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VORTEX DEVELOPMENTS OVER AN ACCELERATED AIRFOIL AT HIGH ANGLES OF ATTACK

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Abstract

Proper control of unsteady separated flow developments over the lifting surfaces of an aircraft may prove to be an effective method of enhancing aerodynamic lift and producing better aircraft performance. Due to the complexity of unsteady flow separation and subsequent flow developments, experimental exploration and observation are essential in providing a source for comparison and verification with theoretical and computational models. In light of these motivations, a new experimental system that is capable of generating wide of range of unsteady flow histories has been developed and employed to visualize flow developments over an airfoil in accelerated-decelerated motion. The paper presents a description of the experimental system and its use in investigating accelerating flow over a flat plate airfoil at high angles of attack. The experimental results reported in the paper may serve as a useful source to guide and verify computational research efforts that are currently in progress.

Introduction

In resent years there has been a growing interest in unsteady flow analysis as it applies to improved aircraft maneuverability and agility. More specifically, research has been performed on the control of vortex structures produced under various unsteady conditions and geometric configurations[1, 2, 3, 4].

Advances in aircraft propulsion systems, controls and structures have improved aircraft performance greatly in the past few decades. Planes now fly faster and higher than ever before. It is a requirement now, that these aircraft also utilize their aerodynamic capabilities to their fullest. Given proper aerodynamics, an aircraft fuel efficiency, maneuverability and overall performance can be optimized for any given flight regime. Combat aircraft are excellent examples of aircraft for which attempts are being made to improve maneuverability utilizing naval aerodynamics. Current research efforts that concentrate on super-maneuverable aircraft brings aerodynamics into its newest frontier of unsteady flow analysis. Due to the complexity of unsteady separated flows, experimentation on them is difficult to perform and special data extraction and reduction tools are needed. Despite the advances in Computational Fluid Dynamics (CFD), experimental data is required in guiding and economizing such efforts.

