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VECTORING JETS INFLUENCE ON UNDER-WING STORES RELEASE TRAJECTORIES WITH & WITHOUT SIDE-SLIP EFFECTS, THEORY & EXPERIMENT

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SUMMARY

The carriage of external stores (bombs and ferry tanks) and their "accurate" and "safe" release and delivery is an important aspect in design and operation of combat aircraft. The ASTOVL aircraft with vectoring jets operate under very "perturbed" flow-fields during the transition phase and large side-slips occur only too easily.

The 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 been placed on adapting empirical models of jets in established wing theory to predict forces and moments over a 3-D flow grid. This information in turn formed the input to a trajectory code.

Results from purely theoretical approach are encouragingly very similar to those obtained from the data based on experiment.

For aircraft with multiple vectoring jets, the flow-field effects on the stores can be amplified and become adverse. This has been confirmed with parametric studies and release trajectories. The side-slip effects are particularly strong. It can be difficult to assess what the safe store locations are in presence of side-slip. "Internally" carried stores will be subject to significant jet effects when emerging from "semi-recesses" or "bays".

Results demonstrate the flexibility and potential of the techniques and several geometries may be explored to determine "safe" store locations. However, further verifications of the model need to be carried out e.g. higher α and β cases with different jet configurations and strengths. The technique may be enhanced (cost & time savings) by the coupling of a six-degree of freedom equation programme with the flow solver. It is believed that aspects considered in this paper will lead to a constructive impact on the current and future ASTOVL aircraft with and without stores.

1. INTRODUCTION & BACKGROUND

The carriage of external stores (bombs and ferry tanks) and their "accurate" and "safe" release and delivery is an important aspect in design and operation of combat aircraft. ASTOVL aircraft operate under very "perturbed" flow-fields during transition and large side-slips, β occur only too easily. Controllability aspects are very significant. Off-design cases need to be safe and predictable.

With multiple vectoring jets (including JSF / ASTOVL aircraft, **Fig.1**, Refs.1-3), the flow-field effects on the stores placed in the vicinity of jets "amplify" and become adverse. The store configurations vary greatly; some have appreciable lifting surfaces. **Fig.2** (Ref.4) shows a typically heavily loaded VSTOL aircraft. Pylons of appreciable dimensions are also influenced by jets. Further, the effects of differential jet deflections need to be understood.

As store size reduces or proximity to the jet increases, the trajectory on release (intended or otherwise) becomes more affected by jets. "Internally" carried stores are under significant jet effects when emerging from the bays.

Towards safe and efficient store carriage and release, it is necessary to identify parameters and effects which may affect the trajectory of stores after release. The store carriage locations on the 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.

The above considerations and exploratory work showing force reversal on a store near a jet, **Fig.3** (Ref.5) have promoted a research programme. The overall 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 considered appropriate.

In previous AGARD-FDP meeting (Ref.6) and ICAS'96 conference (Ref.7), we reported on jet effects and store releases in the symmetric (zero side-slip) case. Strong effects of jets were shown. In this paper we concentrate on the possibly more important aspect of side-slip effects.

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2. EXPERIMENT BASED ASPECTS

Studies have determined the magnitude of the forces and moments induced on a typical store by an inclined 60° jet, when also in the influence of the aircraft flow-field.

Fig.4 illustrates the tests arrangement (wing + body + store), forces & moments survey-volume (3-D grid) and plots of the incremental forces ΔC_N, ΔC_Y and ΔC_A arising due to jets (parameters defined by Jet velocity ratio $R = V_{jet}/V$ and deflection angle Θ_{j0}). These studies indicate complex variations of jet-induced forces over the region surveyed. The jet-induced effects persist many calibres downstream of the jet reference. It is evident that the maximum effect can occur at a considerable distance from the jet reference, for instance maximum negative normal force and side force occurring at 6 to 7 calibres below the jet reference.

The measured jet-induced force and moment surveys were used in a numerical six degrees of freedom equation approach to develop store-release trajectories with jets on and off.

Fig.5 refers to a 1000 lb store typical symmetric case, β = 0°, calculation with forward Jets on and off. The store is assumed to be ejected at a velocity of V_{ej} = 3m/s. Trajectory parameters shown are the positions in space with respect to the store moment reference point relative to the carrriage: x, y, z and the angles: yaw, pitch and roll. **Fig.6** shows the 3-D wire-frame representation. Note the amplified movements with blown jets.

3. THEORY BASED ASPECTS

Since detailed jet models using Navier-Stokes or Euler formulations have not yet reached sufficient maturity to become ready tools for design and analysis; a semi-empirical jet model, **Fig.7** has been formulated. The jet model although essentially for "near-sonic" jets has been also used in the context of high pressure ratio jets with success. Related papers (Refs.8, 9 & 10) have shown confidence in predictive ability for jet interference loads on various types of ASTOVL configurations with and without stores. Wind tunnel interference effects can be large (Ref.10) for strong jets or large jet deflections. The jet parameters are defined by Jet velocity ratio $R = V_{jet}/V$ and deflection angle Θ_{j0} .

Fig.8 illustrates the survey-volume (3-D grid) used to develop the theoretical incremental forces (ΔC_N, ΔC_Y and ΔC_A) and moments (ΔC_l, ΔC_m and ΔC_n) arising due to jets vectored 60°. These predictions were used in a numerical approach to develop store-release trajectories with jets on. This figure also marks the locations of store reference point used in subsequent runs.

Fig.9 shows the trajectory parameters for the basic symmetric case (the same 1000 lb store as in **Figs.5 & 6**). **Fig.10** shows the 3-D wire-frame representation of the trajectory with store location 0.3m and ejection velocity V_{ej} = 3m/s. Note the encouraging agreement between release trajectories based on experimental and predicted jet effects. Slight discrepancy in spanwise character is noted and if desired, this could possibly be improved by a "finer" specification of x & y starting locations.

For present analysis, this gave adequate confidence to proceed and apply the methodology to side-slip cases.

Fig.11 illustrates the survey-volume (3-D grid) used to develop the theoretical incremental forces and moments arising due to jets on a configuration with side-slip 30°. The reference position was x = 4.19, y = 2.51m & z = 3.18 with respect to the jets. The figure also marks the other initial locations of the store used in subsequent runs. This grid has enabled parametric variations of effect of store location on release trajectories.

