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POWERED LIFT MODEL TESTING
FOR GROUND PROXIMITY EFFECTS

by

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S U M M A R Y

The effect of ground proximity on the performance of powered lift vehicles has been investigated on simple models using two different testing methods. Single and double-jet models representing VTOL configurations and an air-cushion model with peripheral jet have been tested both in the wind-tunnel where a stationary plate immersed in the flow was used to represent the ground and on a special rig allowing the models to be moved over a fixed ground plate. The lift and centre of pressure location have been determined with both techniques for various model heights above the ground-plate over a range of momentum coefficients. The results obtained with both methods are compared.
NOTATION

\[ D \]
Diameter of circular-disc VTOL models

\[ D_e \]
Equivalent diameter for triangular VTOL model

\[ H \]
Height of triangular model (base of triangle to vertex)

\[ D_g \]
Base diameter of air-cushion model

\[ d \]
Nozzle diameter for single-jet VTOL models

\[ d_e \]
Equivalent nozzle diameter for double-jet VTOL models

\[ h \]
Distance of models from ground-plate

\[ x \]
Distance of centre of pressure from centre of models or from centre of nozzle for triangular model (positive upstream)

\[ S \]
Model area

\[ q \]
Dynamic pressure corresponding to tunnel or model velocity

\[ v_j \]
Jet velocity

\[ m_j \]
Jet mass flow

\[ C_\mu \]
Static ground suction force on VTOL models

\[ G_s \]
Ground suction force on VTOL models with relative wind

\[ L_s \]
Static lifting force on base of air-cushion model

\[ L \]
Lifting force on base of air-cushion model with relative wind
Introduction.

The VTOL aircraft which derive their lift at zero or low speeds from vertical or near vertical slipstreams may be subjected to large interference effects when operating in close proximity to the ground.

A jet emerging from a lifting surface and impinging vertically on the ground will entrain ambient air between the surface and the ground and as a result, low pressures will be induced on the lower surface. The lifting performance of such a simple system will therefore be reduced. However, the sign and magnitude of the ground effect on the lifting capability depends essentially on the configuration of the VTOL aircraft under study. A multi-jet model, for instance, may produce a favourable ground effect. At low speeds, conditions in ground proximity are usually less favourable than at zero speed, any favourable static effect being reduced or any static ground suction being increased.

Because of the usually small margin of lifting thrust available over the aircraft weight, it is important to determine accurately at an early stage the effect of ground proximity on the performance of a projected aircraft.

Model tests are usually carried out in the wind-tunnel, the ground being represented by a fixed-plate immersed in the flow. This method does not reproduce the full-scale flow characteristics of an aircraft flying close to the ground in no wind condition because of the existence, on the stationary plate in the wind-tunnel, of a boundary layer which separates
in front of the model due to the high pressures induced under it by the lifting jet or jets.

The same argument applies to the air-cushion vehicle which is designed to operate very close to the ground to take full advantage of a large favourable effect.

To investigate the validity of the wind-tunnel fixed-plate technique, a simple rig has been designed which allows the model to be moved over a flat surface representing the ground. A description of the rig has been given in a previous note (ref.6). It operates like a pendulum, the model moving along a circular path in the vertical plane. Comparative experiments carried out on models representing VTOL configurations and on an air-cushion model both with such a rig in the low-speed tunnel with a fixed-plate are described.

Lift and pitching moment induced by the jet or jets have been determined. The results obtained with the VTOL models show substantial differences for small distances of the models from the ground-plate.

For the air-cushion model, the differences are considerable particularly in the higher range of relative wind speeds.

Model description and apparatus.

The models used in the experiments are shown in fig.1.

The first four models correspond to simplified VTOL
configurations with single and double-jet nozzles. With one exception, all plan-forms are circular: one has the shape of an equilateral triangle. They are made of thin metal sheet with the plane parallel to the direction of flow (zero angle of attack). The position of the jet nozzle(s) is indicated in fig.1.

With reference to an investigation carried out at the R.A.E. in the United Kingdom, the size of the triangular model was chosen to produce the same static characteristics as the single-jet circular model. An equivalent diameter $D_e$ equal to the diameter $D$ of the circular model is obtained as shown in fig.1. For the double-jet models, the total nozzle area is equal to that of the single-jet models, an equivalent diameter $d_e$ being defined in fig.1. The models are provided with a small clearance around the nozzle(s) to which they are attached through a two-component strain-gauge balance (lift and pitching moment). Only the aerodynamic loads induced by the jet(s) are therefore recorded.

The fifth and last model of the series tested represents an air-cushion vehicle with a peripheral jet nozzle inclined 30° inward as shown in fig.1.

The wind-tunnel tests were performed in the TCEA low-speed tunnel L1 which has a circular open-jet working-section of 3 m. diameter. The board used for ground representation was made of a metal plate 10 mm thick, with a 1 m span and a length of 1.7 m with a 2 mm thick leading edge. The models were located 0.9 m behind the leading edge.
The rig designed for comparative measurements is shown schematically in fig. 2. It consists essentially of a pendulum of 4 m radius at the end of which the model is attached. The pendulum rotates in the vertical plane, being released, prior to a run, from the vertical position. The model velocity at the bottom of the circular path at the first passage is approximately 16 m/sec, the velocity decreasing at each successive passage.

