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IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF AERONAUTICS

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"Vortex/Boundary Layer Interaction"

Period 1 September 1986 - 28 February 1987

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Summary

The three-year contract period is nominally finished, but we have already requested a "no-cost" extension for up to six months, because the research assistant, Dr.A.D. Cutler, did not commence work until October 1984. We anticipate producing a final report well within this extra six month period: the present document summarizes progress over the last six months, with a brief view of the whole year's achievements. Data acquisition, and most of the analysis, are complete for the first test case, in which the trailing vortex pair from a delta wing merges with a turbulent boundary layer on a flat plate downstream of the delta wing, and data acquisition for the second case, where the vortices remains clear of the boundary layer but induce large crossflow in it is virtually complete.

Present position

Samples of analysed data for the first test case were presented in the last semi-annual progress report, and will not be repeated here. The data for the first test case are all recorded on disc in standard format, and the final passes through our data-analysis and computer graphics routines will be made simultaneously for both test cases. Data analysis for the first test case, already completed, includes evaluation of all the terms in the turbulent kinetic energy balance and the cross stream turbulence diffusion term in the transport equation for the longitudinal vorticity.

As usual, we began our investigation of the second test case (longitudinal vortex above, but not merging with, a turbulent boundary layer) with flow visualization studies, and a selection of photographs will be presented in the final report. The results of quantitative data acquisition for the non-merging test case are shown in figures 1 to 8 of the present report. Only half of each cross-sectional plane is shown. The label "delta wing high" refers to the position of the vortex generator for the second case, the first being "delta wing low": as before, all results are made dimensionless with the span of the delta wing, s = 267 mm (10.5 in.), and a reference velocity U_{ref} equal to the nominal undisturbed flow speed over the plate, about 16 m/s.

Figure 1 shows contours of axial velocity and vectors of the secondary flow velocity at a short distance downstream of the leading edge of the plate. The regular geometrical pattern in the vortex core is simply an artefact of the relatively coarse measurement grid and the lack of smoothing in the contour-plotting routine: in the present test case we are not interested in the details of vortex core, because it never interacts with the boundary layer. Essentially, this figure defines the vortex: note (i) the fairly accurate symmetry about the centre plane z = 0 (ii) the small but significant defect in velocity in the non-rolled-up part of the wake of the delta wing: the vertical strip on the centreline which is the wake of the delta-wing support strut. In the core of the vortex, the axial velocity is high, although the total pressure reaches a minimum there. Measurements in the boundary layer region were made separately, the traverse gear with 4 automated degrees of freedom being replaced by a smaller one with y, yaw and roll movements but no pitch movement, since pitch angles near the surface are, by definition, small. Figure 2 shows mean velocities for the boundary layer region, and it can be seen that crossflow angles at the outer edge of the boundary layer are less than about 8 degrees. The boundary layer thickness at this x position is only about 1 cm or 0.05 times the span of the delta wing. Figure 3 shows (unsmoothed) contours of turbulent kinetic energy in the delta-wing wake. Figure 4 shows the turbulent kinetic energy in the boundary layer region for the same case.

Figure 5 shows the primary and secondary velocity components in the boundary layer region far downstream, where the spanwise variation of the crossflow due to the vortex has resulted in a strong spanwise variation of boundary layer thickness and the formation of a ridge at about $z/s = 1$ (in the first, "merging", test case this ridge was more concentrated and was lifted out of the boundary layer by the vortex as a "tongue" of fluid). Figure 6 shows the corresponding turbulent kinetic energy contours, which, as always, are distorted in roughly, but by no means exactly, the same way as the velocity contours.

The outer part of the "boundary layer" is undoubtedly so distorted by the vortex that the conventional boundary-layer approximation (that streamwise and spanwise gradients of mean velocity shall be small compared to normal gradients) is not satisfied: however, we may still hope that the inner layer of the boundary layer

($y < 0.1\delta$, say) will obey the same simple scaling laws as in a conventional three-dimensional wing boundary layer. Figure 7 shows semi-logarithmic plots of the resultant velocity with the flow measured with a 3-hole pitot probe locally aligned in yaw. If it is assumed that these profiles follow the conventional "law of the wall" a skin-friction coefficient can be deduced: these values of skin friction has been used to produce the plots shown in figure 8. This is a partly, but not entirely, circular process: if the law of the wall does not hold, then the profiles in figure 7 would simply intersect the logarithmic law (shown dotted) at the value of y^+ at which they were forced to match it: however, the profiles follow the logarithmic law over the whole of the expected range, between $y^+ = 40$ and $y/\delta = 0.1$.

Figure 8 shows skin-friction vectors for both test cases: in figure 8(a), for the present test case, the spanwise variations of skin-friction magnitude cover a range of roughly 1.5 as in the first, merged-vortex, test case shown in figure 8(b): however, crossflow angles in the present case are barely half those in the first test case.

Hot-wire data acquisition in the boundary layer region and in the vortex region has been completed for planes at x = 16, 34, 52, 61 and 70 inches as have measurements of total pressure using the 3-hole pitot at x = 16, 34, 52 and 70 inches. As in the first test case, a group of three closely-spaced stations have been measured so that x-derivatives can be accurately evaluated for use in the transport equations. All that remains are a few check measurements.

Other work in progress includes further flow-visualization of the delta-wing wake, as part of an undergraduate project. As mentioned in previous reports, the present work seems to be almost the first detailed investigation of the wake of a delta wing, and the flow has been found to be much more complicated than is implied by the use of simple concentrated-vortex models. We are also devoting considerable effort, at no cost to the present contract, to the development of graphical output routines for this and other three-dimensional experiments. Plots like that of figure 1, in which there is no room for labels on each contour, are much easier to read if the contours are intelligently smoothed, and coloured or separated by colour infill. Work on graphics routines is being assisted by Professor J.K. Eaton of Stanford University, sabbatical visitor at Imperial College, January - June 1987.

Publications

A review of work on vortex flows in the Principal Investigator's group has been written, by invitation, for presentation at the symposium on Perspectives in Turbulence Studies, Gottingen, May 1987. The present experiments are described, without full detail. The data have already appeared in our progress reports to NASA but a copy of the symposium paper is attached for information.

