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# EFFECTS OF TURBULENCE ON LAMINAR SEPARATION ON AERODYNAMIC SURFACES SUCH AS AIRFOILS AND COMPRESSOR BLADING

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## 1. Scientific Significance

The long-term goal of this research program is the determination of the effects of oncoming turbulence on laminar separation on aerodynamic surfaces such as airfoils and axial-compressor blading. In flow through a blade cascade at a Reynolds number of $2 \times 10^5$ or smaller the development of laminar separation on the airfoil suction side leads to prohibitively high aerodynamic losses. The growth of the laminar separation bubble can even yield fully stalled blades. Significant reduction of the aerodynamic losses including prevention of laminar separation is achievable by inducing the development of a profile turbulent boundary layer. Such a turbulent boundary-layer can be generated through supplying oncoming turbulent energy concentrated at scales commensurate with the thickness of the prevailing laminar boundary layer. The mechanism through which adequate accumulation of turbulent energy can be produced and supplied at the desired scales lies in the turbulence amplification characteristic of forward stagnation flow. This selective amplification is governed by the vortex stretching mechanism.

The research program is divided into three phases of increasing complexity. In each phase the evolution of the oncoming turbulent energy, its selective amplification, its management, and ultimately, its effects on the body boundary layer are to be investigated. During the first phase of this program the turbulence amplification in flow about a circular cylinder and the effects of the amplified turbulent energy upon the cylinder boundary layer are being investigated. The knowledge gained from this diagnostic study is to be utilized to identify the vari us phenomena of interest and their application for conducting efficiently t e research tasks of the other two phases. In the second and third phases single airfoils and a blade cascade, respectively, are to be employed.

The theoretical work focused on the furtherance of the vorticity-amplification theory for determining how the amplified turbulence is to be supplied to the boundary layer for retarding and even forestalling laminar separation. To this end, the matching of the outer and inner solutions of the vorticity-amplification theory is to be attempted. Matched asymptotic expansions are to be carried out to meet this objective.

## 2. Current status

The research efforts during the subject period concentrated on: (1) completion of the measurements of turbulence amplification in flow about a circular cylinder; (2) initiation of the measurements of turbulence characteristics in flow about a single symmetric airfoil; and, (3) further examination of various matching numerical methods. Emphasis was placed, however, on the experimental program in order to obtain data on the amplification of the oncoming turbulence and its management.

### 2.1 Flow about a circular cylinder

A paper describing the results of the visualization study of turbulence in flow about a circular cylinder was submitted to and found suitable for publication in the Journal of Fluid Mechanics. A revised manuscript of this paper titled "A Visual Investigation of Turbulence in Stagnation Flow About a Circular Cylinder" was sent to the editor on 6 March 1979. A second short paper summarizing some of the main aspects of the visualization study was accepted for presentation at and publication in the Proceedings of the ASME Symposium on Aerodynamics of Transportation to be held in Niagara Falls, NY from 18-20 June 1979. The title of this paper is "Visualization of Turbulence in Flow About a Bluff Body" and it is scheduled for presentation in the session on Bluff Body Aerodynamics.

The technical report on the effect of amplified turbulence upon the separation on a circular cylinder is in its completion stage. A summary of the results of this investigation was outlined in the last semi-annual status report. It is anticipated that this technical report will be submitted for publication as a NASA CR within four to six weeks. At the present time, a paper based on this forthcoming technical report was accepted for presentation at and publication as a preprint of the AIAA 12th Fluid and Plasma Dynamics Conference to be held in Williamsburg, Virginia from 23-25 July 1979. The title of this paper is "Freestream Turbulence Effect on Laminar Separation on a Circular Cylinder."

The reduction and analysis of the data collected at the planned six subcritical Reynolds numbers ($5 \times 10^4$ to $2 \times 10^5$) is still in progress. Computer codes for conducting this analysis were completed and tested. The results clearly point out the occurrence of selective amplification at scales larger than the neutral one and the existence of a most amplified scale. Amplification ratios up to about 10 were measured at particular scales. The results indicate further that the turbulence amplification can be managed depending upon the combination of the Reynolds number and the upwind grid position. Two technical reports concentrating on the experimental results and the methods of data reduction are being prepared. Furthermore, the experimental results will be incorporated in the forthcoming Ph.D. dissertation of Mr. H. J. Brauer.