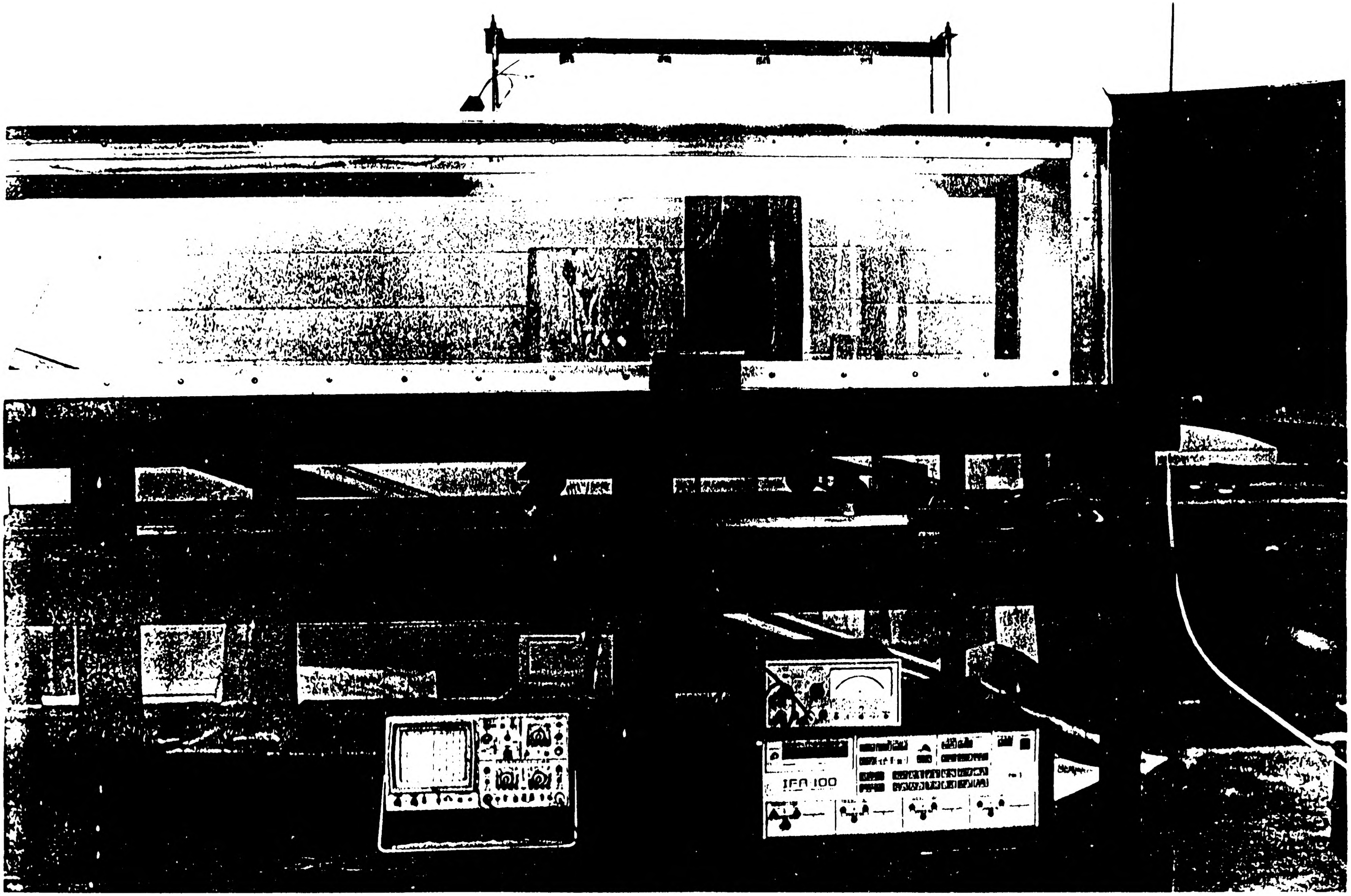

Figure 1: Unsteady Flow Test Section

This research effort is part of ongoing research involving unsteady separated flows dominated by vortex flow fields. The main objective of these efforts is to explore the possibility of utilizing such flows in producing dynamic lift, drag reduction, and improved aircraft performance at high angles of attack[5,6,7]. Last year the detailed of developing a new experimental system for unsteady aerodynamic testing were presented at the OURE UMR Conference. This system is now employed to investigate one of the flow configurations that are currently being investigated both experimentally and computational. The purpose of this article is to present the improvements and capabilities that were added to the system and report the results of the first series of experiments conducted using this system. Detailed unsteady flow visualization results and descriptions of separation and subsequent vortex separation over accelerated airfoils are presented. The improvements include modifications of lighting system, camera mounting, velocity determination.In the following sections, the test facility and experimental setup are briefly described. This will be followed by a discussion of the flow visualization results.

Experimental Set-Up

The system developed for the required experiments is designed and incorporated into an 18" x 18" subsonic wind tunnel that can accommodate interchangeable test sections. The photograph of Figure 1, shows the major components of the experimental unsteady flow test section. The system basically consist of a test model carrier and a clear plexiglass test section. The carrier is employed to produce the unsteady motion of the test model and to carry a lighting system along with a high speed movie camera. These details can be seen in both Figures 2 and 3. The translation of the test model is made possible by a gap in the bottom of the test section which allows a portion of the cart to travel inside the clear plexiglass test section. To prevent air leakage into the tunnel, the gap is sealed with a 16 ft strip of Ultra High Molecular Weight Polyethylene (UHMW).

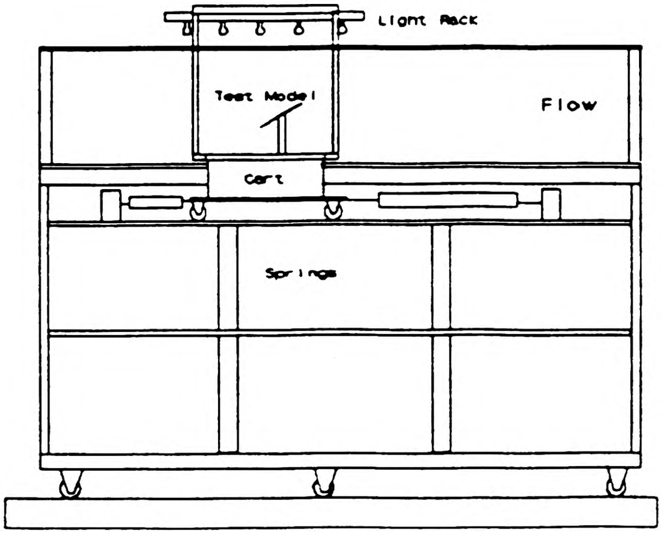

Figure 2 Front View of Experimental Apparatus

As can be seen in Figure 3, this strip is fixed to the cart and is inserted into two grooves along the gap. This allows the strip to travel with the cart while sealing the tunnel. The results of several experiments which were conducted to test the seal performance, indicated that the seal prevented air leakage at flow velocities up to 70 ft/sec.

