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# THEORETICAL & EXPERIMENTAL STUDIES OF VECTORING JETS EFFECTS ON UNDER-WING STORES & THEIR RELEASE TRAJECTORIES

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## SUMMARY

The main objective of all classes of combat aircraft is the carriage of external stores (bombs and ferry tanks) and their "accurate" and "safe" release and delivery. This is true for current generation of VSTOL aircraft with vectoring jets and will be so for the next generation of ASTOVL aircraft. Presently, many ASTOVL design options are being explored, both in terms of possible propulsion arrangements (2-4 vectoring jets), and store types and configurations.

Jet blowing streamwise has little influence on nearby stores, provided they do not enter the actual jet-stream. However, a vectored jet can induce significant forces and moments on adjacent stores, and these effects persist large distances from the jet.

The effects on store release from aircraft with multiple vectored jets (2 to 4) have been assessed in two ways, using experimentally measured data on jet-induced forces and moments, and a theoretical formulation using a semi-empirical model of the jet. The predicted store release trajectories for a heavy and light store show considerable jet-induced effects.

The theoretical technique offers the capability for investigation of several aircraft and store geometric variables to determine "safe" store locations. This has obvious potential for very appreciable cost and time savings. The approach can assist in designing acceptable experiments. Areas for future work are discussed. These aspects should have a constructive impact on the current and future practical VSTOL and ASTOVL aircraft with and without store carriage.

## 1. INTRODUCTION, BACKGROUND, OBECTIVES & TOPICS ADDRESSED

The main objective of combat aircraft is the carriage of external stores (bombs and ferry tanks) and their "accurate" and "safe" release and delivery. **Fig.1** shows a typically heavily loaded current generation VSTOL aircraft (Ref.1) with four vectoring jets. The next generation of ASTOVL aircraft, **Fig.2**, (Refs.2-13) will continue to carry and release external store loads. Presently many ASTOVL design options are being explored, both in terms of possible propulsion arrangements (between 2-4 vectoring jets), and store types and locations.

The store carriage locations on relatively small aircraft are at a premium and it is often necessary to carry stores in locations where after release, or emergency jettison, they may pass close to a vectoring jet efflux. Maximising store carriage implies exploration of all possible locations. The store types vary greatly; some have appreciable lifting surfaces and may be attached to pylons of appreciable dimensions.

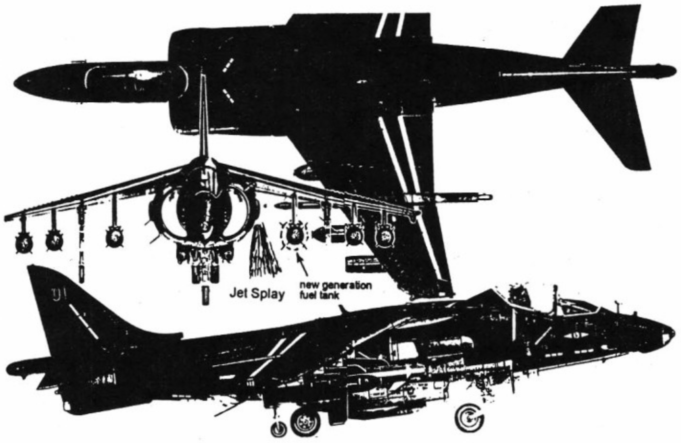

FIG. 1. VECTORING JETS, HARRIER GR.Mk.5 WITH STORES (from Airplane Part 6, Orbis)

Further, the effects of differential jet deflections need to be understood. Controllability aspects are very significant and off-design cases need to be predictable and safe. For safe and efficient store carriage and release on VSTOL / ASTOVL aircraft, it is therefore necessary to identify parameters and effects which may alter the store trajectory.

Induced forces and moments may affect the trajectory on release (intended or otherwise). Such effects will have a proportionally greater effect on the trajectory of less dense stores. High suctions may cause local separations on the stores or on adjacent surfaces. "Internally" carried stores will also be subject to significant jet effects when emerging from the bays.

These considerations have promoted a research programme towards understanding the jet effects on stores and release trajectories.

### Exploratory Experiments & Use of Theory With Jets

Work in the DRA wind tunnels, Ref.14, has illustrated some qualitative and quantitative features of jet-induced effects arising on stores mounted on a wing-body model. Stores near to a jet blowing streamwise, but not actually in the efflux were not significantly affected. However, stores near a vectored jet were subject to large jet-induced forces and moments even at distances far from the jet exit.

In certain cases, as store position relative to the jet was altered, the jet-induced side forces could be subject to sudden reversals in direction (**Fig.3**). Store trajectories therefore may display sudden changes near the jets. This evidence justified the need for continued theoretical and experimental studies.

Jet models using Navier-Stokes or Euler solvers, have not yet reached sufficient maturity to become "ready" tools for design and analysis. Emphasis has been placed on incorporating semi-empirical models of jets in established wing theory.

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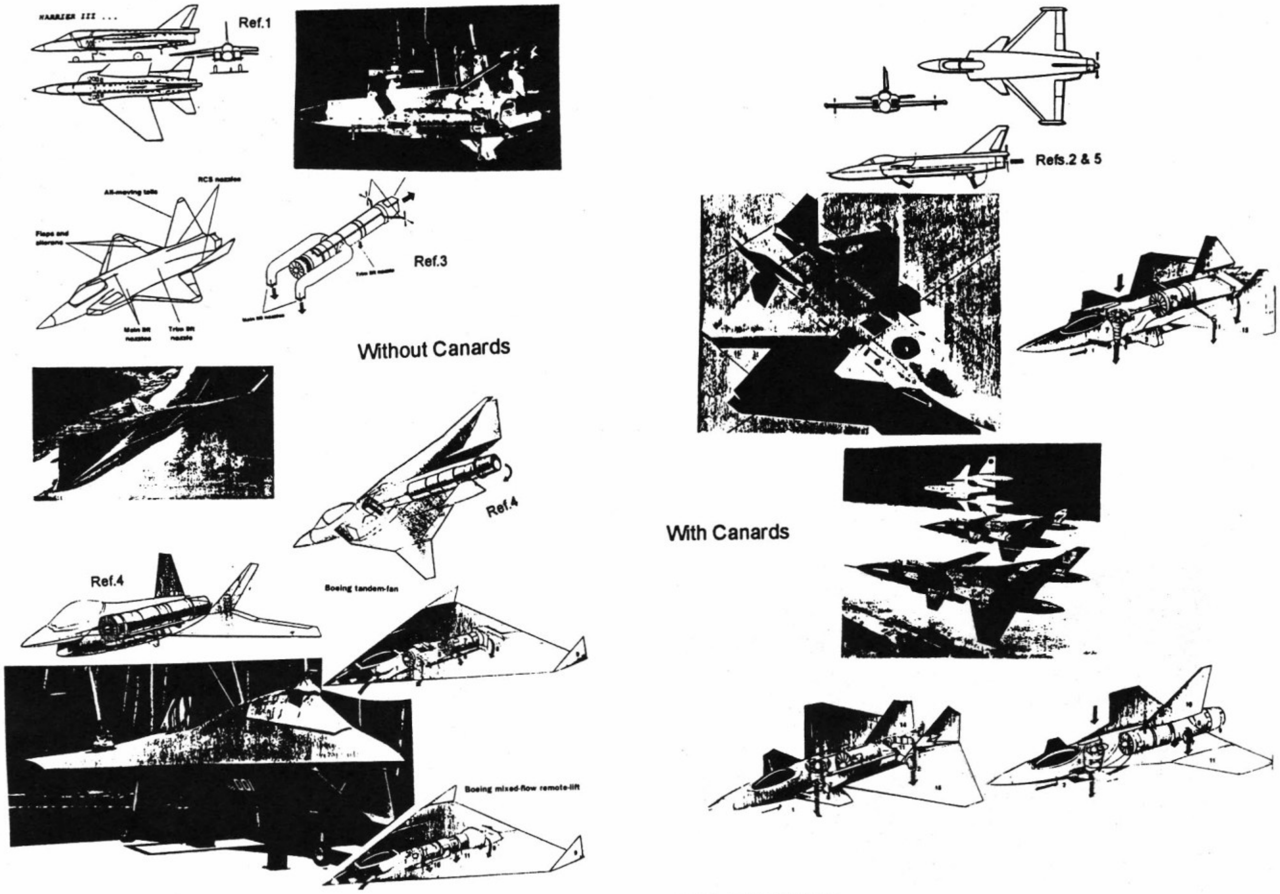


FIG. 2 DIFFERENT ASTOVL PROJECTS

Features of the approach have been summarised in recent ICAS and AGARD publications, Refs.15 and 16. These have given confidence in predictive ability for jet interference loads on different configurations. Wind tunnel interference effects can be large (Ref.17) for strong jets or large jet deflections.

Apart from the obvious implications of cost, time and effort for a study of wide range of parameters, there are inherent limitations in the prediction of store trajectories from wind tunnel measurements e.g. flow-field surveys. The usual "Captive-store" technique implies the absence of relative velocity between the store and the aircraft. Any velocity differences arising in trajectory calculations have to be adjusted e.g. by altering the store attitude and/or dynamic pressure.