## 2.2 Flow about a single airfoil

A preliminary survey of the freestream turbulence evolution in flow about a symmetric NACA 65-010 airfoil with a chord c and a span s of 122 cm (48 in) and 183 cm (6 ft), respectively, was conducted along the stagnation streamline. These measurements were carried out at a zero angle of attack with the turbulence-generating grid installed at an upwind distance of a half chord, i.e., $x_{2g} = 0.5c$ ($x_{2g}$ = 61 cm (24 in)). Amplification of the streamwise turbulent energy-i.e., the mean-square value of the streamwise component of the turbulent velocity $\overline{u_2^2}$-beyond 60% was measured. A sample of the variation of the streamwise turbulent energy with approaching distance to the airfoil leading edge at a profile-chord Reynolds number of $10^5$ (freestream velocity $U_{2\infty}$ = 1.22 m/s (4 ft/s) and air kinematic viscosity at 20°C (68°F) $\nu = 1.5 \times 10^{-5}$ m/s$^2$ ($1.6 \times 10^{-4}$ ft/s$^2$)) is displayed in Fig. 1. This streamwise turbulent energy is made dimensionless with respect to its value at $x_2$ = 7.62 cm (3 in; $\tilde{x}_2$ = 0.0625) where a minimum turbulence intensity of about 8% (based on the freestream velocity $U_{2\infty}$) was monitored. The thickness of the turbulent stagnation boundary layer was estimated based on the variation of the streamwise mean velocity ($U_2$), fluctuating velocity ($(\overline{u_2^2})^{\frac{1}{2}}$) and turbulent energy ($\overline{u_2^2}$). A thickness of about 3.05 mm (0.12 in; $\tilde{\delta}$ = 0.0025) was found and it is demarcated by a dashed line in Fig. 1. It is interesting to point out that this thickness is, as expected, about twice that of the theoretical stagnation laminar boundary layer based on the results for the flat plate stagnation flow. Within the boundary layer, the turbulent energy (and the fluctuating velocity) decays as shown in the inset incorporated in Fig. 1.

A sample of the variation of the discrete turbulent energy at four selected scales is shown in Fig. 2. The discrete energy at each scale $\lambda$ is made dimensionless with respect to its value at $x_2$ = 45.75 cm (18 in; $\tilde{x}_2$ = 0.375) upstream of the airfoil. This station is 15.24 cm (6 in) downstream of the turbulence-generating grid. Amplification of discrete turbulent energy up to about 4.5 times the reference upstream level was obtained at $\lambda$ = 10 and 20 mm (0.39 and 0.79 in; $\tilde{\lambda}$ = 0.0082 and 0.0164). Most of the amplification occurred within an upwind range of 0.01 of the profile chord ($\tilde{x}_2$ up 0.01). This is roughly the linear deceleration velocity range of the stagnation flow. It is further important to point out the occurrence of one or more most amplified scales that are not necessarily the largest ones. For instance, more amplification of turbulent energy was measured at scales of 10 and 20 mm than at a scale of 40 mm (1.57 in; $\tilde{\lambda}$ = 0.0327) as clearly shown in Fig. 2. These preliminary results attest to the selective amplification of turbulent energy at preferred scales according to the vorticity-amplification theory. It is apparent, furthermore, that one can govern the concentration of turbulent energy at selected scales by controlling the grid position and characteristics at a given Reynolds number. This management of the selective turbulence amplification is presently being investigated.

The concentration of turbulent energy at particular scales is governed by the stretching and tilting of the cross-vortex tubes according to the vorticity-amplification theory. As a result, a coherent substructure consisting of a regular array of standing cross-vortex tubes emerges near the body stagnation zone. This coherent substructure was visualized in both the flow about a circular cylinder (see NASA CR 3019, October 1978) and about a single symmetric NACA 65-010 airfoil (see Semi-Annual Status Report, 1 October 1977 to 31 March 1978). As a matter of fact, a technical report including a short movie concerning the visualization of this coherent substructure in flow about a symmetric airfoil is planned.

