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"Vortex Boundary-Layer Interactions"

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Summary

The purpose of this work is to study the interaction of a turbulent boundary layer - on a flat plate - with a strong artificially-generated longitudinal vortex, which may or may not actually enter the boundary layer. Experiments, including extensive hot-wire measurements, have been completed for the case in which the vortex does enter the boundary layer, and measurements for the somewhat simpler case in which the boundary layer and vortex remain distinct are now in progress. The grant nominally ends 28 February 1987, but as the research assistant did not take up his duties until six months after the beginning of the grant we will formally request a six month "no cost" extension - although we anticipate that the planned programme will be complete in somewhat less than three years' elapsed time. Samples of the very large volume of turbulence measurements have been given in previous semi-annual reports: in this report we present contours of total pressure (recently acquired) and of turbulent kinetic energy at various downstream positions to show the overall development of the vortex imbedded in the boundary layer.

Present position

Measurements have now been made, at six stations between the leading edge of the flat plate (Figure 1) and a position 1.78 metres (70 inches) downstream. They include all three components of mean velocity, all six Reynolds stresses, all ten triple products and the

total (but not static) pressure. At one station, we have measured mean temperature and temperature intermittency with small quantities of heat introduced as a tracer in the boundary layer or in various parts of the flow over the vortex generator. In addition, a series of smoke-flow visualization photographs has been taken as a qualitative extension of the temperature-tracing technique.

Six streamwise stations are sufficient to show the development of the flow and to allow streamwise derivatives to be evaluated. The data density in the cross-stream plane is sufficiently high for acceptable contour plots to be produced by an algorithm containing no built-in smoothing. (The contour-plotting algorithm was developed by a summer student, Mr. R.E. Giampaoli of Rensselaer Polytechnic). Plots to be discussed below show that contours of hot-wire results (specifically, turbulent kinetic energy) are as smooth as those of total pressure measured with a pitot tube: since the latter should be essentially free of calibration drift and other random error, the implication is that the hot wire results are also acceptably free from random error. Since fluctuation intensities in this flow are not particularly high, with the possible exception of the vortex core, consistent errors in the hot wire measurements are likely to be attributable only to the universal problems of traverse-gear interference and inadequate spatial resolution, and we believe that both these effects are small - again with the possible exception of the vortex core region. The main traverse gear does produce significant interference near the wall, where the flow speed is least and the effct of the image blockage greatest: however near-wall measurements are made with a simpler

traverse gear without the bulky pitch attachment.

Preliminary results of the work, mainly at 0.7 metres from the leading edge, were presented by Dr. Cutler at the AIAA/ASME 4th Fluid Mechanics, Plasma Dynamics and Lasers Conference in Atlanta Georgia in May (Ref.1). As stated in a previous semi-annual report, a broadly similar paper, with more emphasis on the relevance of the work to aircraft aerodynamics, was submitted to Journal of Aircraft. The paper was rejected on the grounds that, as written, it was of insufficient aeronautical relevance; we felt that the paper would probably be justifiably rejected by AIAA Journal on grounds of insufficient scientific detail, and are therefore abandoning it in favour of a full-length presentation of the interaction results, probably as a two-part paper with one part devoted to each test case.

Sample results

Figure 1, as is traditional, shows the test rig: the spanwise spacing of the vortices is roughly equal to the span, s = 267 mm (= 10.5 in) of the delta wing, and the coordinates in figures 2 and 3 are normalized by s. Figure 2 shows the total pressure at different downstream distances, measured with a pitot tube pitched and yawed to point into the local flow direction. Measurements in the boundary layer have been made separately, with a three-hole yaw meter (pitch angles near the surface being of course small), but simply show the expected interpolation between the previously-obtained surface-flow directions and the secondary-flow patterns further from the surface.

The most noticeable features of the total-pressure plots are the regions of low total pressure in the main vortex core, in the core of the secondary (counterrotating) vortex, and in the "tongue" of fluid dragged out of the boundary layer by the vortex. In figure 2(a), which as usual shows the negative-z half of the flow so that the vortex is seen to rotate in a clockwise direction, the main core is at approximately z/s = -0.4, with the secondary core above it at z/s near -0.5. The non-rolled-up part of the vortex is probably responsible for the region of low total pressure close to the surface at about z/s = -0.5 (the "tongue" is not detectable so close to the plate leading edge). Figure 2(b), at x = 406 mm, shows that the secondary vortex has progressed about 180^{o} round the main vortex, while the "tongue" is now quite noticeable. The region of small total-pressure defect above the tongue is more likely to be the tail of the secondary vortex and the rest of the non-rolled-up part of the delta-wing wake, rather than a precursor of the tongue. The later parts of figure 2 show the further development of the tongue and the gradual growth of the boundary layer into the region of measurement. Figure 2(f) shows that the centre-plane boundary layer is considerable thinner than the (almost undisturbed) boundary layer outboard of the vortex, but that the thinnest boundary layer of all is found slightly inboard of the vortex. Figure 3 shows measurements of the turbulent kinetic energy at three sample positions: some of these results have been previously presented but are included here for comparison with the total-pressure measurements.

Probably the best summary of the experiment is given by Figure 2(f), the total-pressure at the most downstream measurement station. It shows the phenomenon which was the main subject of the investigation, the rolling up of boundary layer fluid into the vortex. It also emphasizes the important subsidiary effect of thinning of the boundary layer, not only in the vicinity of the vortex but all the way to the plane of symmetry, $z = 0$. In our small wind-tunnel experiment, this thinning had the disadvantage of reducing the boundary-layer Reynolds number: this effect would not be present at full scale, but the significant effect of lateral divergence on the eddy structure of the boundary layer (broadly, an extension of spanwise vortex lines) will be equally important at all Reynolds numbers. The low total pressure in the vortex core is of course accompanied by low static pressure, and the net effect is a large peak in axial velocity (as shown in previous reports).