The arm of the pendulum includes the air supply pipe to the model with a flow-meter. Special bearings are fitted at the axis of rotation.

The end of the pendulum arm is turned by 90°, the model being mounted vertically with the jet(s) horizontal. Such an arrangement allows a flat vertical plate to be used for ground simulation and the centrifugal force on the model acts at right angles to the force to be measured.

The strain-gauge balance measurements are made at the bottom of the circular path with a galvanometric recorder. A time counter connected to two photo-electric cells located 0.5 m on each side of the lowest point of the path is used to determine the model speed.

Programme of tests.

1. VTOL models

Lift and pitching moment were measured under the
same operating conditions for both testing methods.

Low-speed flight conditions were obtained by keeping the mass-flow through the jet nozzle(s) constant and varying the tunnel or model speed. The data were obtained for a range of distances of the models from the ground-board of 1.5 to 4 nozzle diameters (or equivalent diameters). The conventional positive lift is considered here as negative i.e., a ground suction force is positive.

A non-dimensional coefficient is obtained by dividing the ground suction force G by the momentum flow through the jet(s) mjvj.

The results are plotted against the momentum coefficient

$$C_U = \frac{mjv_j}{qS}$$

Measurements of pitching moment were used to determine the centre of pressure location with respect to the centre of the model (centre of the jet nozzle for the triangular model). The distance x along the model longitudinal axis is considered positive upstream. The results are plotted in non-dimensional form as distance in per cent of model diameter D or length H against momentum coefficient $C_U$.

Reference to a ratio of jet to tunnel velocity such as given by the momentum coefficient was shown to be suitable by tests performed at two different mass-flow rates. The data obtained under these conditions were in very good agreement when related to $C_U$. Flow visualisation tests by the oil
6.

technique were performed in the tunnel to investigate the surface flow pattern on the ground-plate in the vicinity of the model.

2. Air-cushion model

The same testing procedure was used as for the VTOL models. The normal convention of a positive lift is used in this case i.e. a positive lifting force $L$ on the model base acts in a direction away from the ground-plate. A non-dimensional coefficient is obtained by dividing the lift $L$ with relative wind-speed by the static lift $L_s$.

The distance of the centre of pressure along the longitudinal axis from the centre of the model is given in the results as a percentage of the model base-diameter (positive direction upstream). Data was obtained for 3 values of the height of the model above the ground-plate namely 5, 10 and 20 per cent of the base-diameter and covered in each case a range of momentum coefficients.

Surface-flow visualisation tests were also made on the ground-plate in the wind-tunnel.

Discussion of results.

1. VTOL models

Fig. 3 gives the static ground suction characteristics of the four models tested plotted against the inverse of the
square of the distance ratio $h/d$ or $h/d_e$. The variation is linear for the single-jet models. Conditions are more favourable for the double-jet at the smaller values of the height $h$ due to jet recirculation in the plane of symmetry. The triangular model has, as expected, the same static characteristics as the single-jet circular model.

Figs. 4 to 11 show the ground suction characteristics with relative wind and the centre of pressure location plotted against the momentum coefficient $C_\mu$. No points are shown on the curves as these were obtained from intermediate plots of the experimental data.

For the first three models, the wind-tunnel values of ground suction are optimistic over most of the $C_\mu$ range compared to the pendulum data. Only at small $C_\mu$ values is there a tendency for the curves to cross over.

The fourth model, with the double-jet nozzles on an axis perpendicular to the relative wind, shows opposite characteristics, the wind-tunnel results being pessimistic over the whole range of momentum coefficients.

The differences between the wind-tunnel and pendulum results are substantial for the smaller heights of the models above the ground-plate.

Differences of as high as 10% of jet-thrust have been obtained in certain cases. The differences become generally much smaller as the height increases and tend to disappear for a height ratio of about 4.
The wind-tunnel and pendulum curves show a tendency to cross at a $C_\mu$ of approximately 2.5 or below for the first three models. The surface flow pictures in figs. 12 and 13 obtained in the wind-tunnel show the existence of a strong horseshoe vortex; the separation of the ground-plate boundary layer occurring some distance upstream. The position of this vortex with respect to the model depends essentially on the momentum coefficient $C_\mu$. At small values of $C_\mu$, the effect is such that the flow induced under the model is increased with a corresponding increase of ground suction compared to the pendulum results. At the higher values of $C_\mu$, the vortex is further upstream of the model and produces a kind of blockage with a consequent change in the ground suction force towards its static value. For the fourth model however, the flow picture gives a vortex position which, for the same $C_\mu$ range as for the other models, is located much closer to the model. This corresponds to the higher induced flow case of the other models with a resulting larger ground suction force than given by the pendulum.