Further plans

We expect all data-taking and the final analysis of the data, including evaluation of terms in the transport equations,to be complete within about two months from now. The principal investigator regards the data taken by the research assistant as being of exceptionally high quality, forming a solid basis for further interpretation and calibration of turbulence models. Draft journal papers on both test cases should be complete before the research assistant leaves, and will form the basis of the final report which we expect to submit by the end of the six-month extension period in September 1987.

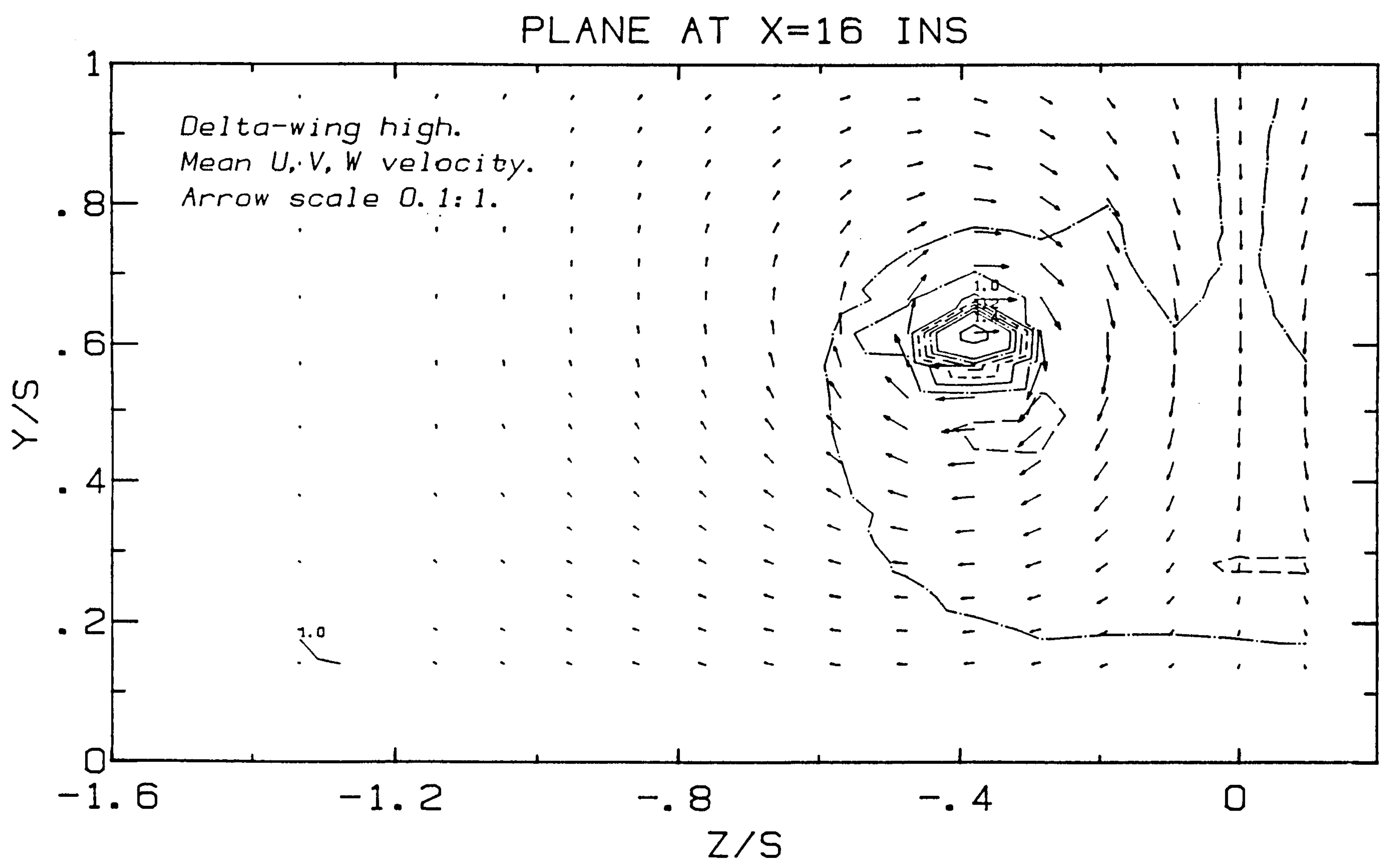

Figure 1 Primary and secondary components of mean velocity for the non-imbedded vortex case at x = 16 inches; the U-component contour interval is 0.05 U_{ref}, and an arrow length of 0.1s corresponds to U_{ref}.

