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Single Jet-Induced Effects on Small-Scale Hover Data in Ground Effect

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Many hover tests performed in the past on similar, relatively simple configurations produced significantly different results concerning jet-induced lift in ground effect. This report presents an investigation performed at NASA Ames Research Center to clarify the reasons for these differences. The test parameters investigated are the effects of the gap size between the model and a single nozzle, the shape of the outer edge of the model, the jet impingement angle to the ground, the size of the ground plane relative to the model, and the effect of large surfaces, other than the ground plane, close to the model. Although no single parameter explains the differences between previous data sets, it has become evident that certain parameters are important when testing small-scale hover models. Results indicate that the size of the ground plane needs to be only as large as the model. However, gap size, edge shape, and test-chamber size are parameters that had a measurable effect on negative jet-induced lift forces and therefore must be chosen and documented appropriately. Other observations and recommendations are made concerning the testing of small-scale hover models.

Nomenclature

C_p = pressure coefficient
D = diameter of the model desk, in.
d = diameter of the nozzle exit, in.
h = height from the model undersurface to the ground plane, in.
R = radius of the model disk, in.
T = jet thrust, lb
ΔL = jet-induced lift increment, lb
ΔL_∞ = jet-induced lift increment out of ground effect, lb

Introduction

THE jet-induced lift forces that act on a planform in the vicinity of the ground become more influential as the planform approaches the ground. Although the net forces can vary widely between configurations, the negative jet-induced lift forces, or suckdown, will usually dominate at the lower heights. The magnitude of these jet-induced forces becomes particularly significant for vertical/short takeoff and landing (V/STOL) configurations while in the takeoff and landing flight regimes. During the conceptual design stage, quick estimates of the aerodynamic forces acting on a configuration in hover are desired. Traditionally, an empirical prediction technique developed by Wyatt[1] has been employed.

Simulation of the flow in either an experimental or computational effort requires an understanding of the flow phenomena and the effect of the geometrical parameters involved. Figure 1 shows the parameters that need to be considered when designing a V/STOL configuration for operation in ground effect during hover. The hot jets pointed downward produce the primary forces that support the aircraft. As the jets impinge on the ground, a wall jet is produced that flows parallel to the ground and radiates outward in all directions. The primary jet, along with the wall (or ground) jet, entrains air from beneath the aircraft and thus creates reduced pressures under the aircraft that reduce the net lift. For multiple-jet configurations, a fountain-like upwash is also formed between the impinging jets. This fountain flow can produce positive pressures on the aircraft undersurface that increase the net lift. However, the positive fountain increments are usually quickly overcome by the suckdown forces as the aircraft approaches the ground. Other effects such as hot-gas ingestion, airframe heating, external-stores heating, ground erosion, and acoustic effects all occur in these complicated flowfields.

Investigations of the jet suckdown of small-scale configurations in hover do not produce the true Reynolds number, nor the actual jet structure and temperature of full-scale aircraft. They can, however, reproduce the predominant characteristics of the flow pattern. The jet flow emanating from a single nozzle entrains the surrounding air, thus accelerating the air beneath the model, creating a pressure difference between the upper and lower sides of the model [shown schematically in Fig. 2a, out of ground effect (OGE)]. When the aircraft approaches the ground, the suckdown is amplified since there is an additional entrainment by the ground jet. As the distance between the jet flow on the ground and the model decreases [Fig. 2b, in ground effect (IGE)], air inflow into the low-pressure area under the planform is accelerated and the pressure beneath the model decreases considerably. Gentry and Margason[2] showed that this flow depends on jet parameters such as Mach number, velocity distribution, pressure, swirl, turbulence level, temperature, etc. Corsiglia et al.[3] have also shown that this flow is sensitive to geometrical factors such as the model edge shape, the angle between the jet and the normal to the ground board, obstructions to the flow in the vicinity of the model, and the volume of the test chamber. At low heights, the suckdown force from a single-jet configuration, emanating from the center of a circular disk, can easily be 120% of the jet thrust. However, out-of-ground-effect suckdown ΔL_∞ is relatively small (1–3% of the thrust).

Discrepancies in Suckdown Data

As previously mentioned, a prediction method for the suckdown produced by a single jet on a planform was developed by Wyatt[1] using data with a single jet issuing from a wide

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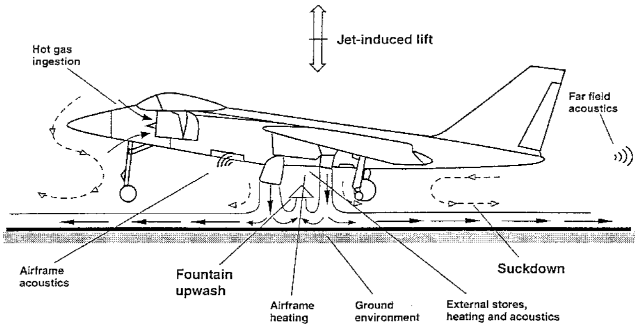

Fig. 1 Schematics of the flowfield around a V/STOL configuration near the ground.