On the other hand, a theoretical approach capable of evaluating many design parameters needs to be appropriately validated so that adequate confidence is built up.

Ref.18 (prepared for AGARD) reviewed early experimental work in addition to describing theoretical work on incorporating the 1-2 jet model in subsonic linearised theory for store release trajectories.

### Programme Objectives & Topics Addressed

The objectives of this programme are to identify possible problems caused by store/jet interaction, and to develop prediction techniques. A two-fold approach embodying experiment and theory has been appropriate. The experimental aspects addressed are:

- Determination of the magnitude of the forces and moments induced on a typical bomb type store by an inclined jet, when also in the influence of the aircraft flow-field. These studies indicate the spatial extent of such store/jet interactions (Section 2).
- The measured jet-induced force and moment surveys are used in a numerical approach to develop release trajectories of a range of store geometries (Section 3).

The theoretical aspects addressed are:

- The jet-induced effects prediction methodology of Refs.15-18 is reviewed and extended. Multiple jets (1 to 4) can be used. Parametric variations can be studied on a wide variety of aircraft and stores and their release trajectories (Sections 4 & 5).
- The results support the existing experiments and yield design data for setting up future experiments.

## 2. EXPERIMENTAL PROGRAMME

The experimental programme was set up to provide data for prediction of store release trajectories (See also Ref.18).

### 2.1. Test Arrangement & Flow Parameters

The tests were conducted in the DRA 13 x 9 ft wind tunnel on a 20% scale half-model (port side) of a VSTOL aircraft with a wing resembling that of the Harrier GR3. The model (**Fig.4**) could be equipped with a vectoring jet nozzle either at a forward or an aft location. For a given tunnel speed, $V_\infty$, the jet exit velocity $V_j$ (ratio, $R = V_j/V_\infty$), was altered by varying the total pressure of the blown air.

The store model used was a 20% scale 1000 lb bomb with 4 fins (ballistic tail). The store loads were measured with a 6-component strain gauge balance on either a straight or a cranked 7° sting fixed to the wind tunnel wake traverse gear.

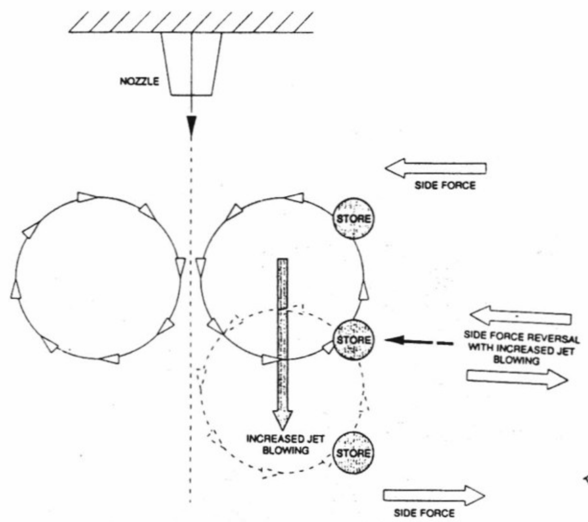


FIG. 3 EMPHASISING FORCE REVERSAL ABOUT A STORE DUE TO JET

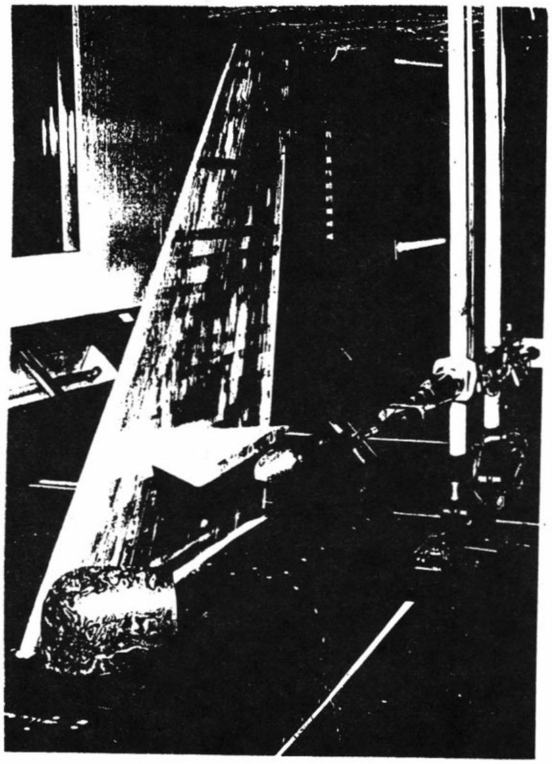


FIG. 4 FORWARD VIEW OF VSTOL HALF-MODEL, 13 x 9 ft WIND TUNNEL, WITH TRAVERSE MECHANISM & WING PYLON

The arrangement, **Fig.4**, allowed the store to be moved within a spatial volume, about 1 m in lateral and vertical directions (y- and z-sense), and 1.7 m longitudinally (x-sense).

The store traverse grid, **Fig.5**, is defined in terms of bomb calibres (diameter) measured along xyz-axes from the origin at the nozzle reference point. Note that x is positive streamwise, y is defined negative outboards towards the port wing-tip, and z is defined positive downwards.

Traverses were made in constant y-planes (1 calibre to 12 calibres) outboard of the reference point. The x-coordinate varied from 2 calibres aft to 20 calibres aft of the reference point. The z-coordinate varied from 2 calibres below to 12 calibres below the reference point. Measurements have been made with the bomb set at 0° i.e. streamwise, and with the 7° cranked sting, at pitch and yaw angles of ±7°.

The test conditions were: $V_\infty = 60$ m/s (197 ft/s) and R = 0 (unblown), 3.09 & 4.54. The forward vectoring nozzle was set at $\Theta_j = 60°$ (**Fig.4**). A flow visualisation of the 60° jet in cross-flow is shown in **Fig.6**.

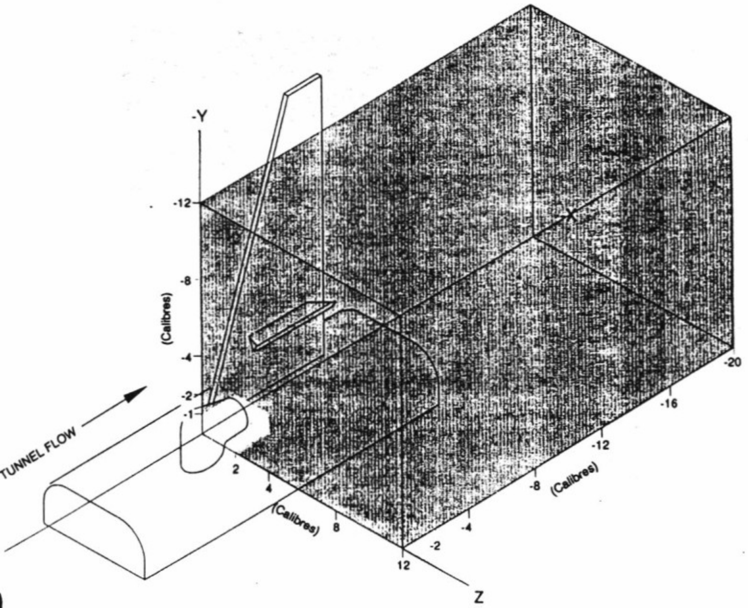


FIG. 5 AXES SYSTEM & MEASUREMENT GRID (Store Calibres in Survey Volume)

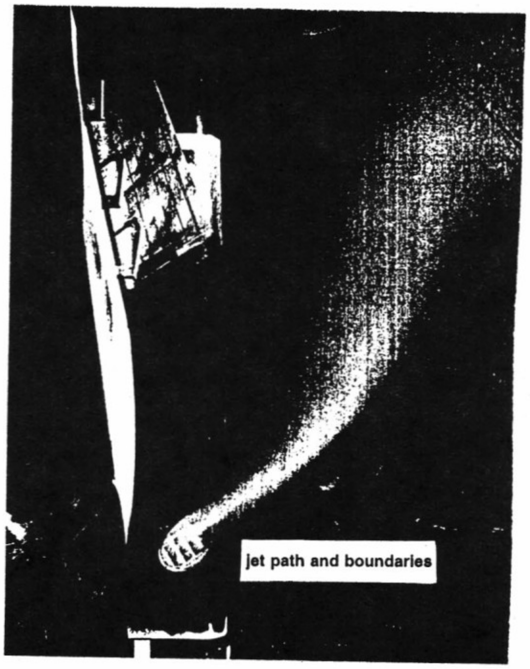
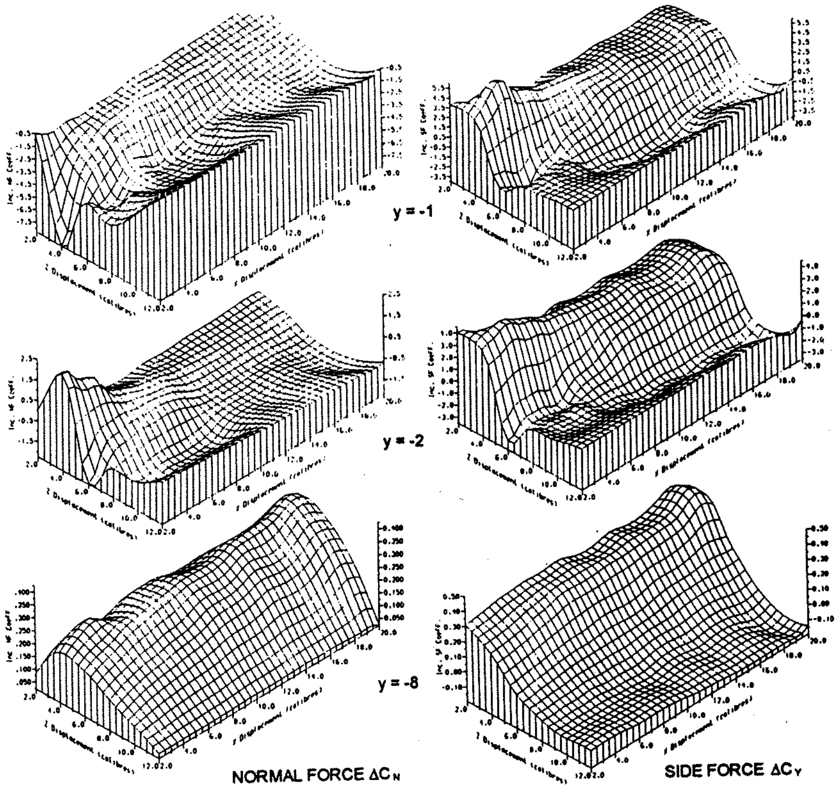


