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INTRODUCTION

The study of unsteady turbulent boundary-layer flows has become very important during the past several years. Physical experiments in this area are difficult to perform because of the complex mechanisms and sophisticated instrumentation that are required. As a result, accurate measurements are scarce. Most of the research effort has been expended on developing computational methods for modeling the related equations, and several numerical experiments have been performed by various authors. However, these numerical studies have seldom addressed the same problem; as a result, little detailed comparison of results has been possible. In the rare case when a physical experiment has been available, the results of the various methods have differed widely, even on so simple a case as oscillating flow on a flat plate (fig. 1). There remain many unanswered questions, and a more coordinated effort is needed so that the effect of numerics can be isolated from the effects of turbulence modeling, as well as from experimental inaccuracy.

Five numerical experiments are proposed herein as standard cases to be studied by all who attempt the analysis of unsteady turbulent boundary-layer behavior. These five problems do not encompass all of the fluid mechanics associated with unsteady boundary-layer characteristics; however, they are suggested as a common starting point for all methods, so that differences between the results of various methods can be studied in a completely defined environment. When the initial and boundary conditions are fully defined, the variances in the results can be studied with a much reduced range of unknown parameters to evaluate.

The test cases are thus presented as an idealized set of experiments analogous to those of the 1968 Stanford conference (ref. 2), except that here the experimental data are mathematically defined. The various methods can then be compared on common grounds, and the results interpreted in a known environment. The test cases have been designed to increase progressively in difficulty and thus test systematically the capabilities of proposed numerical methods. They include steady flow on a flat plate, steady adverse-pressure-gradient flow, oscillatory flow on a flat plate, unsteady adverse-pressure-gradient flow, and ultimately, unsteady reversed flow.

STEADY FLOW USING TIME-RELAXATION

Case 1: Zero Pressure-Gradient

Steady turbulent boundary-layer flow on a flat plate has been chosen as the first test case because it allows evaluation of candidate computer programs in a well-known environment which has been accurately modeled by many steady-flow methods (ref. 2). In addition, the results of these calculations are to be used as starting conditions for flow Cases 3-5. The chosen test case is the Wieghardt flat-plate flow No. 1400 as evaluated in reference 2. In order to permit programs to develop properly the requisite initial profiles for pertinent parameters, computation may begin ahead of the specified starting station and proceed to the starting location while permitting any transient effects of the particular technique to dissipate before computing the required run. The starting condition of $R_\theta \doteq 5000$ $(x = 1.24\ \text{m})$ has been selected to reduce the possible contribution of low Reynolds number effects to the problem; the calculation is to progress to $x = 4.69$ m $(Re_x = 10^7)$.

Required inputs- Match or input the experimental u/U_e vs y/δ^* at $x = 1.24$ m; impose $U_e(x)$ of reference 2 as external velocity condition.

Required procedure- Using the velocity profile u/U_e vs y/δ^* at $x = 1.24$ m as initial conditions at all subsequent x calculation stations, compute the flow as a time-dependent relaxation to steady-state conditions. Indicate the time required for the δ^* to attain 99% of its computed steady-state value at $x = 4.69$ m. This time should be presented in terms of reference lengths traveled by a particle moving at free-stream velocity $(L = 3.45\ \text{m})$. Since this is also a test of the program's capability to adjust to variations in initial conditions, an indication of the size and number of computational steps should be presented. Convergence must be demonstrated in the variation of δ^* vs t for a time equivalent to $0.25\ (L/U_\infty)$ after δ^* has reached 99%.

Required comparisons- Comparisons with experimental data of reference 2 are required for the velocity profiles at $x = 1.24$ m and 4.69 m; note that all y profiles are to be scaled by displacement thickness. In addition, the x distributions of wall shear stress, displacement thickness, and shape factor are required. Optional: Present the variation of shear stress vs (y/δ^*) at the initial and final stations.

Case 2: Adverse-Pressure-Gradient Flow

The analysis of spatial adverse-pressure gradients plays an important role in the study of unsteady turbulent boundary-layer behavior. Therefore, the second test case requires demonstration that each method can properly represent such developments in steady flow prior to addressing the unsteady problem. The Bradshaw adverse-pressure-gradient Flow C (No. 3300 of ref. 2) is proposed for this purpose.