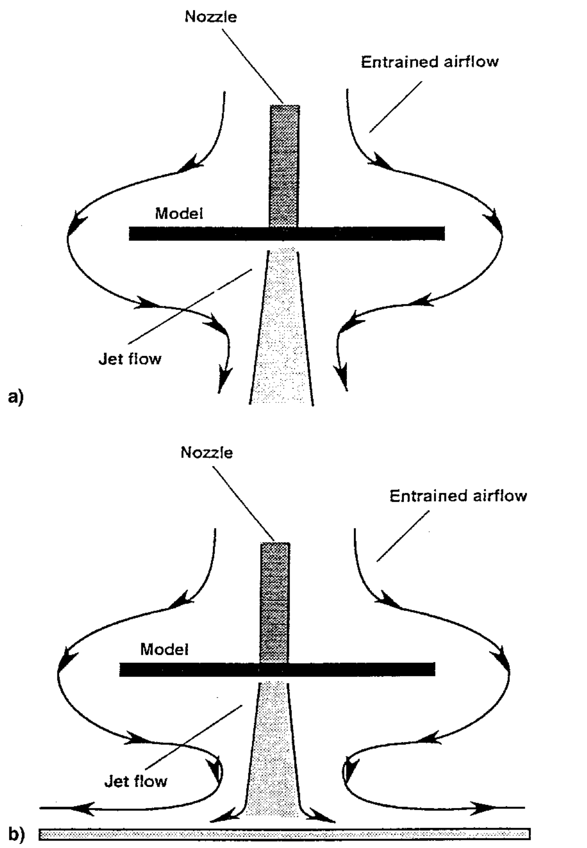

Fig. 2 Flow schematics of single-jet suckdown: a) OGE and b) IGE.

range of sizes and shapes of models. The data from this test were correlated into a single expression for all of the configurations by using a geometrical similitude ratio. Current empirical prediction methods[4] are heavily based upon experimental data and empirical techniques developed by Wyatt.[1] Kuhn[5] has since shown that these prediction methods significantly underestimate the magnitude of the jet-induced forces for configurations (Refs. 2, 6, and 7) similar to those tested by Wyatt.[1]

More recently, jet-induced lift experiments, similar to some of Wyatt's basic experiments,[1] were conducted.[3] These tests were conducted at two different facilities using the same models and instrumentation. The first test facility was in a very large High Bay area at the NASA Ames Research Center. The second facility was at a much smaller test area located at the (then) Lockheed Rye Canyon Facility. This facility was used to obtain data on basic lift loss for several one- and two-jet configurations and hot-gas-ingestion data. The main test parameters were similar to those used by Wyatt.[1] These parameters are presented in the schematic in Fig. 3a and they include the geometrical ratio between the disk and the nozzle diameters D/d and the proximity to the ground h, and the nozzle pressure ratio (NPR, the ratio between the jet stagnation pressure and the ambient pressure). The NPR dictates the jet thrust and flow rate (for a given nozzle) as well as the flow

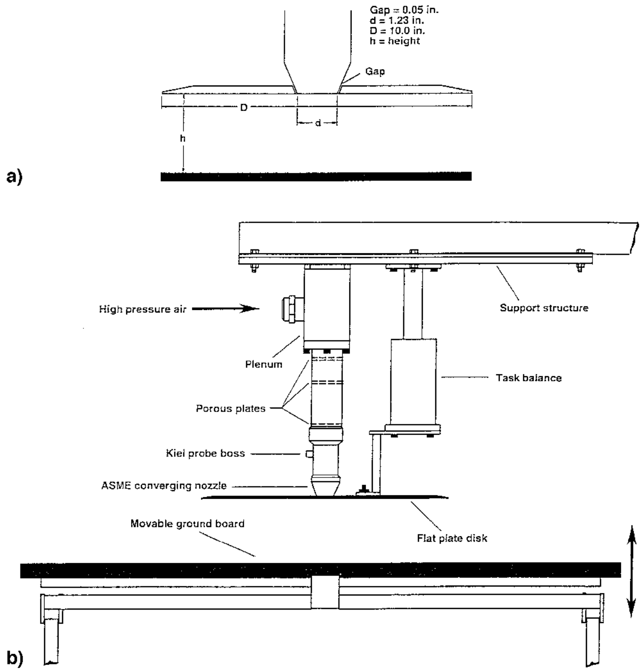

Fig. 3 a) Model parameters for the test at Rye Canyon and b) nozzle and plenum assembly on the hover test rig.

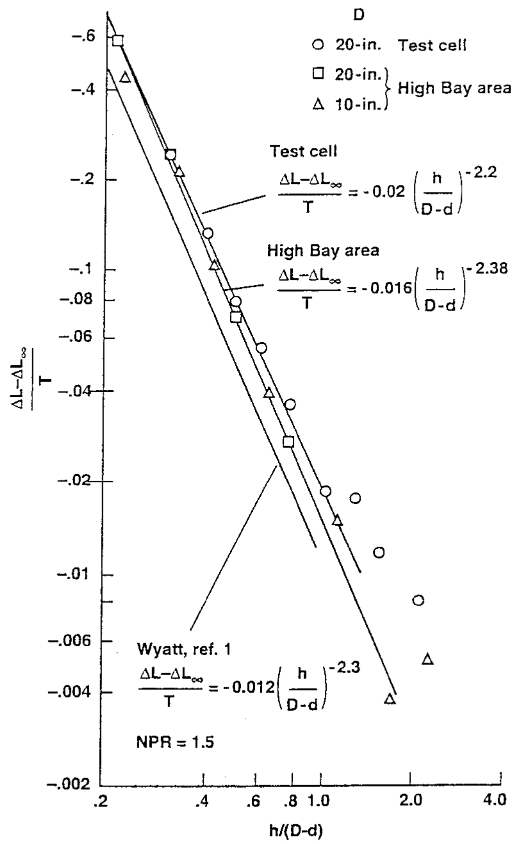

Fig. 4 Comparison between the suckdown measured in various tests as a function of ground proximity.