It should be stressed that in flow about an airfoil the stretching of cross-vortex tubes is primarily dominated by their tilting around the profile. The flow divergence around a streamline body at a zero angle of attack occurs over a much smaller spatial scale and much more swiftly than in flow about a bluff body. This is due to the difference in the bluffness of the body. Pure stretching is, therefore, of lesser significance in flow about an airfoil than around a circular cylinder. On the other hand, the pure stretching plays a more important role with increasing angle of attack of a streamline body. Elucidation of the relative significance of pure stretching and tilting-induced stretching depending upon the bluffness of the body and its angle of attack is a matter of prime interest insofar as the turbulence amplification is concerned. An analysis of the importance and role of these two governing factors in flow about an airfoil has therefore been initiated.

The amplified turbulence is the agent responsible for changing the nature of the body boundary layer and for retarding the separation at subcritical Reynolds numbers (see Semi-Annual Status Report, 1 April 1978-30 September 1978).

This mechanism is discussed in detail in the forthcoming technical report on separation on a circular cylinder.

## 2.3 Analytical work

During the subject six-month period the emphasis was placed on the experimental program and, consequently, only a limited effort was devoted to the analytical work. The critical evaluation of the rapid-distortion and vorticity-amplification theories was pursued. An analysis of the rapid-distortion theory including its applications and limitations was completed. Concurrently, an in-depth review of the vorticity-amplification theory and its extension to the flow about an airfoil have been initiated. The matching scheme of the inner and outer solutions of the vorticity-amplification theory has further been explored using several numerical methods.

## 3. Other Activities

A. Publications completed under this grant:

1. "A Visual Investigation of Turbulence in Stagnation Flow About a Circular Cylinder," (with Brauer, H. J.), NASA CR-3019, October 1978.

2. Ibid. 1, in process of publication in the Journal of Fluid Mechanics.

3. "Visualization of Turbulence in Flow About a Bluff Body," (with Brauer, H. J.), to be published in the Proceedings of the ASME Symposium on Aerodynamics of Transportation, Niagara Falls, New York, 18-20 June 1979.

4. "Freestream Turbulence Effect on Laminar Separation on a Circular Cylinder," (with Brauer, H. J. and Sullivan, P. P.), accepted for presentation at and preprint publication of the AIAA 12th Fluid and Plasma Dynamics Conference, Williamsburg, Virginia, 23-25 July 1979.

5. "A Method for Determining the Weak Statistical Stationarity of a Random Process," (with Koper, C. A., Jr.), AIAA Journal, 16, 11, 1196-1202, November 1978.

6. "Turbulent Transport in the Lower Atmosphere," (with Koper, C. A., Jr.), Proceedings, 15th Annual Meeting of the Society of Engineering Science, University of Florida, Gainesville, Florida, 4-6 December 1978, Sierakowski, R. L., ed., 393-398, University of Florida, Gainesville, Florida, Division of Continuing Education Publication, December 1978.

7. "Investigation of Turbulent Diffusion in the Extreme Lower Atmosphere," (with Koper, C. A., Jr.), Preprints Proceedings, 4th Symposium on Turbulence, Diffusion and Air Pollution, American Meteorological Society, Reno, Nevada, 15-18 January 1979, 665-672, American Meteorological Society, Boston, Massachusetts, January 1979.

Reprints of papers nos. 5 and 7 are enclosed. Papers nos. 5-7 resulted from a research program conducted earlier under a NASA Marshall Space Flight Center Contract NAS8-28590. The subject two papers were completed under the current NASA Lewis Research Center grant.

B. Lectures delivered by the principal investigator

1. "Turbulent Transport in the Lower Atmosphere," Society of Engineering Science 15th Annual Meeting, University of Florida, Gainesville, Florida, 4-6 December 1978.

2. "Investigation of Turbulent Diffusion in the Extreme Lower Atmosphere," AMS 4th Symposium on Turbulence, Diffusion and Air Pollution, Reno, Nevada, 15-18 January 1979.

