Vertical Takeoff Lift Augmentation: the "Sculptured Deck" Concept

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Experimental results are presented which demonstrate that the lift of a hovering VTOL aircraft can be increased greatly by appropriately contouring the ground surface under the vehicle. The augmented lift is created by redirecting the jet exhaust flow so that it impinges on the aircraft underbody. One configuration of the ground plane is shown to augment the total upward force on the vehicle by a factor of 2.4 and at the same time increases the roll, pitch, and yaw stability of the aircraft. The measurements were taken from a particualr VTOL model and two types of ground plane, but the idea can be generalized to include arbitrary aircraft planform, any number of jets, any shape jet exit, and a wide assortment of ground plane topographies. The high degree of design flexibility intrinsic to the concept may be sufficient to offset the serious problems of underbody heating, hot-gas reingestion, and the necessity of a prepared takeoff site.

Introduction

THE net aerodynamically induced lift on a VTOL aircraft in proximity to the ground is determined by the competition between two opposing propulsion-induced phenomena: the "suckdown effect" and the "fountain effect." The suckdown effect is caused by jet entrainment of ambient fluid, which tends to lower the static pressure on the aircraft underbody and results in a net downward force on the vehicle. The fountain effect occurs only with multiple jet configurations and is characterized by a centrally located region of upwash which impinges on the aircraft underbody, increases static pressure, and results in a net upward force on the vehicle. The net strength of both the suckdown effect and the fountain effect is strongly dependent upon the elevation above the ground plane and the spacing of the jets relative to the aircraft planform. In practice, the strength of the suckdown effect is considerably greater than that of the fountain effect, resulting in as much as 15% loss of total thrust. This propulsion-induced loss of thrust during takeoff and landing is a very serious problem to those involved with VTOL design because it significantly decreases mission radius. Margason[1] estimates that a 3% loss of thrust during hover, when translated into a reduction of fuel capacity, results in a 10% reduction of design range. Consequently, any modification to the system which tends to increase fountain impulse and/or decrease suckdown force is of interest to the VTOL community.

The theoretical prediction of a VTOL ground-effect flowfield is an exceedingly complex task, and we know of no published accounts that treat the multiple jet problem successfully. However, much experimental work has been done. Margason[1] examines the entire spectrum of ground-effect problems, including the suckdown effect, the fountain effect, hot-gas reingestion, and cross-winds, all with single and/or multiple jets. He presents data that show between 1.5% and 3.0% loss of thrust for a single jet in absence of the ground. This is consistent with the theoretical analysis of an axisymmetric jet issuing from an infinite plane by Wignanski.[2] Margason also presents data which show that the impulse carried by the fountain upwash can be as great as 10% of the total thrust of the vehicle. Davenport and Spreemann[3] demonstrate that increasing the number of jet exits provides the most favorable thrust characteristics in proximity to the ground, with the annular jet performing best of all. A recent and general discussion of propulsion-induced effects on VTOL flight, with special emphasis on the transition flight regime, is presented by Winston et al.[4] Finally, modifications of the aircraft underbody for the purpose of capturing the fountain impulse can improve hover performance noticeably. The "strake-box" concept currently is being used on the Harrier AV-8B and results in a significant increase of payload capability.[5]

Since we knew of no attempts in the literature at ground plane modification as a means of combating the suckdown effect or augmenting fountain strength, we decided to investigate this possibility. The basic idea of the "sculptured deck" concept is to modify the topography of the ground plane so that it turns the jet exhaust flow through 180° and causes it to impinge on the aircraft underbody. This objective can be realized in different ways (Figs. 1 and 2). The exhaust flow can be turned inward to impinge on an area internal to the jet thrustors, forming a stronger-than-usual fountain (Fig. 1), or it can be turned outward to impinge on an area external to the primary sources of thrust (Fig. 2), thus forming an external fountain and partially eliminating the secondary entrained flow which causes the suckdown effect. By placing a skirt around the periphery of the vehicle, the return flow can be redirected toward the ground, imparting additional lift to the craft.