Fig.12 shows the effect of initial chordwise location of the store on the store release trajectory. The main changes are in pitch and yaw angles that are more adverse for the forward location.

Fig.13 illustrates the effect of initial spanwise location of the store on the store release trajectories. The main changes are in pitch and yaw angles that are more adverse for the outboard location.

Fig.14 shows the 3-D wire-frame representation of the store trajectory with Vej = 3m/s. The store pitches down, yawing negatively as it falls.

Fig.15 shows the effect of store initial positions on starboard and port side of the configuration. This can also be interpreted, alternatively as the effect of positive and negative side-slip, β. Note the lack of symmetry and much larger variations for the positive β case. **Fig.16** shows the 3-D wire-frame representations to emphasise the trends. The positive β case shows pitch-down and large negative yaw whilst the negative β case shows a moderate pitch-up and a small positive yaw. The shift in y (inwards) is much greater with positive side-slip, compared with shift in y (outwards) with negative side-slip.

The foregoing analysis emphasises the non-linearities in the motion of stores in the vicinity of jets.

The present technique offers the capability for investigation of several geometric variables to determine "safe" store locations for different types of STOVL and ASTOVL aircraft. **Fig.17** illustrates an ASTOVL aircraft with tandem jets (forward and aft) and a typical grid 3-D survey volume for stores near the front jet at β = 0°.

4. INFERENCES, POSSIBLE BENEFITS & IMPLICATIONS IN WIDER CONTEXT

Typical results presented have demonstrated the flexibility and potential of the techniques. The symmetric / asymmetric jet effects are strong and usually adverse.

The present technique offers the capability for study of several geometric variables to determine "safe" store locations for different types of ASTOVL aircraft.

The experience has been that, the forces and moments on the store will tend to increase as the store size reduces. This will 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".

The technique relies heavily on jet effects evaluated over a 3-D flow grid and this process can be time consuming for arbitrary grids. The jet-induced effects are strong and they can be "peaky" for stores in close proximity and a closely spaced 3-D flow grid may be required. Widely spaced grids may compromise quality. Therefore, further verifications of the technique need to be carried out e.g. higher α cases with different β and different flying speeds.

This implies that to shorten the process, we need to couple a six-degree of freedom equations solver with the flow solver. This should be the next step that needs to be undertaken and then we will have the potential for the obvious benefits of very appreciable cost and time savings on many other parameters to be explored. Manoeuvering aircraft effects on stores can also be considered.

In view of the considerable non-linearities in jet-induced flow-fields, the approach can assist in designing acceptable experiments, or for checking the validity of existing information.

5. FUTURE WORK POSSIBILITIES

On basis of the work carried out so far, several avenues for further work have arisen; some important ones are e.g.

(1). Coupling of six-degrees of freedom equations with the flow-solver.

(2). Manoeuvering aircraft effects on stores trajectories.

(3). High pressure ratio jets and Supersonic Jet modelling to same sophistication level as present "near-sonic" jet.

(4). Consideration of modern ASTOVL configurations. This will call for extending the capabilities to stores emerging from cavities, bays and with "splitter" doors.

(5). Considering Over-wing stores.

This list is by no means exhaustive. Further avenues are likely to emerge as experience grows.

6. CONCLUDING REMARKS

The carriage of external stores (bombs and ferry tanks) and their "accurate" and "safe" release and delivery is an important aspect in design and operation of combat aircraft. The ASTOVL aircraft with vectoring jets operate under very "perturbed" flow-fields during the transition phase and large side-slips occur only too easily.

The 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 been placed on adapting empirical models of jets in established wing theory to predict forces and moments over a 3-D flow grid. This information in turn formed the input to a trajectory calculation code.

Results from a purely theoretical approach were very encouragingly similar to those obtained from the data based on experimental measurements.

For ASTOVL aircraft with multiple vectoring jets (including JSF !), the flow-field effects on the stores can be amplified and become adverse. This has been confirmed with a series of parametric studies and release trajectories. The effects of side-slip are particularly strong. It can be difficult to assess what the safe store locations are in presence of side-slip. "Internally" carried stores will also be subject to significant jet effects when emerging from "semi-recesses" or "bays".

The forces and moments will tend to increase as the store size reduces. This will affect the trajectory on release (intended or otherwise). High suctions may cause local separations on the stores or on adjacent surfaces.

Results presented have demonstrated the flexibility and potential of the techniques and several geometric variables may be explored to determine "safe" store locations. However, further verifications of the model need to be carried out e.g. higher α and β cases with different jet configurations and strengths. The technique may be enhanced (cost & time savings) by the coupling of a six-degree of freedom equation programme with the flow solver.

The approach can assist in designing acceptable experiments, or for checking the validity of existing information.

Areas for further work and improvements of the model have been mentioned. In particular, the coupling of a six-degree of freedom equation programme with the flow solver, must be a top priority.

It is believed that these aspects will have a constructive impact on the current and future practical VSTOL and ASTOVL aircraft with and without store carriage.

ACKNOWLEDGEMENTS

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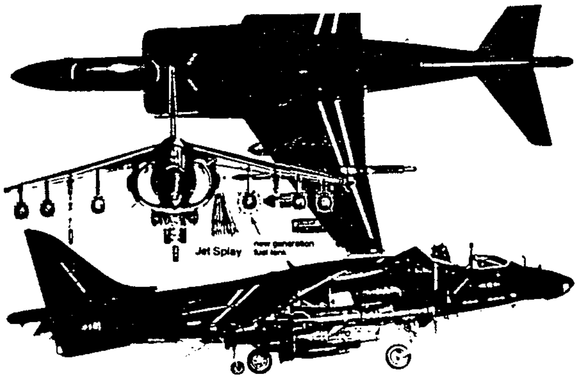


FIG. 2 VECTORING JETS, HARRIER GR.Mk.5 WITH STORES (from Airplane Part 6, Orbis)

