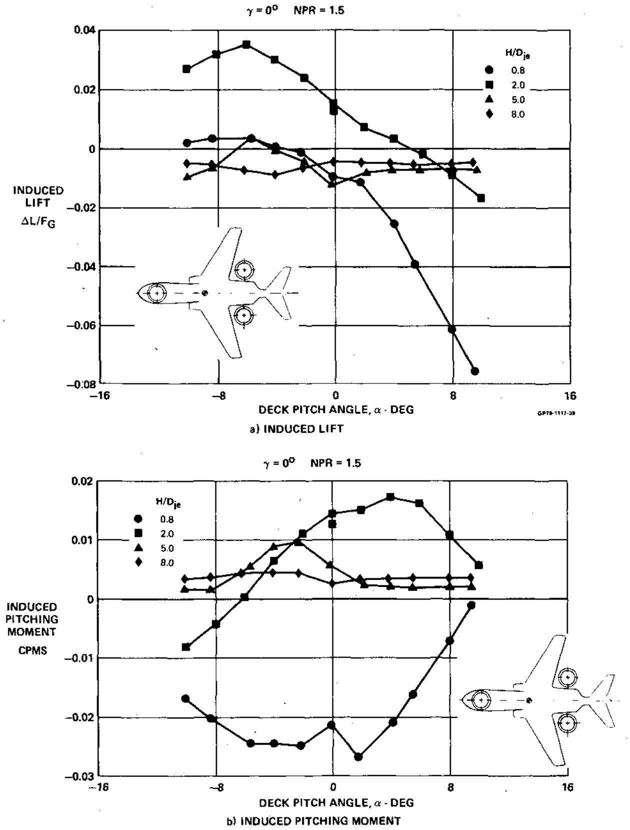

Fig. 7 Effects of deck pitch.

Effect of Model Contouring

To determine the degree of configuration simulation required for jet-induced aerodynamic testing, the subsonic configuration was tested as 1) a fully contoured model, 2) a semicontoured model with contoured lower fuselage and raised tail, and 3) as a simple flat-plate planform model with a raised tail. The results, shown in Fig. 9, indicate the effect of fuselage contouring. The flat-plate planform model has a significantly higher induced lift in ground effect, although the peak induced lift occurs at nearly the same height.

Tests using a similar planform model instrumented with pressure taps[3] indicated that most of the fountain force is concentrated between the two rear nozzles. The fully contoured model, being curved in this region, produces a weaker fountain impingement force. The data for the semicontoured model agree well with the fully contoured model down to a height of 1.5 nozzle diameters, below which the semicontoured model has about 1.5 to 2% higher induced lift. The higher lift is attributed to a higher fountain impingement force on the flat-plate planform extension which was added to simulate the aft end. The upper fuselage surface contouring appears to have very little effect.

Effect of Lift Improvement Devices

The fountain impingement force can be effectively amplified with LIDs on the lower fuselage, as demonstrated on the AV-8B Harrier.[4] In these tests, three-sided LIDs were designed from the study described in Ref. 3, and the resultant effect on induced lift is shown in Fig. 10.

The LIDs stagnate the impinging fountain flow and redirect it downward, providing increased lift up to an H/D_{je} of about 2. Near the deck, where lift is especially critical to V/STOL aircraft mission performance, the LIDs improve the lift dramatically—by more than 10%. This added lift can be used to accelerate the aircraft through the ground effects region and to offset adverse effects, such as thrust loss due to exhaust gas ingestion.