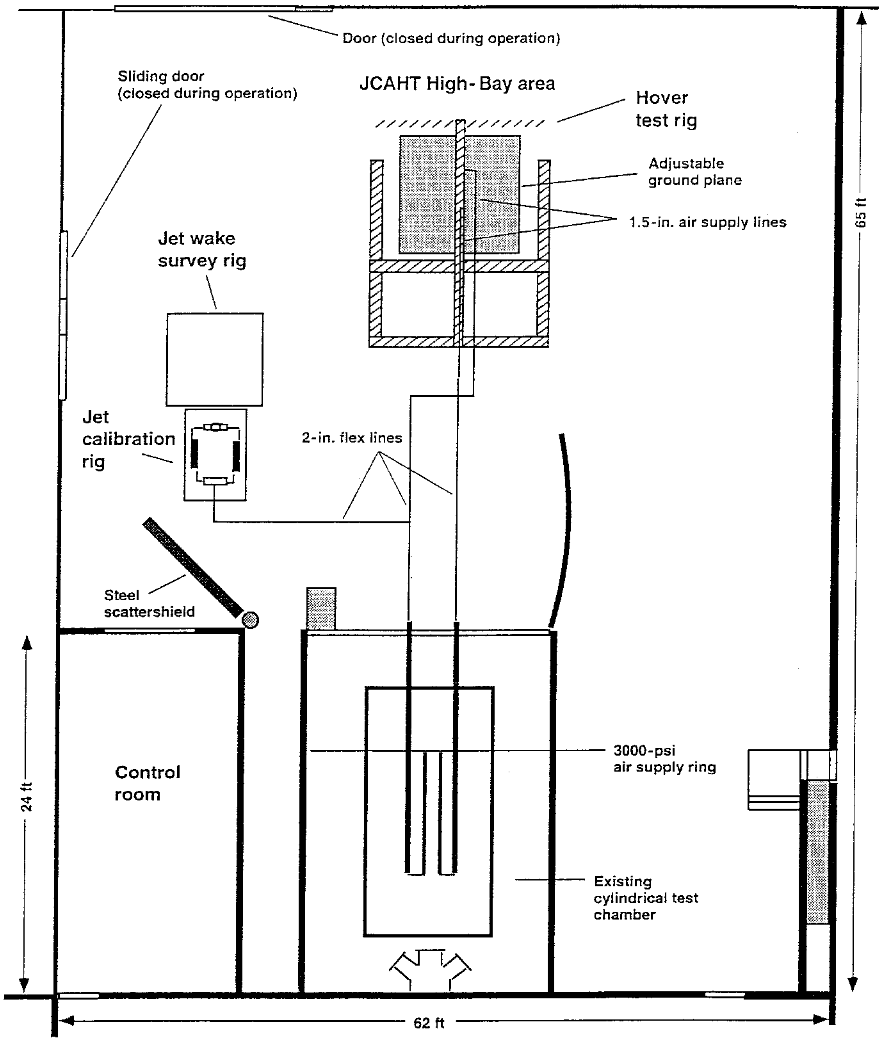

Fig. 5 Layout of the JCAHT facility.

pattern at the nozzle exit (e.g., subsonic, sonic, and supersonic). The results of these tests are presented in Fig. 4.

Test Setup

Further thought indicated several test setup parameters that may have contributed to the difference in suckdown data. These parameters include the 1) gap between the nozzle and the model, 2) jet structure, 3) jet impingement angle to the ground, 4) shape of the outer edge of the model, 5) ground plane size relative to the model, and the 6) size of the test chamber and obstructions above or near the model that could affect the downflow induced by the flow in ground proximity.

The effects of the previous test parameters were investigated at the Jet Calibration and Hover Test (JCAHT) facility at NASA Ames Research Center. Results and observations from this investigation will be reported in the next section. The same test rig, shown in Fig. 3b, that was used for the tests at the NASA Ames Research Center and Rye Canyon facilities discussed previously[3] is now part of the JCAHT facility.[8] A schematic of the JCAHT facility is shown in Fig. 5. The room size is approximately 10 times that of the Rye Canyon test cell. Additionally, the same flat-plate circular disks and nozzles were used as for the tests of Ref. 3. For the effects of gap size and model-edge shape, several new 10-in.-diam disks were made. It should be noted that the balance attached to the model in Ref. 3 and in the JCAHT facility measured only the aerodynamic forces acting on the model. This setup is achieved by a small gap (0.05 in.) between the nozzle and the model that allows a smaller, higher resolution balance to be used to measure model suckdown. A separate calibration rig is used to measure the nozzle thrust and to calibrate thrust as a function of nozzle pressure. This calibration is then used during model testing.