An upper limit on the peformance of the "sculptured deck" can be determined by idealizing the jet exhaust flow as a well-ordered volley of, say, machine-gun bullets. Assuming that the cupped array and aircraft underbody can turn this impinging volley without frictional loss, then the arrangements

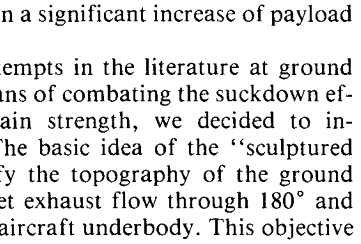

Fig. 1 The inboard cupped array with highly schematic flowfield.

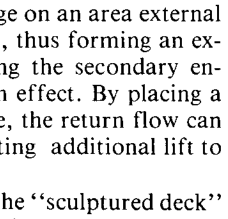

Fig. 2 The outboard cupped array.

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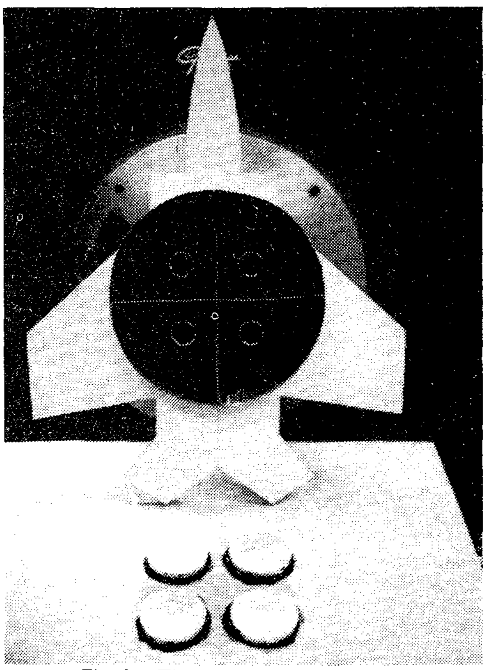

Fig. 3 The experimental apparatus.

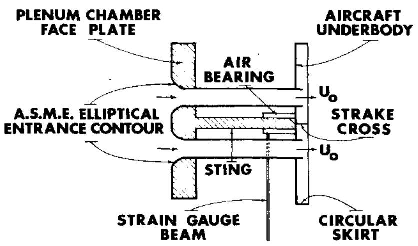

Fig. 4 Schematic side view of the force-measuring device.

shown in Figs. 1 and 2 theoretically could augment the total upward force on the vehicle by a factor of 3. (Call the initial momentum flux of the jet P; then, when the upwash strikes the underbody and is turned through 180°, it imparts a force of $2P$ to the vehicle. The net upward force is therefore $3P$.) We were thoroughly amazed when, at one point in the experiments on this device, a force augmentation of 2.85 was measured!

Scope of Investigation

Preliminary investigations by Hill and Jenkins[6] indicate that both fountain augmentation and fountain stability can be improved by extending the jet nozzles below the plane of the aircraft underbody. Experimentation during the course of the present study on ground-plane modification suggested that the extended jets worked particularly well in conjunction with a cupped ground-plane. Although many configurational perturbations are possible if one allows cups, strakes, skirts, and extended jets as modifications to the basic geometry of the system, we investigated in detail only those combinations of modifications which appeared intuitively promising.

Based on the flowfields postulated in Figs. 1 and 2, we constructed and investigated four different configurations: 1) the inboard cupped array with extended jets; 2) the outboard cupped array with extended jets; 3) configuration 1 plus a circular skirt and strake cross on the vehicle; and 4) configuration 2 plus a circular skirt and strake cross on the vehicle. For simplicity, all ground contours were hemispheres, and all vehicular control surfaces were thin vertical blades. Measurements were recorded using one jet array (four jets, equally spaced and equal in strength) and a circular aircraft underbody. A photograph of the experimental setup is shown in Fig. 3. An aircraft planform is included to show typical jet spacing relative to the underbody. The planform was removed during the force measurements.