FIG. 6 FLOW VISUALISATION OF A 60° JET IN CROSS-FLOW

## 2.2. Typical Forces & Moments Arising on Store

A sample of the results for the 1000 lb store emphasise the extent and magnitude of jet induced effects. The force and moment coefficients have been non-dimensionalised with respect to the store cross-sectional area and a reference length of 1 calibre. It is convenient to show the jet effects in terms of incremental forces between the "jet-on" and "jet-off" cases, plotted against the grid geometry parameters x and z at different y stations outboard.

**Fig.7** shows the incremental normal and side forces, $\Delta C_N$ and $\Delta C_Y$ for y = 1, 2 and 8 calibres. These results show a complex variation of $\Delta C_N$ and $\Delta C_Y$ over the region surveyed. At y = 1 calibre, $\Delta C_N$ varies between -0.5 and -7.5, whilst $\Delta C_Y$ varies between +3.5 and -3.0. The jet induced effects persist many calibres downstream of the jet reference.



NORMAL FORCE $\Delta C_N$ SIDE FORCE $\Delta C_Y$

FIG. 7 JET-INDUCED FORCES $\Delta C_N$ & $\Delta C_Y$ IN zx-PLANE AT y = -1, -2 & -8 calibres

As the survey plane is moved outboard, the je interference effects generally decrease. At y = 2 calibre outboard of the jet reference, $\Delta C_N$, variation is between +2. and -2.0, whilst $\Delta C_Y$ varies between +4.0 and -3.5. It is eviden that the maximum effects can occur at a considerable distance from the jet reference e.g. the maximum negative normal force and side force occurrs at 6 to 7 calibres below the jet reference.

Even at lateral distances of 8 calibres outboard, **Fig.7**, $\Delta C_N$ and $\Delta C_Y$ in excess of 0.5 can be induced. From the known isolated aerodynamics of the 1000 lb bomb, such incremental effects are equivalent to effective incidence and yaw of about 8° being induced near the store.

Although the examples depicted are for $\Delta C_N$ and $\Delta C_Y$, similar behaviour was observed for pitching, yawing and rolling moments. Again the magnitude of the jet-induced effects can be large, and the interactions vary in a complex manner depending on the proximity of the store to the jet. Generally, ignoring the complexity of the observed variations, effects are larger near the jet and reduce in magnitude as distance from the jet increases, but effects remain at significant levels even at considerable distances from the jet.

An example of the blown jet effect on store suction (axial) force, $\Delta C_A$ or drag is shown in **Fig.8**, at y = 1 calibre outboard of the reference point. The axial force is defined positive forward. Regions exist where the jet induces a forward suction on the store. This effect was also identified in Ref.14. It was shown that the suction measured could be correlated with levels of below ambient static pressure existing downstream of a jet in cross-flow (Ref.19).

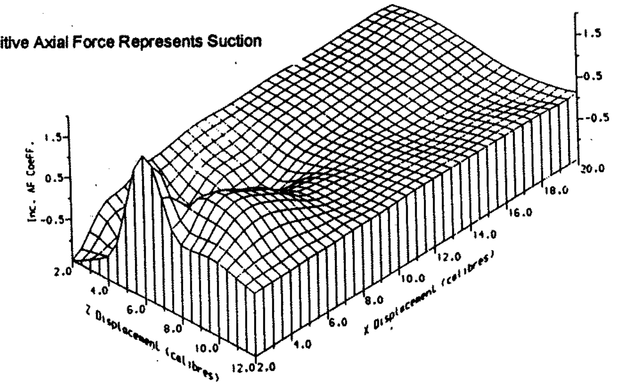

Positive Axial Force Represents Suction

FIG. 8 JET-INDUCED AXIAL FORCE $\Delta C_A$ IN zx-PLANE AT y = -1 calibre (outboard of Jet Reference point)

The discussion here has centred on the test results performed with the bomb set at 0° to the aircraft datum. The character of the jet interactions measured with the bomb set to +7° in pitch and ±7° in yaw with respect to the aircraft datum remained similar to that for 0°.

The complete data sets, obtained with the store set at incidence angles of +7° and at yaw angles of ±7° are needed for the estimation of store release trajectories.

## 3. RELEASE TRAJECTORIES BASED ON EXPERIMENTAL SURVEYS

The knowledge that large forces and moments are induced by jets, is in itself of little operational importance. However, if these effects cause significant deviations in the store release trajectory, then this represents great operational concern.

### 3.1. Analysis Method for Trajectories

The data sets of forces and moments on a store, over a grid of known points in the vicinity of an aircraft, for both jet-off and jet-on cases form the input for a trajectory programme (Ref.20). The trajectory is calculated using step-by-step integration, with the loads and moments at any time-step being generated from the store free-air loads and moments and the non-uniform interference loads and moments interpolated from the data grid, together with the prescribed initial conditions.

### 3.2. Trajectory for a 1000 lb Bomb

The full-scale, store release trajectories of a 1000 lb bomb have been calculated for jet-off and jet-on cases in the aircraft flow-field. The trajectories for the first 0.6 second, were started with the bomb positioned as for carriage on a typical wing inboard pylon. Representative ejection forces were assumed, together with the correct mass and inertia values.

The jet blowing effects on the release trajectory are apparent from **Fig.9**. This illustrates the time history of the displacement of the store CG relative to the position of the jet reference point, and the angular displacements of the store about its CG. The resultant store trajectories are shown for no jet blowing, R = 0, and blown R = 3.09 & 4.54. The store trajectories for the cases with no jet blowing and with maximum blowing are illustrated pictorially in wire-frame diagrams of **Fig.10**.

Without jet blowing, the store separates cleanly and shows no undesirable effects, falling away steadily, exhibiting little sideways movement, no yaw displacement, and a very small nose-down pitching motion.

With jet blowing, the release trajectory is altered, even with the lower blowing level R = 3.09. A large angle of inwards yaw reached during the first 0.5 seconds. This yaw in turn causes the store to move inboard, although in this case due to the high mass of the store, the inwards movement is modest and is of the order of 8 inches (203 mm) for the highest level of blowing. Blowing causes the store to roll. The store pitches to a *significant nose-up attitude* with both levels of jet blowing. Due to the large mass of the store, the vertical separation of the store from the aircraft is, however, altered very little.

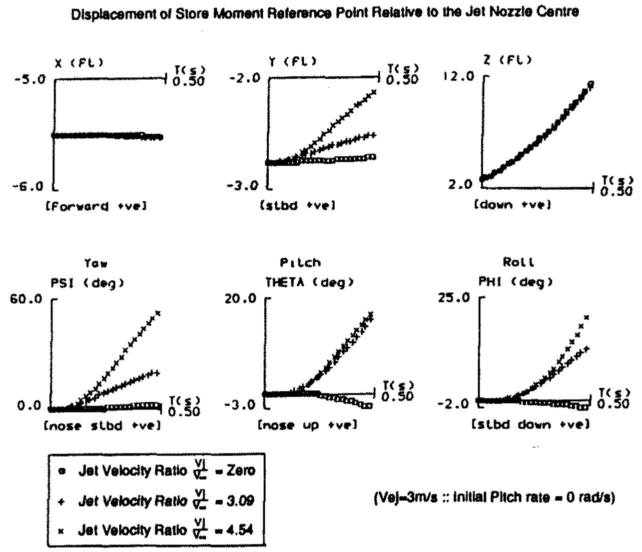


FIG. 9 COMPARISON OF 1000 lb BOMB RELEASE TRAJECTORIES, JET OFF (R = 0) & WITH JET (R = 3.09 & 4.54, $\Theta_j$ = 60°), LOW α

