FLOW VISUALIZATION STUDY OF FAR FIELD WAKE VORTEX INTERACTIONS

Brian M. Babie, Robert C. Nelson
University of Notre Dame, Notre Dame IN 46556

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ABSTRACT

An experiment to study the interaction of a wake consisting of four vortices is currently under development in the Hessert Laboratory at the University of Notre Dame. The four vortices are created by an apparatus consisting of four half span high aspect ratio wings. Each wing is mounted to a stepper motor that permits accurate control of the wing angle of attack. Furthermore, the lateral spacing between the wings can be manually adjusted. Thus the spacing, circulation and sense of rotation of each vortex in the wake can be controlled. The goal of this study is to investigate how a wake consisting of four vortices can be made unstable so that it decays rapidly in the downstream direction.

The vortex instability modes under investigation generally occur at large distances downstream from the origin of their generation. The primary method of validating the new multiple vortex interaction facility is through visualization of the vortices. A major challenge in observing the extent of attenuation in the far field of the wake is in maintaining seeding of the vortex structures at large distances downstream. Methods for achieving such a flow seeding will be discussed in detail. The visualization method that has shown the most promise for tracking multiple vortices many span lengths downstream of the wake generating device is through helium bubble visualization. This paper discusses the use of helium bubbles to mark the vortices, lighting and other issues that needed to be resolved to be able to track the vortex wake evolution.

1 GENERAL INTRODUCTION

1.1 Motivation for Experiment

All aircraft create a trailing vortex wake that can persist for several miles behind the generating aircraft, depending on atmospheric conditions. This trailing vortex wake is often referred to as wake turbulence and potentially poses a flight safety hazard to other aircraft that may pass through the wake. Aircraft-wake encounters are most likely to occur during the take-off and landing stages of flight due to the close proximity of other departing or landing aircraft. This limits the spacing between aircraft within the take-off and landing corridors at busy airports. Air traffic control authorities adopted a set of operational procedures that have provided commercial aviation with a safe solution to the problem of aircraft wakes. The operational procedures include segregating aircraft by size, controlling take-off and landing flight paths, and maintaining a fixed separation
between aircraft based on the weight of the lead aircraft. Because of the uncertainty in knowing where the vortices are located relative to the flight path as well as their strength, the separation distances between aircraft had to be selected to be overly conservative. These procedures limit the traffic capacity at many major airports. Figure 1 illustrates various types of wake encounters.

![FIG. 1 - Aircraft wake vortex encounter](image)

Research in Europe and the United States has focused on increasing airport capacity by minimizing the wake vortex hazard. One area of research focuses on developing a vortex detection system that can be used to safely reduce aircraft spacing [2], while the other research area focuses on techniques to hasten vortex wake breakup by enhancing wake instabilities.

### 1.2 Vortex Instabilities

The existence of vortex instabilities relating to aircraft wakes has been the subject of numerous investigations. Most notably, Crow [3] presented a numerical analysis by which a perturbed vortex pair would exhibit a growing instability, amplified by the mutual induction of one vortex on another. Crow suggests, through the use of a two-vortex model, that wake vortices exhibit sinusoidal motions that are generally confined to fixed planes, inclined to the horizontal. Crow also maintains that the spacing between the vortices in his analysis play an integral role on the growth of the instability. Crow and Bate [4] extended their analysis to include perturbations caused by atmospheric conditions. It was further suggested that the time to vortex linking is a function of the effective span of the vortices.

A centrifugal form of wake vortex instability has also been suggested as a candidate for aircraft wake attenuation [8]. The Rayleigh-Ludwieg instability is a form of instability that occurs naturally for two unbent, parallel vortex lines of opposite rotation. The original analysis [10] was completed for rotating annular pipe flow, but was later generalized [11,12] to include free-vortex flows. The Rayleigh-Ludwieg instability is recognized by a destabilizing centripetal force of greater magnitude than the restoring pressure force, resulting in the rapid expansion of the vortex core and...
the diffusion of vorticity in the wake. Studies in Europe indicate that this form of instability is feasible for aircraft trailing vortex wake attenuation.