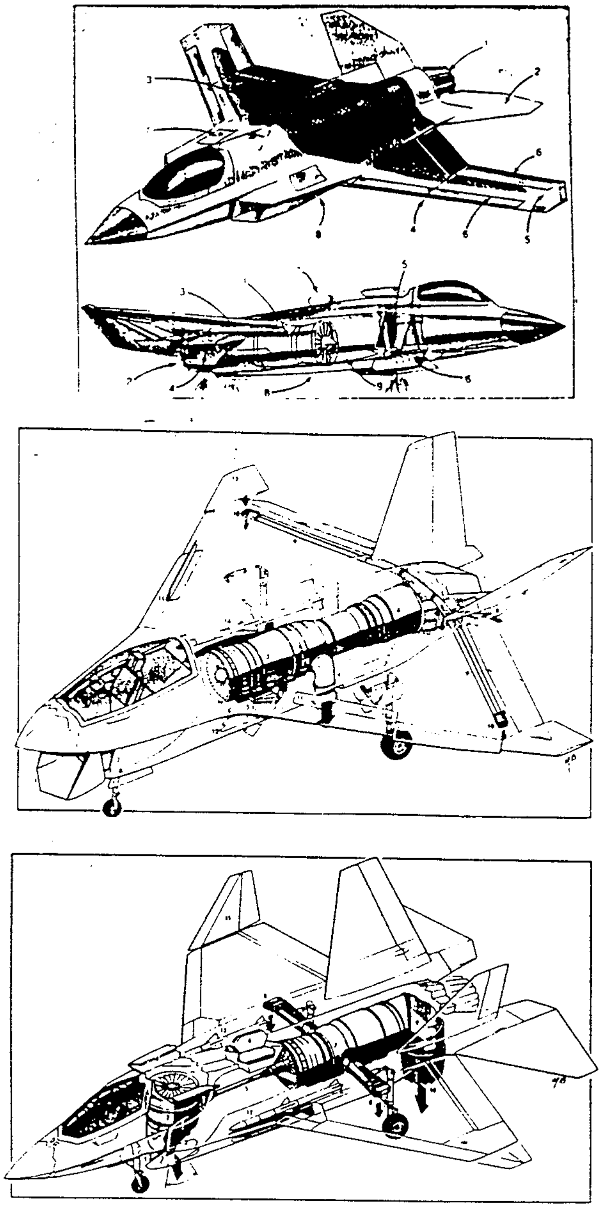


FIG. 1 DIFFERENT ASTOVL JAST PROJECTS

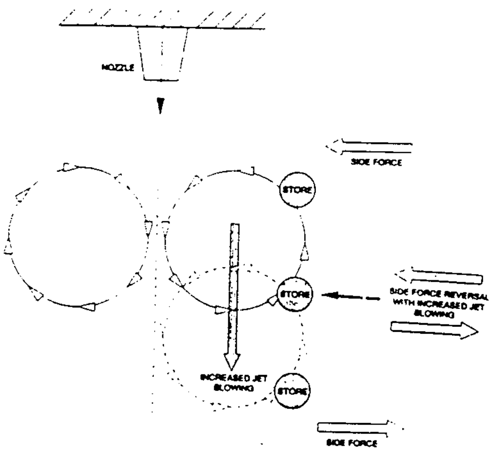
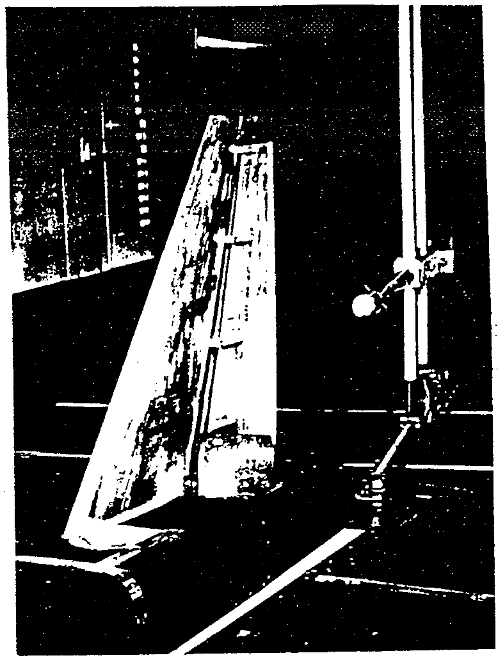
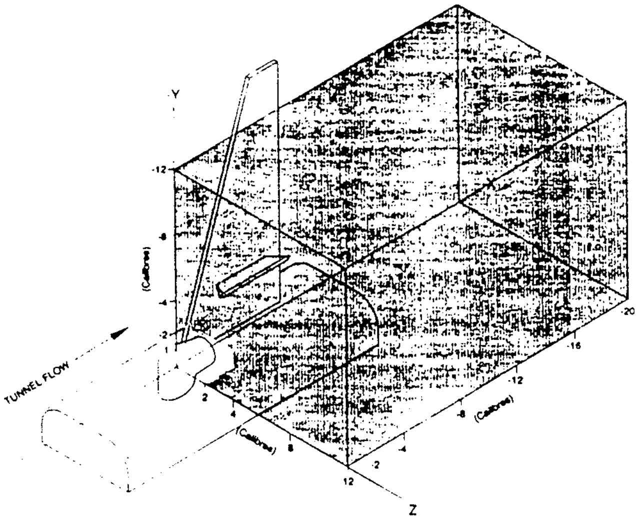


FIG. 3 EMPHASISING FLOW REVERSAL ABOUT A STORE DUE TO JET



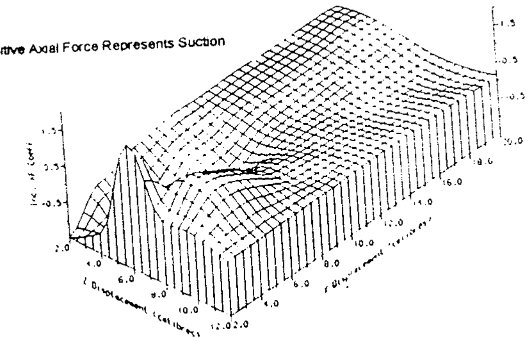
FORWARD VIEW OF VSTOL HALF-MODEL, 13 x 9 ft
WIND TUNNEL, WITH TRAVERSE MECHANISM & WING PYLON