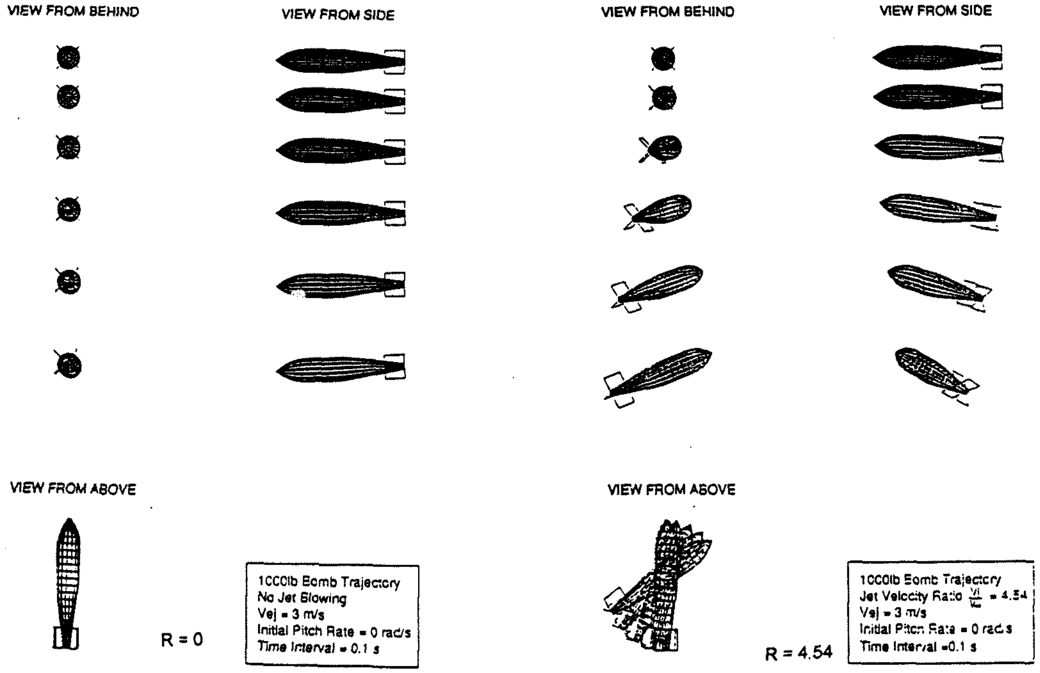


FIG. 10 WIRE-FRAME COMPARISON OF 1000 lb BOMB RELEASE TRAJECTORIES, JET OFF (R = 0) & WITH JET (R = 4.54, $\Theta_j$ = 60°), LOW α

### 3.3. Trajectory for an Empty 1200 litre Fuel Tank

In view of the very significant jet effects on the release trajectory of the "dense" 1000 lb store, the assessment was extended to jet effects on a very much larger but lighter, empty fuel tank. Because of the reduced mass and inertias, store response to the jet effects is likely to be greater. The store geometry was based on a Jaguar 1200 litre fuel tank.

In absence of test data, it was assumed that the jet interference effects would be similar to those measured for the 1000 lb bomb. Interference grids for the 1000 lb bomb were used in conjunction with the free-air aerodynamics of the empty fuel tank and appropriate mass and inertias. The initial conditions for the trajectories were those appropriate to carriage on a typical inboard pylon (ejection velocity of 3 m/s and an initial nose-down pitch rate of 0.5 rad/sec). In view of the the strong jet-induced forces, the tank geometry, and the area covered by the test data, this approximation is reasonable.

The effects of jet blowing on the trajectory are shown in **Fig.11**, CG and angular displacements, and **Fig.12** for three-view diagrams of the trajectories. For this lighter store, the jet effects on trajectory are more dramatic than for the 1000 lb bomb. The initial benign trajectory, with clean separation, modest nose-down pitch, and little or no lateral movement is significantly altered.

The effects of the jet blowing soon overcome the effect of the initially imparted nose-down pitch rate and the tank pitches upwards. This causes the store to generate lift, and arrests its separation from the aircraft, and the store CG "hovers" some 2.5 ft (0.75 m) below its carriage position. At the same time the store first yaws violently nose inboard followed by an even more violent outboards yawing motion. These yawing motions in turn cause the store to first move inboard by approximately 2.5 ft (0.75 m), followed by an outboard movement, leading to the situation where the store has entered a large lateral oscillatory movement whilst vertical separation remains constant. A significant rolling motion is induced by the jets.

A striking and an unusual effect, is the forward movement of the tank caused by the jet-induced suction forces generated over the store nose region. This effect was not apparent for the 1000 lb bomb, but arises for the lighter fuel tank with its downward progress inhibited, it remains in the "suction region" longer.

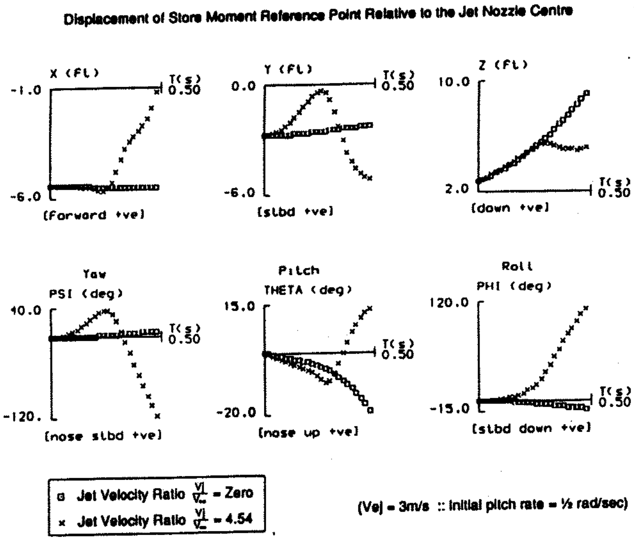


FIG. 11 COMPARISON OF 1200 lb TANK RELEASE TRAJECTORIES, JET OFF (R = 0) & WITH JET (R = 4.54, $\Theta_j$ = 60°), LOW α

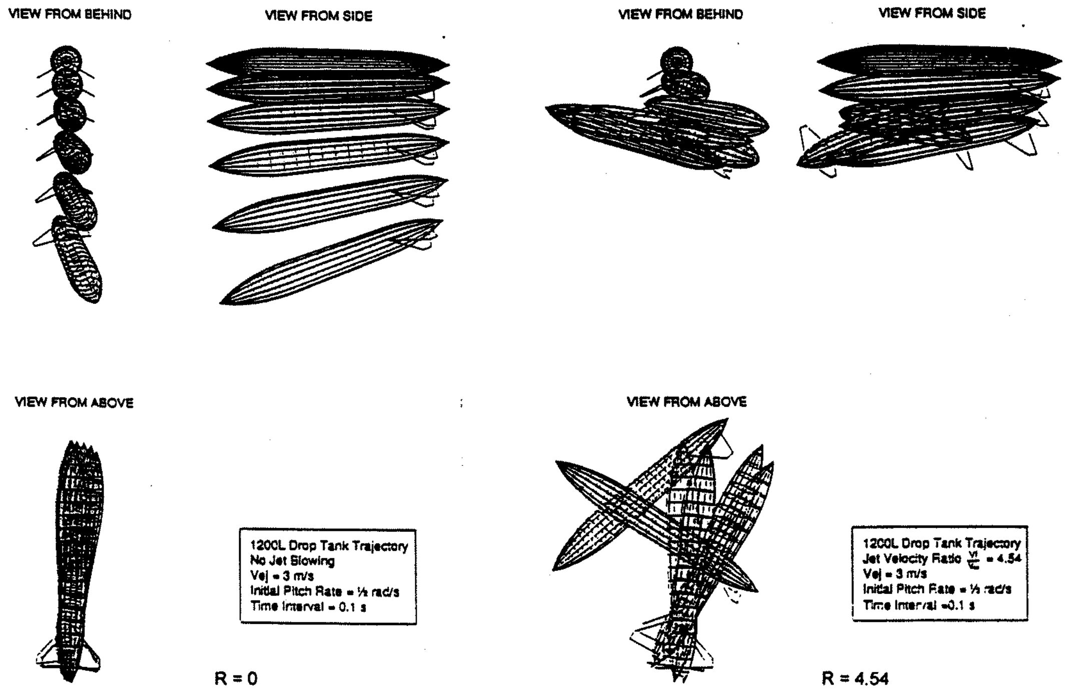


FIG. 12 WIRE-FRAME COMPARISON OF 1200 lb TANK RELEASE TRAJECTORIES, JET OFF (R = 0) & WITH JET (R = 4.54, $\Theta_j$ = 60°), LOW α

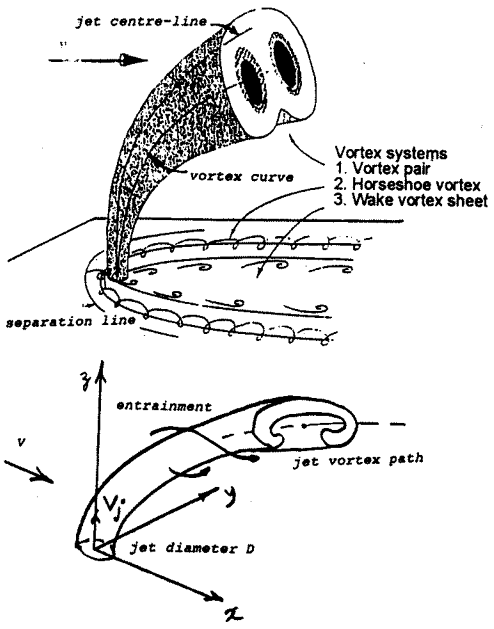


FIG. 13 JET DEFORMING IN CROSS-FLOW, SEMI-EMPIRICAL MODELLING

## 4. THEORETICAL APPROACH, JET-INDUCED EFFECTS

The release trajectories based on test data provide very significant challenges and clues for the theoretical approach. The origin of the jet induced forces and moments, and indeed the order of magnitude of the observed forces, can be related to the twin vortex structure developed downstream of a jet in cross-flow. We review the modelling aspects related to jet effects.