In an effort to represent an aircraft wake, it is desirable to use a four-vortex model consistent with the vortices generated by the wing tips and inboard flaps of a transport aircraft in a take-off or landing configuration. In this representation, there generally exists two pairs of vortices. The first pair is comprised of the two outermost vortices, representative of the roll up of both the wing tip and outboard flap vortices [5]. In terms of the bound vortex circulation, this pair is the stronger of the two and creates a region of downwash between the two. The second pair of vortices exists inside the region of downwash and represents the vortices generated by the inboard flaps. As previously suggested, this vortex pair has a weaker bound vortex circulation and also circulates in a manner opposite the wing tip/outboard flap pair. This model has been used in several experimental efforts [5-9]. Such a configuration has also been used to investigate the effects of varying wing loading on wake interactions in numerical simulations [13,14]. Visually, this configuration is well illustrated by Corsiglia et al [5] in Figure 2. Further, it has been hypothesized that the stability of this wake can be strongly influenced by altering the spacing and circulation strength of the inboard flap vortex pair.

Several studies have investigated the instabilities that persist in the wakes of four-vortex models, both experimentally [5-9] and numerically [13,14]. These studies have also suggested the growth of instability is a function of the circulation strengths of each of the vortex pairs. Several control methods have also been suggested as a result of these studies. While many of these previous efforts have successfully proven that this four-vortex wake may be strongly influenced by controlling the spacing and the circulation of the vortices within the field, most are tailored toward a specific application. It is therefore the intent of this investigation to take a systematic approach to the study of wake vortex interactions. This is to be achieved by generating four vortices using four independent rectangular wings. Using this configuration, it is possible to investigate a large test matrix of spacing and circulation combinations. It is consequently the goal of this study to understand the fundamental flow physics within a four-vortex model, such that a feasible control solution may be suggested.
2 EXPERIMENTAL METHODS

2.1 Experimental Set-Up
To generate a system of four-vortices, four wings of rectangular planform were molded from black epoxy. The wings were designed as half-span models with an aspect ratio of 8, to simulate commercial transport aircraft. The wings are of constant cross-section throughout the 20-inch (50.8 cm) semi-span. Each wing has a NACA 0015 airfoil cross-section of 5 inches (12.7 cm) chord length. The NACA 0015 airfoil cross-section was selected for this experiment as each wing should produce zero lift at zero angle of attack and the mold was available from an earlier study. The sizing of the model was based on a two-dimensional vortex interaction simulation in which the effects of the tunnel walls were evaluated. Sizing of the model was also based on Reynolds number, such that it would be possible to compare results to references in which similar experiments were conducted. Wing tips were rounded in a further effort to simulate a realistic aircraft wing.

The four identical wing models (two shown in Figure 3) are mounted to the floor of the first module of the test section of an atmospheric boundary layer wind tunnel via stepper motor. The stepper motors serve to adjust the angle of attack of each wing resulting in a change of circulation of each wake vortex. The models are arranged in a manner consistent with Figure 2, and can be seen in figure 3. The outer wings are spaced at a fixed distance of 24 inches (61 cm). Between the outer wing pair, a 20 inch (50.8 cm) slot has been milled out of the floor to allow for variation in spacing of the inner wing pair. Again, the spacing selected for these models was based largely on numerical simulation results that evaluated the effects of the test section walls.

The atmospheric boundary layer wind tunnel at the University of Notre Dame provides a suitable facility to conduct an experiment that is intended to simulate the interaction of four vortices, as would persist in the wake of an aircraft with the flaps down. The atmospheric wind tunnel has a cross-section that measures 5ft × 5ft (1.52m × 1.52m) and spans 50ft (15.24m) in length. Because the wings are mounted in the leading module of the test section, it is possible to observe with flow

Fig. 3 – Photograph of vortex generation devices with bubble injection rake
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Visualization, the wake for approximately 29 semi-spans downstream of the vortex generating device. The walls of the test section have also been painted flat black in order to provide a contrast between the illuminated helium bubbles and the test section walls.