Although, as our flow-visualization photographs show so clearly, there is very little fine-grained turbulent mixing in the core of the vortex, fluctuation intensities there are quite high, as seen in the "turbulent" kinetic energy contours in figure 3. Vortex-core perturbations and bursting are the subject of another proposal, recently submitted to NASA Ames Research Center, and are only peripherally relevant to the present study. However, during the course of the present work, we have acquired a considerable amount of useful information about the behaviour of delta-wing trailing vortices, which we propose to submit for publication, either with the main interaction results or as a separate paper.

Measurements in the "strong interaction" case, where the vortex actually enters the boundary layer, are complete. A new delta-wing vortex generator, identical to the previous one except for its support strut, is now being used for the second test case, the "weak interaction" case in which the vortices and the boundary layer remain distinct until near the end of the test section. Keeping to a full delta-wing vortex generator means that the non-rolled-up part of the delta-wing wake will merge with the boundary layer on the test plate, instead of passing below it as in the original configuration with the vortices closer to the test-plate surface, but the central part of the wake seems to be less of a nuisance than the secondary vortex mentioned above, which passes over the top of the test plate in both configurations.

Measurements for the second configuration should be a matter of routine, and since spatial gradients will be smaller than in the strong-interaction case it should be possible to use a coarser measurement grid. We are confident of completing the measurements, the data analysis (including evaluation of terms in the turbulent energy equation) and the preparation of papers for journal publication, within the three-year period - i.e. before September 1987, recalling that the start of actual work was delayed by six months. If time permits, we will usesome of our well-developed techniques, including flow visualization, for studies of the effect of pressure gradient or other perturbation of the flow.

References

1. Cutler, A.D. and Bradshaw, P. The interaction between a strong longitudinal vortex and a turbulent boundary layer. AIAA-86-1071, 1986.

2. Cutler, A.D. and Bradshaw, P. Vortex/boundary-layer interaction in an idealized close-coupled-canard configuration. Imperial College unpublished paper, 1986.

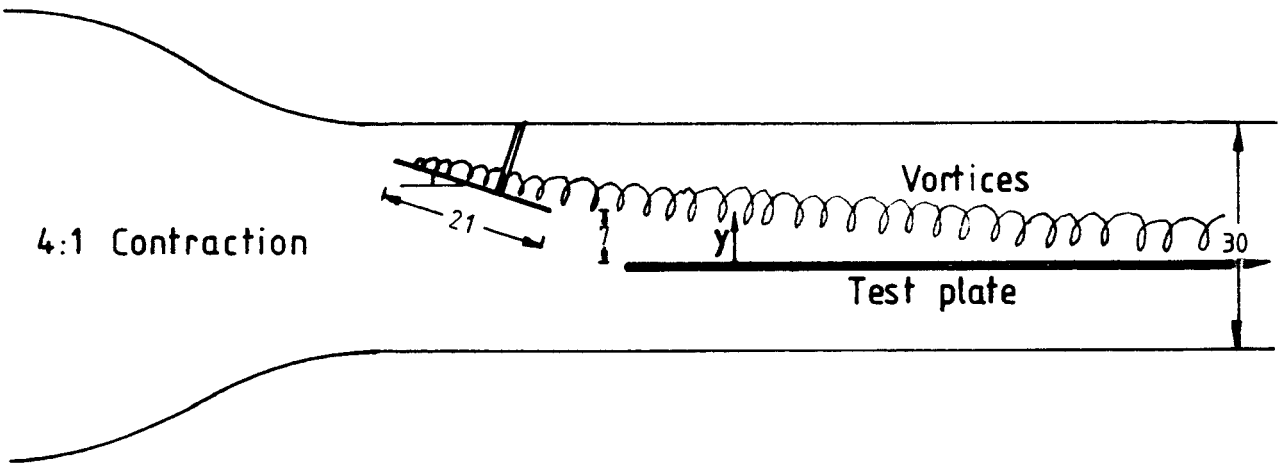
Figure 1 The wind tunnel (second configuration, with vortices outside boundary layer)

Figure 2 Total pressure contours, normalized by reference dynamic pressure: in order from outside, contours are at 0.98, 0.95, 0.90, 0.85, 0.8, .. (underlined values are shown by full lines and labels)

(a) (b) (c) (d) (e) (f)

Figure 3 Contours of turbulent kinetic energy, normalized by U_{ref}^2: in order from outside, the contours are at 0.0001, 0.0025, 0.0050, 0.0075, 0.0010, ..(underlined values are shown by full lines and labels)

(a) (b) (c) (d) (e) (f)



