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Respectfully,

H. B. Gibbons
Associate Director

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FINAL REPORT

FOR THE PERIOD ENDING

26 June 1966

Contract No. NASw-956 (Modification 1)

"STUDY OF VORTEX BOUNDARY LAYER INTERACTIONS"

Ling-Temco-Vought, Inc.
LTV Research Center
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INTRODUCTION

Although the main purpose of this report is to present the progress during the fourth quarter of this contract period it also summarizes the effort of the total three year program and is the final report for this program and contract.

The objective of this research program has been to study the effects of strong persistent vortices on a turbulent boundary layer. The program has been primarily experimental, making use of a facility designed particularly for basic studies of incompressible boundary layer flow.

The subject study was initiated in 1963 under the Ling-Temco-Vought independent research and development program. Funds for supplementing the existing effort were solicited and resulted in Contract NASw-730[1] effective 26 June 1963 and extended through Contract NASw-956[2] effective 26 June 1964 and Contract NASw-956 (Modification 1)[3] effective 26 June 1965. The work statements included in the three contract periods are as follows:

1963 - 1964 Contract No. NASw-730

1. Develop methods for experimentally initiating and controlling vortex elements in a turbulent boundary layer. The vortex elements desired will include both the ring-type and the spiral longitudinal-type.
2. Determine the effects of the vortex-boundary layer interaction in the boundary layer, as seen by total pressure profiles, turbulence intensity profiles, and direct skin friction measurements. This is to be performed for various scales and intensities of vortex elements for given boundary layer conditions, and over a range of length Reynolds numbers.
3. Begin analyses of the experimental data in the light of previous applicable theoretical and experimental studies, and attempt to explain the flow mechanisms involved.

1964-1965 Contract No. NASw-956

1. Continue systematic experimental studies of the effects of persistent vortices on turbulent momentum transport and, in particular,

on skin friction drag and net drag, including form drag of the elements.

2. Investigate the flow in the viscous sublayer of a turbulent boundary layer for a smooth wall and with wall-mounted disturbance elements. This will include steady-state and instantaneous velocity and wall shear stress measurements. Analysis will be made with regards to recent theories of stability and mixing in a turbulent boundary layer.
3. It is expected that an evaluation of the effectiveness of reducing net drag by producing persistent vortices will be made during contract year 1964-1965. If this evaluation shows that drag reduction is possible, effort will be applied to optimizing the effect, and it is recognized that accordingly less effort will be applied to Task No. 2.
4. If, after a thorough investigation, it appears that no net drag reduction is possible due to persistent vortices, accordingly more of the effort will be applied to Task No. 2, and Task No. 3 will not be considered. In addition, a study will be initiated regarding other possible techniques for reducing drag in the turbulent boundary layer.

1965-1966 Contract No. NASw-956 (Modification 1)

1. Conclude the experimental studies and the required analyses on the effects of added vorticity and disturbances on drag reduction in the turbulent boundary layer.
2. Investigate the mechanism of the fully developed turbulent boundary layer by observing the turbulent flow in the boundary layer channel at very low speeds. This includes the introduction of smoke both in bulk and locally along with velocity profile measurements.

Following is a discussion of the overall program described in these work statements and the results that have been obtained.

EXPERIMENTAL FACILITY AND INSTRUMENTATION

The experimental facility and instrumentation have been described in some detail in references 4 and 5 and will be covered only briefly here.

All experiments performed under this contract were conducted in the LTV boundary layer channel facility which is an open-circuit wind tunnel designed for study of the boundary layer produced on the wall of the 25-foot long test section. Details of this facility are given in reference 6.

Instrumentation consisted of a fast response pressure transducer (Equibar Model 121 Pressure Meter) for velocity and pressure measurements, constant temperature hot-wire probes for turbulent velocity fluctuations and mean velocity measurements, and a floating element skin friction balance for shear stress measurements. The skin friction balance is described in detail in reference 7.

VORTEX-BOUNDARY LAYER INTERACTIONS

The first phase of the study into the effects of ordered vorticity added to a turbulent boundary layer was concerned with spiral longitudinal vortices. The vortices were generated by lifting flat plate elements fixed to the test section wall. These results have been reported in reference 8. The conclusions from this report are as follows:

"1. For the configuration tested, designed to produce strong mixing in the boundary layer, the skin friction is both decreased and increased locally, but the integrated effect, greater than a few element heights downstream, is to increase the skin friction.