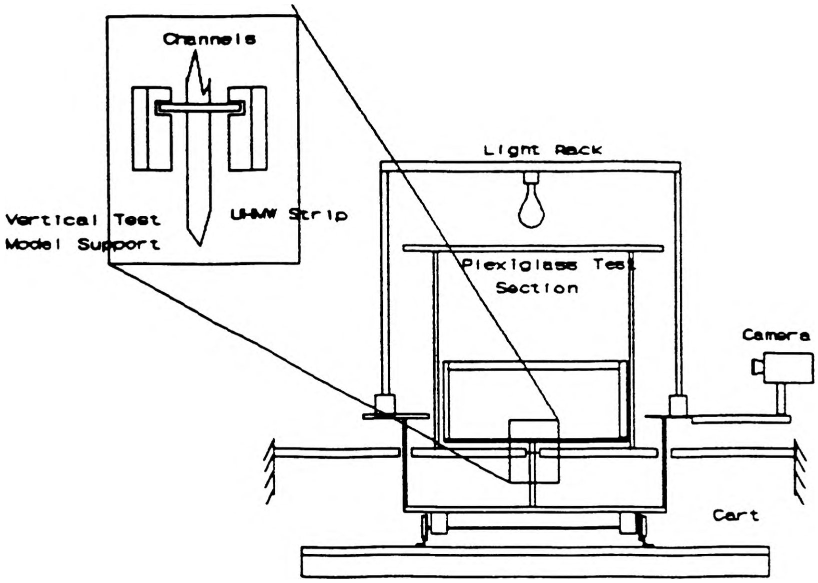

Figure 3 Side View of Experimental Apparatus

The motion of the test model carrier is controlled by springs, which provide an accurate and predictable method of accelerating and decelerating the test model. As can be seen in Figure 2, the cart is mounted between two sets of springs which are fixed between two blocks. With this configuration, the cart can be accelerated and decelerated in a distance of 36". The rate of acceleration will approximately be equal to the rate of deceleration provided the springs on both sides have equal spring constants. Both the mechanical resistance in the system and the drag on the model do not allow for truly equal rates.

The acceleration and velocity of the cart during testing is determined from the angular acceleration and velocity of one of the carts wheels . The aluminum wheel has steel studs mounted around the perimeter which are detected by a magnetic pickup.
The pickup produces a low voltage signal which is proportional to the velocity of the studs. This pickup is connected to a data acquisition board in a lab computer. A program has been produced which calculates the acceleration and the velocity of the cart.

Flow Visualization Approach

As stated in the introduction, the generation and control of vortex flows about aircraft in flight could have many beneficial effects during unsteady flight conditions such as high angle of attack maneuvers. In order to further the understanding these effects, detailed study of vortices must be performed under similar conditions. Flow visualization techniques could be very useful in revealing the details of such complex flow developments. Since the expected vortex developments initiated at the surface of test model, it is essential to employ flow visualization approach that relies on direct injection of a visualization substance to the surface of the test models. Based on this fact, the vortex tagging techniques were selected to visualize the flow developments. This was established by injecting liquid Titanium Tetrachloride[8] to the test model surface. This liquid reacts with the humidity in the air and produces a white smoke which tags the generated vorticity near the solid surface of the test model. To photograph the smoke, a movie camera mounted on the test carrier was employed. Figure 3, shows the positioning of the camera with respect to the test model and the test section.

Experimental Method

Experiments were conducted on a flat plate wing model with a 2" chord for an angle of attack range between 30 and 90 degrees. This series has been chosen to illustrate the effects of increasing angles of attack on the flow structures over the same flat plate.

The plate was mounted to the test model carrier such that the span was perpendicular to the velocity vector of the flow. The cart was then displaced a distance of -12" from the equilibrium point of the spring force and held in place. Liquid Titanium Tetrachloride, was applied to the surface of the flat plate. The motion picture camera was started, and the cart was then released and allowed to accelerate. Once the cart passed the point of spring force equilibrium the opposing force of the springs then caused the cart to decelerate. If this motion was allowed to continue, the cart would oscillate between the two blocks with decreasing amplitude due to losses.