Dimensions in inches

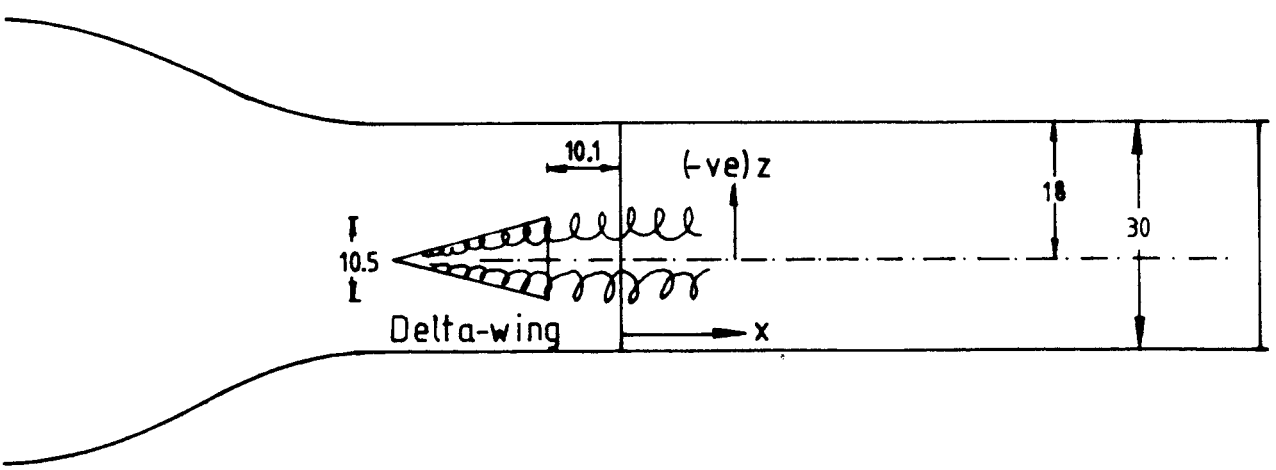
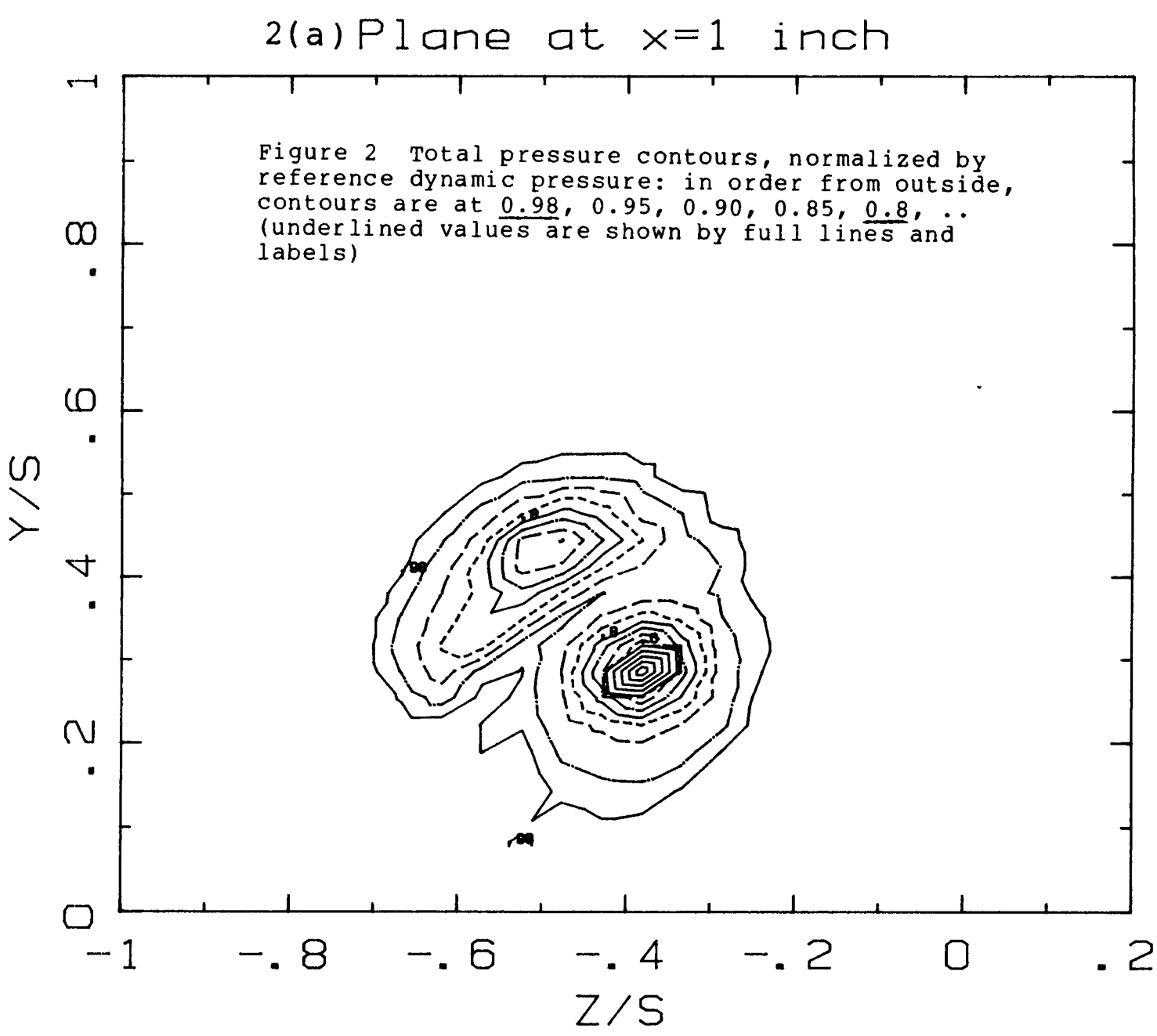


Figure 1 The wind tunnel (second configuration, with vortices outside boundary layer)