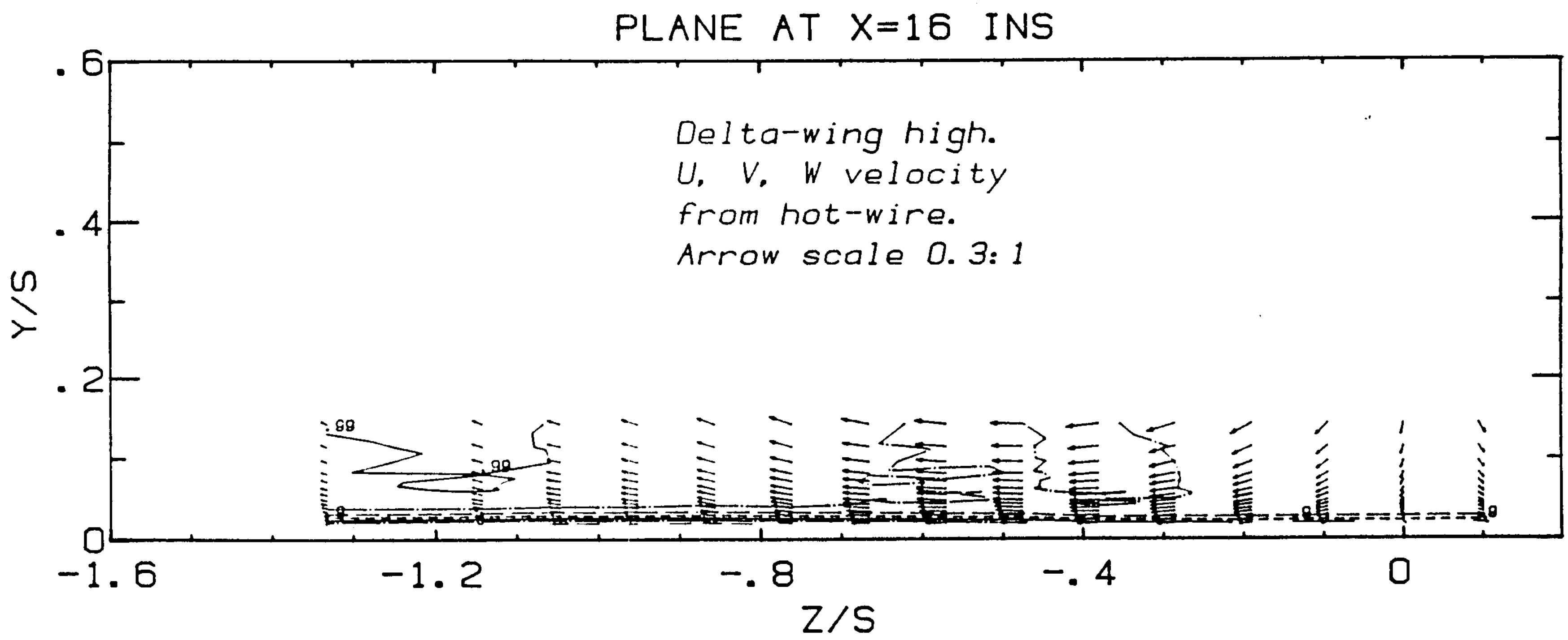

Figure 2 Primary and secondary velocities near the surface; U-component contour interval is 0.025 U_{ref} and an arrow length of 0.3s corresponds to U_{ref}.

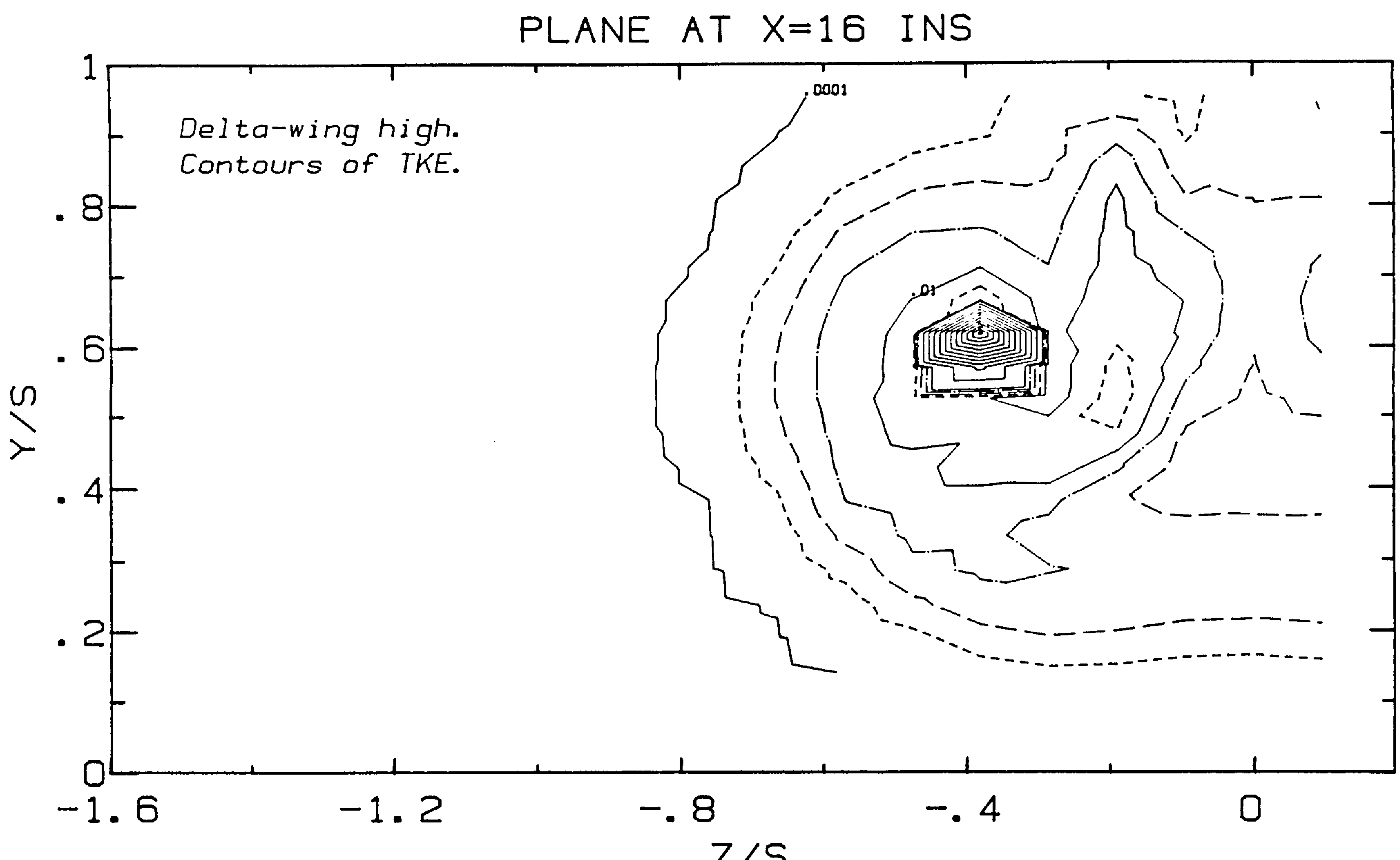

Figure 3 Contours of turbulent kinetic energy for the non-imbedded vortex case at x = 16 inches: the interval between contours is 0.0025 U_{ref}^2.