2. The major effect on skin friction is found to be due to the mixing added by the vortices, whereas the effect of the form drag of the elements is not significant.

3. Vortices generated well inside the turbulent boundary layer affect the skin friction and velocity profile far downstream of the point of origination.

4. There is an indication from the limited data taken with the different spacing arrangements that the average effect on skin friction depends only on the number of elements per unit transverse length and not on the spacing. This implies that the mutual interference effects of the vortices are small for the spacings tested.

5. For the configurations tested, the ratio of angular velocity to form drag is a maximum, and the angular velocity approaches a constant

value, near an element angle of attack of eight degrees. Therefore, an unnecessary form drag penalty is incurred by operation of this type of element at greater angles of attack, regardless of the application of the increased mixing."

As can be seen from the above conclusions, the results of this phase of the program were negative in so far as drag reduction is concerned. However, these experiments provided new information which might be useful to anyone interested in the use of vortex generators to improve the momentum deficit near the wall in turbulent shear flow.

The second phase of the study, which was concluded during the last contract period, was concerned with transverse vortices. The results of these experiments are reported in detail in reference 9. The summary from that report and the conclusions drawn from the study are as follows:

"As part of an experimental investigation of techniques for reducing turbulent skin friction drag, small transverse disturbances were introduced into a turbulent boundary layer. The boundary layer was formed on the test section wall of a facility designed especially for low-speed boundary layer studies. Periodic jets of air were injected into the boundary layer from a continuous circumferential slot in the test section wall resulting in reduced values of skin friction drag and boundary layer turbulence. Skin friction measurements, velocity profiles, and turbulence intensity measurements are presented as a function of blowing rate, pulse frequency, and location in the flow field. The experiments show an interesting relation between turbulence intensity and skin friction drag, but no promise is shown for realizing a net drag reduction due to the power requirements of the particular system".

"These experiments are by no means sufficient to completely describe the mechanism responsible for reducing skin friction drag. A thorough understanding of the phenomenon will require much more work. However, several conclusions may be drawn from the results reported herein.

1. A skin friction reduction has been accomplished by the introduction of low turbulence air into a turbulent boundary layer. The fact

that this is possible with either periodic or continuous blowing discredits the importance of any vortical motion for the size disturbances used in this study.

2. The turbulence intensity near the wall is reduced coincident with the skin friction. This effect, along with the effects on the law of the wall, indicate that the skin friction reduction is due to a thickening of the viscous sublayer rather than a gross modification of the velocity profile as might be expected with large scale vortices such as in reference 2. (Eggers, A. J., and Hermach, C. A., NASA RM A54L13,1955).

3. The power required to accomplish the skin friction reduction is prohibitively large to allow a net drag decrease except possibly for certain resonant conditions in the system. This suggests that further work toward developing a more efficient mechanical apparatus might be worthwhile.

4. The turbulence reduction is probably due to the mixing of low turbulence air with the turbulent flow in the boundary layer. The fact that stronger effects occur with periodic rather than continuous blowing at a given blowing rate suggests that a more efficient mixing process is achieved with the former due to the higher jet velocities."

With these results the vortex-boundary layer interaction study was terminated; however, the results suggest several areas of interest that may merit additional attention in the future.

TURBULENT PIPE FLOW AT VERY LOW SPEEDS

The latter portion of the present contract period has been concerned with fully developed turbulent flow at low speeds as specified in task 2 of the work statement for 1965-1966. By operating the boundary layer channel so that the maximum stream velocity is in the range of two to four feet per second (Reynolds number on the order of 6,000 based on channel diameter) a condition very close to fully developed turbulent pipe flow may be achieved by properly tripping the flow near the channel entrance. This flow condition is of interest for two reasons; the turbulent mixing action occurs slowly enough to allow visual observation, and the viscous sublayer becomes thick enough (approximately 1/4-inch) to allow surveys not normally possible in turbulent flow at higher velocities.