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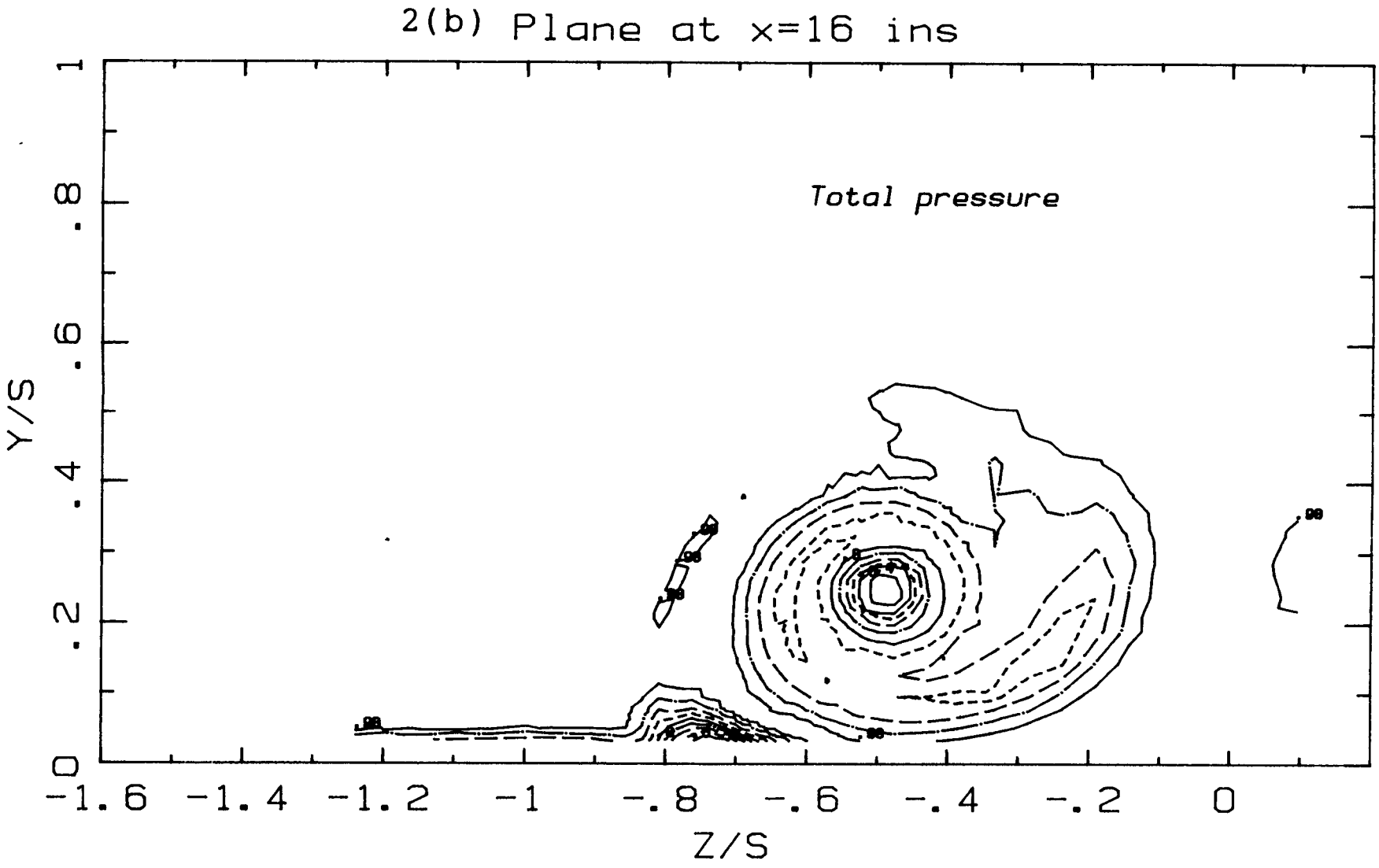