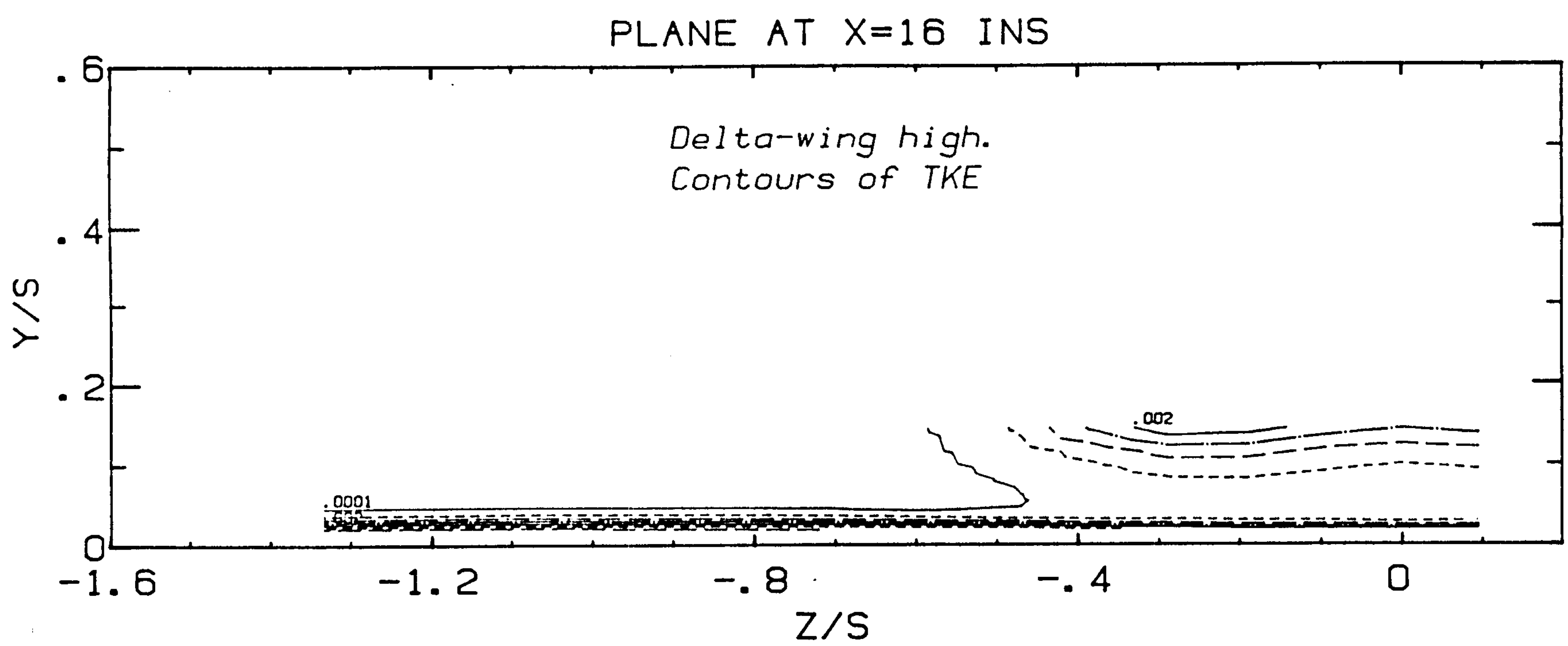

Figure 4 Contours of turbulent kinetic energy near the surface; the interval between contours is 0.0005 U^2_{ref}.

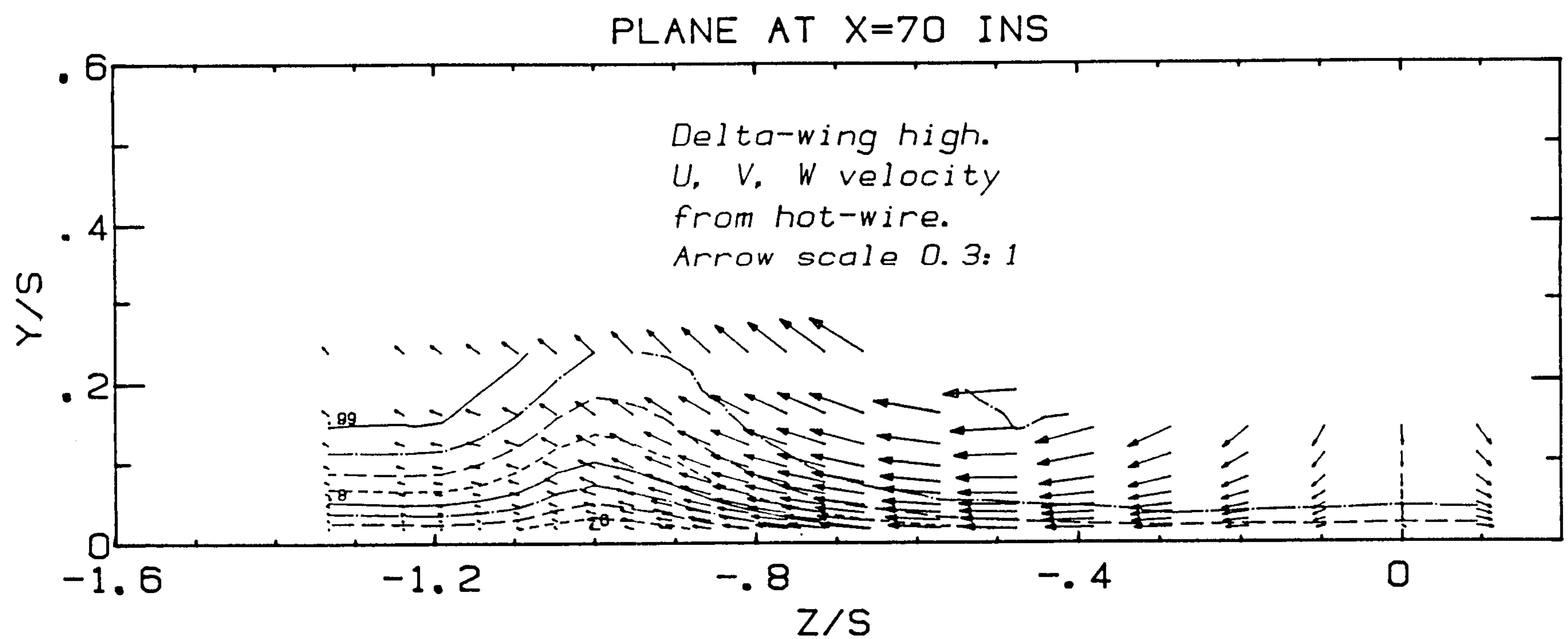

Figure 5 Primary and secondary components of mean velocity for the non-imbedded vortex case near the surface at x = 70 inches; the U-component contour interval is 0.05 U_{ref} and an arrow length of 0.3s corresponds to U_{ref}.