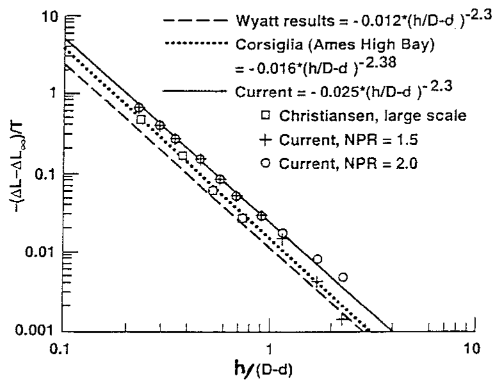

Fig. 6 Comparison of suckdown results.

Figure 6 compares the current data with data from Wyatt,[1] Corsiglia,[3] and Christiansen.[7] Although the trends are similar, the present single-jet suckdown is almost 50% higher than that found two years earlier by Corsiglia[3] and 100% higher than that found by Wyatt.[1] At this time, these discrepancies cannot be explained, but we are confident that measurements were properly taken and we have high confidence in the accuracy of the data. It should be noted that at $h/(D - d)$ around 0.5, the differences between our current 10-in.-disk data and the data from the High Bay could be explained by a height difference Δh of approximately 0.3 in. During the present tests we were able to make height measurements to within 0.03 in. and data repeatability was very good (Fig. 7). Even if the data were somehow biased, the differences observed by changing gap size, etc., should be valid since the bias would be subtracted out.

Discussion

The suckdown data from the current investigation at the JCAHT facility are presented and discussed separately for each test parameter. The data are presented in a logarithmic scale to cover the vast range of the measurements.

Gap Size

It is usually desirable to maintain a metric break between the model and nozzle(s) so that only the model jet-induced forces are measured. This metric break allows for higher accuracy in the measurement of the jet-induced lift, especially OGE, where the forces are small. Although the metric break is easily achieved by a physical gap between the model and the nozzle(s), this gap will allow air to be drawn into the jet flow from the top side of the model. This air entrainment through the gap allows less flow to be pulled in from around the model lower surface. The lower flow requirement on the model lower surface produce lower air velocities, higher pressures, and therefore less total suckdown. If gaps are large, the area in which the negative pressures will act is smaller. This gap effect is also applicable to multiple-jet configurations. The nominal gap size for the current investigation was 0.05 in.

An effect similar to that of the gap around the nozzle occurs at the root chord of movable canards, where a gap exists between the canard and the fuselage. This gap, however small, has been theoretically shown by Dugan and Hikido[9] to cause a lift loss of up to 65%. However, boundary-layer effect reduces the gap size effectively, and lift loss is on the order of 10% of the lift in a practical situation.[10] Such a possible lift reduction was recognized by Wyatt.[1] He estimated the effect of the gap, including an additional reduction of the suckdown because of the wall thickness of the nozzle, to be about 3–6%. In our study, four different gap sizes were tested (0.05,

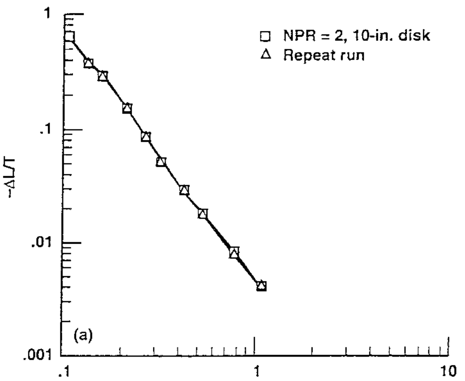

Fig. 7 Presentation of repeat-run data for a logarithmic scale as compared with a linear scale.

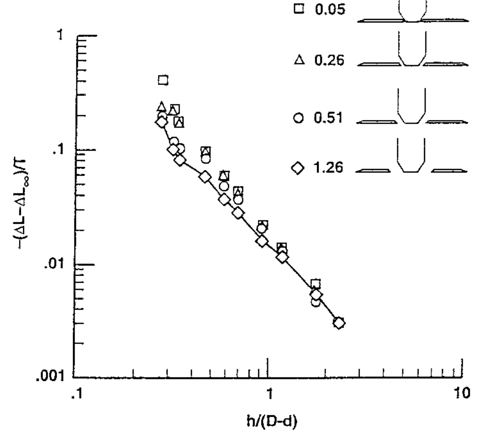

Fig. 8 Effect of gap size on suckdown; 10-in. disk at NPR = 2.0.