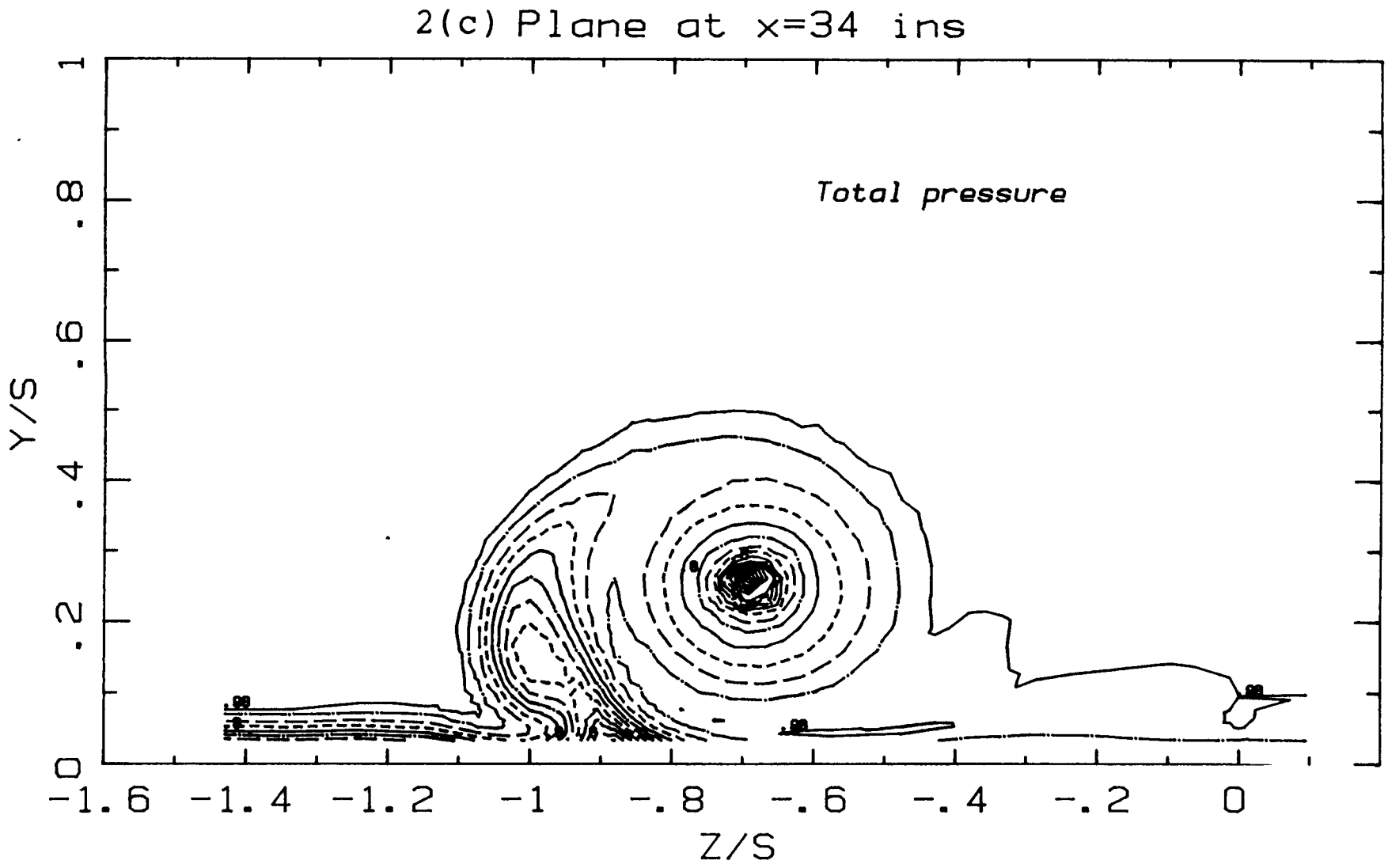