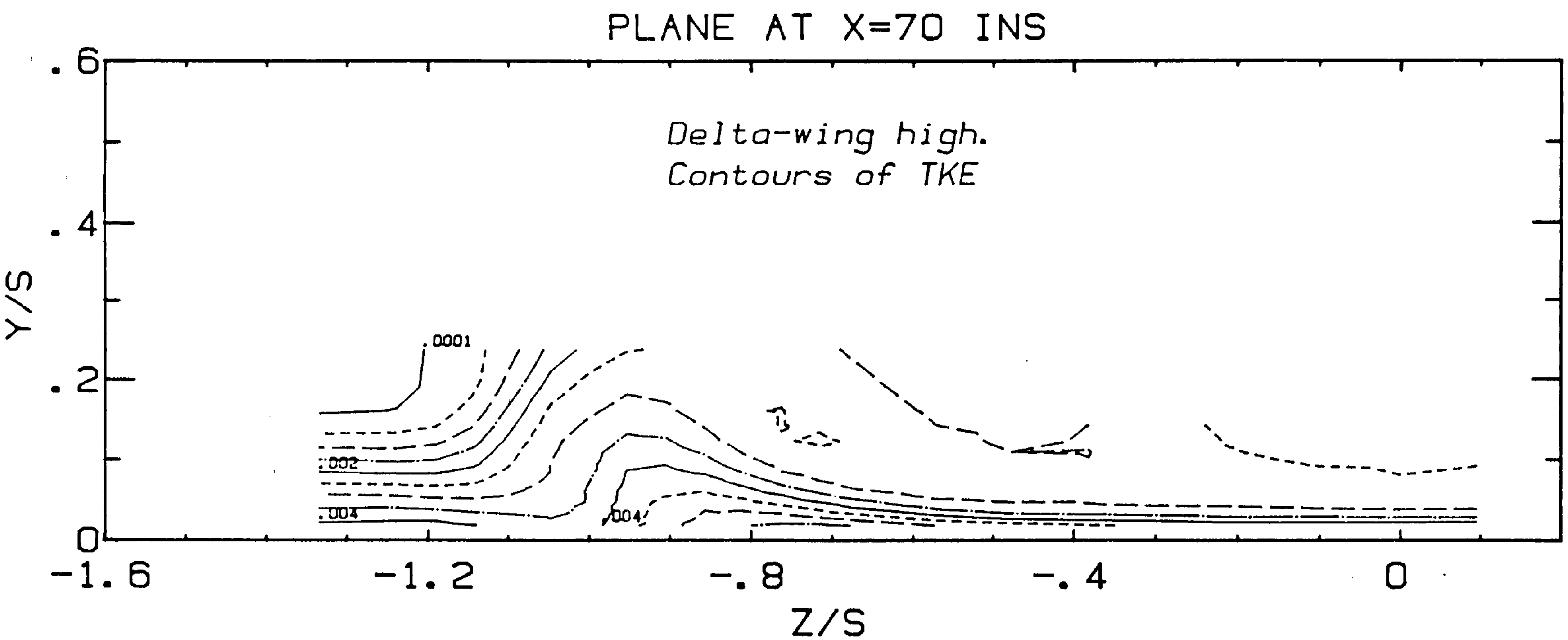

Figure 6 Contours of turbulent kinetic energy; the interval between contours is 0.0005 U^2_{ref}.