Required inputs- Match or input the experimental u/U_e vs y/δ^* at $x = 0.61$ m (2.0 ft); impose $U_e(x)$, and $DU_e(x)$ as given in reference 2 as external velocity and dU_e/dx conditions.

Required procedure- Use the velocity profile u/U_e vs y/δ^* at $x = 0.61$ m as the initial condition for all computation stations from $x = 0.61$ m to $x = 2.13$ m (7.0 ft). Following the method of Case 1, compute the flow showing the time required for δ^* at $x = 2.13$ m to reach 99% of the computed steady-state value. If a program is not capable of accepting this starting condition, the numerical experiment can be started using the tabulated experimental profile data of reference 2. In either case, show δ^* as a function of time for $0.25(L/U_\infty)$ past the time noted above to demonstrate convergence.

Required comparisons- Comparisons with experimental data of reference 2 are required for the velocity profiles plotted vs y/δ^* at $x = 0.61$ m and $x = 2.31$ m. The x distributions of wall shear stress, displacement thickness, and shape factor between the beginning and ending stations are required. Optional: Present the variation of the shear stress plotted vs (y/δ^*) at the initial and final stations.

UNSTEADY FLOWS

Case 3: Oscillating Flow on a Flat Plate

The oscillating flow over a stationary flat plate offers the simplest extension of turbulent boundary-layer methods to unsteady flow, both physically and mathematically, because the turbulent structure and scaling laws are not complicated by the additional effects of spatial pressure gradients. It is also a case for which some experimental data already exist (refs. 3 and 4). Even in this case there is a great diversity of results, as shown in figure 1. However, the differences may possibly be attributed to different interpretations of the initial and boundary conditions, a difficulty that will be alleviated by the use of the proposed standard-case conditions.

Since the steady flow on a flat plate is a universal starting place for turbulent boundary-layer theories, the well-documented Wieghardt flow of Case 1 has been selected as the initial conditions for the proposed oscillating flow test. Again, the starting condition is chosen at an R_θ such that no low Reynolds number effects will be present. Note: the reference length for reduced frequency computation corresponds to the length of the unsteady portion of the flow rather than the distance from $x = 0$. This length has been chosen because the flow is considered to be quasi-steady up to $x = 1.24$ m; therefore, this initial distance will not contribute to unsteady effects.

Required inputs- The required inputs are:

1. $t \geq 0$, $x = 1.24$ m: Wieghardt flat-plate profile as determined for Case 1, with $R_\theta = 4860$, modified to correspond to local edge-velocities such that $R_\theta = 4860\ (U_e/U_\infty)^{0.8}$

2. $x \geq 1.24$, $t = 0$: results of computation of Wieghardt flat-plate flow as determined in Case 1 for $x = 1.24$ m to $x = 4.69$ m

3. Edge conditions: $U_e/U_\infty = (1.0 + A \sin \omega t)$

4. Test conditions: $\omega = 0.5, 1.0, 5.0, 10.0$, where $\omega = \Omega L/U_\infty$, $U_\infty = 33$ m/s, $L = 3.45$ m; $A = 0.1$ for all frequencies (Optional: $A = 0.5$)

Required procedures- Using the specified inputs, compute three cycles of oscillation for each frequency. All output data are to be based on the third cycle of computed results, with information available at 30° increments through this cycle.

Required outputs- The required outputs are:

1. Fourier analysis of the velocity profile at $x = 4.29$ m, presenting the mean and first harmonic as a function of y/δ^* for each frequency (see fig. 2). When available, present the shear stress profile at $x = 4.29$ m in the same manner for each frequency.

2. Plots of the wall shear stress, displacement thickness, and shape factor as functions of ωt for the last cycle, showing all frequencies computed.

3. Plots and tabulation of phase and amplitude of wall shear stress, displacement thickness, and shape factor as functions of $\omega(x - 1.24)U_\infty$ up to $\omega L/U_\infty$ for each frequency. Optional: Plot of the phase data as a function of $(x - 1.24)$ showing the development of the phase angle along the plate up to $\omega L/U_\infty$.