The images of the flow were recorded with a 16 mm Bolex motion picture camera with a film rate of 64 frames per second (fps). The motion picture camera allows for a series of photographs to be produced showing the development of the flow structures.

Governing Equation of Test Model Carrier

As can be seen in Figure 4, the forces acting on the test model carrier are mainly the spring and the friction forces. Based on Newton's second law, one can write

$$m \frac{d^2x}{dt^2} = -kx - c\frac{dx}{dt}$$

where m, x, t, k, and c are the mass, displacement, time, spring constant, and friction respectively .

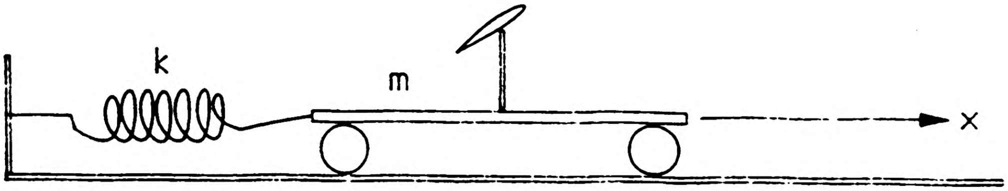

Figure 4 Forces Acting on Cart Assembly

To estimate the cart position, velocity, and acceleration, this second order differential equation is numerically integrated using the fourth-order Runge-Kutta method. This was accomplished by rewriting this equation as

$$\frac{dx}{dt} = V$$

$$\frac{dV}{dt} = -\frac{k}{m}x - \frac{c}{m}\frac{dx}{dt}$$

The integration routine is incorporated into an interactive computer program that is developed to allow for parametric exploration of the cart performance over a wide parameter range of springs (stiffness) and friction (damping) parameters

The inputs into the program include the initial spring displacement, the spring stiffness, the mass of the cart and model , and the friction experienced by the cart. The program presents the output graphically in the form of displacement vs. time, velocity vs. time and acceleration vs. time plots.

Flow Visualization Results

The flow visualization data of the conducted experiments are compiled in photographic sequences that document the time dependent flow developments. The sketch of Figure 5, shows typical vortex separation from the wing surface at high angles of attack. As sketched, the flow developments are dominated by leading edge and trailing edge vortices and secondary or reverse vortex over the wing surface. The frames in all sequences are ordered from top to bottom, and then from left to right as indicated by the numbering setup shown on the sequences. The flow is always from right to left.

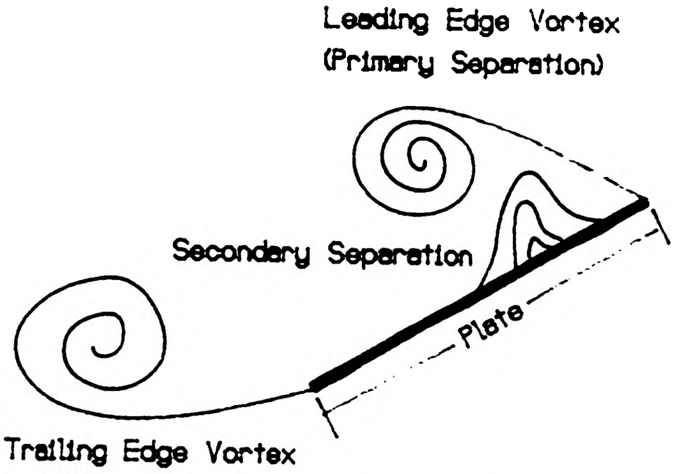

Figure 6 Sketch of Flow Structures About Test Model

Figure 6 shows a photographic sequence of accelerating flow developments over a 2" flat plate airfoil setting at 30 degrees angle of attack. As can be seen in column A, the separation of a leading edge vortex is clearly visualized. This vortex induces a secondary vortex near the leading edge as shown in frames 7& 8 of column A. Column B visualizes the roll-up of the primary leading edge vortex and continued separation of the secondary vortex. In frames 7&8 of column B, the re-attachment of the secondary vortex can be observed. This is due to the convection of the primary leading edge vortex down stream and the induction of a trailing edge vortex at the wing trailing edge. The trailing edge vortex evolution and can be clearly seen in column C. Due to the wing deceleration the secondary vortex is almost trapped over the surface of the wing by the influence of the leading and trailing edge vortex structures.