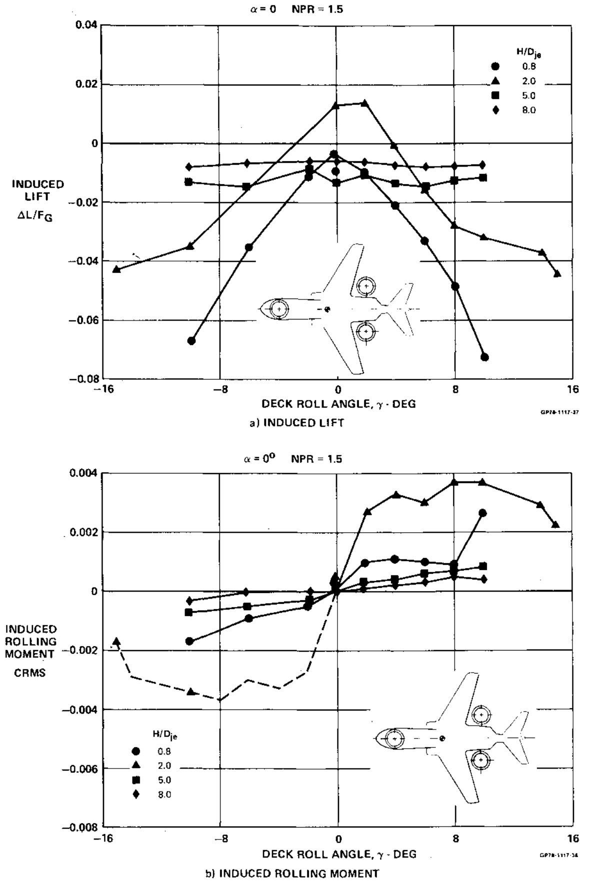

Fig. 8 Effects of deck roll.

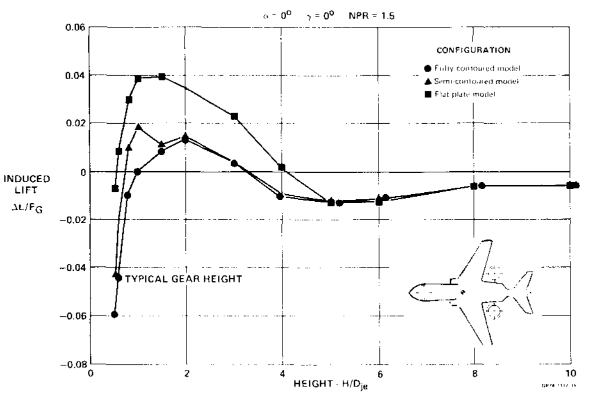

Fig. 9 Fuselage contouring effects.

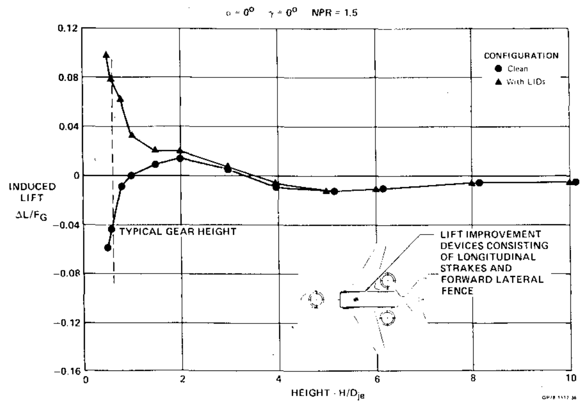

Fig. 10 Effect of lift improvement devices.

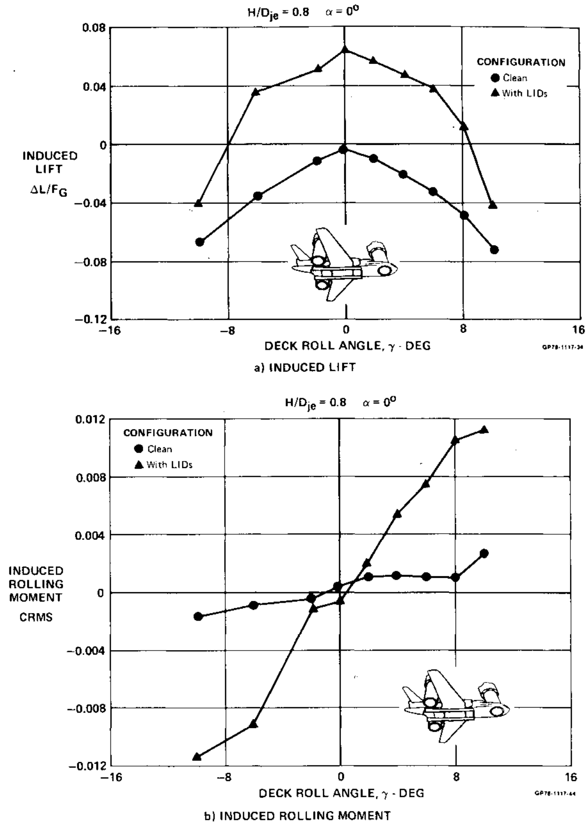

Fig. 11 Roll effects on induced aerodynamics with LIDs installed.