### 4.1. Semi-empirical Jet & Prediction Technique

**Fig.13** shows a jet of diameter d and velocity ratio $R = V_j/V$, in cross flow (deflection angle $\Theta_j = 90°$). In the semi-empirical model, the strength of the jet is modelled with doublet and source distributions (see Refs.15 & 16). The vortex path has been described so that there is agreement with measurements of pressures induced as well as of jet stagnation lines. The model has been generalised for $\Theta_j <= 90°$. This jet model is incorporated within the framework of subsonic singularity methods (Ref.18). Thin or thick wing assumptions may be used. Currently the technique has been extended to multiple jets which enables store trajectories to be predicted in conjunction with developments of the NEAR code (Refs.21-22).

### 4.2. Brief Details on Verification of Jet Effects

**Fig.14** shows the effect of varying R (or blowing coefficient $C_T$) and on a body + wing (Aspect ratio 3.4) configuration for two nozzle positions (forward and aft). Lift loss is predicted for both nozzle locations. Comparisons with experiment show very encouraging correlation. The spanwise loads shown for one data point depict good agreement. Other related cases for verification appear in Refs.15 and 16.

### 4.3. Store Location & Jet Effects

**Fig.15** shows an aspect ratio 4 swept-wing (semi-span s) with a store (or a tank) located underneath. Pylons have been omitted for simplicity. The Cp distributions on the tank along 12 generators show the effects due to either forward or aft jet blowing. The effect of splaying the aft jet by 10° is also shown. The results show the high -Cp values arising due to the jets proximity. Splaying jets increases the -Cp.

This test case emphasises that the forces and moments arising are strongly dependent on store geometry and its placement relative to the jet.

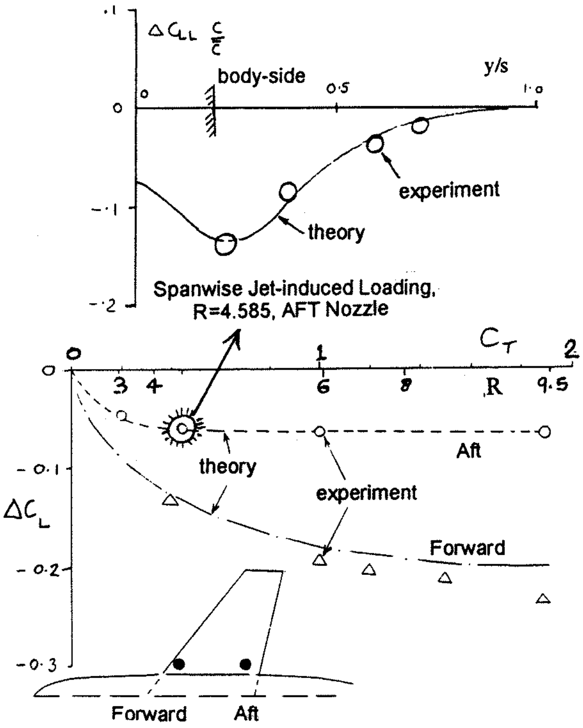


FIG. 14 LIFT LOSS DUE TO FORWARD or AFT JETS FROM NOZZLES, $\Theta_j$ = 60°, R & $C_\mu$ VARY

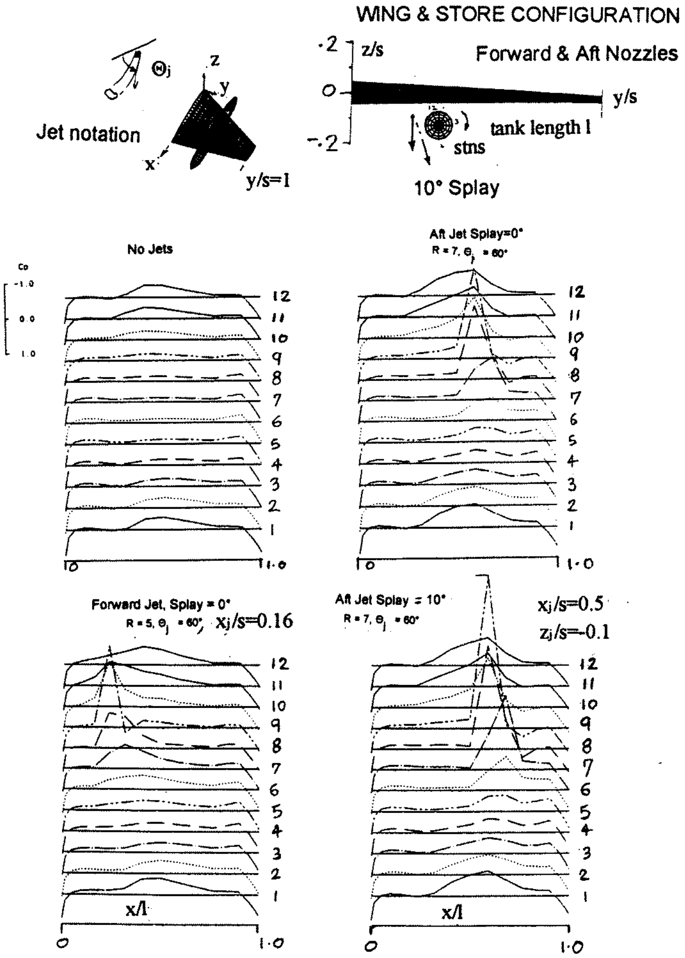


FIG. 15 Cp DISTRIBUTIONS ALONG 12 STORE GENERATORS, EFFECT OF FORWARD & AFT JETS, SPLAY ANGLE 0° & 10°

## 5. TYPICAL PREDICTED STORE TRAJECTORIES

We show release trajectories of an under-wing store (1000 lb type) for two aircraft configurations, one with a trapezoidal wing (2 or 4 jets), and the other with a "diamond" wing(3 jets).

### 5.1. Trapezoidal Wing-Body Configuration

The configuration of **Fig.4**, with two pairs of jets has been used to develop typical parametric variations. Calculations were made for the first 0.6 second from a store ejected at 3 m/sec.

For configurations with both front + aft jets blowing at $R = V_j/V = 6$ and deflection $\Theta_j = 60°$, **Fig.16** shows the effect of spanwise location of the store on its trajectory. This effect on the store persists to more than half a wing semi-span. At the inboard location, large changes occur in pitch and yaw angle of the store. The tail tends to move inwards initially and the calculations of trajectories could only be continued if the tail remains away from the jet path. The effects are strongest for the inboard location and are dominated by the front jets for this particular geometry.

The effect of varying jet velocity ratio R for fixed spanwise location is illustrated in **Fig.17**. At R = 4 and 6, the tail of the store moves inwards towards the jet core and predicted trajectories can not be continued beyond 0.25 secs. At R = 8, the store has a more pronounced pitching and yawing motion and eventually points downwards and rearwards.