Figure 7 shows a photographic sequence of accelerating flow on the same flat plate airfoil at an angle of attack of 60 degrees. At this angle of attack, similar flow developments can be observed. However, the primary leading edge vortex seems to be less stable. As can be seen in column B, this vortex brakes up to a number of vortices. The secondary vortex trapping can be observed clearly in columns C&D.

Figure 8 shows a photographic sequence when the wing angle of attack is 90 degrees. At this angle of attack, the trajectory of the primary vortex is far away from the wing and no secondary vortices were observed. Column D visualizes the strong interactions between the leading edge and the trailing edge vortices. As can be seen in the last two frames the leading edge vortex stretches by the trailing edge.

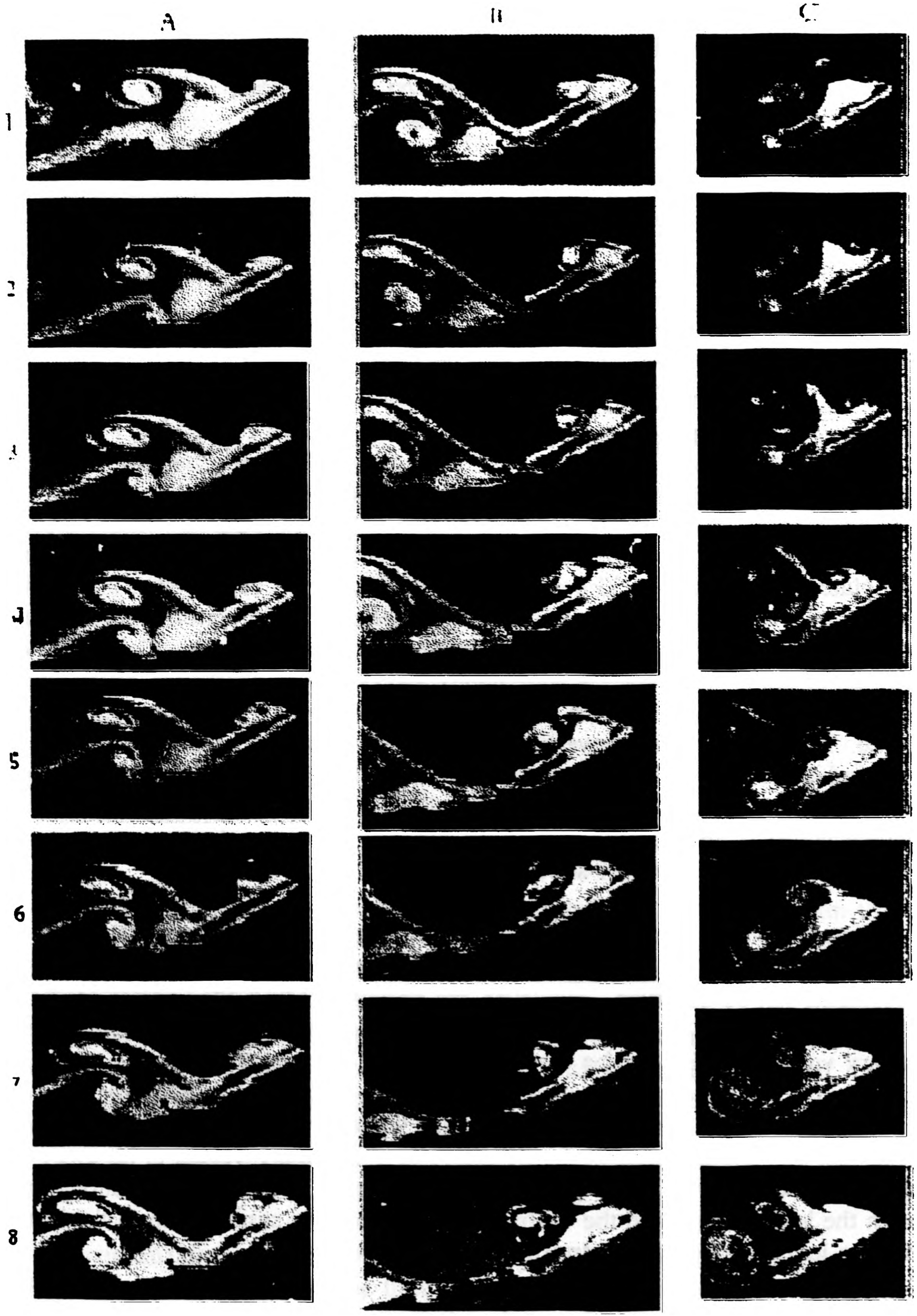

Figure 7 Photographic Sequence visualizes Accelerating Flow Developments over A Flat Plate Airfoil
alpha = 30, t = 1/64 sec, c = 2"