C. Miscellaneous

The principal investigator was elected to the New York Academy of Sciences in recognition of his achievements.

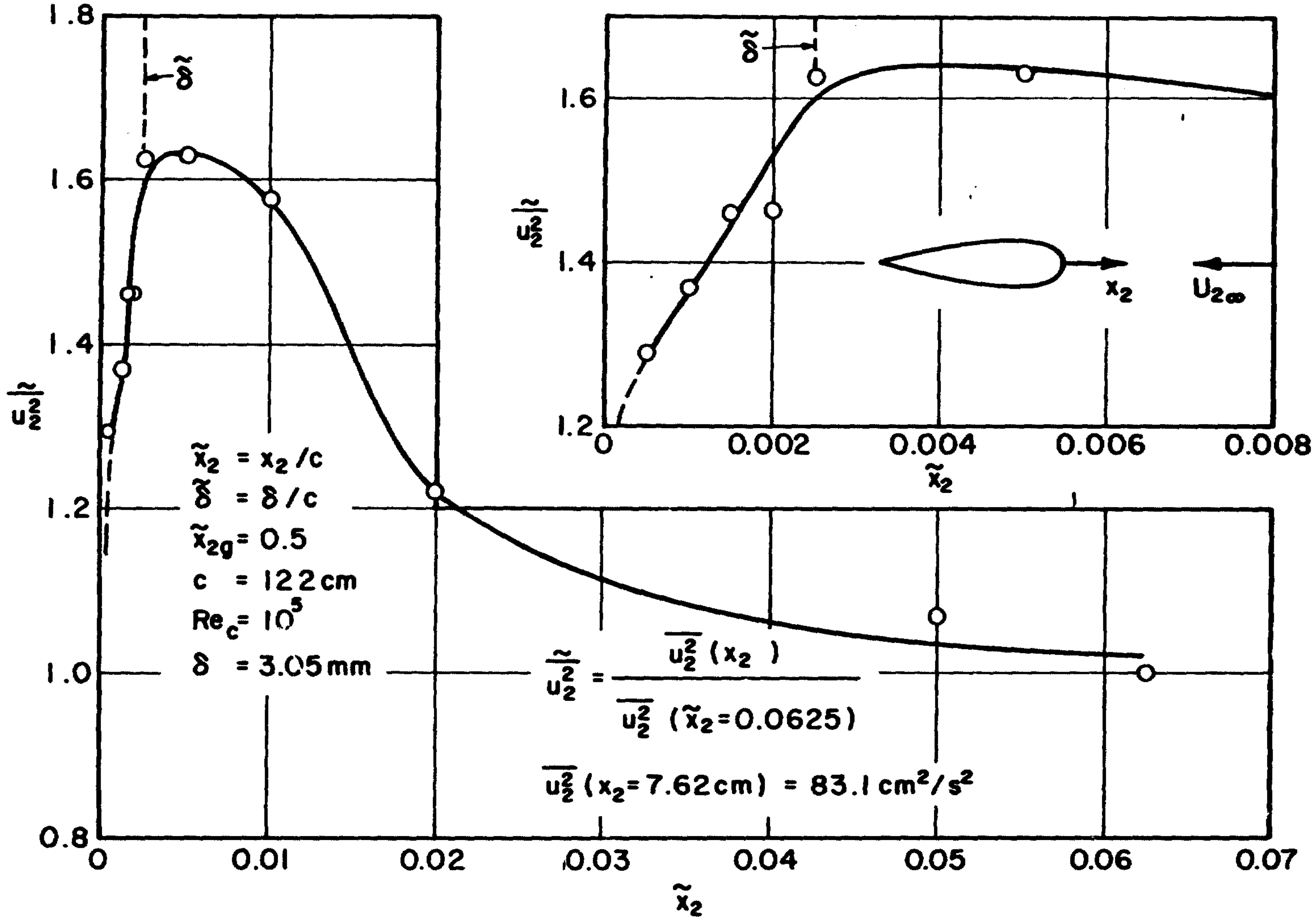


Fig. 1. Amplification of the streamwise turbulent energy in flow about a symmetric NACA 65-010 airfoil.