Case 4: Unsteady Adverse-Pressure-Gradient (Unsteady Howarth Flow)

Although some experiments are in progress (cf. ref. 5), no fully documented experimental data presently exist that demonstrate the effects of strong, unsteady adverse-pressure-gradients on turbulent boundary layers. Previous analyses have considered flows with complicated combinations of spatial and temporal pressure gradients (refs. 6 and 7), making it difficult to assess the effect of unsteadiness on specific boundary-layer properties. In contrast, the unsteady Howarth flow chosen here starts from a well-established steady flat-plate flow, on which a linear deceleration of U_e is imposed at $t = 0$. After $t = 0$, the value of dU_e/dx is increased linearly with time. This case has been selected in order to simplify the relation between spatial and temporal pressure gradients while demonstrating the important features of unsteady turbulent boundary layers experiencing adverse pressure gradients. The test case will only be calculated to the point of flow reversal at the surface, so that no difficulty is introduced by ill-defined downstream boundary conditions.

A primary effect of unsteadiness on boundary-layer flows experiencing adverse pressure-gradients is to delay and even to reduce the importance of the strong singularity normally occurring at flow reversal (ref. 8) in steady flows. In the unsteady environment, this singular behavior does not always appear and the flow near the wall can stagnate without strong changes in the character of the integral parameters. (This is illustrated by the solid curves in figure 3 for the conditions described below.)

Required inputs- The required inputs are:

1. $t \geq 0$, $x = 1.24$ m: Wieghardt flat-plate profile as determined for Case 1 at $x = 1.24$ m ($R_\theta = 4860$), maintained as a quasi-steady input profile for all subsequent time

2. $x \geq 1.24$, $t = 0$: results of computation of Wieghardt flat-plate flow as determined in Case 1 from $x = 1.24$ m to $x = 4.69$ m

3. Edge conditions: $U_e/U_\infty = (1.0 - AXt)$, $1.24 \leq x \leq 4.69$ m, $X = (x - 1.24)/L$

4. Test conditions: $U_\infty = 33$ m/s; $L = 3.45$ m; $A = 2.4\ \text{sec}^{-1}$

It may be noted that for the values of the constants chosen, a fluid element in the free stream will have moved approximately 4L by the time the local edge-velocity at the final x station reaches stagnation.

Required procedures- The flow is to be assumed quasi-steady up to $x = 1.24$ m; the velocity distribution is then imposed as a linear function of x and t until the wall-shear stress equals zero at the final station. Two conditions are to be studied: (1) compute the flow until the wall shear stress reaches zero at the final station under the influence of the fully unsteady free-stream flow; and (2) calculate the unsteady turbulent boundary layer that develops when the $U_e(x)$ distribution that results at the completion of condition (1) is suddenly imposed on the flat plate flow of Case 1. Compute the flow until the X location of the flow reversal point stabilizes. Indicate the time at which separation is considered to have occurred.

Required outputs- The required outputs are:

1. Velocity profiles vs y/δ^* at $x = 2.29$, 2.89, 3.79, and 4.69 m ($X = 0.3$, 0.48, 0.74, and 1.0) at the completion of condition (1), and the final result for applicable X values for condition (2). Optional: Present the shear stress vs y/δ^* for each of the above conditions.

2. Present the variation of wall shear stress, displacement thickness, and shape factor as a function of x from 1.24 to 4.69 m for the two conditions cited (see fig. 3).

Case 5: Unsteady Flow-Reversal Without Separation (Constant-Focus Hyperbola Unsteady Turbulent Bubble)

A modified form of the unsteady turbulent bubble originally proposed in reference 9 has been selected as the test case for evaluating the use of unsteady boundary-layer methods for analysis of flows where significant flow reversal appears before separation occurs. The bubble overcomes one of the major difficulties in studying reversed flows in steady boundary layers; namely, that there is seldom a realistic way to model the incoming flow from the down-stream boundary of the separated region. The constant-focus hyperbola has been selected because the discontinuity at the velocity minimum of the original case of reference 9 has been found to contribute significantly to flow behavior in other regions of the flow field.