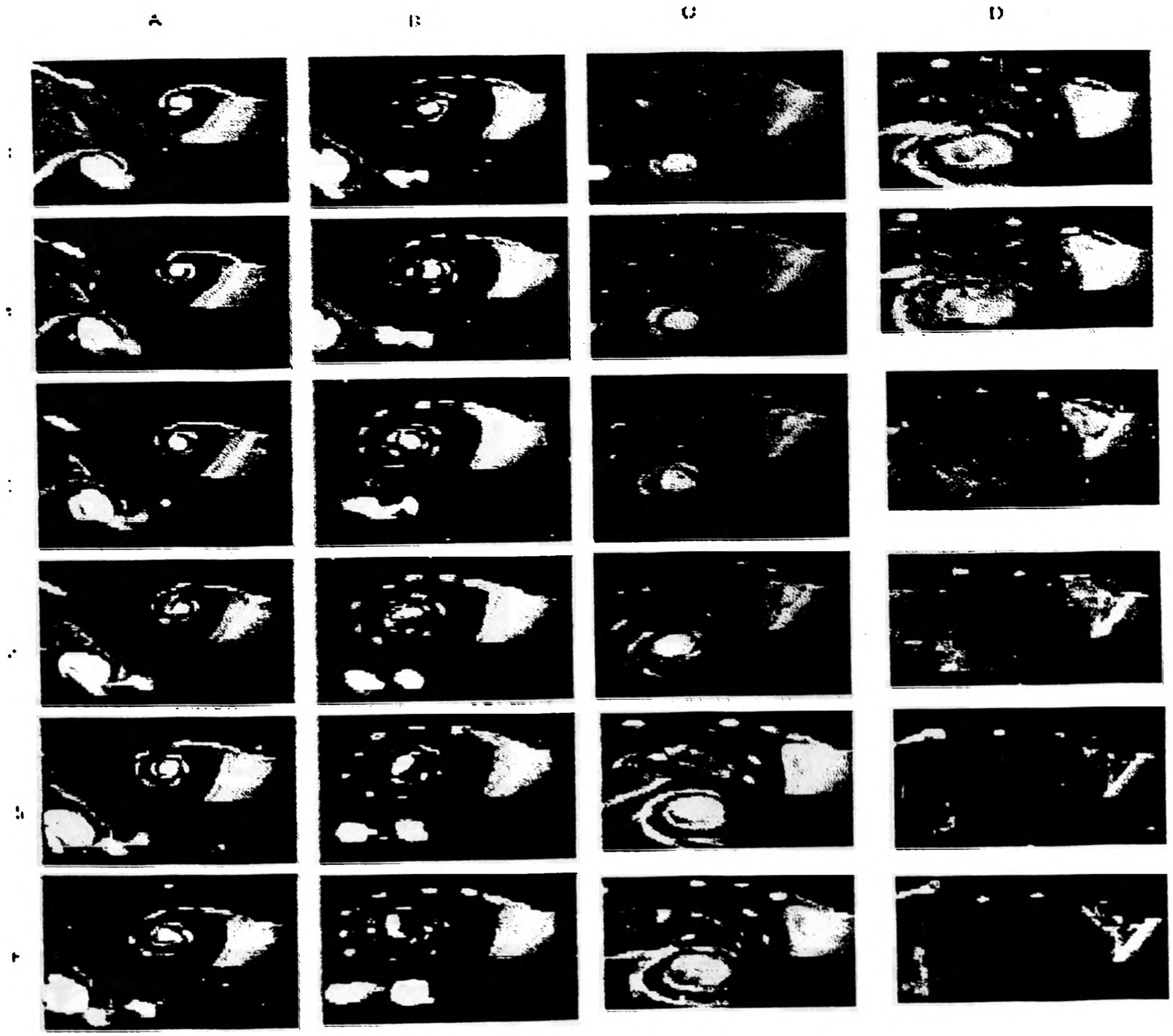

Figure 8 Photographic Sequence visualizes Accelerating Flow Developments over A Flat Plate Airfoil
alpha = 60, t = 1/64 sec, c = 2"