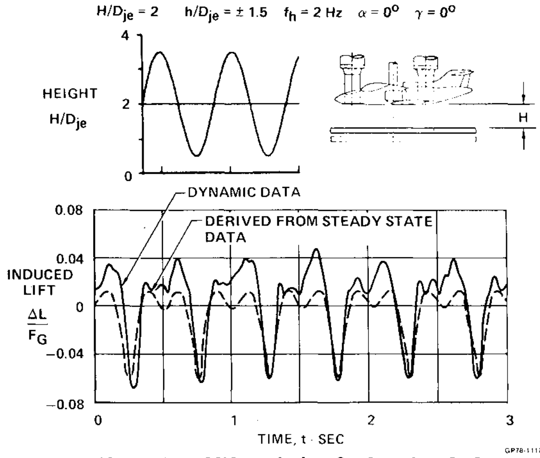

Fig. 12 Induced lift variation for heaving deck.

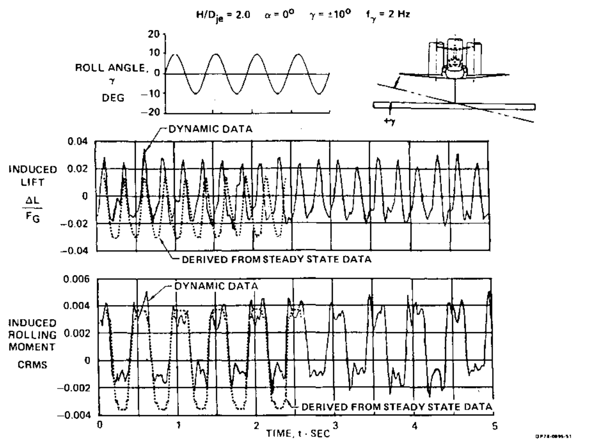

Fig. 13 Induced lift and rolling moment for rolling deck.

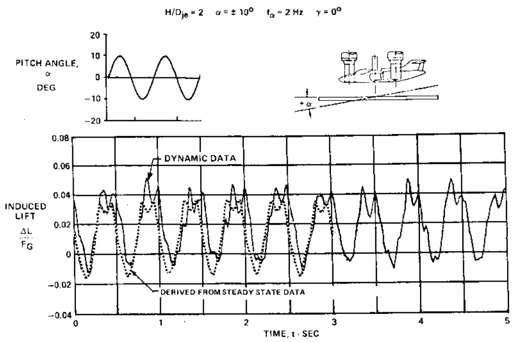

Fig. 14 Induced lift for pitching deck.

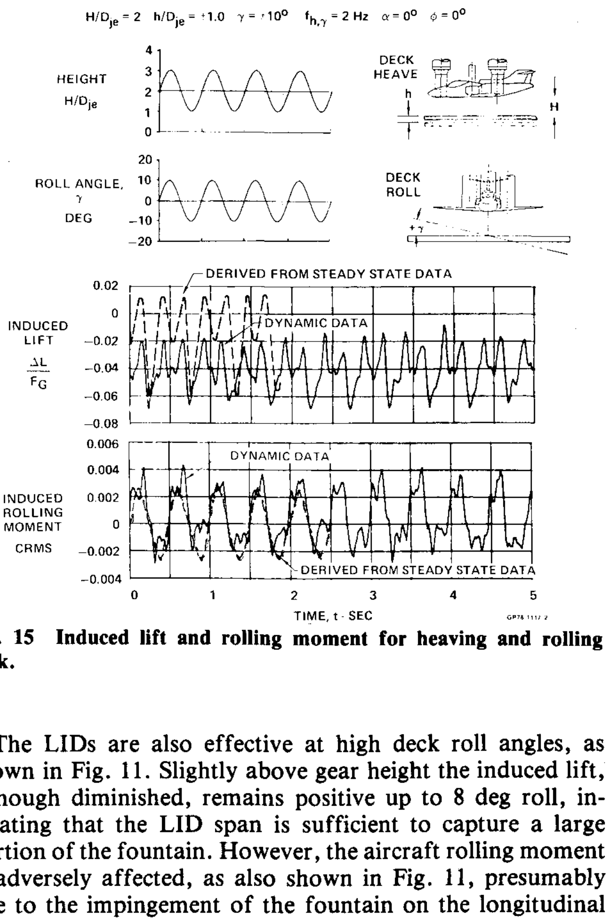

Fig. 15 Induced lift and rolling moment for heaving and rolling deck.