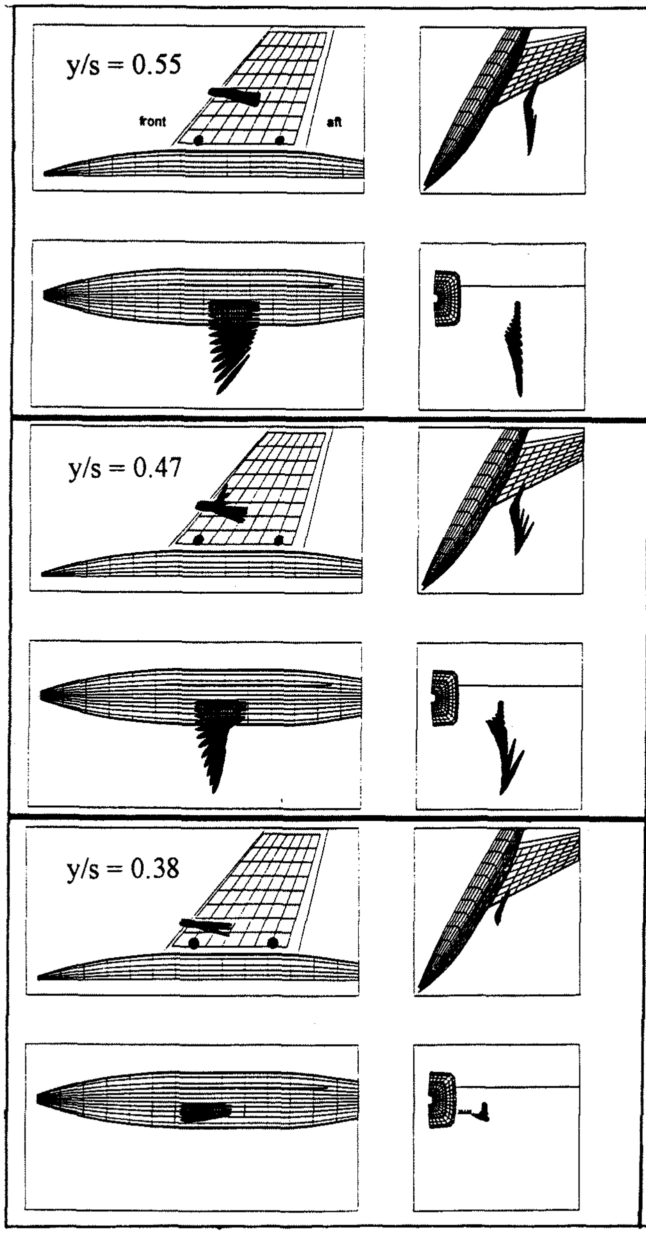


FIG. 16 EFFECT OF STORE SPANWISE LOCATION ON STORE TRAJECTORY, FRONT + AFT JETS, $\Theta_j = 60°$, R = 6, LOW $\alpha$

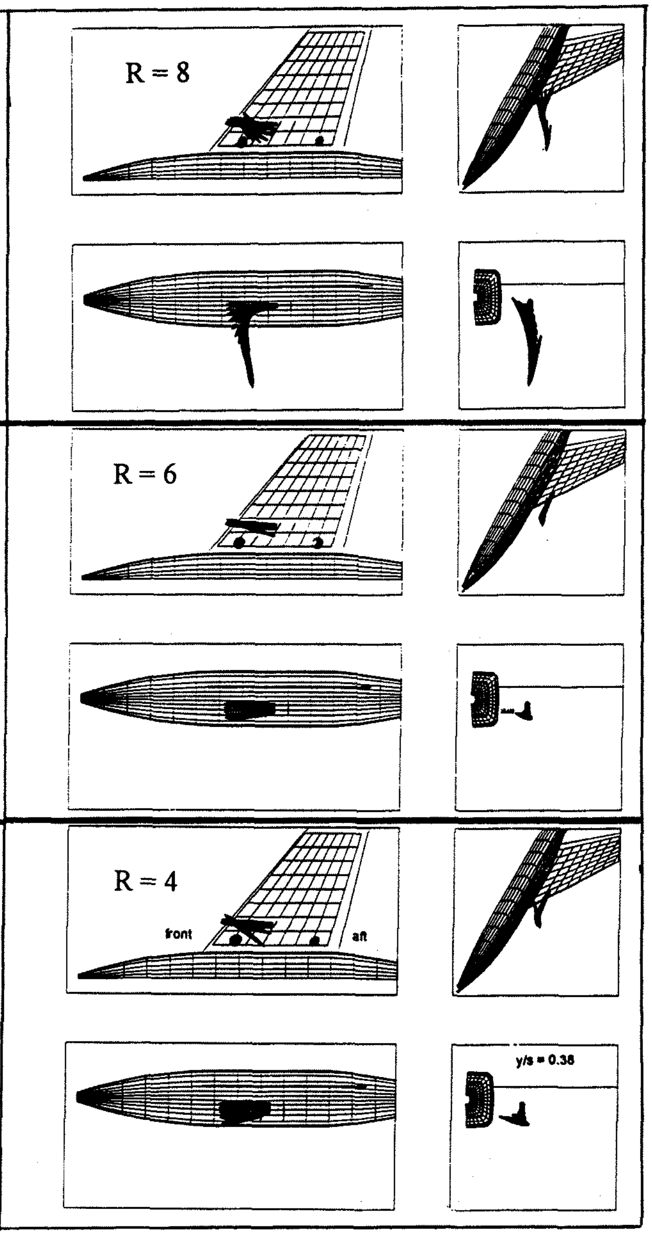


FIG. 17 EFFECT of R VARIATION (4, 6 & 8) ON STORES TRAJECTORY, FRONT + AFT JETS, $\Theta_j = 60°$, LOW $\alpha$

For three jet configurations: forward, aft, and forward + aft jets blowing at R = 6, **Fig.18** shows the store trajectories. The store is near the LE and the the aft jets have a small effect only here.

For store locations further back on the wing, however, strong effects of aft jets can be detected as shown in **Fig.19**. This shows a more "downstream" location of the store and as in previous figure, three jet configurations: front, aft, and front + aft jets blowing at R = 6 are considered. Note the near "chaotic" behaviour of the store trajectory under influence of all jets.

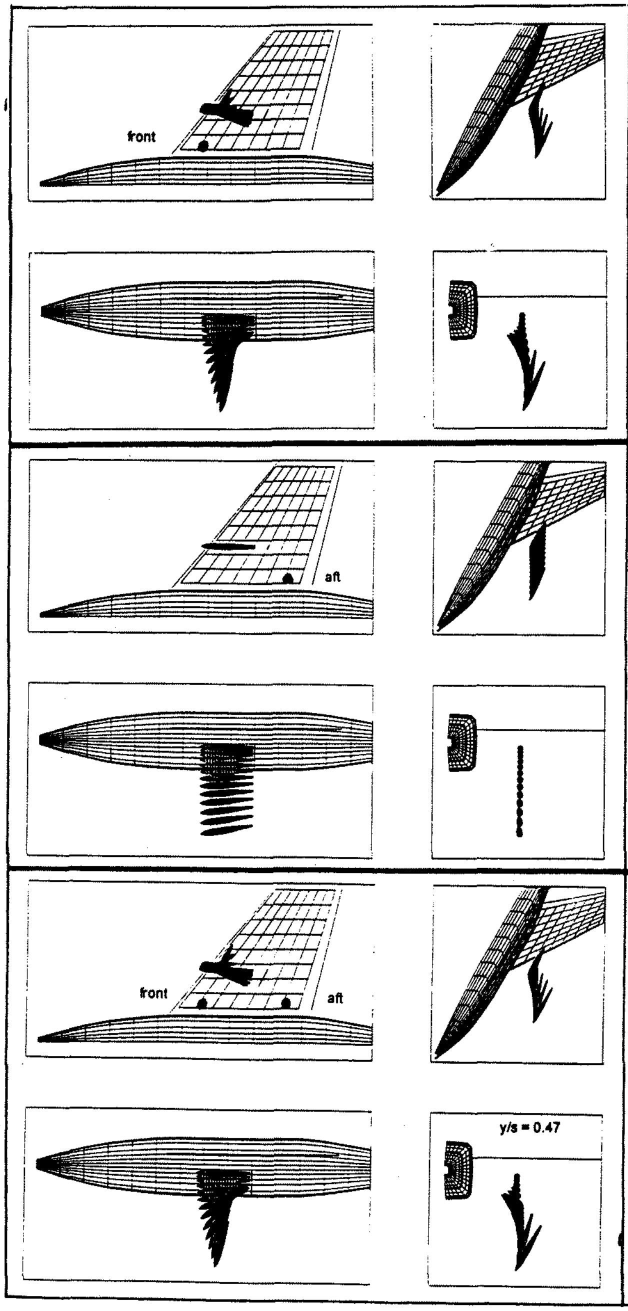


FIG. 18 EFFECTS ON A "FORWARD" STORE TRAJECTORY, DIFFERENT JET CONFIGURATIONS: FRONT, AFT & FRONT + AFT, $\Theta_j = 60°$, R = 6, LOW $\alpha$