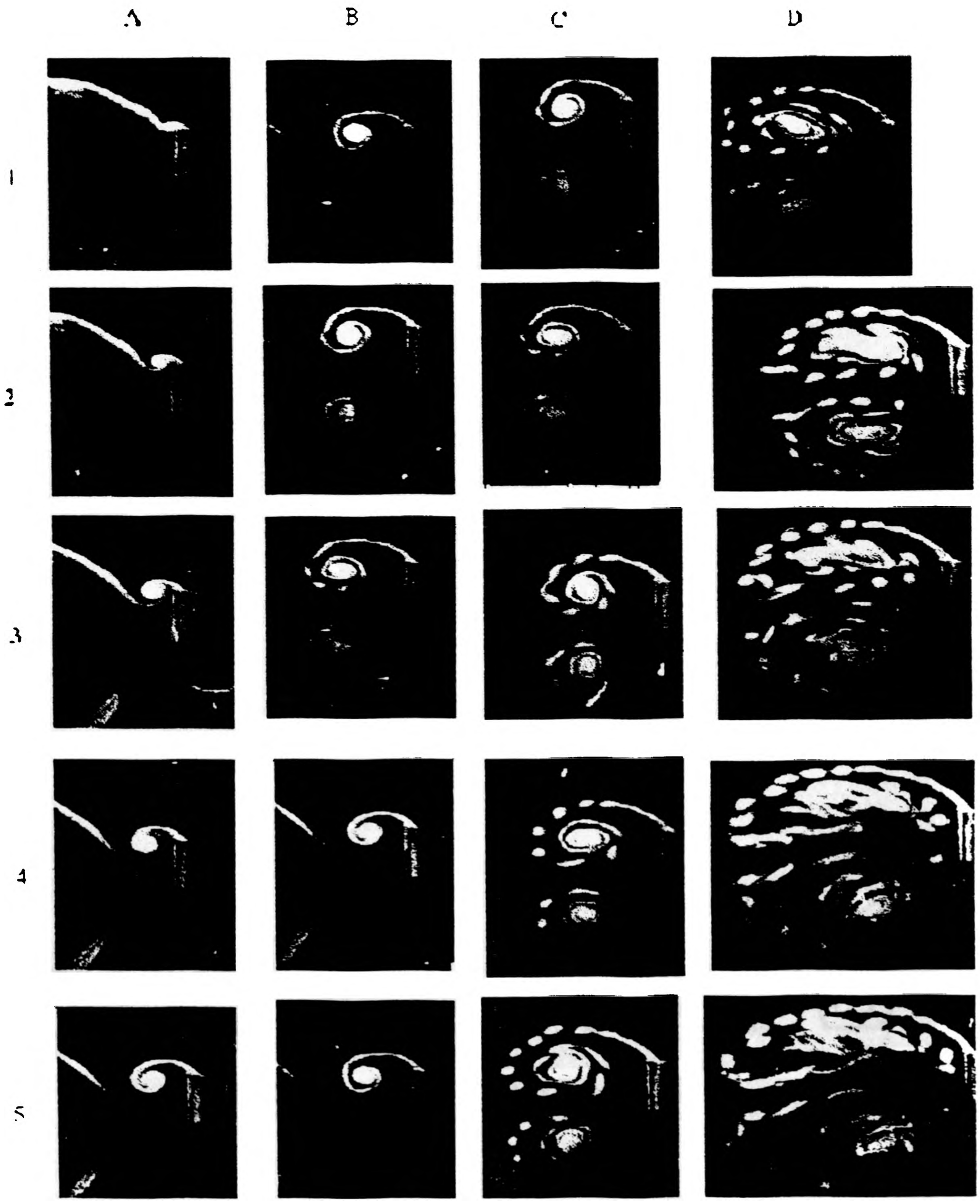

Figure 9 Photographic Sequence visualizes Accelerating Flow Developments over A Flat Plate Airfoil
alpha = 90, t = 1/32 sec = 2"

Concluding Remarks

An experimental system that generates and visualizes unsteady flows has been developed and employed to visualize vortex structures and processes over a flat plate airfoil at high angles of attack. Detail of flow separation and subsequent vortex for formation are presented in complete photographic sequences. Due to space limitation, only a few sequences were presented. Additional flow configurations will be presented in the upcoming SAE Aerospace Conference this year. It is hoped that the results of this study serve as a reference on vortex structure and processes over accelerated airfoils and as a useful guide for measurements and parametric computer studies that are currently in progress.

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