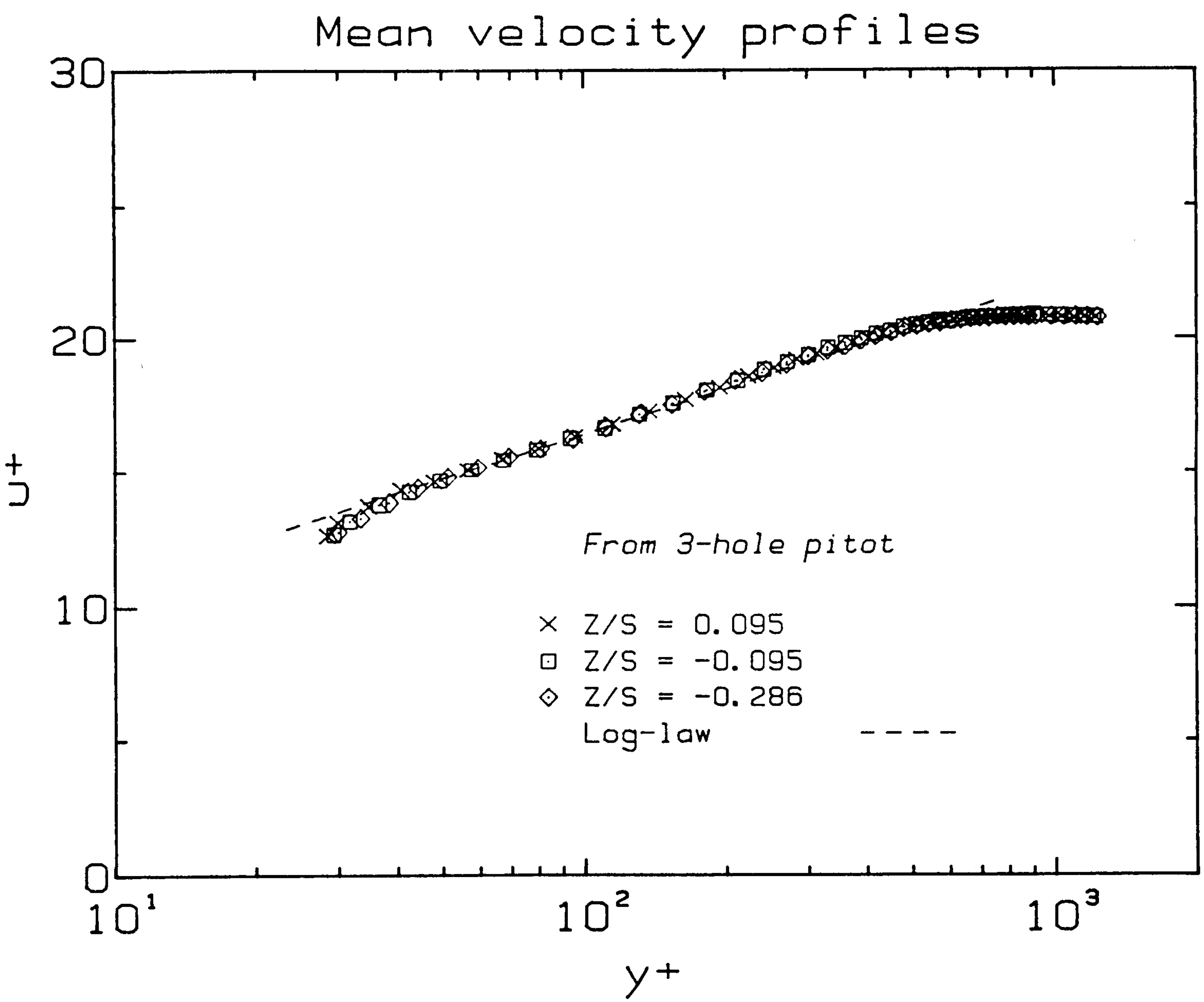

Figure 7(a) Semi-logarithmic plots of mean, resultant velocity at x = 70 inches. (skin friction from best fit to the log law) near centre line

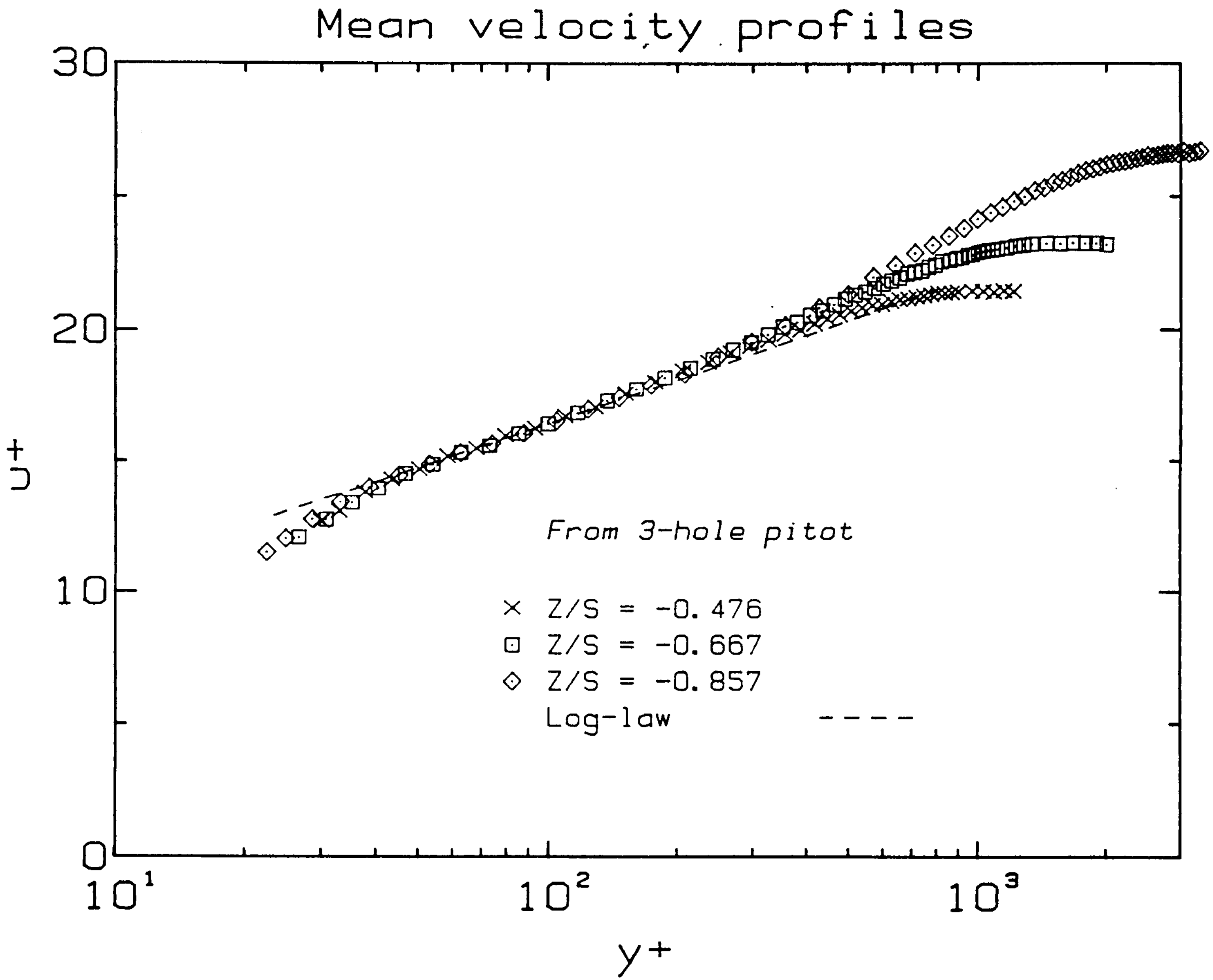

Figure 7(b) Semi-logarithmic plots of mean, resultant velocity at x = 70 inches. (skin friction from best fit to the log law) under vortex