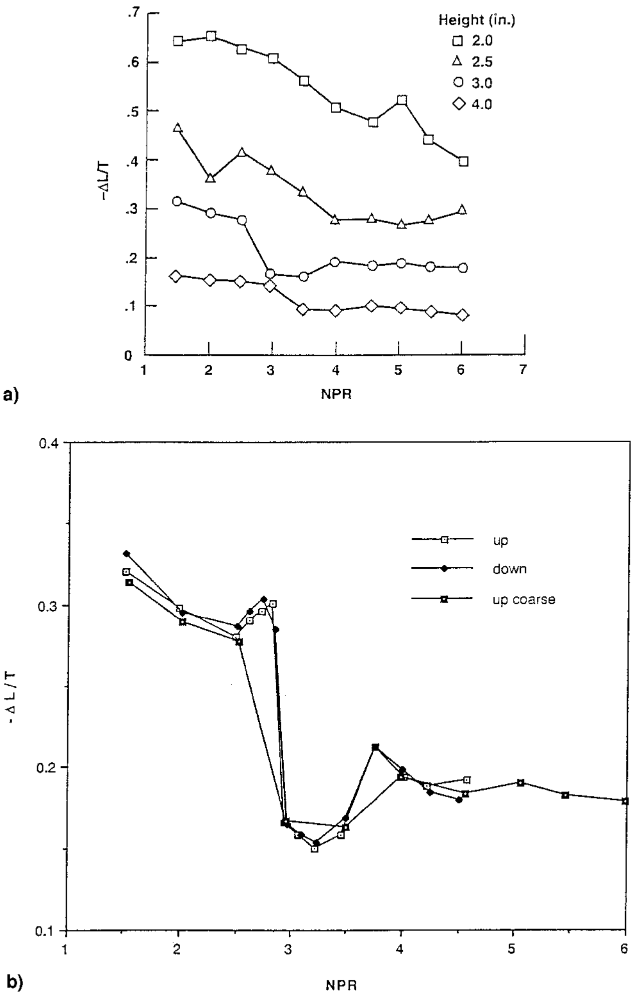

Fig. 9 a) Variation in suckdown by varying NPR at various fixed heights; 10-in. disk and b) crossplot of suckdown at various NPRs for the 10-in. circular disk.

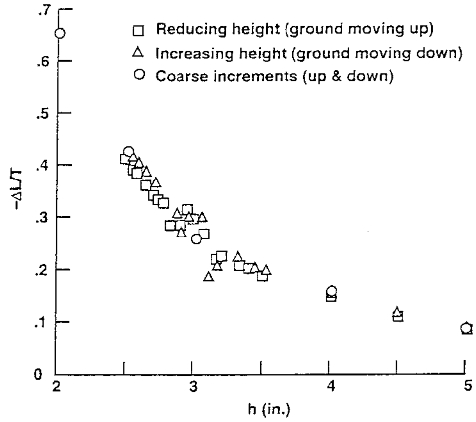

Fig. 10 Variation of the suckdown with various increments in the ground distance at NPR = 2.75.

0.26, 0.51, and 1.26 in.). The results presented in Fig. 8 show that the 1.26-in. gap reduces the suckdown by 40–50% and the 0.51-in. gap reduces the force by as much as 10% at the lower heights. It is not known how eliminating the smallest gap would affect suckdown, but some pressure data from an earlier NASA Ames Research Center test showed that for no gap the pressure decreases on the lower surface within about 0.1 in. of the gap, but remains unchanged elsewhere. The assumption is made (although not verified) that the smallest gap (0.05 in.) would produce little if no measurable (0.5% or less) reduction in suckdown.

The gap-size effect is also connected to icing problems that occurred when testing with cold airflow. The expansion of the dry high-pressure air caused icing on the exterior of the nozzle. Although precautions were taken to prevent ice from bridging the gap and transmitting forces between the nozzle and the plate, the ice did reduce the effective gap size. This reduction in gap size could introduce a bias between testing of cold vs heated flow, or even testing in different weather conditions. Since gaps around the jet exit do not exist in current aircraft configurations, elimination of the gap is recommended in future tests. On the other hand, large gaps could be used in actual