The calculations are to be started using a constant zero-pressure-gradient flow (Case 1) and then the adverse-pressure-gradient is to be introduced as a function of x and t. When the bubble forms, the fluid elements contained within the unsteady turbulent bubble have all been introduced into the flow from the upstream boundary at an earlier time. Therefore, the history of all the fluid elements is known throughout the calculation, and the fluid elements can be traced as they are brought to rest and reverse within the bubble. The fluid elements wihin the reversed-flow region retain their gross turbulence characteristics, and therefore an eddy-viscosity as well as more sophisticated modeling may apply.

The selected problem is one which encompasses a significant region of reversed flow where integral parameters have not been grossly distorted, as well as a region of reversed flow where such distortion does occur. The shape factor is of particular interest, because it seems to indicate a demarcation between regions of simple reversed flow and reversed flow where the momentum thickness has significantly increased, thus causing a rapid drop in shape factor (fig. 4). This test case is suggested as a case that may help determine the limitations of boundary-layer theory in the study of unsteady turbulent boundary layers.

Required inputs.- The required inputs are:

1. $t \geq 0$, $x = 1.24$ m: Wieghardt flat-plate profile as determined for Case 1 at $x = 1.24$ m ($R_\theta = 4860$), maintained as a quasi-steady input profile for all subsequent time

2. $x \geq 1.24$, $t = 0$: results of computation of Wieghardt flat-plate flow as determined in Case 1 from $x = 1.24$ m to $x = 4.69$ m

3. Edge conditions: $U_e/U_\infty = 1.0$, $x < 1.24$ m, $U_e/U_\infty = 1.0 + [A^2 + (Bt)^2(X - X_o)^2]^{1/2} - [A^2 + (BX_ot)^2]^{1/2}$, $X = (x - 1.24)/L$, $1.24 \text{ m} \leq x \leq 4.69$ m

4. Test conditions: $U_\infty = 33$ m/s; $L = 3.45$ m; $A = 0.05$; $B = 3.4 \text{ sec}^{-1}$; $X_o = 0.7$

Required procedures.- Assume flow is quasi-steady up to $x = 1.24$ m, then impose the constant-focus hyperbola velocity distribution as a function of x and t. The final time will be determined by the performance of each individual program. If results indicate that the developments observed in figure 4 occur, then compute until the plateau in shape factor is well defined. This specification is intentionally vague, since this case is offered as a test of the limitations of boundry-layer theory as well as a standardized test for turbulent boundary-layer calculations, and no arbitrary stopping point can be accurately established.

Required outputs.- The required outputs are:

1. Velocity profiles vs y/δ^* at $x = 2.29$, 2.89, 3.79, and 4.69 m ($X = 0.30$, 0.48, 0.74, and 1.0) at time intervals associated with $0.4\ L/U_\infty$, and at last time step calculated. Optional: Present the shear stress vs y/δ^* for each location.

2. Present the variations of wall shear stress, displacement thickness, and shape factor as functions of x at time intervals associated with $0.2\ L/U_\infty$. The carpet-plot technique of figure 4 may be used, or a conventional plot of the data in fixed coordinate form is acceptable. Indication should be made of the first time at which flow reversal is detected.

CONCLUSIONS

Five special test cases have been presented in an effort to bring all the various unsteady turbulent boundary-layer calculation methods together, at least for a few common points where direct comparisons can be made. Some correlation with experiment in steady flow is included to verify the basic performance of the various methods, but the emphasis is on analysis of the importance of unsteadiness in zero pressure-gradient, adverse-pressure-gradient, and reversed flows. These tests are not expected to explain all aspects of the fluid mechanics of unsteady turbulent boundary-layer flow behavior; rather, they are offered as a common starting point for further studies. It is the author's hope that the use of these cases will mean that future numerical experiments can be better coordinated with existing knowledge, that the results of these numerical experiments can be better understood, and that new methods can then be judged based on a common standard. The author would appreciate receiving tabulated samples of any computations of these test cases; a compendium of results will be prepared for later publication.