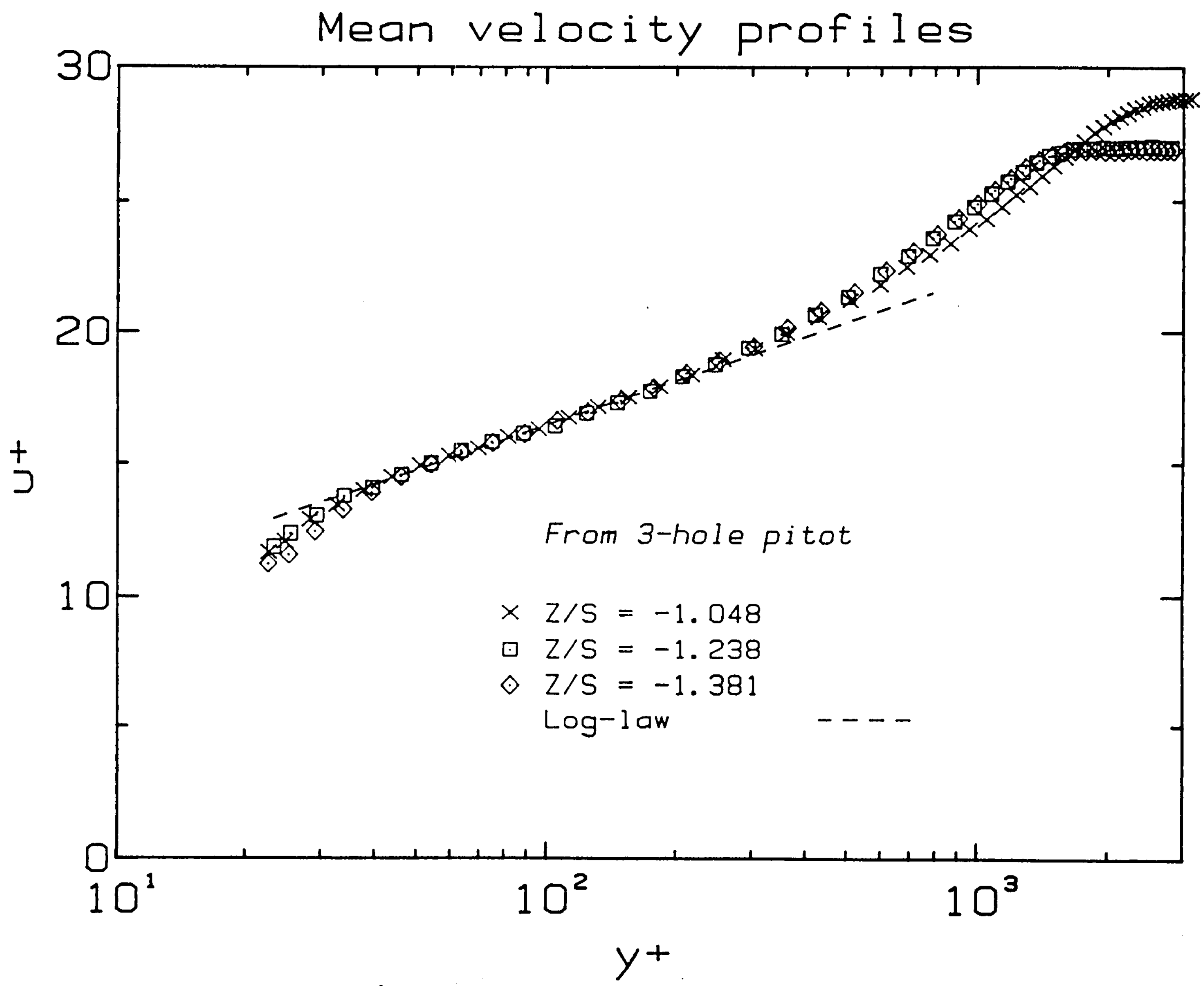

Figure 7(c) Semi-logarithmic plots of mean, resultant velocity at x = 70 inches. (skin friction from best fit to the log law) outside vortex.