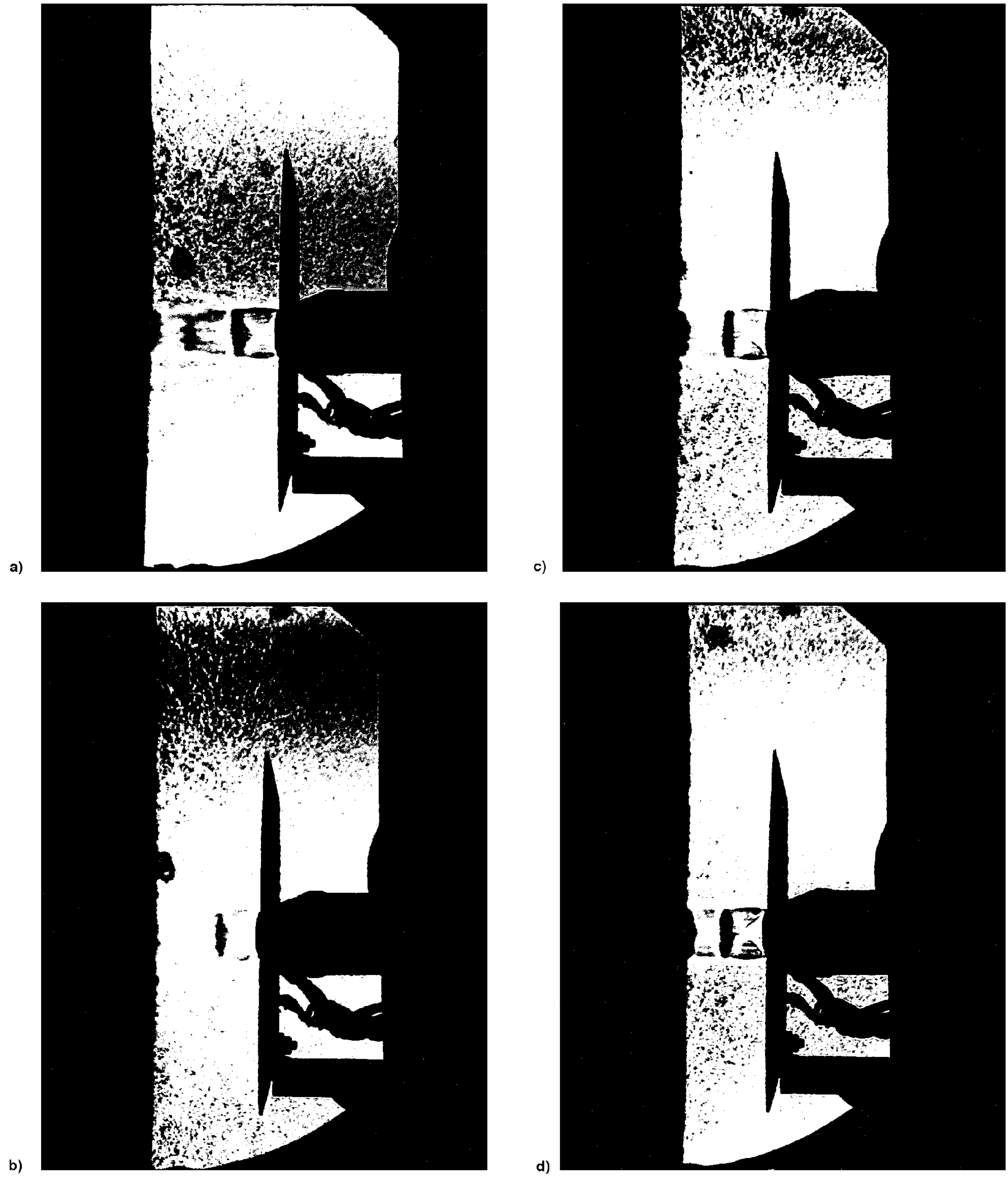

Fig. 11 Schlieren flow visualization photographs of the 10-in. disk at NPR = 4.0: a) $h/(D-d) = 0.485$, (h = 4.25 in.); b) $h/(D-d) = 0.405$, (h = 3.55 in.); c) $h/(D-d) = 0.360$, (h = 3.15 in.); and d) $h/(D-d) = 0.336$, (h = 2.95 in.).

vehicles as a method for considerably decreasing the suckdown effect.

Jet Structure

A long convergent nozzle with three porous plates was installed at the exit of the stagnation chamber (plenum). This nozzle/plenum arrangement (Fig. 3b) was designed to avoid the effects of the long piping of the high-pressure air supply. The flow rate was measured in two different places: one at an orifice along the high-pressure line and a second in the nozzle. The nozzle thrust was measured directly with a calibration stand at the JCAHT facility and calculated as a function of the pressure measured in the nozzle. Although parameters such as velocity distribution, temperature, and swirl were not measured during this investigation, they could affect the decay rate of the jet and therefore the entrainment rate and suckdown. The only variable parameter of the jet that was investigated was the NPR (with the obvious changes of mass flow rate and thrust associated with NPR). Since the comparison between the different sets of data is based on a common NPR, and the suckdown is normalized by the thrust, the NPR should not be a parameter in the anomalies investigation. However, the results for the suckdown variation with NPR presented in Fig. 9a show that the effect of the NPR is not necessarily monotonic for underexpanded jets. There are large variations of suckdown that are dependent on the NPR and the height above the ground. This effect was further investigated with an increased number of NPR values (Fig. 9).

A similar variation of the suckdown was found near $h/(D - d) = 3$, with small changes in the ground distance for a constant NPR (Fig. 10). These variations of the suckdown seemed to depend on the structure of the flow very close to the ground. For supersonic flows it appears that some structure changes occur abruptly at certain heights, even with small changes in the ground distance and the NPR held constant. Schlieren flow visualization photographs were taken to document this phenomenon for the 10-in. disk. In one case, the NPR was held constant at 2.75 while the height was reduced from $h/(D - d) = 0.485$ through $h/(D - d) = 0.336$ (Figs. 11a–11d, respectively). A change in the wave (or shock) structure is apparent. The jet structure in Figs. 11a–11c is oscillating and makes a high-pitch sound; when the structure becomes stable (Fig. 11d), the sound intensity and suckdown both dramatically decrease. These changes in the jet structure seem to influence greatly the suckdown properties and they are thought to be related to the jet entrainment properties.

Jet Impingement Angle

The ground board is the movable part of the test system, and, therefore, an unintentional tilt may develop during its upward or downward motion. Such an effect was investigated by introducing a 5-deg tilt, which is considerably larger than any unnoticed or unknown tilt that could have occurred. The results show no effect on single-jet suckdown except at the lowest heights $[h/(D - d) < 0.5]$, where an increase of up to 20% in the suckdown occurred. Since the accidental tilting of the ground plane, if it did occur, would be smaller by an order of magnitude, its effect would not be meaningful except possibly at very small heights.

Mode Edge Shape

As previously mentioned, the pressure difference between the upper and lower sides of the model induces airflow into the lower pressure region. The airflow around the model edges is similar to the flow around wing edges and is affected by the shape of the edge.