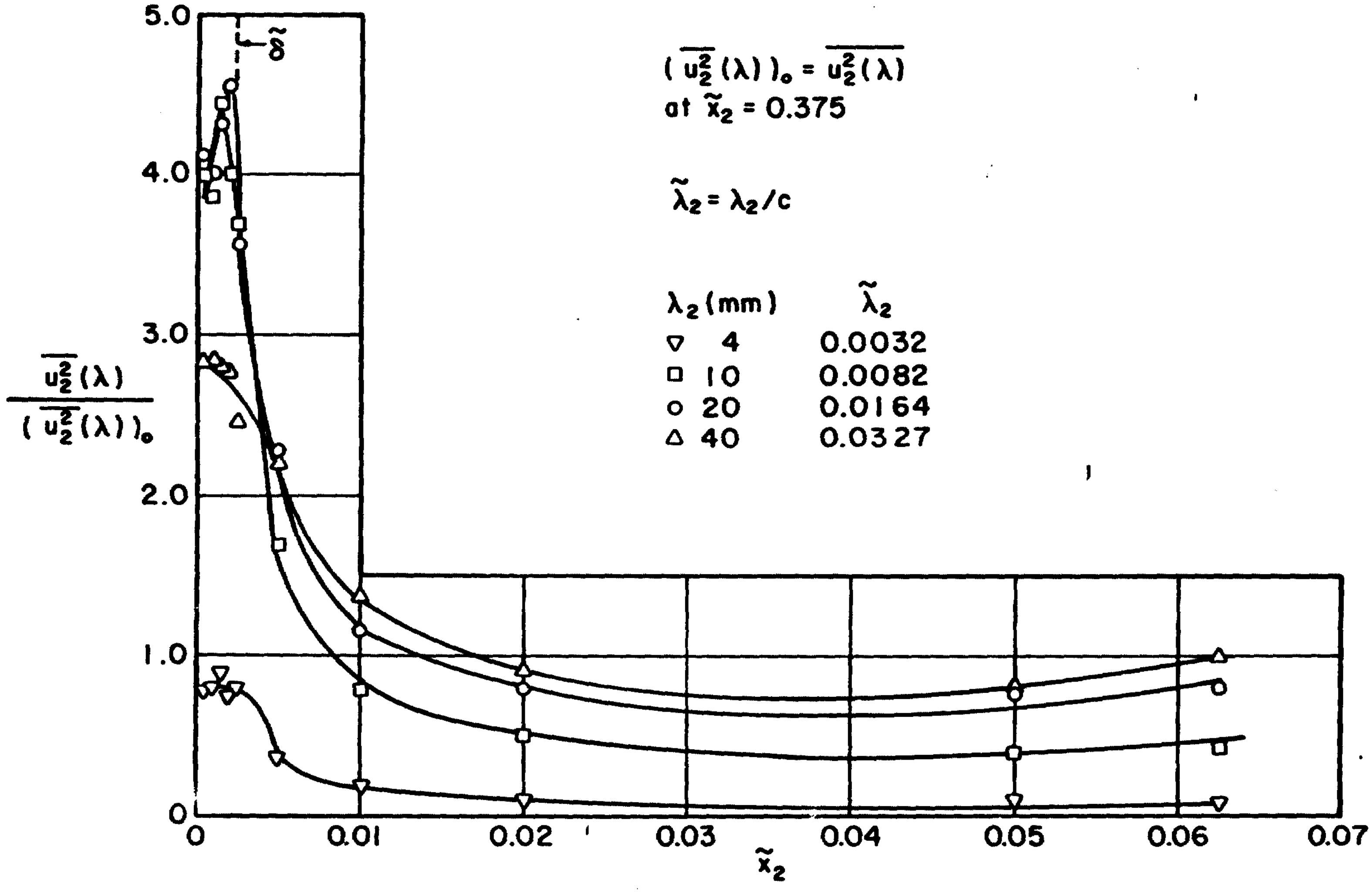


Fig. 2. Amplification of discrete turbulent energy at four selected scales in flow about a symmetric NACA 65-010 airfoil.