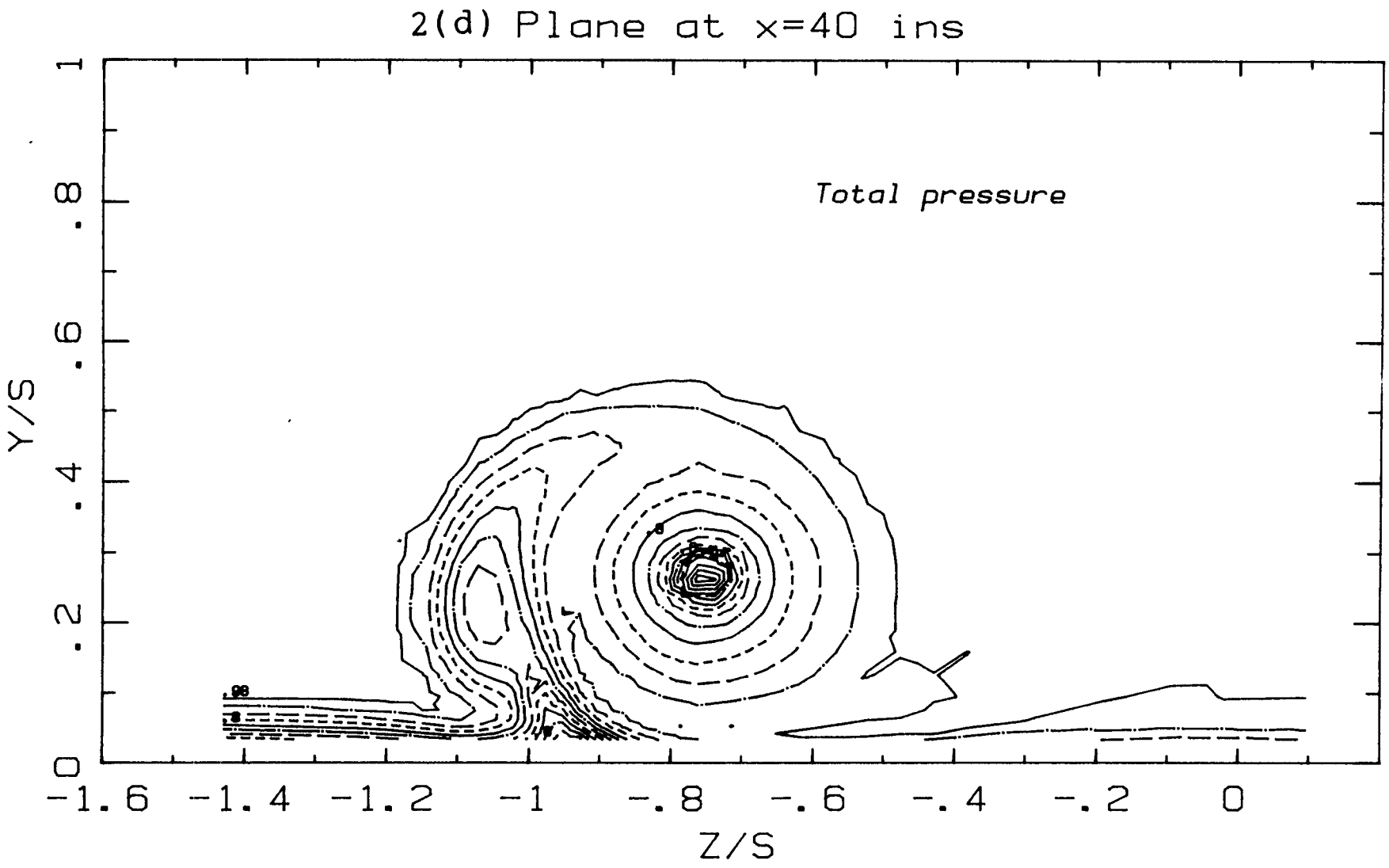
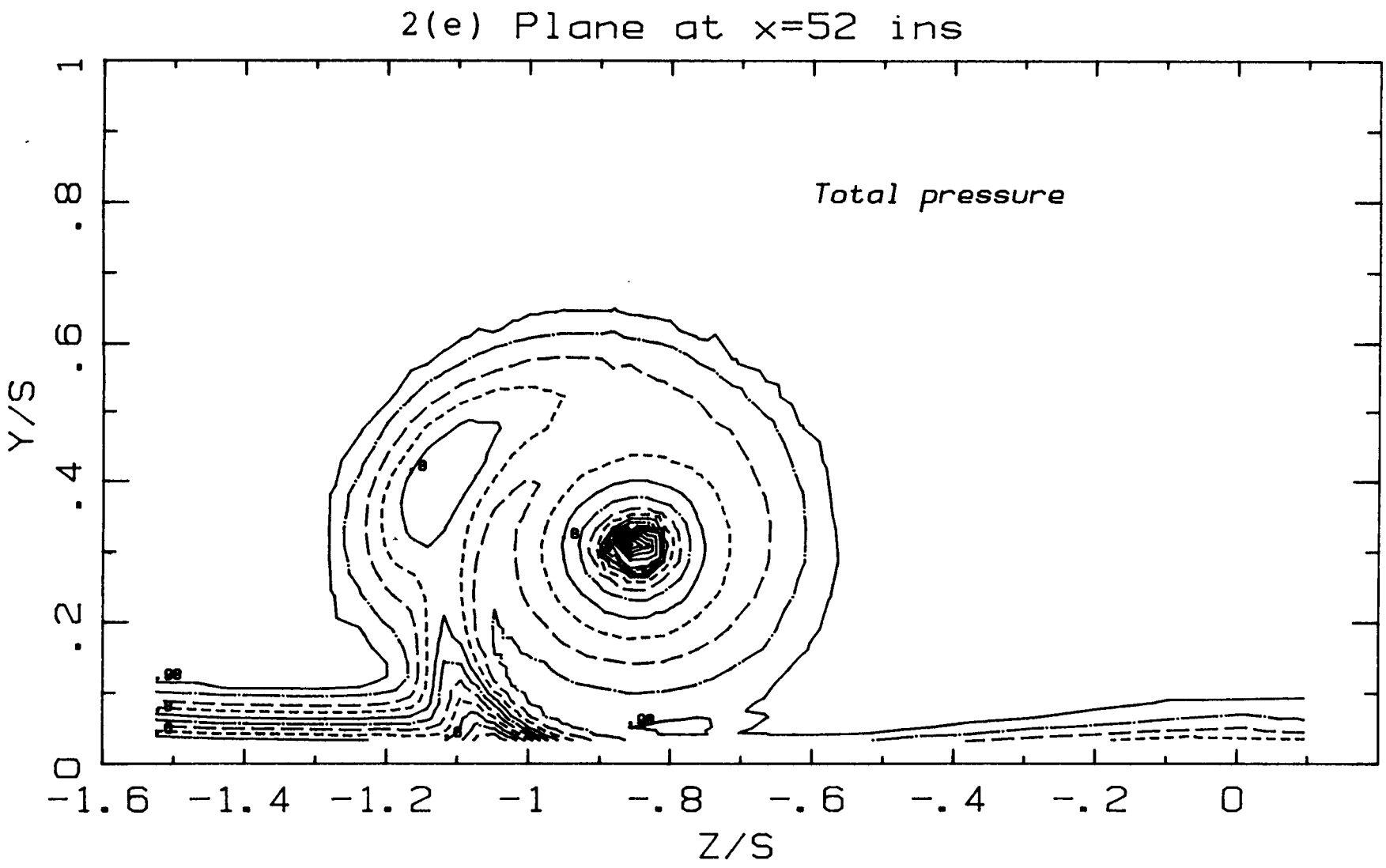