2.2 Helium Bubble Visualization Technique [15]

Visualization of the vortex cores is achieved using a helium bubble technique. Helium bubbles are generated using a Sage Action, Inc. (SAI) Model 5 helium bubble generator. Bubbles are generated in a mini-vortex filter by supplying compressed helium through rubber tubing into the plug-in head. A bubble film solution (BFS), provided by SAI, is also supplied to the plug-in head. The head itself consists of two concentric stainless steel tubes, allowing the helium to flow through the inner tube and the BFS to flow through the annulus between the inner and outer tubes. At the tip of the plug-in head, which is inside the boss, helium filled bubbles are generated. Compressed air is also supplied to the mini-vortex filter through a large tube within the head, concentric with the other pair of tubes. The injection of air through the head blows the bubbles into the mini-vortex filter. Under the appropriate conditions, the SAI Model 5 bubble generator creates up to 400 bubbles per second.

The mini-vortex filter serves to remove any bubbles that are not neutrally buoyant. The mini-vortex filter is comprised of a clear plastic cylinder that uses the jet of air from the plug-in head to create a vortex motion within the cylinder. The resulting radial forces on the non-neutrally buoyant bubbles drive these bubbles to the outside of the plastic cylinder, where they are burst upon contact with the wall of the filter. The neutrally buoyant bubbles remain near the center of the filter and are eventually driven out of the cylinder via an outlet tube. The outlet tube is then connected to a rubber tube for injection into the flow field. It should also be noted that the size of the resulting, neutrally buoyant bubbles is on the order of $\frac{1}{20}$” (0.127cm) in diameter.

Based on the work of Hale et al [16], it was decided that the bubbles should be injected into the flow field upstream of the vortex generating wings. Hale et al [16] concluded that the neutrally buoyant bubbles would become entrained in the vortex core if injected at the appropriate location,
some 5 chord lengths upstream of the model. To accomplish this, a cross-bar mechanism was constructed to hold a $\frac{3}{8}$" (9.53mm) OD rigid plastic tube at the location where it was desirable to inject the bubbles. The cross-bar is a $\frac{1}{4}$" (6.35mm) solid steel bar that spans the width of the test section and is supported by two, vertical $\frac{1}{2}$" (12.7mm) steel bars at either side of the test section. The injection tube is held in place by a custom support, constructed of plastic. To inject the bubbles, the rubber tubing from the mini-vortex filter was brought through the floor of the test section, and run along the cross-bar assembly, where it is connected to the plastic injection tube.

The appropriate lighting of this experiment is of critical importance to the flow visualization. Again based on the recommendations of Hale et al [16], it was desirable to maintain a bright light on the entrained bubbles and off of the test section walls. This produces the ideal contrast between the illuminated bubbles and the test section. The desired lighting is provided by a 750W theatrical spotlight, which is positioned outside of the test section and directs light upstream. The spotlight is equipped with a set of shutters to adjust the light beam aperture. This allows the operator to keep the light focused on the entrained bubbles and off of the test section walls, providing the desired contrast. Future lighting techniques will introduce the use of a similar light source mounted inside the test section directly downstream of the region of investigation.

To record flow visualization images, a digital camera, with 3.76 mega pixel resolution, was used. The laboratory lights were turned off in an effort to minimize reflections from the test section windows. It was also of critical importance to operate the digital camera as close to the test section windows as possible, to capture the maximum amount of light being reflected from the bubbles. All images were taken within 2ft (0.61m) of the test section windows. It was also necessary to adjust the shutter speed of the camera in order to capture enough of the light being reflected from the entrained bubbles. This produced an image of a series of streaklines, as opposed to an instantaneous snap-shot of the flow field. Images were recorded at distances up to 17 spans downstream of the vortex generating model.