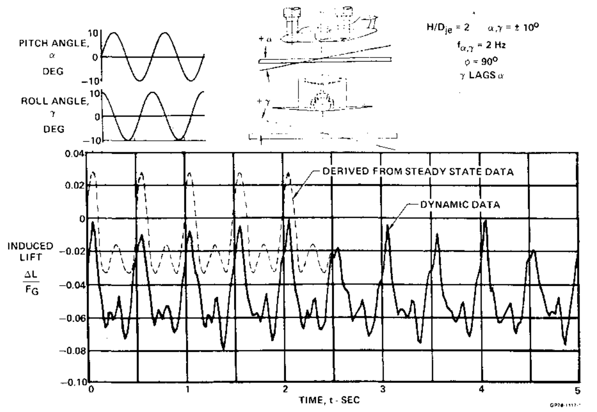

Fig. 16 Induced lift for pitching and rolling deck.

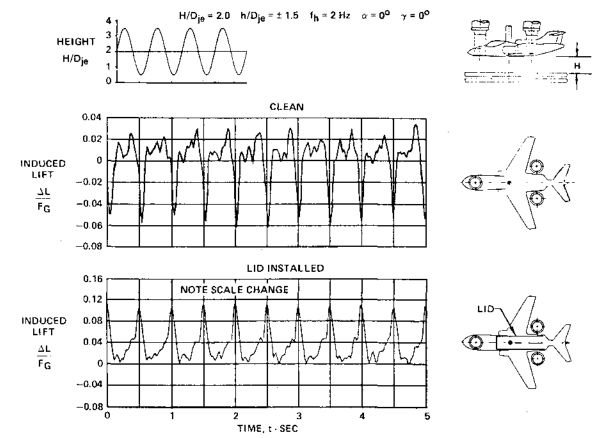

Fig. 17 Effect of lift improvement devices with heaving deck.

The LIDs are also effective at high deck roll angles, as shown in Fig. 11. Slightly above gear height the induced lift, although diminished, remains positive up to 8 deg roll, indicating that the LID span is sufficient to capture a large portion of the fountain. However, the aircraft rolling moment is adversely affected, as also shown in Fig. 11, presumably due to the impingement of the fountain on the longitudinal strakes.

Jet-Induced Aerodynamic Data with Deck Motion

Tests were performed at scaled deck motion frequencies and amplitudes which bracketed values predicted from Ref. 2. Data obtained with fixed deck positions were used to predict the induced force and moment responses to deck motion by assuming that the motion can be treated as quasisteady state. The prediction can be made by obtaining from the steady-state data the induced aerodynamics corresponding to the height, pitch, or roll angle values at selected time intervals.

Response to Deck Heave

The influence of deck heave on the induced lift of the fully contoured model is shown in Fig. 12. The heave amplitude was 1.5 D_{je} at 2 Hz, with the neutral point set at the height for maximum induced lift ($H/D_{je}=2$). Thus, the height of the model above the deck varies sinusoidally at an H/D_{je} of 0.5 to 3.5. The induced lift response is of a complex periodic nature, but is fairly repeatable.

At a typical gear height, the lift loss is about 3% of the gross thrust. As the deck heaves away from the model, the induced lift reaches a peak near an H/D_{je} of 2.0 and then decreases slightly as H/D_{je} approaches 3.5. However, when the deck heaves toward the model, the peak lift is about 2% higher at an H/D_{je} of 2 than when the deck is retreating. This is attributed to a compression or increased cushioning effect of the fountain, due to the velocity of the deck (approximately 6.3 ft/s or 1.9 m/s maximum). The predictions based upon steady-state data are in good agreement with the dynamic data except for the increased fountain cushion effect.

Tests conducted at other heave frequencies indicate consistent changes in the induced lift, which appear to be proportional to the change in deck velocity and the resultant fountain compression effect. In addition, induced lift data for other configurations tested in the Ref. 1 program suggest a decompression effect in the fountain and a possible increase in suckdown when the deck is retreating.

