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New Method for the Eduction of Natural Coherent Structures

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Introduction

NATURAL large-scale coherent structure eduction is generally known to be troublesome. Even though these large-scale structures are repetitive, they are difficult to educe due to jitter and the natural variations in the structure shape, size, orientation, passage time, and trajectory.[1–3] Earlier these structures were studied using artificial excitation (acoustical, mechanical, etc.). It was assumed that the excited structures were approximately the same as the natural ones if low-level excitation were used.[2,4]

Conditional sampling techniques have been used extensively in the measurement of the coherent structures in the shear flows with or without external excitation.[2,4,5] In this technique, a reference probe is fixed in space and used for detection of coherent structure passage while a measurement probe is moved in space. Utilizing the information from the reference probe, quantitative data are often phase averaged to reveal the deterministic structure properties. One phase-averaging method used for eduction is the pattern recognition method. This method is based on the alignment of the events using amplitude, slope, and intermittencies. This method is believed to limit the selection and artificially modify the extracted pattern.

In order to educe the structures in an axisymmetric freejet, Zaman and Hussain[4] used several triggering criteria. They investigated the effects of the threshold level, triggering window, joint probability of longitudinal and lateral instantaneous signals, reference probe location, etc. on education. Their conclusion, "triggering on the positive peaks of the longitudinal velocity signal derived from the high speed side of the mixing layer," gave the best education. According to Bruun,[3] triggering on the high-speed-side peaks of the reference signal also obtained good results. However, when the peak amplitude of the longitudinal velocity signal is small, as in the current case, i.e., flows with fully turbulent pipe flow exit conditions, a better method was desired.[6]

Experimental Arrangement

In the present study, air was introduced into a circular delivery tube 45 diameters long with an inner diam of 5.08 cm. The jet was then allowed to impinge vertically onto a flat plate. All flowfield measurements were acquired with an X-wire, while a reference probe, a straight wire, was used to detect the coherent structure passage. Hot wires were sampled simultaneously at 2 kHz.

The Reynolds number based on the jet diameter D was 13,000, and the jet to plate spacing was $4D$. The measurement plane was formed by the jet centerline and the radial direction. There were 330 grid points in the measurement plane (30 streamwise and 11 radial R). After extensive fast Fourier transform (FFT) surveys, the reference wire was placed at $X/D = 1.0$ and $R/D = 0.25$. To minimize reference probe interference, the X wire was positioned on the jet's opposite side.

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Life Cycle Method

After careful conditional sampling (structure identification and selection) phase averaging is employed by means of structure phase alignment. The time average of the reference signal is used to establish the threshold level for both triggering and cycle determination. Using this average value, the reference wire time series is interrogated. When the reference signal experiences a positive, traveling across the threshold level, that location in the time series is marked as the beginning of a cycle (Fig. 1). The end of the cycle is determined when the reference signal makes a second positive going across. This establishes the beginning and end of each cycle in the time series. Likewise, the corresponding X-wire time series is also marked and saved as a cycle.

Once a cycle is established the number of data points in the cycle is determined. If the number of data or phase points in a cycle is within the predetermined range ($M \pm N$), then the cycle is accepted for future phase averaging. Here, M is a measure of the structure time scale (life time) and N determines the tolerance above and below a chosen scale. So there are M phase points in the phase-averaged cycle. Depending on the size of vortical structures that are intended to be educed, values of M and N are selected. A sample of such a histogram is presented in Fig. 2. As seen from the histogram, if the number of phase points in a cycle is very large (i.e., very large structures) only a limited number of the total population of vortical motions in the flowfield would be represented. Similarly, choosing short cycles would only enable the eduction of the smaller vortical structures. The present goal was to educe typical large-scale vortical structures. That is, those structures whose period, as determined from an FFT of the reference wire signal, was approximated to be 12.5 ms.

Preparing for phase averaging, normalization of the cycles is needed (Fig. 3). Normalization is achieved by nondimensionalization of the cycle by its period. This is referred to as phase alignment. Cycles which have less than M data points can be stretched, and cycles with more than M data points are compressed.

Several cases for various M and N values were evaluated for the current experimental data. Because of space considerations only two cases are presented: 1) $M = 30$ and $N = 7$ and 2) $M = 20$ and $N = 7$. An examination of the histogram indicates that these two cases account for 23% and 33%, respectively, of the cycles represented by the triggering hot-wire time series. A value $N = 7$ indicates that the structure interval is ± 3.5 ms. The educed coherent vorticity using this technique is shown in Fig. 4.

In summary, a new conditional-sampling/phase-averaging method is introduced for the eduction of the natural large-scale coherent structures. Constant threshold level methods, which give rather satisfactory results in the eduction of the coherent structures in excited flows, fail in the unexcited case of the complex flows. The life cycle method described in this paper offers a good way of educing the natural coherent structures in highly complex flows in which a number of modes are present. It is named the life cycle method because the conditional sampling and phase-averaging technique is based on the coherent structure's life time, which is the period between its birth and destruction.[7]

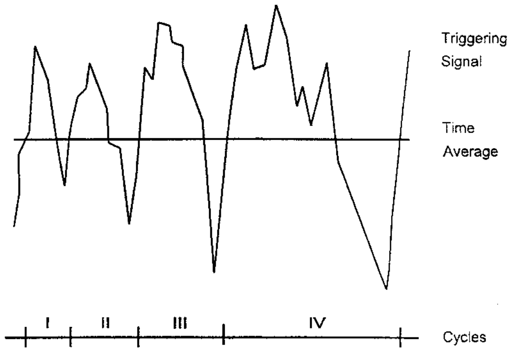

Fig. 1 Cycle definition.