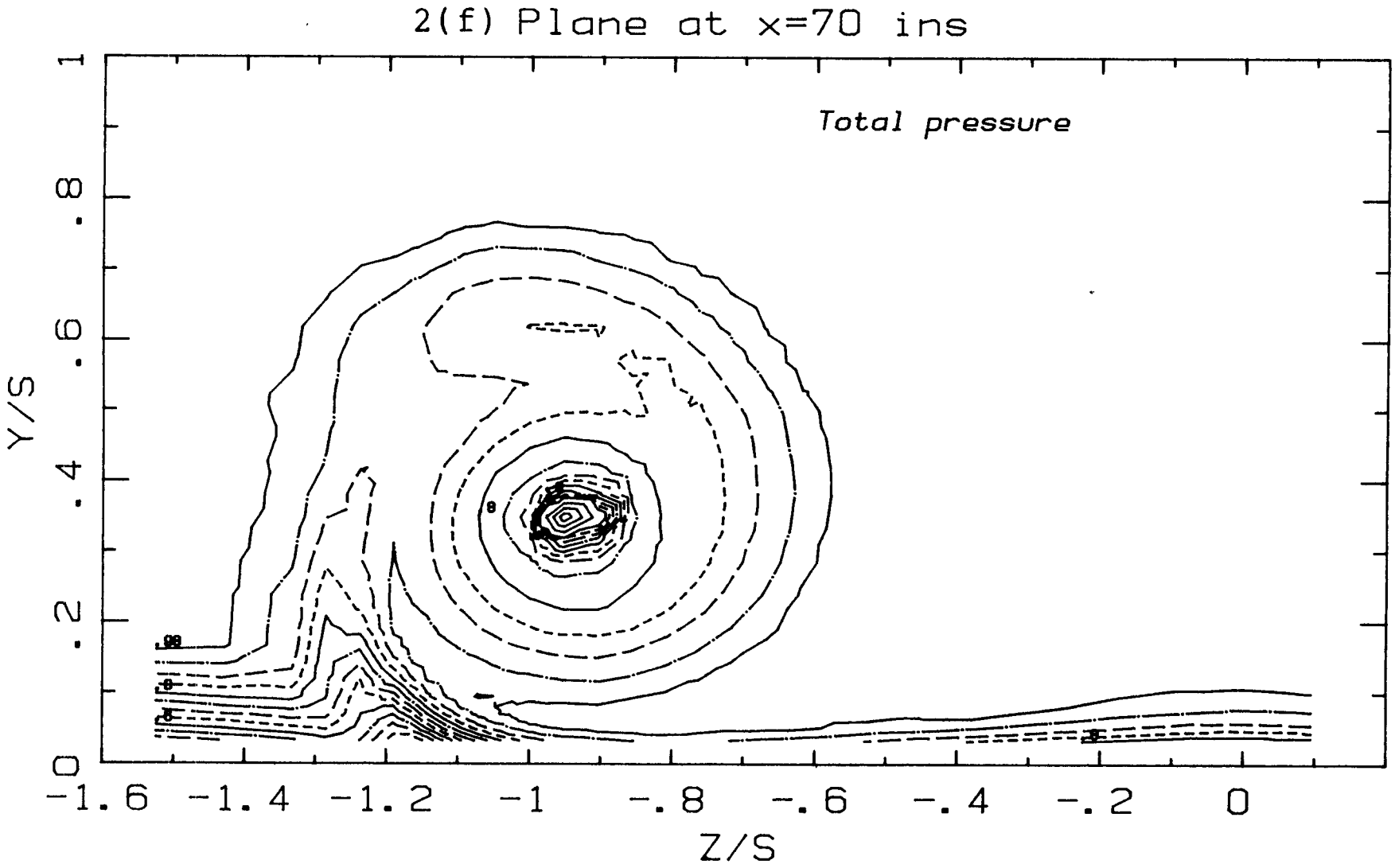
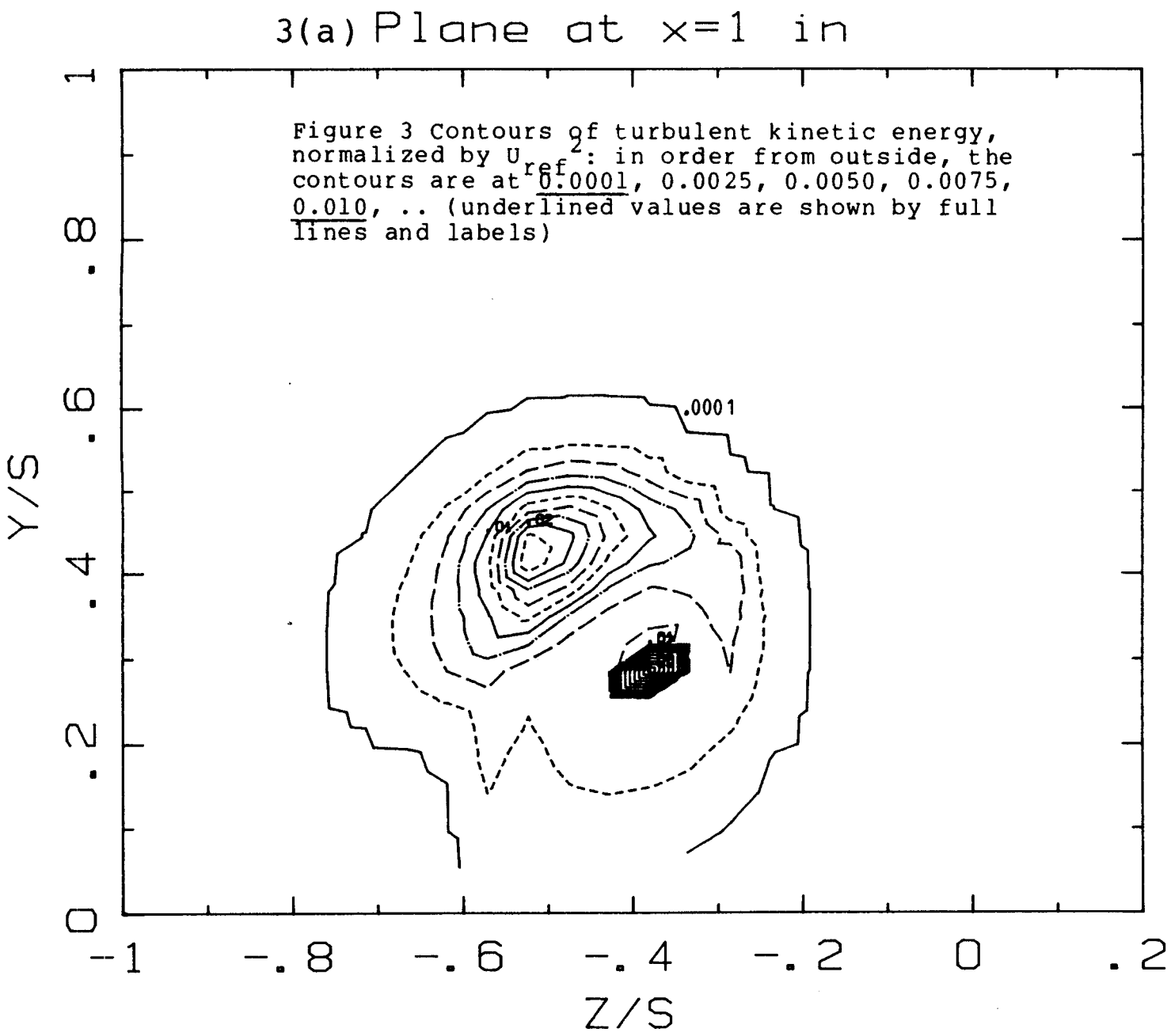