Because of the complexity of the problem, no attempt was made to optimize the flow-turning efficiency of any of these contours. Clearly, the optimal design must take into account not only maximum lift augmentation, but also stability of the aircraft with respect to pitch, yaw, roll, and translation; local heating rates; acoustically induced vibrations; and inlet reingestion problems. In the final analysis, the topography of the aircraft underbody must mesh with that of the ground plane, in an action-at-a-distance sense, so that all of these ground-effect criteria are satisfied within design limitations. Equally important is the ease with which the aircraft can retract and conceal its ground-effect control surfaces to accommodate the transition and cruise modes of flight.

Experimental Method

The Grumman Aerospace Research Department's jet mixing apparatus was used as the source of pressure for the jets of the VTOL model. The jet mixing rig has a contraction ratio in excess of 300:1, a free stream rms turbulence level of less than ½%, and a maximum exit-plane Mach number capability of 0.250. In addition, the apparatus features a wide-angle segmented diffuser that helps to limit the total length of the device, a continuously adjustable transmission that simplifies the reproduction of plenum pressure settings, and a traversing mechanism with three orthogonal degrees of freedom.

The induced force on the VTOL model is measured by allowing the underbody to translate in an axial direction independently of the four-jet array. To reduce static friction to a minimum, the underbody is supported by an air bearing. The force generated by the deflection of a cantilevered beam holds the underbody stationary with respect to the jet array. The cantilevered beam is instrumented with strain gages and allows a numerical readout of the force required to balance the underbody against the aerodynamically induced force on the vehicle. A schematic of the force-measuring device is presented in Fig. 4.

The induced lift on the vehicle is referred to the calculated thrust of the four-jet array in absence of both the ground plane and the aircraft underbody. This reference thrust is calculated on the basis of the jet exit-plane momentum flux and is not measured directly. All of our measurements were taken at a gage plenum pressure of 8 in. of H_2O, which corresponds to an exit velocity of 190 fps, an exit Mach number of 0.173, and a total thrust of 1.83 lbf. This thrust calculation makes no allowance for boundary-layer growth inside each nozzle; the actual thrust of the system is therefore slightly less than 1.83 lbf.

Discussion of Results

Lift Measurements

In this section, we present dimensionless curves of the interference lift on the vehicle as a function of the elevation above the ground surface. As a matter of consistency, the "elevation above the ground" is defined in all cases as the distance from the uppermost protrusion of the ground surface

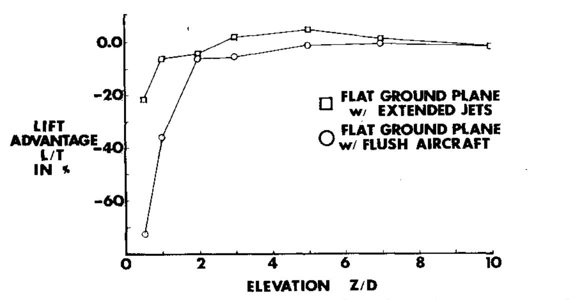

Fig. 5 Comparison of the lift characteristics of the flush underbody vs the extended jet configuration.

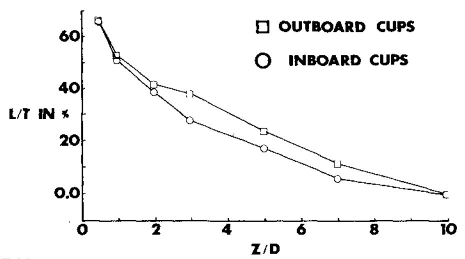

Fig. 6 Lift characteristics of the inboard and outboard cupped arrays. Both cases have extended jets but no other modification to the underbody.

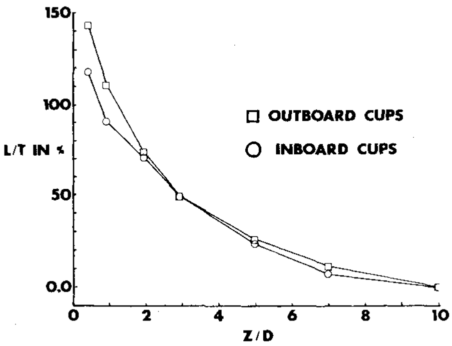

Fig. 7 Same as Fig. 6, but a strake cross and circular skirt have been added to the aircraft underbody.

to the lowermost excursion of the aircraft underbody. This distance, expressed in terms of jet diameter, appears as the abscissa in all of the following performance curves.