FLOW VISUALISATION OF A 60° JET
IN CROSS-FLOW



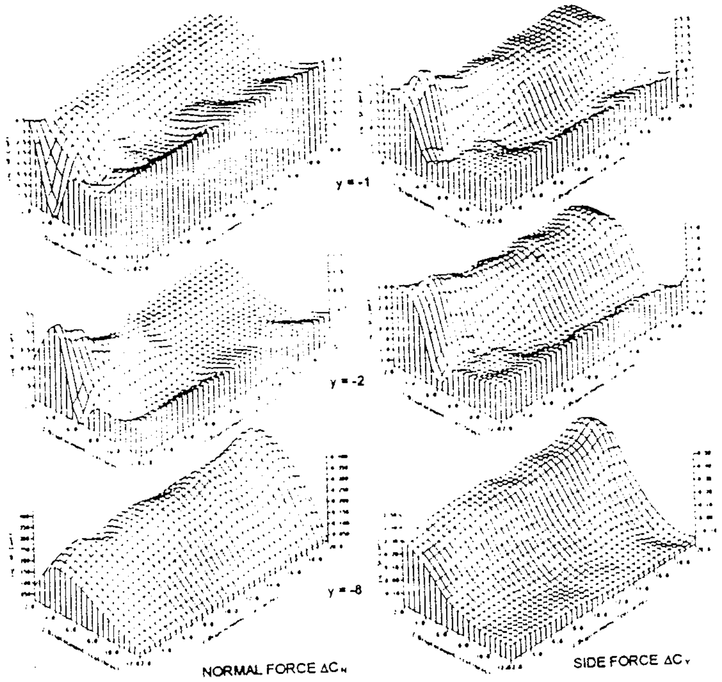
AXES SYSTEM & MEASUREMENT GRID
(Store Calibres in Survey Volume)

Positive Axial Force Represents Suction



JET-INDUCED AXIAL FORCE ΔC_A IN zx-PLANE

AT y = -1 calibre (outboard of Jet Reference point)



JET-INDUCED FORCES ΔC_N & ΔC_Y IN zx-PLANE AT y = -1, -2 & -8 calibres

FIG. 4 WIND TUNNEL MODEL ARRANGEMENT, JET VISUALISATION, MEASUREMENT GRID & TYPICAL JET-INDUCED FORCES

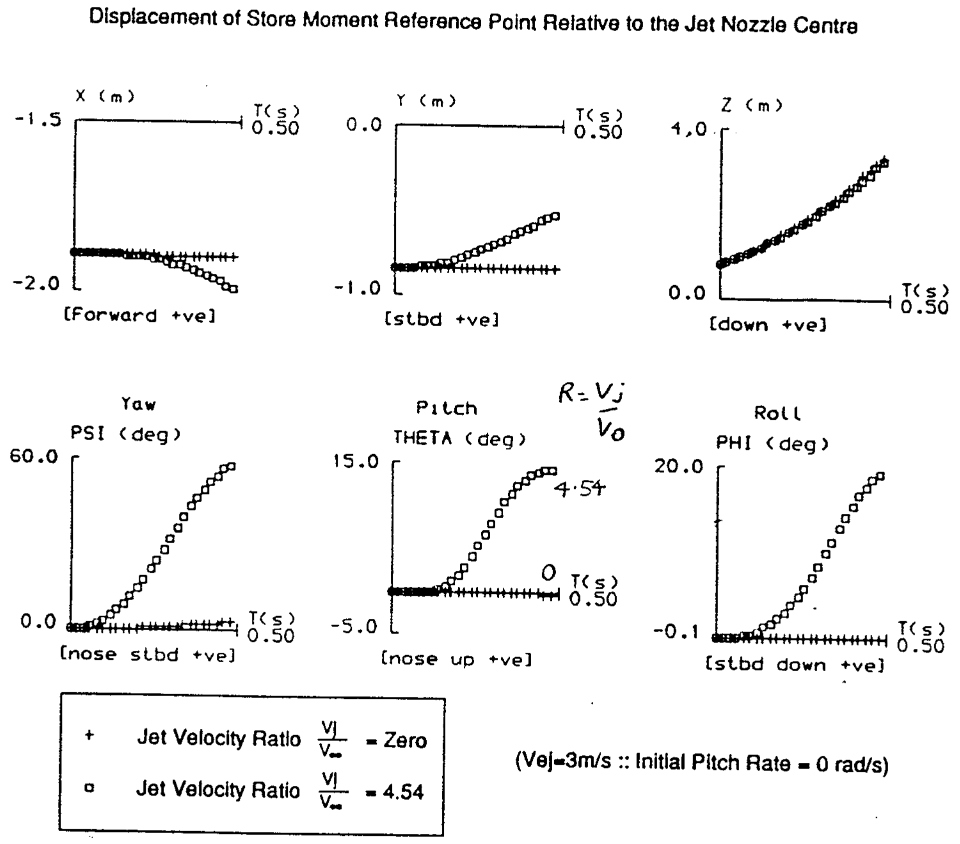


FIG. 5 COMPARISON OF 1000 lb BOMB RELEASE TRAJECTORIES, PARAMETERS, EXPERIMENT, JETS-OFF (R = 0) & WITH FORWARD + AFT JETS (R = 4.54, Θ_j = 60°)