In order to confirm that the flow at these low velocities was in equilibrium the velocity profiles at two, three, and four feet per second (measured at the center of the stream) were compared with Coles'[10] empirical curve for the law of the wall. The three profiles are shown in Figure 1. The data for two feet per second are shown to lie somewhat above Coles' curve and it was first thought that the flow was not fully reaching equilibrium. However, Gill and Scher[11] have shown that this is to be expected at very low Reynolds numbers and the data compare favorably with their analysis. Also, as reported previously[5], smoke probes of sub-critical size were employed to visually check the turbulence of the flow. Whereas at relatively high velocities the smoke emanating from the probe seemed to diffuse immediately into a conical pattern stretching downstream, the same test at the low velocities showed a distinct filament of smoke that wavered around in a random pattern. By taking multiple exposure photographs of the smoke filament in the low velocity stream the random pattern was seen to be confined in a conical region similar to that seen at the higher velocities. From these observations it was concluded that the flow was turbulent with the only difference in the various velocity ranges being in the scale and mixing rates of the turbulence.

Many interesting experiments could have been performed with the low velocity turbulent flow, but it was necessary to decide what effort would be most beneficial to the overall program that could be accomplished in the remaining contract period. One significant result of the vortex-boundary layer interaction study indicated that the observed skin friction reductions were due to a modification of the viscous sublayer through a reduction in turbulence intensity. It is well known that disturbances are damped as they feed through the viscous sublayer toward the wall, but little is known about the actual process. An analytical study has been underway to attempt to determine the functional form of the damping process so that a method might be found for predicting the sublayer thickness in terms of flow parameters. This would hopefully lead to better ways of predicting skin friction effects in turbulent flow.

One requirement for the analytical study was to know at what speed, relative to the stream, that turbulent eddies or disturbances were propagated and what distribution, if any, the propagation speed had over a cross section of the flow field. Sternberg[12] used correlation techniques with turbulence data from the literature to show that large scale disturbances propagate at a constant longitudinal speed throughout the turbulent core; that speed being approximately 80 percent of the maximum stream velocity. Sternberg also theorizes that all disturbances in the viscous sublayer are induced by the large scale disturbances outside the sublayer and thus must have the same propagation speed. This says, in effect, that large scale disturbances (one-half the boundary layer thickness of greater) move at the same relative speed regardless of their location. Because of the general lack of data available from studies of the sublayer Sternberg was not able to confirm his theory for this region. This then became the point of interest for the remainder of this contract study.

Constant temperature hot-wire probes were again used for the experiments. The first probe had two similar but separate wires mounted, one behind the other, with 0.3-inch separation. The wires were set parallel to the wall and normal to the stream direction. The probe was adjusted on the traversing mechanism so that both wires were always the same distance from the wall. The signals from the two probes were fed into a dual channel oscillograph. The oscillograph traces showed the two signals to be generally similar but the spatial correlation was only fair and yet the time delay between the appearance of the same disturbance on both channels was too small to measure with suitable accuracy. Larger separations of the wires improved the ability to graphically measure the time delay but this caused even poorer correlations. Smaller separations had the opposite effects.

Assuming that observation of the vertical component of velocity fluctuations rather than the longitudinal component might allow better identification of large scale disturbances a different type of double-wire probe was built. The new probe had two wires with axes parallel to the mean flow direction and lying on a common line. The wire centers were 0.8 inches apart. These wires were primarily sensitive to vertical and transverse fluctuations. The signals obtained with the two wires were remarkably similar even though the wire separation was relatively large. The time difference in the two signals was great enough to allow measurement with nominal accuracy.

A series of measurements were made with the longitudinal wire probe at several flow rates in the boundary layer channel. The probe was traversed from the wall to the channel centerline. Several measurements were taken and averaged at each position. Knowing the distance between wires and the average time difference in the signals the disturbance velocities were calculated and plotted versus distance from the wall. A typical plot of these data is shown in Figure 2 for a velocity at the channel centerline of 4.03 feet per second. The repeatability of the measurements was good enough that the distribution trend shown is believed to be correct. It will be noticed that the disturbance velocity is not constant across the flow field and is actually somewhat similar in shape to the mean velocity profile.