Figure 5 contrasts the suckdown effect produced by a flat ground plane and a flush aircraft underbody with that produced when the jet nozzles extend ½ diam, as suggested by Hill and Jenkins.[6] The suckdown effect for this particular flush underbody is remarkably strong; more than a 70% loss of thrust is incurred at ½ diam above the ground surface. The extended jet configuration produces a lift advantage over a significant range of height above the ground.

Figure 6 contrasts the lift advantage produced by the inboard cupped array with that of the outboard cupped array. In both cases, the jet array extends ½ jet diam beneath the aircraft underbody. The momentum exchange promoted by the cupped array is remarkably strong in both cases, but the outboard array is considerably more efficient in turning the jet exhaust flow.

Figure 7 shows the performance curves that result when the cupped arrays are used in conjunction with a circular skirt, strake cross, and extended jets on the vehicle. Again, the outboard-mounted cups produce more lift advantage than the inboard array, but the difference is not as pronounced as in Fig. 6. The outboard array at an elevation of ½ jet diam produces a lift advantage of 143% of the basic thrust of the system; that is to say, the total thrust of the system (i.e., jet thrust plus induced lift) is augmented by a factor of 2.43 above what it would be in absence of the ground plane and the aircraft underbody. At ¼ diam, the total thrust is augmented by a factor of 2.85, remarkably close to the theoretical limit of 3.

The lift augmentation decreases as the ground plane recedes because the axial momentum of the jet diffuses laterally with increasing distance from the jet (i.e., the jet "spreads"), so the cupped array captures and turns around less and less of the original momentum of the jet with increasing elevation. However, the situation may be improved significantly in the sonic case because sonic jets spread at a slower rate than subsonic jets. (Although core length is defined poorly for the sonic jet because of the presence of barrel shocks, shock diamonds, etc., the sonic core length is almost twice that of the subsonic jet. Donaldson and Snedeker[7] discuss plume structure for sonic jets of various pressure ratios and note their persistence with increasing Z/D.) The fact that the bulk of the jet momentum remains close to the axis for greater distances in the sonic case suggests the alluring possibility that the lift advantage produced by a cupped array in the presence of sonic jets may persist to greater altitude than observed in the subsonic case.

Stability Investigation

General Discussion

Attitude stability is a fundamental design concern for those involved with the hover mode of VTOL flight, and it becomes of particular concern when induced forces and moments depend strongly on the orientation of the aircraft with respect to the ground. Most studies consider a planar ground surface, and for this case only the roll and pitch instabilities present a problem. But in the case of the cupped ground plane array, the situation is more restrictive, and both yaw and translational instabilities must be considered, in addition to roll and pitch.

Roll instability for a conventionally designed VTOL is caused by two different mechanisms. First, the strength of the suckdown effect increases with decreasing elevation. Therefore, when the aircraft rolls, those underbody surfaces that dip toward the ground are attracted more strongly to the ground, and those that rise are attracted less strongly. This creates a destabilizing roll moment. Second, when the aircraft rolls, the effective impact point of the fountain shifts in a destabilizing direction, increasing further the destabilizing roll moment.

The cupped array has the desirable property of *increasing* the strength of the return flow with decreasing elevation and therefore has potential as an automatic stability control device. The outboard mounted cupped array is particularly well suited for enhancing roll and pitch stability because, although the strength of the return flow increases no more than for the inboard case, the distance between the aircraft center of gravity and the fountain center of pressure (i.e., the effective moment arm) is greater than for the inboard-mounted cupped array. In short, either cupped array creates restoring roll and pitch moments, but the outboard cupped array produces a greater restoring moment than the inboard array.

Experiments

Since the test apparatus was not equipped to measure aerodynamic moments as a function of attitude perturbation, a light-weight hovercraft of exactly the same dimensions as the aircraft underbody used in the lift augmentation study was constructed. The jet nozzles of the VTOL hovercraft model were powered by plenum pressure from the jet mixing rig, the connection being made by four 10-ft lengths of 1-⅛ in.I.D. thin-wall Tygon tubing. Although not sufficiently quantitative to produce stability characteristic curves, the hovercraft model provided an effective demonstration of attitude stability.