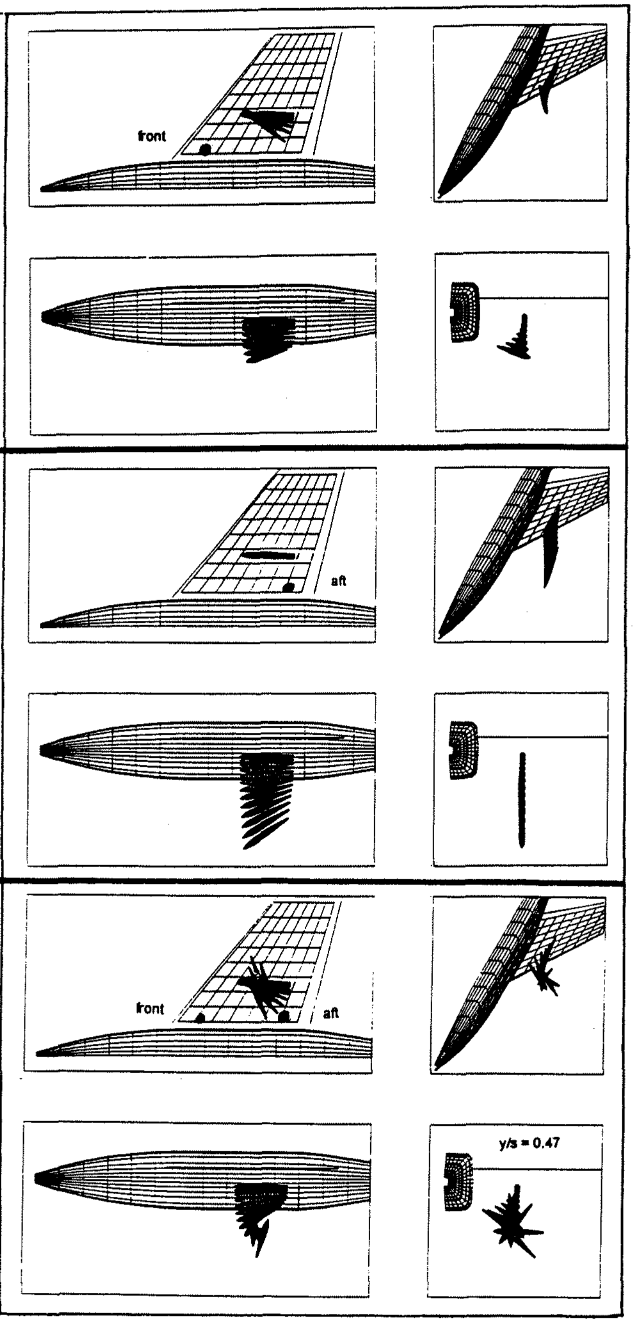


FIG. 19 EFFECTS ON A "DOWNSTREAM" STORE TRAJECTORY, DIFFERENT JET CONFIGURATIONS: FRONT, AFT & FRONT + AFT, $\Theta_j = 60°$, R = 6, LOW $\alpha$

With all jets operating, the effect of jet deflection angle $\Theta_j$ variation (30°, 45°, 60° and 75°) can be inferred from **Fig.20**. In this sequence, R is held constant = 6. The jet effects are particularly strong for $\Theta_j = 45°$ and 60°. The case for $\Theta_j = 75°$ shows lesser effect mainly because the store trajectory has not "reached" the immediate vicinity of the jet in the first 0.6 secs. Similar trend was observed $\Theta_j = 90°$.

These analyses have emphasised the non-linear nature of jet interactions. It is interesting to note that the trends shown by these results are reminiscent of those displayed in Section 4.

### 5.2. A Simplified "Diamond-wing" ASTOVL Type Aircraft

This geometry was developed from the previous configuration by altering the wing planform. This type of "modern" ASTOVL configuration is likely to feature a front central jet in addition to two jets aft of centre of gravity. The nozzles are likely to operate at different pressure ratios and hence different R values result at a given flying speed. For present purposes however, we have assumed same jet deflections, pressure ratios and jet exit velocity ratios for all the three jets.

**Fig.21** shows the effect of R variation (4, 6 & 8) on a "forward" store trajectory. The jet deflection angle is held constant at 60°. Note the large changes in pitch and yaw angle of the store. For R = 8, the tail tends to move inwards and eventually the store points outwards and slightly upwards. For R = 6, the store "finally" points rearwards, outwards and downwards. For R = 4, the store "finally" points forwards, outwards and downwards.

The effect of Jet deflection angle variation (60°, 75° and 90°) can be inferred from **Fig.22**. In this sequence, R is held constant at 6. Note the large changes in motion of the store for 60° and 75° jet deflection when compared with the trends for the 90° jets. For the 90° case, the store trajectory has not "reached" the immediate vicinity of the jets in the first 0.6 secs.

The foregoing analysis emphasises the non-linearities in the motion of stores in the vicinity of jets on ASTOVL type aircraft.

### 5.3. Potential of Technique

The results presented have demonstrated the flexibility and potential of the technique for different configurations. The jet effects can be strong and are usually adverse.

The technique offers the capability for investigation of several geometric variables associated with both aircraft and storesto determine "safe" store locations. This will have the potential for the obvious benefits of very appreciable cost and time savings.

The approach can assist in designing acceptable experiments, or for verifying preferred configurations.

## 6. FUTURE WORK POSSIBILITIES

Several aspects need to be addressed theoretically and experimentally in future, e.g.

- Higher α cases
- Effect of LE and TE Flap deflections
- Multiple lifting surfaces
- Detailed Comparisons with Experiments
- Varying store location with respect to jets
- Multiple Jet effects
- Differential jet deflections
- Asymmetric Configurations, sideslip, roll
- Manoeuvering Aircraft effects on stores.

These aspects will have a constructive impact on the current and future practical VSTOL and ASTOVL aircraft with and without store carriage.

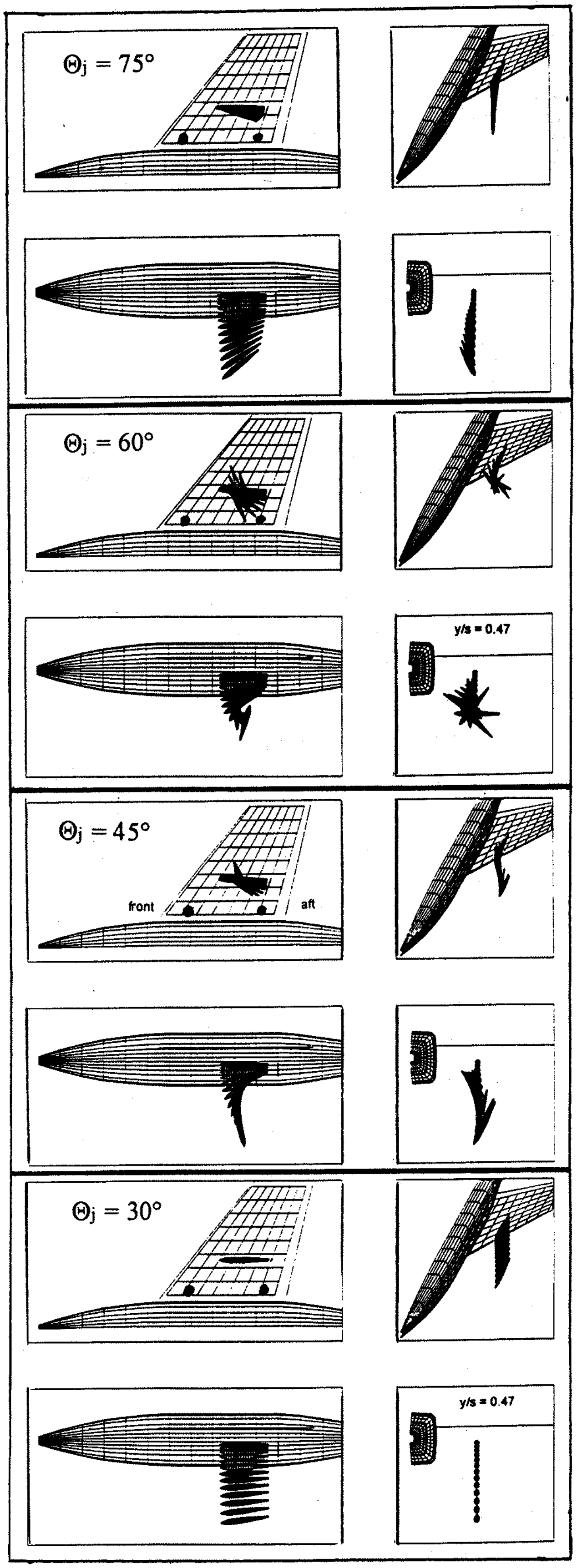


FIG. 20 EFFECT of $\Theta_j$ VARIATION ON STORE TRAJECTORY, FRONT + AFT JETS, R = 6, LOW α

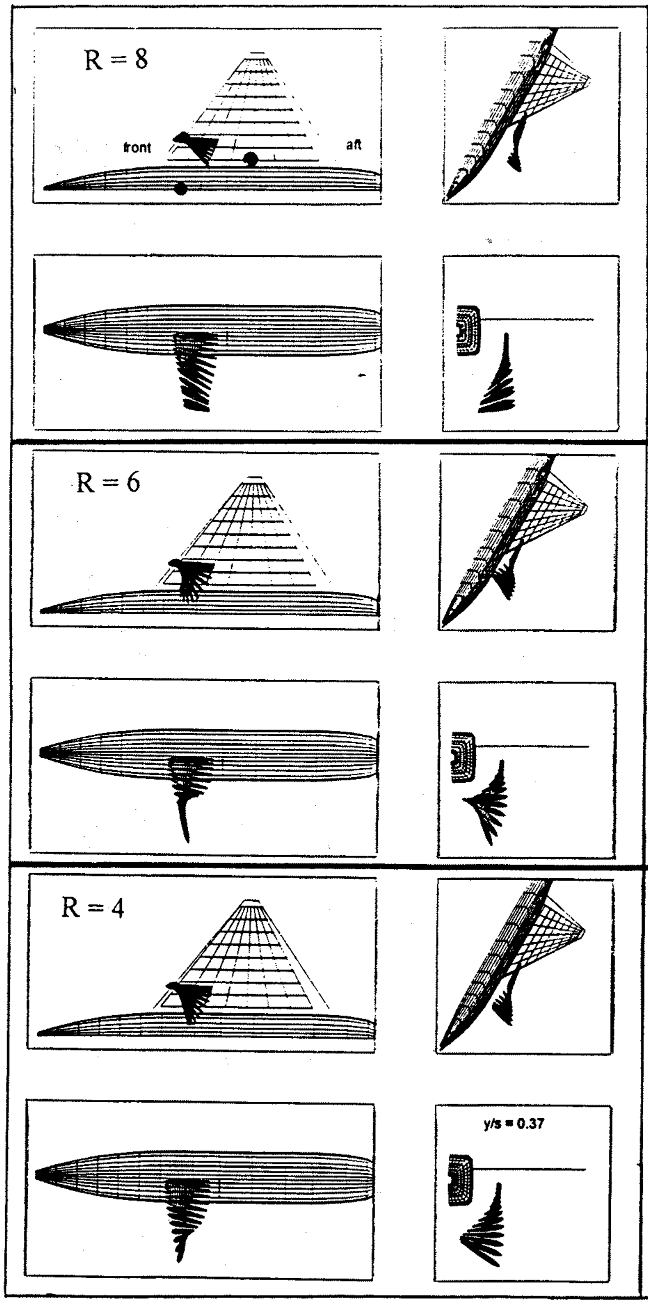


FIG. 21 SIMPLIFIED "DIAMOND-WING" TYPE, EFFECT of R VARIATION ON STORE TRAJECTORY, ONE JET FRONT + A PAIR AFT, $\Theta_j$ = 60°, LOW $\alpha$