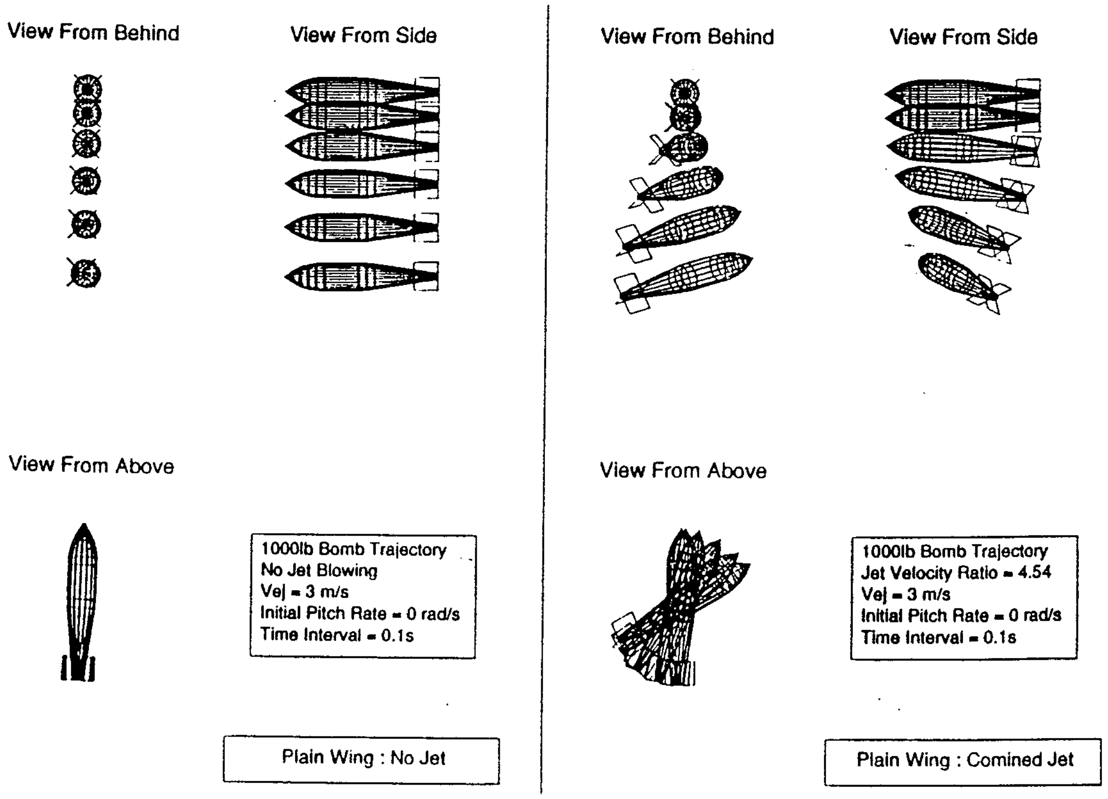


FIG. 6 COMPARISON OF 1000 lb BOMB RELEASE TRAJECTORIES, 3-D WIRE-FRAME, EXPERIMENT, JETS-OFF (R = 0) & WITH FORWARD + AFT JETS (R = 4.54, Θ_j = 60°)

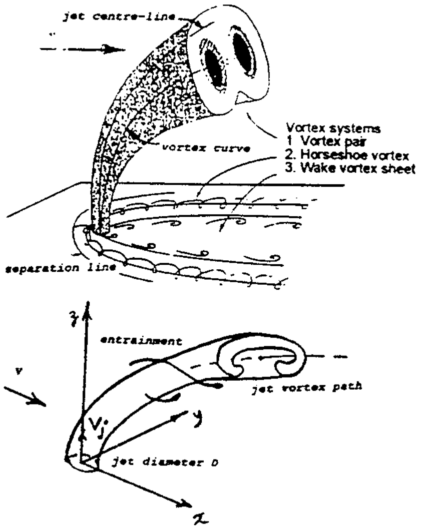


FIG. 7 JET DEFORMING IN CROSS-FLOW, SEMI-EMPIRICAL MODELLING

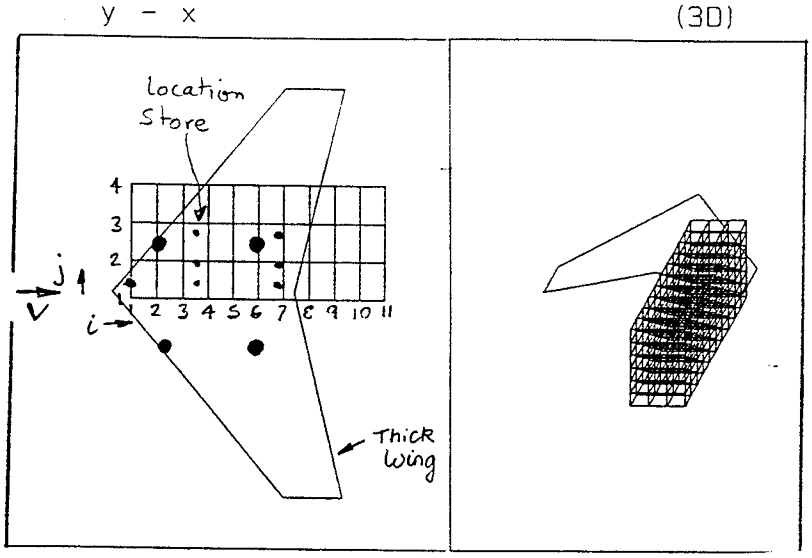


FIG. 8 3-D SURVEY VOLUME, THEORY, ß = 0°, TO DEVELOP INCREMENTAL FORCES & MOMENTS DUE TO JETS ON THE STORE

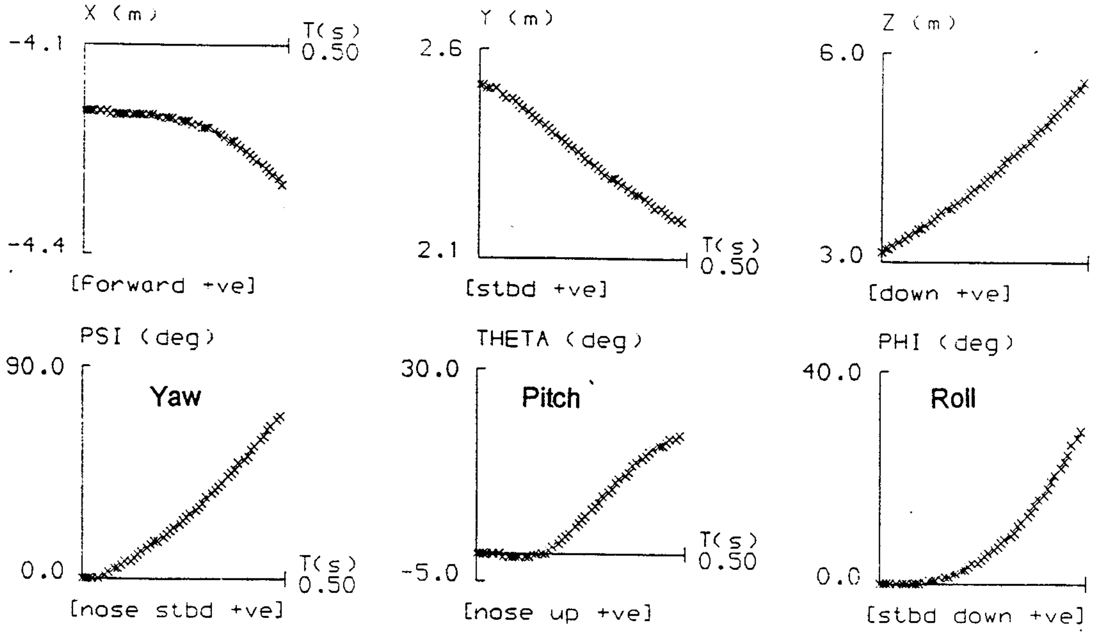
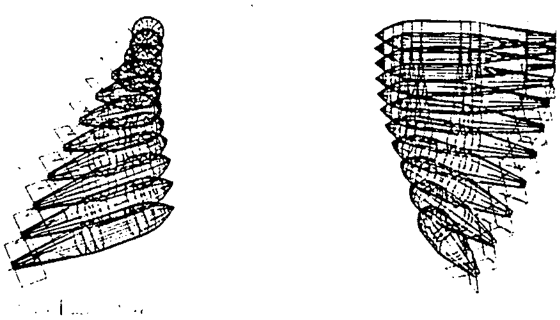
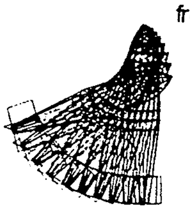