A word of explanation is in order concerning the mean velocity profile. It will be noticed that the flow is slightly asymmetrical with respect to the centerline with the maximum velocity occurring about one inch below the channel center. This was later identified as a thermal effect due to a slight difference in the temperatures (1° - 2° F) of the channel wall and the air stream. In fact the degree of asymmetry and the location of the maximum velocity either above, below, or coincident with the centerline could be controlled by providing mixing and temperature control to the air before it entered the channel. The disturbance velocity data were taken in the lower half of the channel and should be compared to the corresponding branch of the mean velocity profile.

Since the initial experiment indicated that the disturbance velocity was not constant across the flow field it was desired to devise a means of more accurate measurement. The double-wire probe with wires mutually parallel but transverse to the flow was used once again but with the wires closer together. This time a method of electronically measuring the time displacement of the disturbance signal was tried. For two signals identical in all respects except phase it may be shown mathematically that the phase difference is related to the ratio of the rms value of the algebraic difference in the two signals to the rms value of one of the signals. Specifically, for two signals such as

$$u_1(t) = \int_0^{\infty} [a_n \cos 2\pi nt + b_n \sin 2\pi nt]\, dn$$

$$u_2(t) = \int_0^{\infty} [a_n \cos 2\pi n(t + \tau) + b_n \sin 2\pi n(t + \tau)]\, dn$$

the time difference in phase, τ, may be shown to lie between the limits

$$\frac{1}{n_o + \Delta n} \frac{\sqrt{\overline{[u_1(t) - u_2(t)]^2}}}{2\pi \sqrt{\overline{u_1^2}}} \leq \tau \leq \frac{1}{n_o} \frac{\sqrt{\overline{[u_1(t) - u_2(t)]^2}}}{2\pi \sqrt{\overline{u_1^2}}}$$

By subtracting the signals electronically and inspecting a single frequency component, n_o, with a wave analyzer the above limits may be determined. For an ideal case in which the bandwidth, Δn, of the wave analyzer is zero the limits converge giving a specific value for τ. For an actual case, the accuracy with which τ may be determined depends on the ratio of Δn to n_o. The success of this technique also depends on the phase difference being sufficiently small such that

$$\cos 2\pi n\tau \simeq 1$$

$$\sin 2\pi n\tau \simeq 2\pi n\tau \quad .$$

Unfortunately, acceptable results have not yet been obtained with this approach. The problem may be due to an insufficient representation of the signal waveform or to the approximations that were made in the above analysis. Another source of error was a mutual interference effect between the two hot wires which was found to be dependent on both the wire spacing and the local stream velocity. In order to check the measuring techniques an artificial periodic disturbance was put in the flow by blowing into the entrance section with the blowing apparatus used in the vortex-boundary layer experiments. With the two wires spaced approximately 0.030 inches apart and no net flow in the channel the signals from the artificial disturbances were found to be out of phase by 180° as shown by the two wires. With very low velocities in the channel the signal from the downstream wire was attenuated, the attenuation increasing with velocity. At some velocity on the order of one or two feet per second the downstream wire signal would vanish while the signal from the upstream wire appeared to be unchanged. As the stream velocity was further increased the downstream wire would again show a signal which was nearly in phase with that of the upstream wire and increased in intensity with velocity. If the heating current to either wire was turned off the signal from the other wire would take on an entirely different appearance. This was proved to not be wake effects by orienting the wires in various arrangements so as to be sure one was not in the wake of the other. These anomolies are believed to have been due to conduction effects caused by the proximity of the wires in a manner somewhat similar to the effects observed when a hot wire is placed close to a relatively large body of a different temperature such as the channel surface. This phenomenon might be partially responsible for the apparent distribution in the data shown in Figure 2. However, the probes used in those tests were spaced far enough apart that the effects should have been very slight.

One other approach was made to the problem whereby the two signals were electronically moved together in phase and the amount of phase shift required was a measure of the time displacement of the two signals. A capacitance, resistance network was devised which would allow one signal to be shifted in phase with respect to the other signal. Ideally, when the two were in phase their algebraic difference would be zero. In practice, the phase of one signal was adjusted until the difference in signals reached a minimum level. At this point the RC time constant of the circuit was a measure of τ. Again, this technique provided no improvement in the results, probably because of the same reasons stated before.