It should be mentioned that the surface flow pictures show a pronounced similarity with those obtained with building models when tested on a fixed-plate in the wind-tunnel.

A previous programme of experiments (ref. 6) on a circular-disc model with a central jet showed that the boundary-layer thickness on the fixed-plate in the wind-tunnel did not appear to affect the ground suction force induced by the jet, the main effect being produced by the
separation of the boundary-layer with the resulting change in flow pattern.

2. Air-cushion model

Figs. 14 and 15 give the lifting characteristics and centre of pressure position in terms of momentum coefficient for the air-cushion model. The surface-flow pictures taken in the wind-tunnel are given in fig. 16. The difference between wind-tunnel and pendulum results is considerable in the lower $C_μ$ range and may be as large as 30 per cent and higher of the static lift value. The flow pictures are similar to those obtained with the VTOL models.

The lift obtained in the wind-tunnel is always optimistic which means that the blockage effect mentioned for the VTOL models seems to apply throughout the $C_μ$ range tested. Unless momentum coefficients are reached in the lower range such that the upstream part of the peripheral jet is turned backward before the ground is reached, the front of the horseshoe vortex is always located sufficiently upstream for the effect mentioned above to apply. The lift measured in the wind-tunnel tests therefore, tends toward the static value much more rapidly than in the pendulum tests.

CONCLUSIONS.

A simple rig has been described for testing VTOL or air-cushion types of models in ground proximity in a more
representative manner of the full-scale conditions than in the wind-tunnel when a fixed-plate is used to represent the ground.

Within the scope of the present investigation, substantial differences are obtained for the VTOL models in the ground suction force measured with the rig and in the wind-tunnel for small distances of the models from the ground plate. The sign and magnitude of the differences depend essentially on model configuration and are related to the position of the horseshoe vortex associated with the separation of the boundary layer on the fixed-plate in the wind-tunnel.

In the case of the air-cushion model considerable differences are observed in the lifting characteristics, and wind-tunnel tests with a fixed ground-plate would appear to be unsatisfactory, particularly in the high speed range.
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VTOL MODELS

\[ \frac{D}{d} = 8 \]
\[ \frac{D_e}{d} = 8 \]
\[ D_e = \frac{1}{\pi} \int_0^{2\pi} r \, d\theta \]

\[ \frac{D}{d_e} = 8 \]
\[ d_e = \sqrt{2} d' \]
\[ D = D_e = 232 \text{ mm} \]
\[ d = d_e = 29 \text{ mm} \]

AIR CUSHION MODEL

\[ D_g = 198.5 \text{ mm} \]
\[ t = 0.7 \text{ mm approx.} \]

Fig. 1
Figure 2
Fig. 3   STATIC CHARACTERISTICS OF VTOL MODELS
Fig. 5

\[ x/D \]

- \( h/d = 1.5 \)
- \( h/d = 2 \)
- \( h/d = 3 \)
- \( h/d = 4 \)

PENDULUM

WIND-TUNNEL
Fig. 9

\[
\frac{h}{d_e} = 15
\]

\[
\frac{h}{d_e} = 2
\]

\[
\frac{h}{d_e} = 3
\]

\[
\frac{h}{d_e} = 4
\]

PENDULUM

WIND-TUNNEL
Fig. 11

- PENDULUM
- WIND-TUNNEL

Graphs showing the variation of $x/D$ with $C_\mu$ for different $h/d_e$ values.

- $h/d_e = 1.5$
- $h/d_e = 2$
- $h/d_e = 3$
$C_{\mu} = 0.8$

$C_{\mu} = 2.5$

$C_{\mu} = 5$

FIGURE 12
FIG. 13 - $C_u = 5; \frac{h}{d}$ or $\frac{h}{d + e} = 2$
Fig. 14  
AIR-CUSHION MODEL

- ○ PENDULUM
- - - - - △ WIND-TUNNEL

\[ \frac{L}{L_s} \]

\( \frac{h}{Dg} = 0.05 \)

\( \frac{h}{Dg} = 0.10 \)

\( \frac{h}{Dg} = 0.20 \)
Fig. 15  AIR-CUSHION MODEL

- ○ PENDULUM
- △ WIND-TUNNEL

\[ \frac{h}{Dg} = 0.05 \]

\[ \frac{h}{Dg} = 0.10 \]

\[ \frac{h}{Dg} = 0.20 \]
FIG. 16

AIR-CUSHION MODEL $C_{\mu} = 4$

\[ \frac{h}{D_g} = 0.05 \]

\[ \frac{h}{D_g} = 0.10 \]

\[ \frac{h}{D_g} = 0.20 \]
The effect of ground proximity on the performance of powered lift vehicles has been investigated on simple models using two different testing methods. Single and double-jet models representing VTOL configurations and an air-cushion model with peripheral jet have been tested both in the wind tunnel where a stationary plate immersed in the flow was used to represent the ground and on a special rig allowing the models to be moved over a fixed ground plate. The lift and centre of pressure location have been determined with both techniques for various model heights above the ground-plate over a range of momentum coefficients. The results obtained with both methods are compared.
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