FIG. 9 BASIC 1000 lb BOMB RELEASE TRAJECTORY, PREDICTED WITH JETS (R = 4.54, Θ_{j0} = 60°)



from behind

from side



from above

FIG. 10 1000 lb BOMB RELEASE TRAJECTORY, 3-D WIRE-FRAME, THEORY, WITH JETS (R = 4.54, Θ_{j0} = 60°)

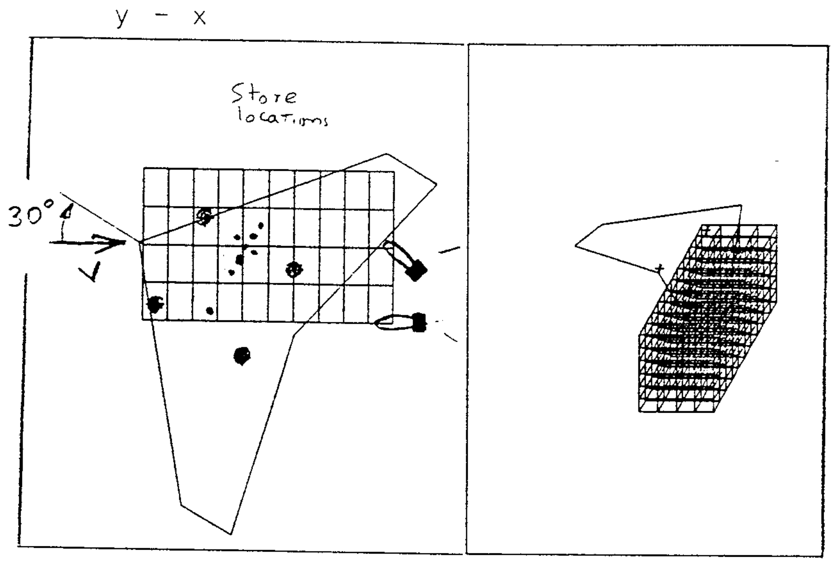


FIG. 11 3-D SURVEY VOLUME, THEORY, ß = 30°, TO DEVELOP INCREMENTAL FORCES & MOMENTS DUE TO JETS ON THE STORE

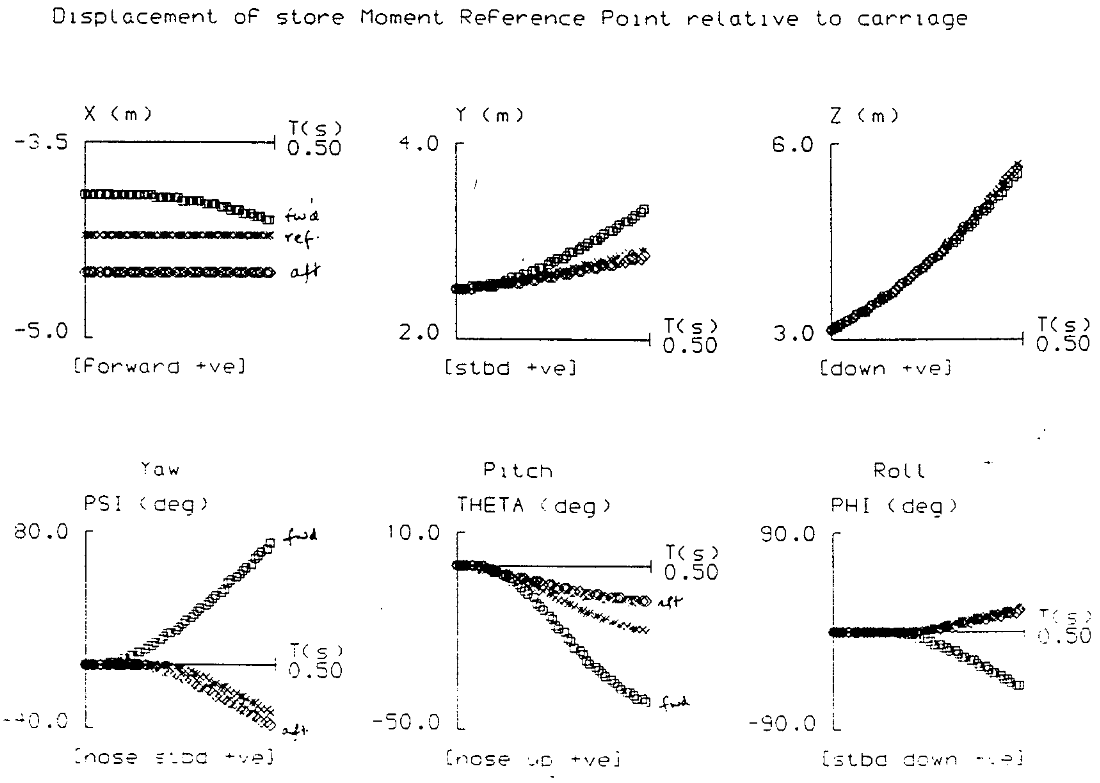