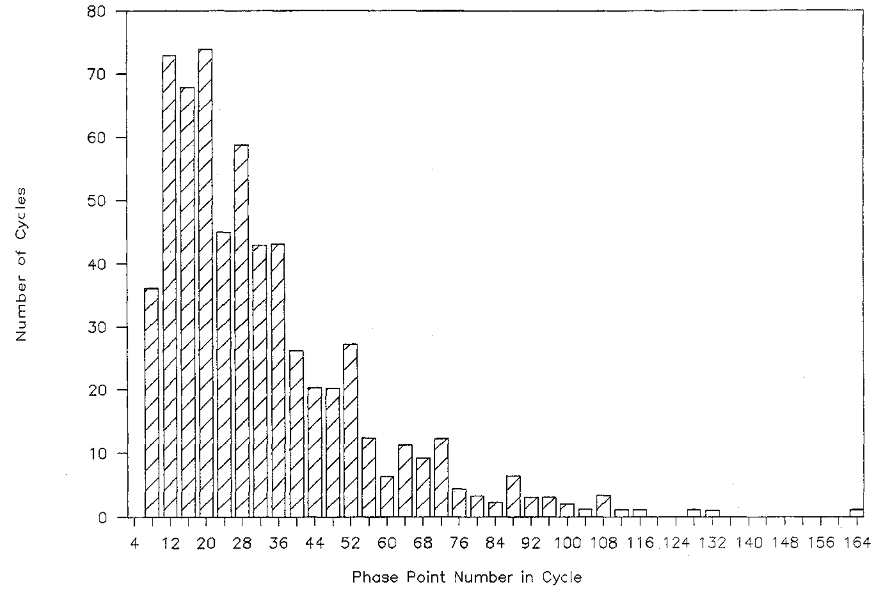

Fig. 2 Histogram for cycle population.

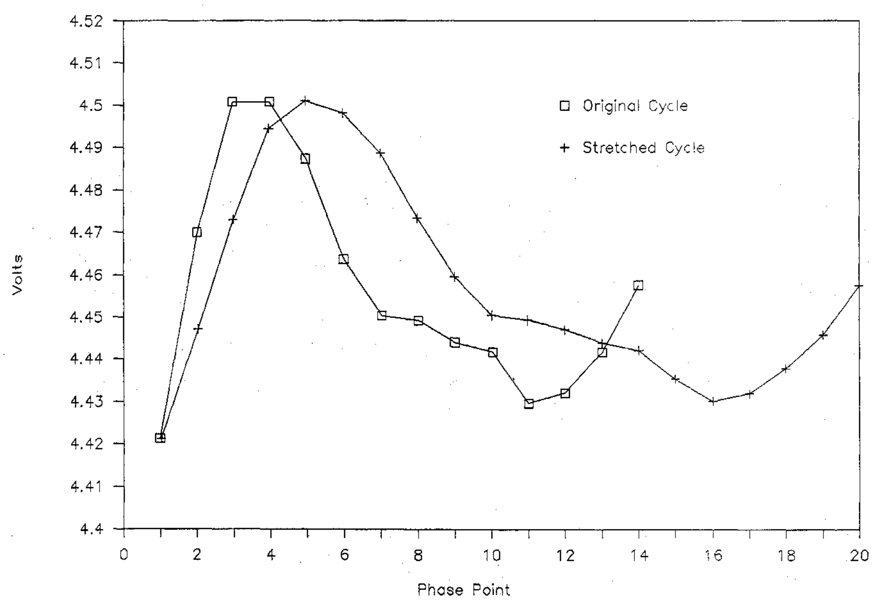

Fig. 3 Normalization of a cycle.