It is still believed that an accurate measurement of the disturbance velocities can be made by some electronic means with suitable probes. Time limitations have curtailed efforts in this area at the present time but additional efforts will be made at a later date. This report concludes the work on this program covered by NASA support, but it is intended that the program will continue at LTV on a limited basis as time allows.

GENERAL

Professional personnel assigned to this contract during the fourth quarter were:

W. A. Meyer - Principal Investigator, one-fifth time.

J. G. Spangler - Research Scientist, one-half time.

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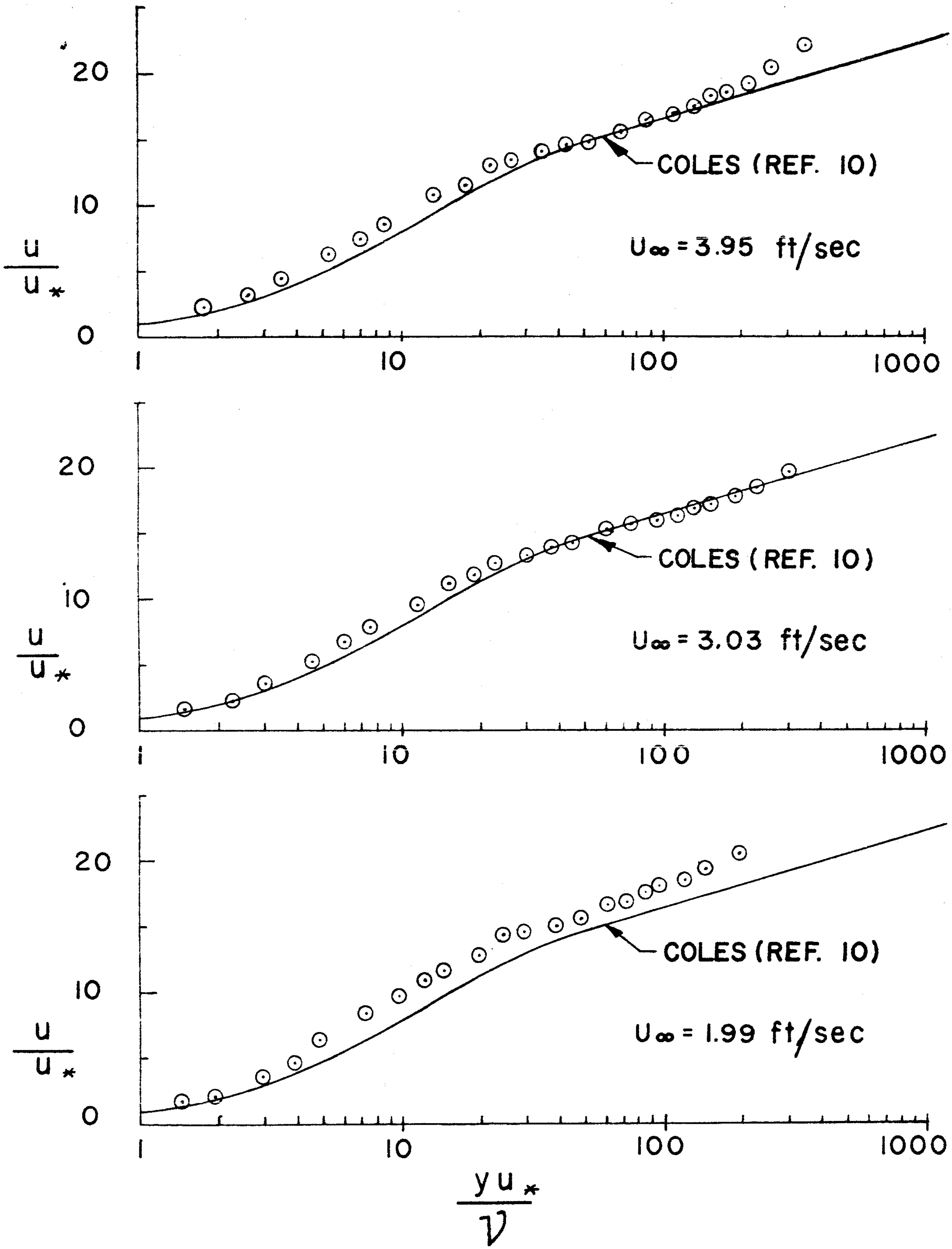

Figure 1 Law of the wall velocity profiles.