Three edge shapes were tested to determine the magnitude of this effect: 1) round, 2) square, and 3) beveled. The results (Fig. 12) show a meaningful increase (30%) in the suckdown at the lower heights for the beveled edge as compared with the round and square edges. However, at the high heights there are no differences. The differences at the low heights might be attributed to the separation of the flow around the model edge, in which case the shape and size of the separation bubble is affected by the edge shape. Consequently, the magnitude of the suction could be affected in a way similar to the effect of separated flow over the leading edge of a delta wing at high angles of attack. The effect of the edge shape could also be influenced by the model scale of experimental or computational simulations. This possibility may be especially pertinent in cases where the actual configurations do not have sharp edges and, therefore, the full-scale Reynolds number will affect the flow around the edge. Figure 13 shows pressure differences between the model undersurface pressure distribution for infinite and finite circular disks OGE.[2] The pressure at the tip of the finite plate decreased because of a vortex formed by separation of the induced flow around the edge of the disk. Similar results have been reported by Ing and Zhang.[11]

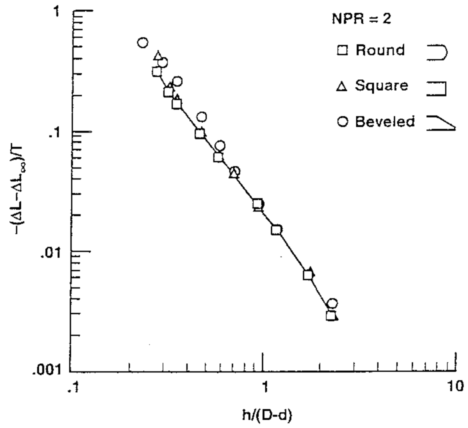

Fig. 12 Effect of planform edge shape on suckdown.

Ground-Plane Size

The ground plane should be much larger than the model to be tested to produce the actual ratio of ground plane to model area ratio. However, the dimensions of the ground board are limited because this board is usually the movable part of the system. An increased suckdown (1–2%) caused by a larger-size board was reported by Benepe[12] after a brief investigation with circular planforms with a single jet. Benepe[12] recommended that the ground plane be "no less than 20 times the effective diameter of a circle which circumscribes the outer periphery of a multijet configuration, unless the full-scale landing surface is of limited dimensions, such as a ship landing platform."

To investigate further the size of the ground plane, six ground boards were tested: (nominal) 96 × 96, 48 × 48, 28 × 28, 20 × 20, 15 × 15, and 10 × 10 in. Suckdown was measured for both the 10- and 20-in. circular model plates. The results presented in Fig. 14 show that, in contrast to the Benepe[12] data, no effect of the ground-board size was noticeable as long as the ground board was larger than the model. This result indicates that the suction is generated mainly by the ground jet beneath the plate and that this part of the ground jet is not influenced by the size of the board as long as the board is as large as the model. Besides nullifying the possibility that the ground-board size might explain the differences between past tests of similar configurations, the previous data might become useful for actual cases where landing space is limited, as for example, on a ship deck. This information might also suggest a possible way to reduce ground erosion problems by elevating a small area where the touchdown occurs.

Size of the Test Chamber

In earlier studies[3,11] the effects of test-chamber size were evident when the test chamber was rather small (20 × 28.5 ×

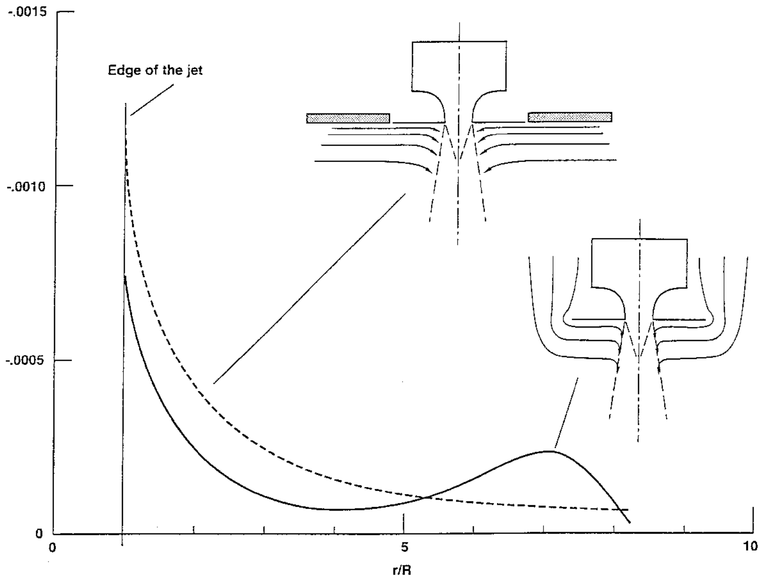

Fig. 13 Effect of the edge on the OGE pressure distribution on the model undersurface as a function of the planform radius *r* nondimensionalized by the radius of the jet *R*. Reference 2, NPR = 2.03.

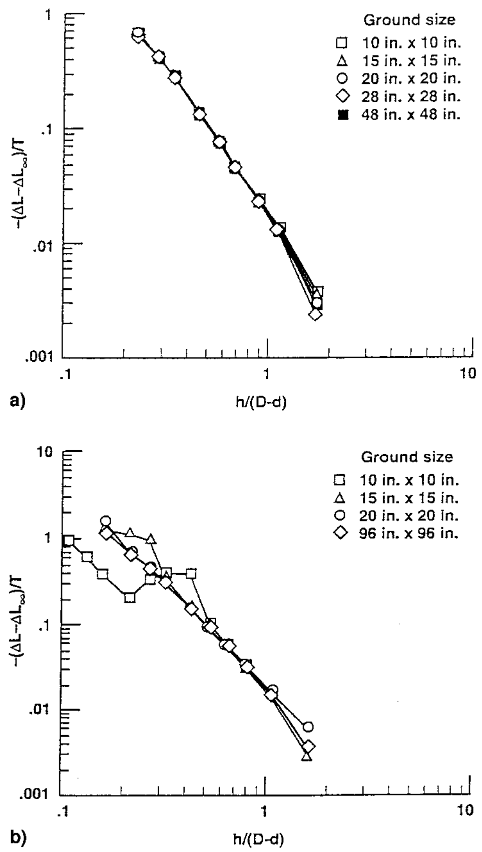

Fig. 14 Effect of ground-plane size on suckdown at NPR = 2.0: a) 10- and b) 20-in. disks.