FIG. 12 EFFECT OF STORE CHORDWISE LOCATION ON RELEASE TRAJECTORY PREDICTED, ß = 30°, R = 4.54, V_{ej} = 3 m/s

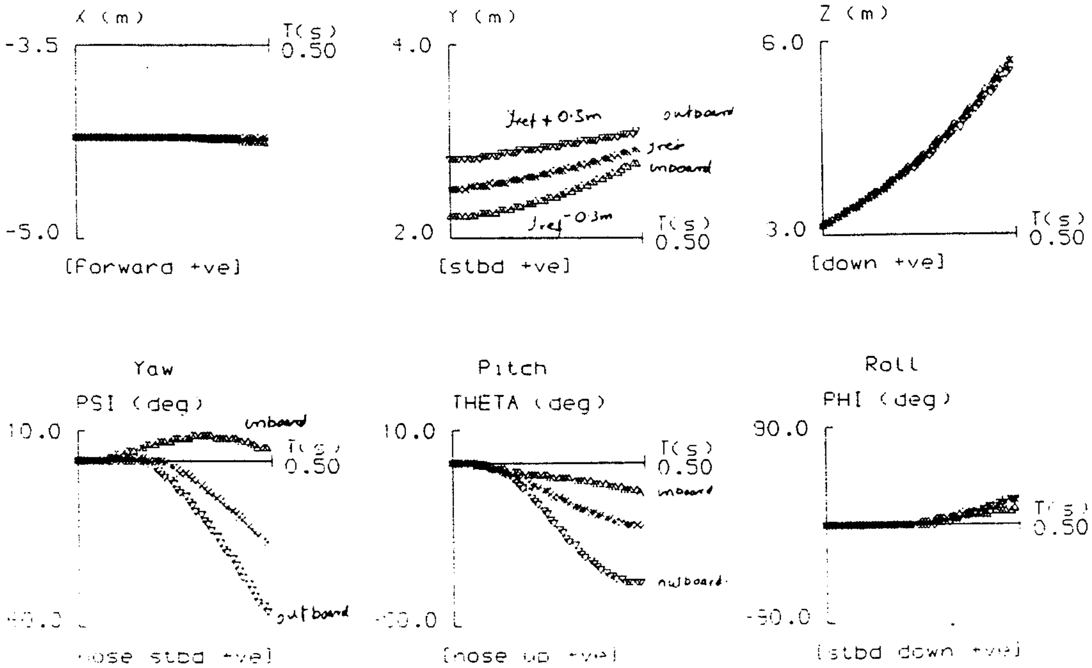


FIG. 13 EFFECT OF STORE SPANWISE LOCATION ON RELEASE TRAJECTORY PREDICTED,
ß = 30°, R = 4.54, V_{ej} = 3 m/s

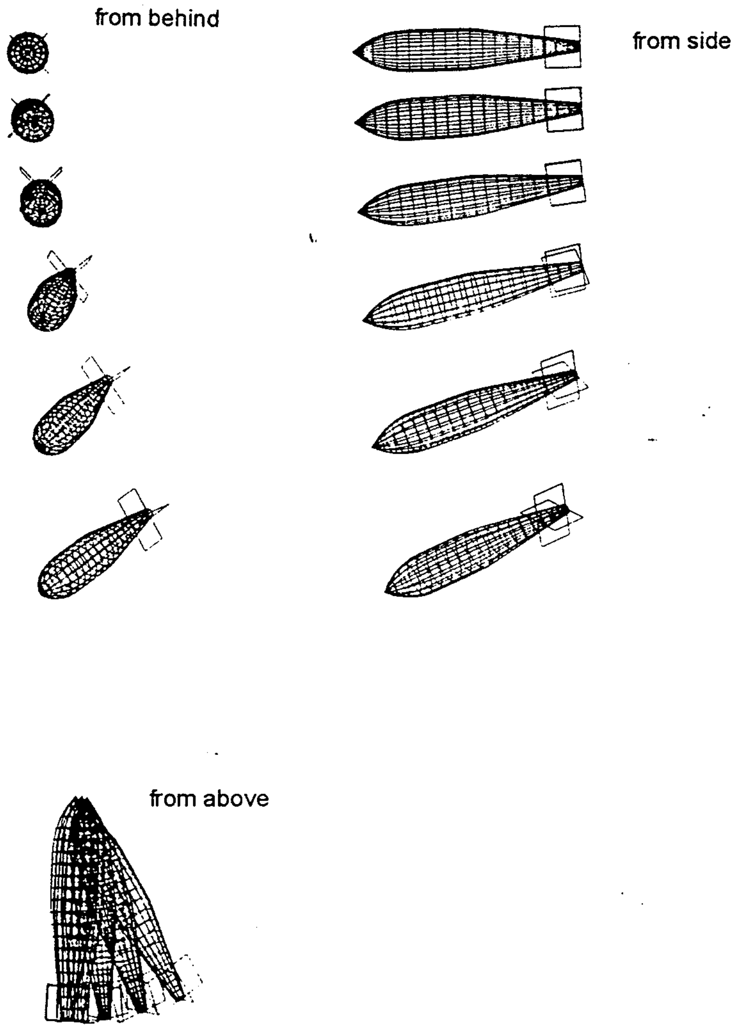


FIG. 14 3-D WIRE-FRAME RELEASE TRAJECTORY FOR REFERENCE POSITION,
ß = 30°, R = 4.54, V_{ej} = 3 m/s

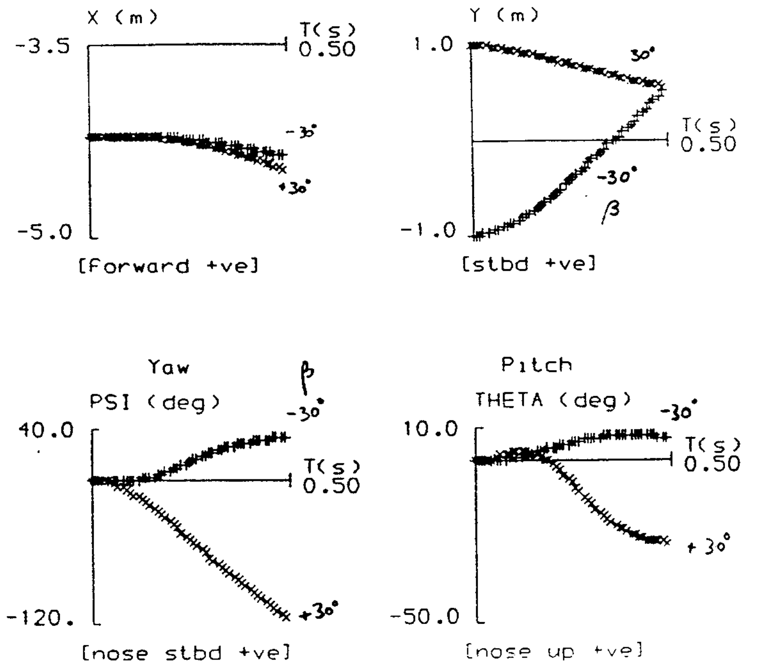