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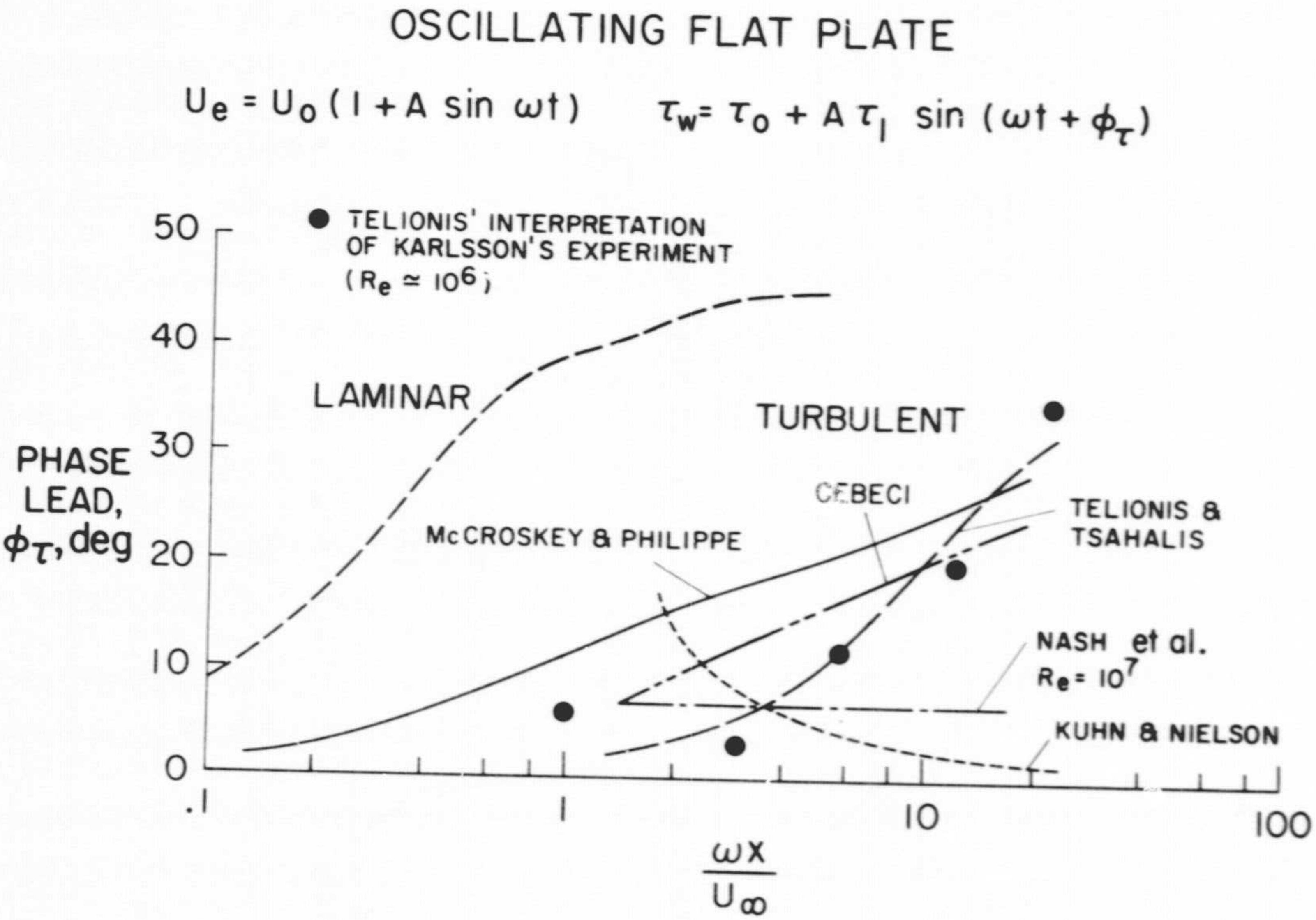
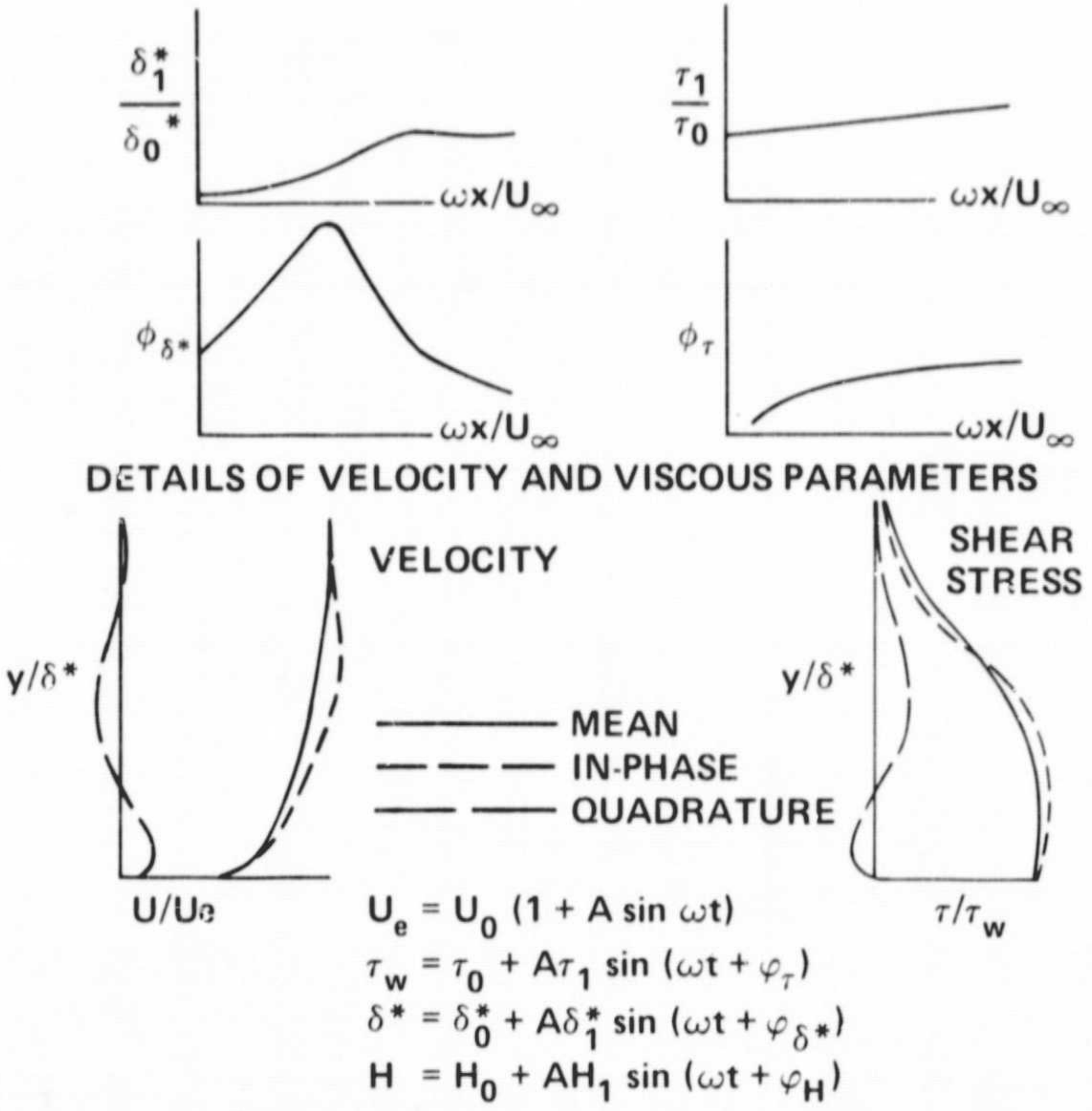