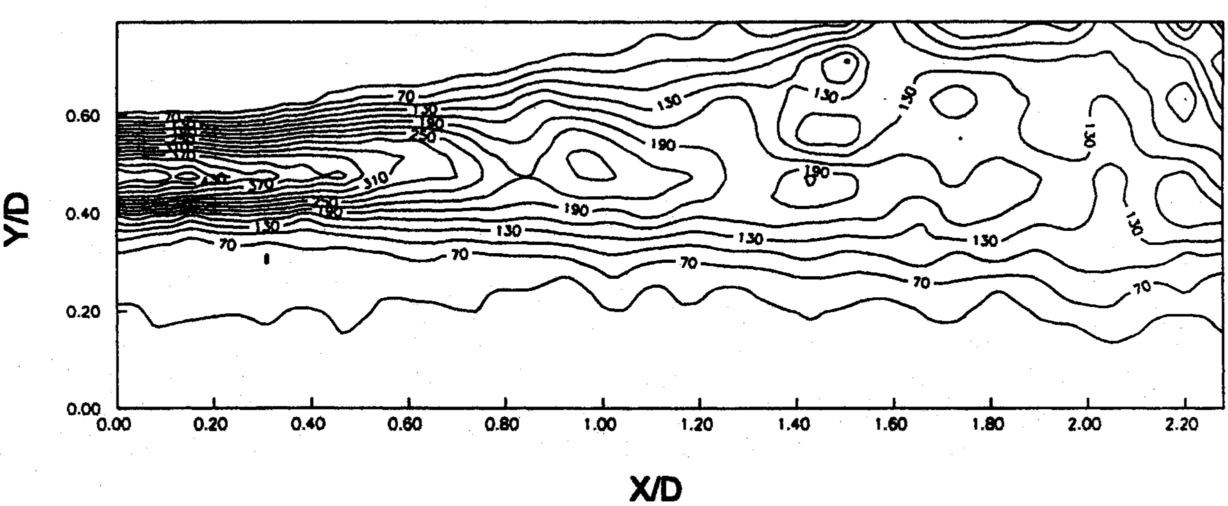

Fig. 4 Sample phase-averaged vorticity contours.

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Shrinkage Flow Effects on the Convective Stability of NH_4Cl-H_2O Directional Solidification

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Nomenclature

A = discretization matrix left-hand side
a = wavenumber, 1/cm
B = discretization matrix right-hand side
B_C = coefficient of solutal expansion, 1/wt%
B_T = coefficient of thermal expansion, 1/°C
C = solutal concentration, wt%
C_p = specific heat, J/g °C
C_t = dendrite tip solutal concentration, wt%
c = constant in permeability model
D = solutal diffusivity, cm²/s
d = characteristic length for Forchheimer inertia term, cm
dl = length of solutal diffusion layer in all liquid region, cm
$d1$ = primary dendrite arm spacing, cm
F = Forchheimer inertia term, 1/cm
Gl = temperature gradient at solid-liquid interface, °C/cm
g = gravitational acceleration, cm/s²
g_e = Earth's gravitational acceleration, 980 cm/s²
k = partition coefficient
L_f = latent heat, J/g
m = liquidus slope, °C/wt%
P = pressure, dynes/cm²
T = temperature, °C
t = time, s
u = fluid velocity in x direction, cm/s
V = solidification growth rate, cm/s
$\bar{V}$ = fluid velocity vector, cm/s
W, w = fluid velocity in z direction, cm/s
x = solution vector, W, T, C
y = horizontal coordinate normal to gravitational acceleration, cm
z = vertical coordinate parallel to gravitational acceleration, cm
zt = height of two-phase region, cm
zl = far-field distance, cm
α = thermal diffusivity, cm²/s
γ = solidification shrinkage parameter, $(\rho_s - \rho_l)/\rho_s$
κ = permeability, cm²
ν = kinematic viscosity, cm²/s
ρ = density, g/cm³
ρ_l = liquid density, g/cm³
ρ_s = solid density, g/cm³
σ = temporal growth parameter, 1/s
Φ = liquid fraction

Subscripts

0 = value at $z = 0$
∞ = far-field value
s = base state value

Superscripts

$'$ = perturbation value
$*$ = critical value

Introduction

CONVECTIVE flows occurring during solidification have been studied extensively. For multicomponent systems, the flows are primarily a manifestation of density differences within the liquid arising from phase change solutal redistribution. The resulting fluid motion can have a dramatic consequence with respect to the results of the solidification process. Both constituent segregation and solid structure are influenced by convection, and significant effort has been expended in trying to model these effects.[1–11] Because convective flows create constituent segregation, i.e., channelling and freckling, within the final solid matrix, they are generally considered undesirable, and it is of interest to determine solidification conditions for which convective flows will not occur.

Background

The importance of gravity level for vertical directional solidification (VDS) has been examined using linear stability analyses by Nandapurkar et al.[9] Worster,[10,11] and Hopkins.[8] The importance of other parameters has also been examined. Neilson and Incropera[1] showed the effects of permeability on nonlinear convection during the solidification of Pb-Sn. Worster[10,11] used a novel linear model to show the effects of permeability and Prandtl number, among other parameters, on the transition. He found two regimes for the breakdown, one associated with the fluid layer and the other associated with the mushy zone. Hopkins[8] examined the influence of the two-phase region on breakdown, performing both linear stability calculations and experiments. Each of these studies illustrated the importance of one or more parameters on the transition to convection for VDS. The study reported here emphasizes the importance of a factor which has received little attention, shrinkage flow.

The physical situation associated with the convective stability of the melt for a solidifying system is as follows. A solutal diffusion layer develops within and in front of the growing two-phase mushy zone, and, if the solute is less dense than the bulk fluid, the potential for buoyant flow exists. Figure 1 shows the temperature, solute, and density profiles for this situation. For stability calculations concerning many materials (including the NH_4Cl-H_2O discussed here), it is of interest to determine to what degree the shrinkage flow influences the transition to convective flow.

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