The most important result of our experimentation with the hovercraft is that a local, inherent state of attitude stability can be produced, provided that the proper flowfield control measures are taken. In general, the degree of stability of each ground plane/underbody configuration parallels its lift augmentation characteristics, in that the configuration with the greatest lift augmentation also has the greatest attitude stability, and that the degree of stability falls off with increasing elevation above the ground surface.

Each configurational modification to the system can be associated directly with the enhancement of a particular stability mode. The outboard cups are responsible directly for enhancing roll and pitch stability; the strake cross is responsible for enhancing yaw stability; the circular skirt enhances translational stability. The extended jet nozzles act as further vertical control surfaces and tend to increase the stability of all modes.

All modes were found to be unstable when the hovercraft model was placed over the cupped array so that the jets impinged on the areas between the cups. In an attempt to eliminate this sensitivity to misalignment in yaw, two additional ground planes were constructed: the inboard and outboard axisymmetric troughs. These annular surface depressions proved to be totally ineffective at reversing the jet exhaust flow and produced no noticeable lift augmentation. (They were not, however, subjected to quantitative force measurements.) In fact, the hovercraft barely got off the ground above the annular surface depressions, whereas at the same plenum pressure with the cupped array the craft floated at an elevation of 3 jet diam.

One obvious problem presented by the application of the sculptured deck concept to an ocean-going aircraft carrier (particularly the smaller aircraft carriers which might be designed specifically for VTOL deployment) is stability sensitivity to roll and pitch motion of the deck. To this end, we noticed that the fully equipped aircraft underbody (i.e., extended jets, strake cross, and circular skirt), when floating above the outboard cupped array, remained stable when the deck was rolled or pitched at angles up to 5°. The dynamic problem of changing deck orientation at various frequencies was not considered.

Another related problem associated with aircraft carriers is landing on a rolling and pitching deck with fluctuating crosswinds, a task certain to be dangerous in any case, and probably impossible if the pilot is trying to land precisely over a lift-augmenting cupped array. We believe a lift-agumenting *landing* site would be superfluous, though, because as a result of fuel expenditure during takeoff, transition, the weight of a VTOL at landing is considerably less than at takeoff. Since the weight is less, the lift penalty imposed by the suckdown effect is not as serious a problem as during takeoff. Accordingly, the danger involved, together with the fact that lift augmentation is not really necessary during this phase of VTOL flight, preclude using the sculptured deck as an assist device during landing.

To summarize, the outboard-mounted cupped array in conjunction with a strake cross, circular skirt, and extended jet nozzles on the vehicle produced an inherently stable local state of attitude equilibrium. All other configurations were lacking in one or more of the basic stability modes. As with the lift augmentation study, no attempt was made at optimizing the various geometries.

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Summary

The sculptured deck concept presents an assortment of benefits and penalties to hovering VTOL aircraft, and the ultimate fate of the concept will depend on the interplay between the two. On the negative side, perhaps the biggest problem is the necessity of a prepared takeoff site. In addition, the designer must cope with increased underbody heating and hot-gas reingestion. On the positive side, the suckdown effect has been eliminated completely, and roll instability is replaced by local roll stability. The fact that the lift augmentation is so great near the cupped array suggests two modes of takeoff: the aircraft could lift off at half throttle and slowly increase power with increasing altitude, or the aircraft could be anchored to the deck and suddenly released at full throttle, i.e., a vertical catapult. In this case, the pilot would experience an initial upward acceleration of roughly 1.4 *g*'s, certainly within human limitations.

Perhaps the most encouraging result of this work is that attitude stability and lift augmentation are by no means mutually exclusive properties in the context of ground plane modification; indeed, every attempt to enhance stability also increased lift advantage, and vice versa. The reader should keep in mind that the force data presented in this paper represent the integrated effect of momentum exchange in a *subsonic* flowfield, and that the ground-effect flowfield of a real VTOL is certain to be *supersonic*, at least locally. There is good reason to believe that the lift advantage produced by the cupped array will persist to greater altitude in the supersonic case, because of the slower spreading rate of sonic jets. Any additional experimentation should address this possibility.

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