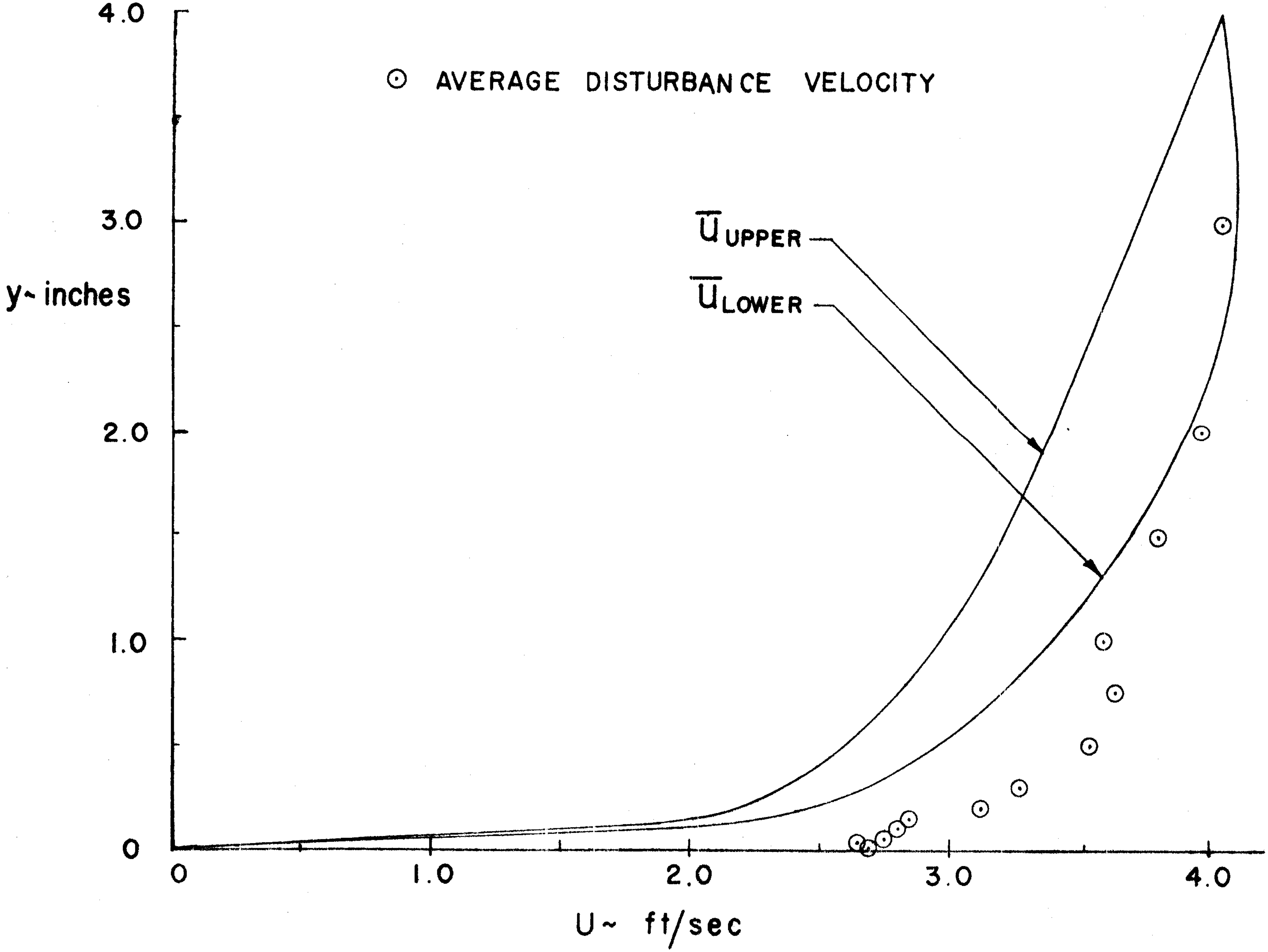

Figure 2 Mean velocity and disturbance velocity profiles.