Figure 1.– Phase angle of the wall shear on a flat plate with an oscillating free stream (from ref. 1).



$$U_e = U_0\,(1 + A \sin \omega t)$$
$$\tau_w = \tau_0 + A\tau_1 \sin (\omega t + \varphi_\tau)$$
$$\delta^* = \delta_0^* + A\delta_1^* \sin (\omega t + \varphi_{\delta^*})$$
$$H = H_0 + AH_1 \sin (\omega t + \varphi_H)$$

Figure 2.– Typical flow parameters for a flat plate with an oscillating free stream.

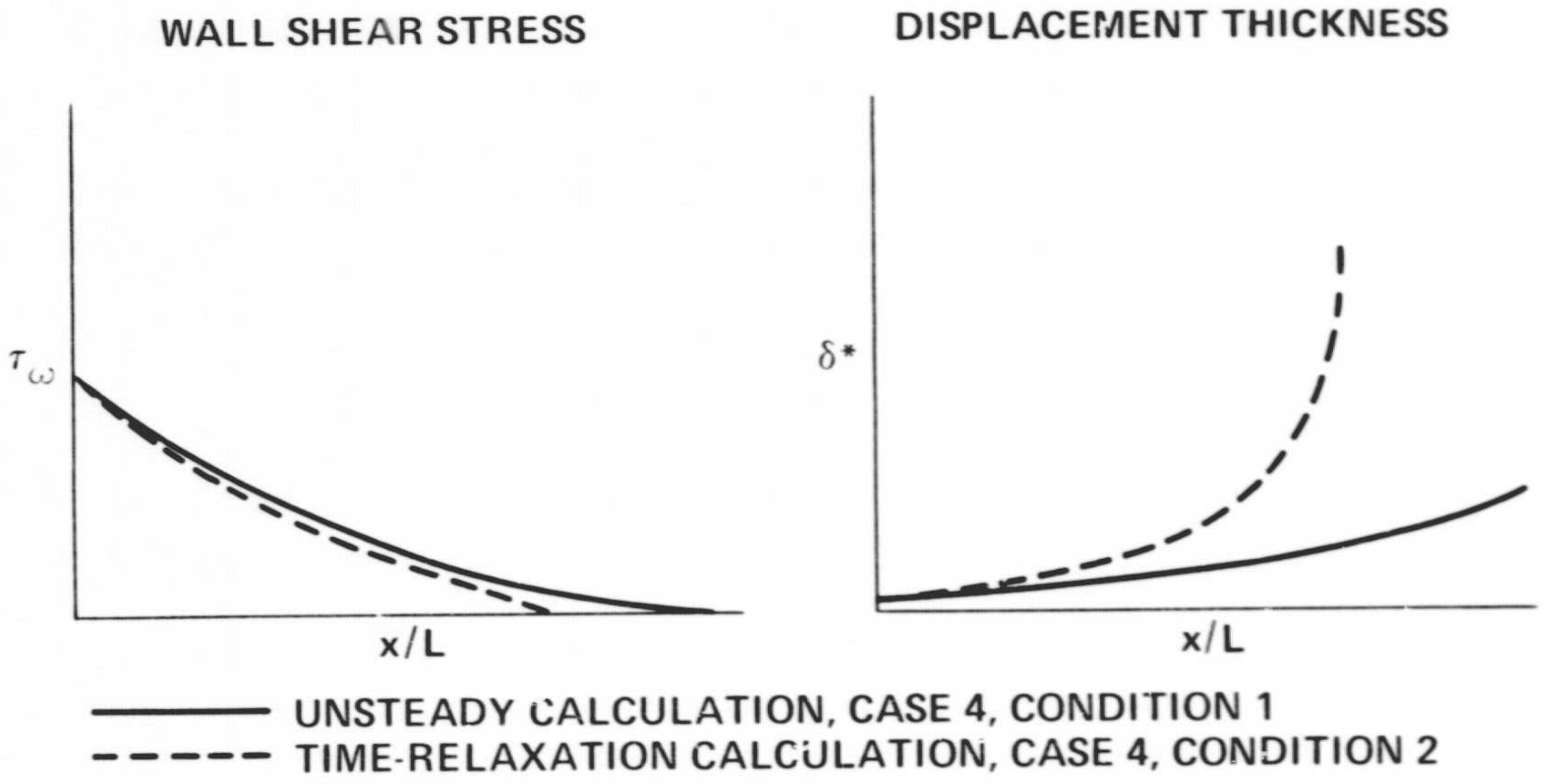


Figure 3.— Wall shear stress and displacement thickness as a function of X/L for the unsteady Howarth flow test case.