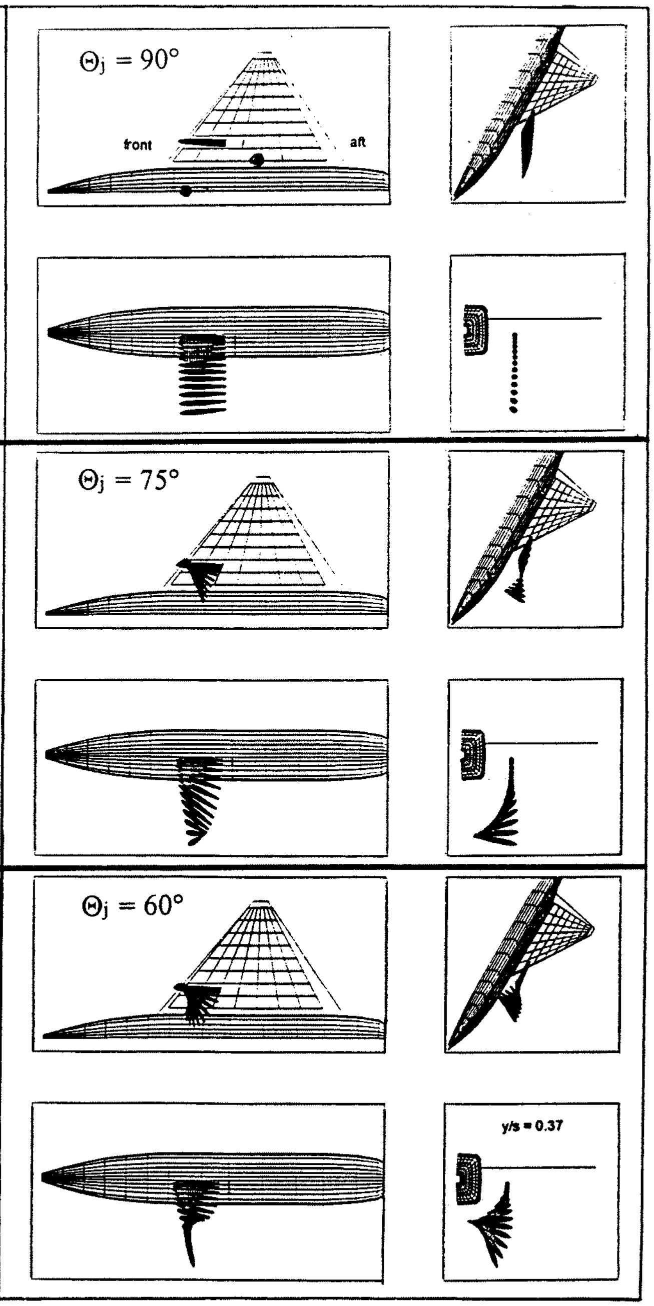


FIG. 22 SIMPLIFIED "DIAMOND-WING" TYPE, EFFECT of $\Theta_j$ VARIATION ON STORE TRAJECTORY, ONE JET FORWARD + A PAIR AFT, R = 6, LOW $\alpha$

## 7. CONCLUDING REMARKS

The main objective of combat aircraft is the carriage of external stores (bombs and ferry tanks) and their "accurate" and "safe" release and delivery. For aircraft with multiple vectoring jets (including conventional VSTOL or ASTOVL), the flow-field effects on the stores can be amplified and may become adverse.

The jet-induced loads arising are strongly dependent on the store placement relative to the front and aft vectoring jets, and likely to be dependent on details of store geometry (inertias, fins etc.). These affect the trajectory on release (intended or otherwise). High suctions may cause local separations on the stores or on adjacent surfaces. "Internally" carried stores will also be subject to significant jet effects when emerging from "semi-recesses" or "bays".

These considerations have promoted a research programme aimed at understanding the vectored jet effects on stores and release trajectories.

### Experimental Aspects

Preliminary studies showed that a jet blowing streamwise has little influence on nearby stores, provided they do not enter the actual jet-stream. However, stores near a vectored jet were subject to large jet-induced forces and moments even at distances far from the jet exit.

The experimental studies performed on a 20% scale VSTOL aircraft model with blown forward nozzles vectored 60°, have quantified the significant jet-induced effects on all forces and moments. The jet effects vary in a complex manner near the jet, and can be subject to sudden reversals in direction. Large jet-induced suctions can also be detected on the store.

The origin of the jet induced forces and moments, and indeed the order of magnitude of the observed forces, has been related to the twin vortex structure developed downstream of a vectored jet.

The way in which the jet induced loads and moments vary as a store pitches or yaws relative to its zero incidence position in carriage has been established.

### Trajectories Based on Experimental Data

The experimental data has been used to predict the jet effects on the release trajectories of two types of stores: a 1000 lb bomb (dense store) and an empty 1200 litre tank. The trajectory of the heavy 1000 lb bomb is altered very significantly, causing the store to yaw and translate inwards. In the case of the lighter fuel tank, the jet effects change a benign and safe trajectory into a violent and unsafe trajectory. The store hovers close to the aircraft whilst undergoing large excursions in yaw, and large lateral oscillations.

### Theoretical Aspects & Trajectories

Formulations of the jet models using Navier-Stokes or Euler solvers, have not yet reached sufficient maturity to become "ready" tools for design and analysis. Emphasis has therefore needed to be placed on adapting semi-empirical models of jets in established wing theory. Thin or thick wing assumptions may be used. One of the technique extensions enables store trajectories to be predicted using developments of the original NEAR code.

The methodology has been applied to a parametric study of store release trajectories. Results are encouragingly similar to those based on experiment. These demonstrate the flexibility and potential of the techniques applied to fairly complex flow situations. The jet effects can be strong and are usually adverse. Further verifications of the model are being carried out e.g. higher α cases.

The technique offers the capability for investigation of aircraft and store geometric variables to identify "safe" store locations. This will have the potential for the obvious benefits of very appreciable cost and time savings.

The approach can assist in designing acceptable experiments for the verification of preferred configurations.

Areas for future work have been identified. These should provide a constructive impact on the current and future practical VSTOL and ASTOVL aircraft with and without store carriage.

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Lastly, it should be mentioned that any opinions expressed are those of the authors.

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## LIST OF SYMBOLS & ABBREVIATIONS

| | |
|---|---|
| b | = 2s, span |
| c | local chord |
| $c_{av}$ | = c, Average chord |
| $C_A$ | = A/(qS), Axial Force Coefficient, A is Axial Force |
| $\Delta C_A$ | Incremental Axial Force Due to Jets |
| CG | Centre of Gravity |
| $C_L$ | = L/(qS), Lift Force Coefficient, L is Lift force |
| $C_{LL}$ | Local Lift Force Coefficient |
| $C_N$ | = N/(qS), Normal Force Coefficient, N is Normal Force |
| $\Delta C_N$ | Incremental Normal Force Due to Jets |
| $C_{NL}$ | Local Normal Force Coefficient |
| $C_p$ | Pressure Coefficient |
| $C_T$ | = T/(qS), Blowing Force Coefficient, T is Nozzle Thrust |
| $C_Y$ | = Y/(qS), Side Force Coefficient, Y is Side Force |
| $\Delta C_Y$ | Incremental Side Force Due to Jets |
| d | Jet Diameter |
| L | Lift Force |
| LE | Leading Edge |
| q | $= \frac{1}{2} \rho V^2$, Dynamic Pressure |
| R | $= V_j/V$, Jet Velocity Ratio |
| s | wing semi-span |
| S | Wing area |
| TE | Trailing Edge |
| u,v,w | perturbation or induced velocities in x,y,z directions |
| V or $V_\infty$ | Airstream Velocity |
| $V_j$ | Nozzle Jet Velocity |
| x,y,z | Orthogonal Co-ordinates |
| α | Angle of attack |
| ß | Angle of sideslip |
| $\Theta_j$ | Nozzle Jet Deflection angle |
| $\eta$ | = y/s, Non-dimensional spanwise Distance |
| ρ | Air Density |