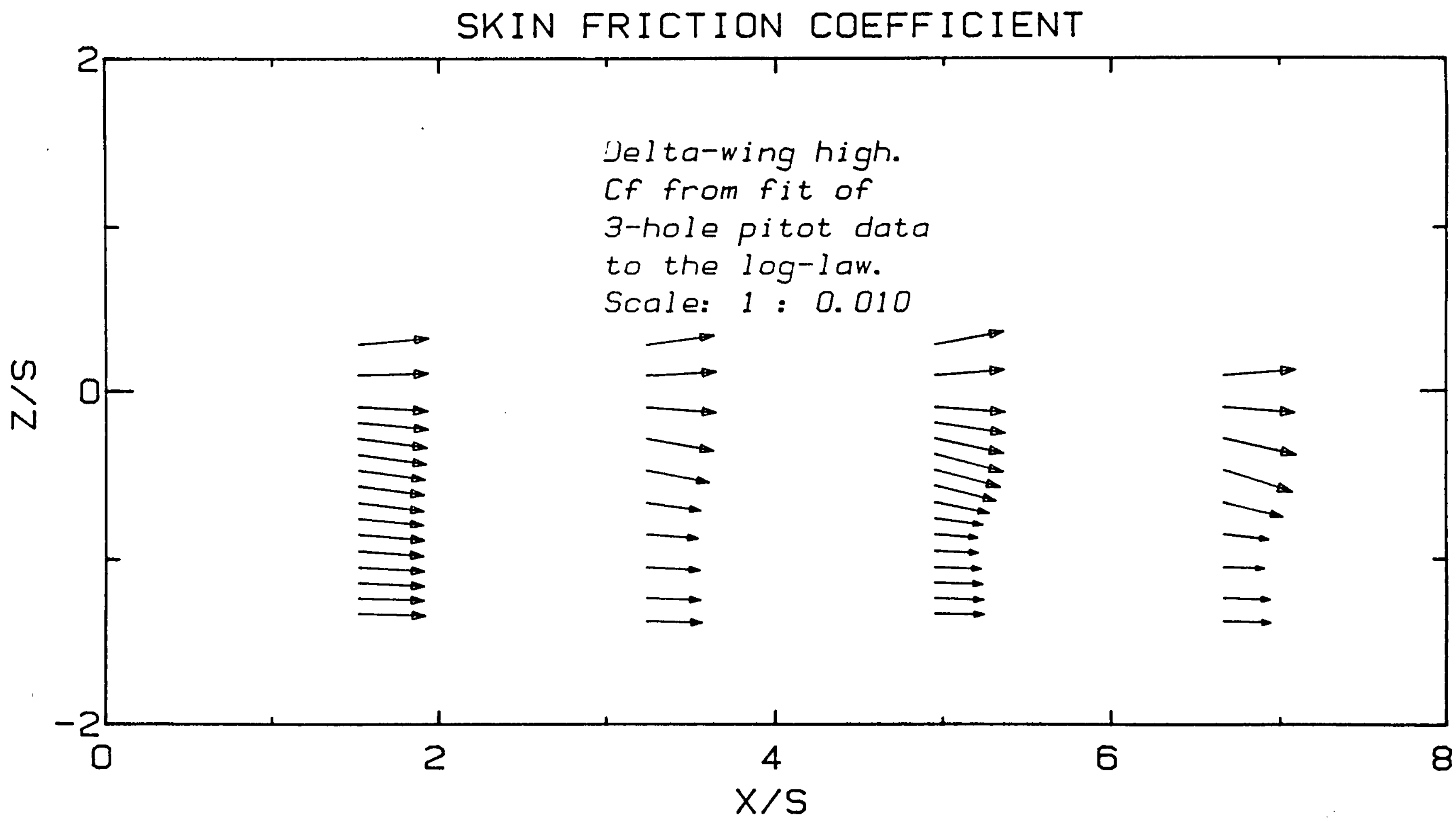

Figure 8(a) Skin friction coefficient vectors, vector length equal to s corresponds to $C_f = 0.01$, delta wing high (unmerged),

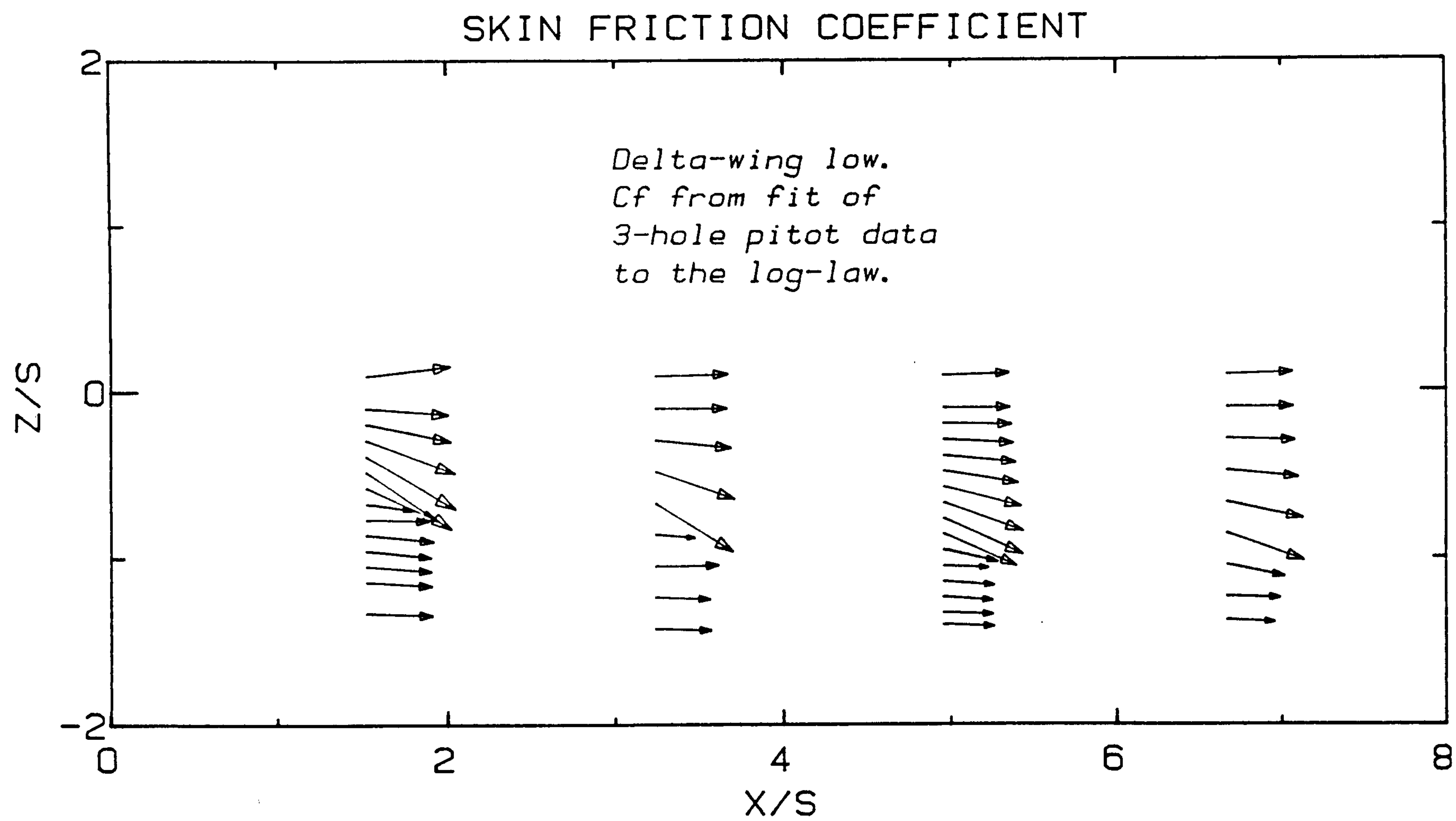

Figure 8(b) Skin friction coefficient vectors, vector length equal to s corresponds to $C_f = 0.01$, delta wing low (first test case)