15 ft). The volume was approximately 8500 ft^3. During testing in this test chamber, appreciable recirculation in the room was noticed. Opening large (11 × 16 ft) rollup doors at the end of this test chamber reduced the measured OGE suckdown. In the current investigation at the NASA Ames JCAHT facility, the test chamber was much larger (62 × 65 × 25 × ft, volume approximately 100,000 ft^3), and it was free of obstacles close to the model that could interfere with flow around the model (Fig. 5).

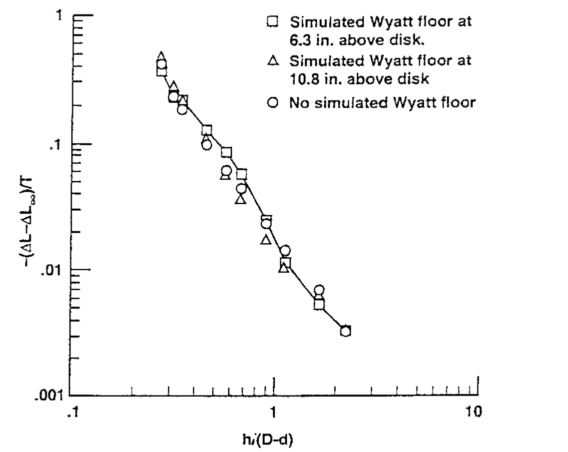

Fig. 15 Effect of simulated floor boundary, 10-in. disk at NPR = 1.5.

Obstructions Close to the Model

Most of the suction induced on a configuration is created in a small, near-field region beneath the model. Far-field effects could occur, however, since the wall jet spreads to large distances and static air is pulled into this flow and the low-pressure region around the model. It follows that obstacles to each of these flowfields (near and far) might influence the jet-induced characteristics. Such an obstacle seems to exist in Wyatt's test apparatus.[1] In Wyatt's test,[1] the direction of the jet was upward (Fig. 3) and the actual test-chamber floor became a boundary upstream of the jet exit. This boundary did not exist in most other tests and would not normally occur in actual hover flight. To measure the bias of such a boundary in the current investigation, an 8 × 8 ft board was installed at two different heights (6.3 and 10.8 in.) directly above the model. The effect of this simulated floor boundary was not consistent, as shown in Fig. 15. There was, however, a clear bias in the suckdown data, especially for $h/(D - d) < 1$. The magnitude of the differences was in the order of ±10%. The tests at NASA Ames Research Center High Bay area[3] also had an inverted setup similar to Wyatt's.[1] In this case, however, the 20-in. disk was approximately 60 in. above the floor, or approximately 2.4 times the distance from the ground (normalized by model diameter) as compared with Wyatt's test setup.[1] This setup would correspond to a floor height of 30 in. in Fig. 15 and should have little if any effect on suckdown.

Summary

No single test or model parameter explains the differences between Wyatt's results[1] and more recent data, including the current data. In most cases, earlier results could not be reconstructed because insufficient information was available on some of the test or model parameters that were deemed important. This problem was especially true about the facility used by Wyatt.[1] Test parameters that varied in the present study were the gap size between the model and the nozzle, the jet impingement angle to the ground, the size of the ground plane relative to the model, and the effect of large obstructions close to the model. Several of these parameters had noticeable effects on the model suckdown, whereas others seemed to have little or no effect. The following list summarizes the parameters that were considered important and those that were considered less important to suckdown measurements. 1) Important (major factors): gap between nozzle and model; outer edge shape of the model; test-chamber obstacles and size; jet structure details, uncertain and 2) less important (minor factors): small deviations in jet impingement angle and ground-plane size, must be at least as large as the model. It has become evident that certain parameters are important when testing small-scale hover models. Therefore, choices of model and test parameters must be carefully made and clearly documented. The following guidelines are offered:

1) *Gap size*: this should be kept to a minimum, or if, possible, eliminated.

2) *Edge shape*: model edge shape should be matched to the configuration being investigated. When comparing with other model tests, the same edge shape should be used.

3) *Test-chamber obstacles and size*: large flat surfaces, including all chamber boundaries, should be kept as far away from the model as possible. All scale models should be tested in a relatively large room to reduce or eliminate recirculation, especially when measuring OGE jet-induced parameters.

4) *Jet impingement angle*: the current study showed that jet impingement angle is a small factor in overall single-jet suckdown. Impingement angles as large as 5 deg produced no measurable effects except at the very low heights, $h/(D - d) < 0.5$.

5) *Ground-plane size*: for the single-jet cases, the ground needs to be only as large as the model. This assumption should also be valid for multiple-jet configurations. No testing was done to determine the effects of the ground size in terms of hot-gas ingestion.

6) *Jet structure*: jet structure appears to be an important factor in suckdown measurements. A wide range of suckdown variations can be produced, depending upon how the supercritical jet interacts with the ground. The only advice offered here is that the actual jet should be modeled as closely as possible.

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