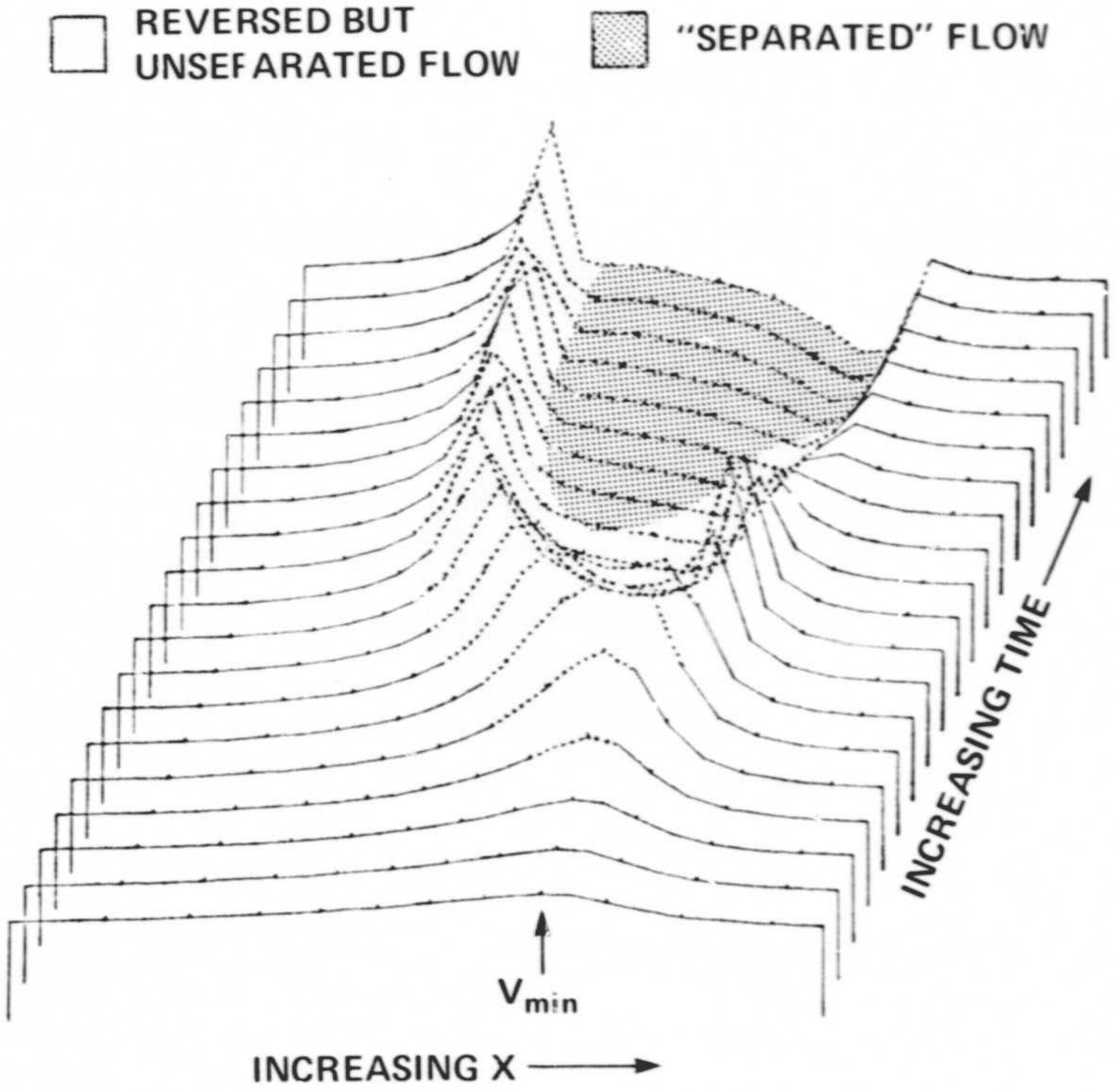


Figure 4.– Shape factor as a function of time and X for constant-focus hyperbola unsteady turbulent bubble.

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15. Supplementary Notes

16. Abstract

Five numerical experiments are proposed as standard cases to be computed by all who plan to analyse unsteady turbulent boundary-layer behavior. In this way, differences between the results obtained by various methods can be compared in a completely defined environment. The test cases range in difficulty from time-relaxation study of the steady flow on a flat plate to the analysis of unsteady reversed flow. Initial and boundary conditions are fully defined for each case and representative outputs are presented. It is recommended that tabulated samples of computations of these test cases be published in a compendium of results.

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