FIG. 15 EFFECT OF INITIAL STORE SPANWISE LOCATION (y = ±1m, PORT OR STARBOARD) ON RELEASE TRAJECTORIES PREDICTED, ß = ±30°, R = 4.54, V_{ej} = 3 m/s

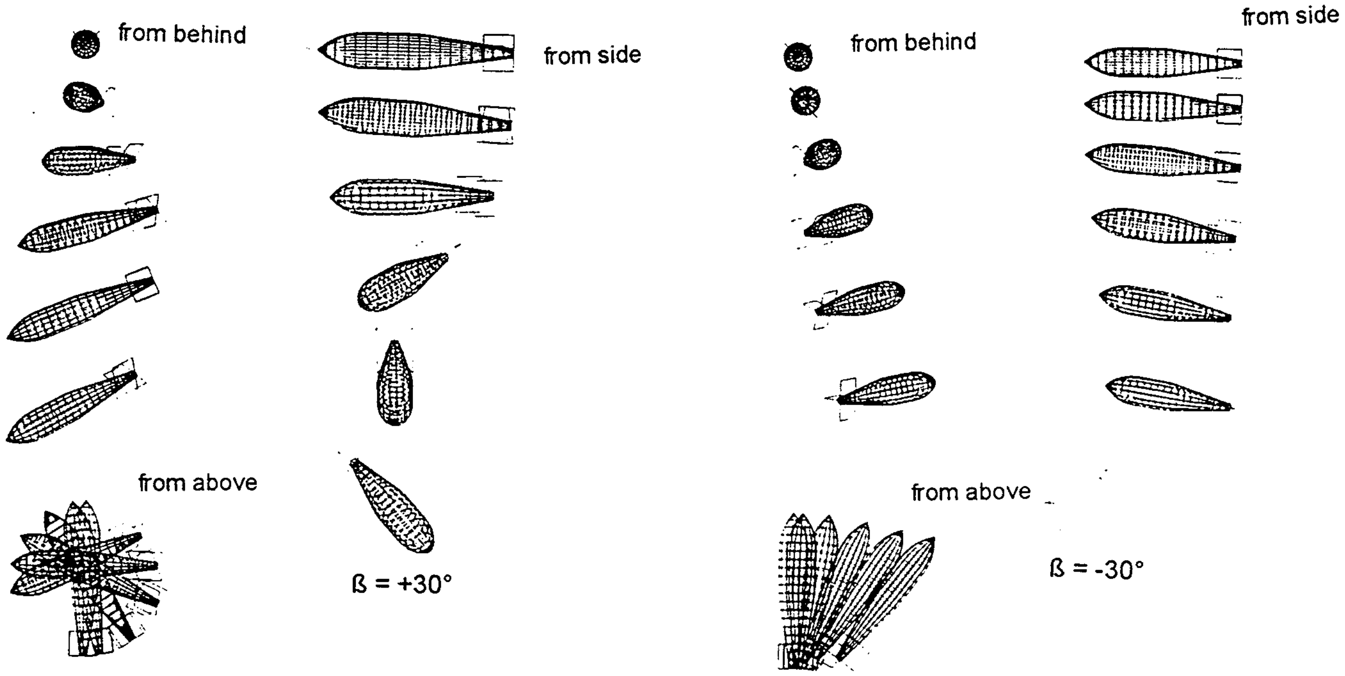


FIG. 16 EFFECT OF SIDE-SLIP SENSE ON STORE RELEASE TRAJECTORY
ß = ±30°, R = 4.54, V_{ej} = 3 m/s

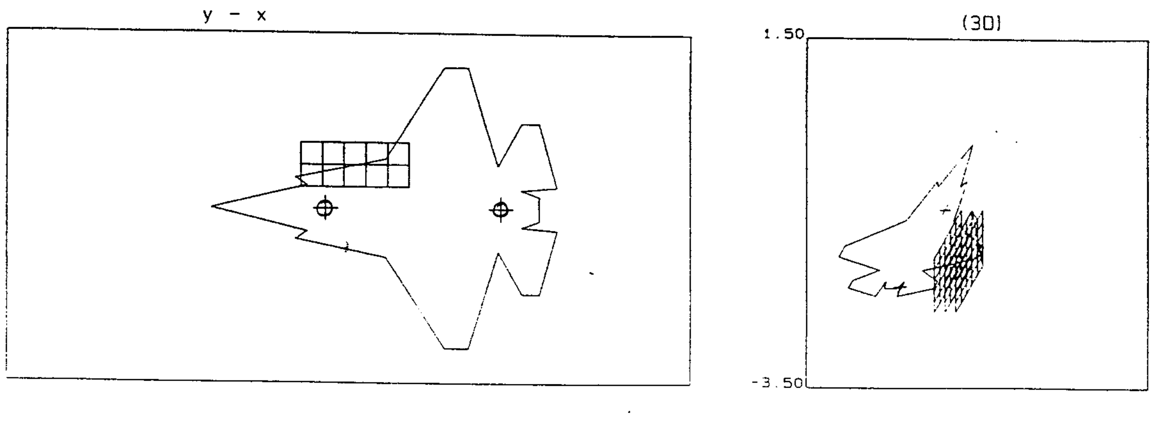


FIG. 17 AN ASTOVL AIRCRAFT, 3-D SURVEY VOLUME NEAR FRONT JET, THEORY FOR ß = 0°