2(b) Plane at x=16 ins
Total pressure
Y/S
Z/S
0
.2
.4
.6
.8
1
-1.6
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0

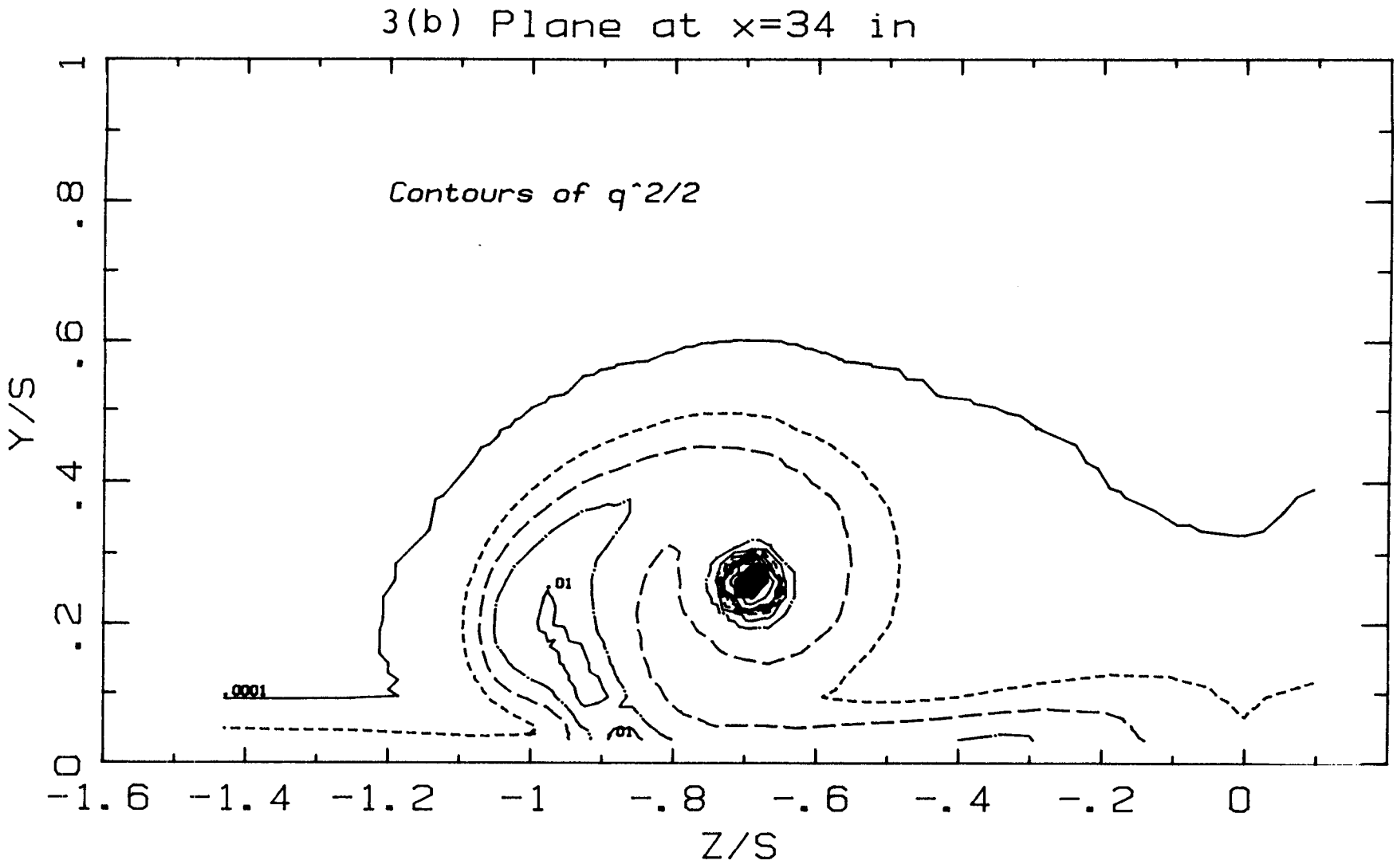

2(c) Plane at x=34 ins
Total pressure
Y/S
Z/S
0
.2
.4
.6
.8
1
-1.6
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0

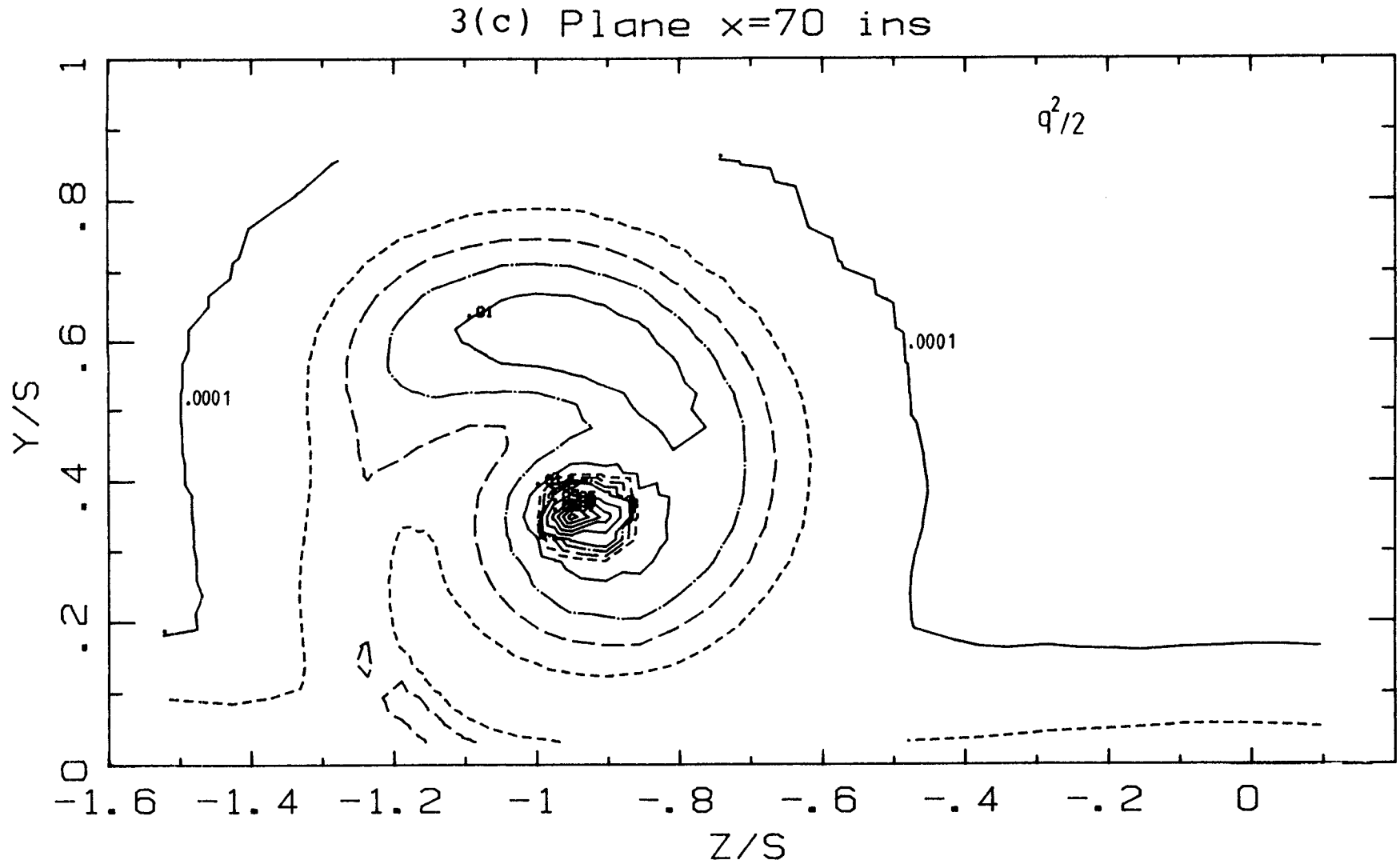

2(d) Plane at x=40 ins
Total pressure
Y/S
Z/S
0
.2
.4
.6
.8
1
-1.6
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0


2(e) Plane at x=52 ins
Total pressure
Y/S
Z/S
0
.2
.4
.6
.8
1
-1.6
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0


2(f) Plane at x=70 ins
Total pressure
Y/S
Z/S
0
.2
.4
.6
.8
1
-1.6
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0


3(a) Plane at x=1 in
Figure 3 Contours of turbulent kinetic energy, normalized by U_{ref}^2: in order from outside, the contours are at 0.0001, 0.0025, 0.0050, 0.0075, 0.010, .. (underlined values are shown by full lines and labels)
.0001
Y/S
0
.2
.4
.6
.8
1
-1
-.8
-.6
-.4
-.2
0
.2
Z/S


3(b) Plane at x=34 in
Contours of q^2/2
Y/S
Z/S
0
.2
.4
.6
.8
1
-1.6
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0
.0001
.01
.01


3(c) Plane x=70 ins
$q^2/2$
.0001
.01
.0001
Y/S
Z/S
1
.8
.6
.4
.2
0
-1.6
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0