3. RESULTS

3.1 Single-Wing Evaluation

As a basis for the evaluation of the wake vortex interaction facility, the first step was to visualize the wake of a single wing. As was mentioned previously, maintaining an acceptable seeding in the vortex core is of primary importance. Helium bubbles were introduced into the flow field upstream of the wing model as described in section 2.2. In the near field of the wing tip, it was expected that a large percentage of the neutrally buoyant helium bubbles would become entrained in the core of the wake vortex, as the core is a region of low pressure within wake. Using the adjusted shutter speed, it was anticipated that the bubbles would appear as a white streak tracking the vortex core. As expected, the majority of the injected bubbles were entrained in what appears to be the vortex core. The lighting of the flow field was also sufficient to visualize the bubble streaks. The wake vortex flow in the near field of the generating wing appears in Figure 5.
Further downstream, it is expected that the majority of the bubbles entrained in the vortex core at the generating wing will remain in the core. From an inspection of the flow field at 10 semi-spans downstream of generation, the visualization suggests that the region of bubbles has expanded. It appears that some of the bubbles are outside the vortex core, although still maintaining a strong sense of circulation about the centroid of vorticity. The causes for bubbles exiting the vorticity centroid is unknown at the present time. It should be noted that a quantitative measurement technique such as particle image velocimetry (PIV) will be used to determine the effects of viscosity and turbulence within the flow field.

The last visualization photograph of the single wake vortex was completed near 17 semi-spans downstream of generation. The recording of images at this distance downstream of generation becomes increasingly difficult as it appears that fewer bubbles remain in the core as compared to the
previous two cases. It was however apparent from an inspection of the wake at this location that a strong sense of circulation still exists within the flow field, as the trajectories of the helium bubbles exhibit a helical motion as they convect downstream.

![Visualization of a single wake vortex at 17 semi-spans downstream of generation](image)

Fig. 7 – Visualization of a single wake vortex at 17 semi-spans downstream of generation

Visualization of a single vortex core was successfully used to identify a centroid of vorticity up to 17 semi-spans downstream of the generation device. Photography of the helium bubble visualized wake is still in need of some improvement. The results presented in this section suggest that the atmospheric boundary layer tunnel is an appropriate facility for this type of experiment and helium bubble visualization provides a suitable flow visualization technique for a preliminary investigation into far field wake vortex interactions. It should also be reiterated that further quantitative flow measurement techniques are needed to confirm results drawn from these flow visualization experiments and also to evaluate the effects of viscosity and turbulence within the wake.

### 3.2 Multiple-Wing Evaluation

Based on the success of the single wing evaluations, the next phase of the evaluation is to track multiple vortex cores at large distances downstream of generation. The immediate next phase of this validation is to use two wings to generate a vortex pair and evaluate the influence of one vortex on the other. With satisfactory completion of this stage, it will then be possible to proceed to the full four-vortex model. Once it has been demonstrated that four vortices can be visualized in the wake of the full system, an extensive test matrix of vortex circulation and wing spacing combinations will be evaluated as candidates for accelerated wake vortex breakdown.
4. CONCLUSIONS AND RECOMMENDATIONS

Flow visualization has been presented as the primary method for validating a new, multiple vortex interaction facility at the University of Notre Dame. Helium bubble visualization has been the primary method of flow visualization to this point, as it has proven to be the best candidate for tracking multiple vortices many span lengths downstream of generation. Techniques for bubble injection, proper lighting arrangement and photography have also been discussed. Results have been shown for the single wing scenario. It was also noted that a multiple wing evaluation of the facility is the next stage of testing. Further validation of the far field wake vortex interaction facility is required to assess the facility when four wings are being used. For future work, it will also be necessary to conduct a quantitative flow survey of these test cases to confirm the presented flow visualization results.

5. REFERENCES