Response to Deck Roll and Pitch

Deck roll is generally the motion having the highest frequency and amplitude, and thus may have the most impact on V/STOL aircraft operations. For example, the DD 963 class ship can respond to a rough sea condition with a roll of approximately ±10 deg and a full-scale period of about 8 s.[2] Deck pitch is only about ±2 deg. However, for this study equal pitch and roll amplitudes were investigated, since it was assumed that the V/STOL aircraft could land or takeoff at any orientation relative to the deck.

The induced lift and rolling moment variations for the subsonic model that resulted from ±10 deg of deck roll at an H/D_{je} of 2 are presented in Fig. 13. A significant lift loss occurs with rolling motion due to a loss in the fountain lift as explained above for results obtained with fixed deck roll angles. The lift loss is accompanied by a destabilizing rolling moment. Fairly good agreement is seen in the comparison of the steady-state and dynamic results.

The induced lift variation for ±10 deg of deck pitch is presented in Fig. 14. Consistent with the data acquired at fixed deck angles (Fig. 7), lift losses are apparent at positive pitch angles. The dynamic data indicate a higher induced lift, which is attributed to the fountain compression effect with deck motion.

Response to Combined Motion

Actual sea state conditions, being random, cause a complex response from ships, as indicated in Fig. 1. Therefore, several combinations of heave, pitch, and roll were investigated. Even though a highly complex turbulent flowfield exists, the dynamic data indicate a well-defined, repeatable, complex periodic response to the combined motions.

The variations in induced lift and rolling moment for a combination of heave and roll in phase, are shown in Fig. 15. The prediction was obtained from the parametric plot of induced lift as a function of roll angle for several discrete heights (Fig. 8). For any given roll angle, the induced lift can be determined by interpolation.

It can be seen in Fig. 15 that the actual induced lift with combined motion is lower than predicted from the steady-state data. The extremely complex, turbulent flowfield created under such combined motions is believed to increase the mixing and entrainment and weaken the fountain, therefore increasing the lift loss. The rolling moment variation with dynamic motion is slightly higher than the prediction.

Results for a combination of pitch and roll, 90 deg out of phase, is given in Fig. 16. For this case, the dynamic induced lift variation is substantially lower than the prediction. These results further substantiate the adverse effects attributed to the increased turbulent mixing action during combined motion.

Configuration Effects with Deck Motion

Configuration-related effects are readily apparent in the dynamic data and are generally consistent with the trends indicated by the steady-state tests. As an example, the effectiveness of the LIDs can be seen in Fig. 17 for deck heaving motion. The maximum induced lift of about 12% is larger than that measured in the steady-state tests. This is attributed to the fountain compression effect when the deck is approaching the model. Results presented in Ref. 1 also indicate that the LIDs are effective at high roll angles, consistent with the steady-state data.

In summary, the general trends of the induced aerodynamic response to ship deck motion can be reasonably represented using steady-state data. However, the predictions based upon these data are often optimistic, particularly for the more complex combined deck motions. This result is particularly significant, since ground effects tests, for reasons of cost and simplicity, are customarily conducted at steady-state conditions. It is clear that such data could lead to an underestimate of the control power requirements and to potential payload penalties for V/STOL aircraft.

Conclusions

1) Induced aerodynamic data acquired with deck motion can differ significantly from predictions based upon steady-state data and often indicate higher lift loss and moment variations, particularly for combined deck motions. This is attributed primarily to modified fountain impingement forces and increased turbulent mixing due to the deck motion.

2) The induced aerodynamic responses to deck motion are of a complex periodic nature and are affected by deck velocity.

3) For a configuration having a strong fountain, the induced lift resulting from fountain impingement increases as the deck heaves toward the model and little effect is seen with a retreating deck. On the other hand, results reported in Ref. 1 indicate that for a configuration with high suckdown, a higher lift loss occurs when the deck heaves away from the model.

4) The contouring of the lower fuselage, particularly in the fountain impingement region, can significantly affect the induced aerodynamics in ground effect. In the absence of wind, simulation of upper surface contouring on models appears to be unimportant.

5) Properly designed LIDs can significantly enhance the induced lift in ground effect and are effective even at high roll angles.

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