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Experimental study of effects of discrete jets on tip vortex attenuation

Charles Scott Matthewson

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To the Graduate Council:

I am submitting herewith a thesis written by Charles Scott Matthewson entitled "Experimental study of effects of discrete jets on tip vortex attenuation." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

A. Vakili, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
To the Graduate Council:

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A. Vakili, Major Professor

We have read this thesis and recommend its acceptance:

[Signatures]

Accepted for the Council:

[Signature]

Associate Vice Chancellor and Dean of the Graduate School
EXPERIMENTAL STUDY OF EFFECTS
OF DISCRETE JETS ON TIP VORTEX ATTENUATION

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Charles Scott Matthewson
December 1996
ACKNOWLEDGMENTS

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The staff at UTSI were very supportive and always helpful. I am thankful for the support and guidance offered me by my thesis committee members, Dr. Lo and Dr. Wu. A special thanks goes to my advisor, Dr. Vakili, whose insight and drive were indispensable and greatly appreciated. The technical support of the lab personnel was excellent, especially the support provided by Ricky Meeker without whom the rotor blades - among other critical components - would not have been completed. Thanks also to the machinist Gary Payne - for his well grounded advice and superior trade skills.
ABSTRACT

An experimental study of the effects of destabilizing the tip vortices from a model wing and a model rotor using perturbations introduced by discrete jets located at the tips was conducted. A study on a fixed wing was conducted in a water tunnel using hydrogen bubble flow visualization for qualitative observations. Results of steady spanwise blowing indicated increased flow unsteadiness, as well as decreased tangential velocities and a displaced vortex core. Pulsed injection at selected frequencies increased the unsteadiness in the flow, resulting in a wake flow with no observable vortex core. This preliminary study offers the potential for continued work in optimizing pulsing and jet configurations for maximum tip vortex instability and dispersion. Preliminary testing was also conducted on a static rotor test stand to study the potential use of discrete jets on rotor blades to reduce the effects of blade vortex interactions - a common problem in rotor aerodynamics. Hot-film measurements in the wake of a ‘hovering’ rotor were used to quantitatively compare velocities associated with tip vortices between a baseline and an experimental blade. Results for baseline tests (no blowing) were consistent with previous studies. Results from the experimental blade showed dramatic reductions in maximum velocities. Typical reductions were observed from $0.475V_{tip}$ (baseline) to $0.25V_{tip}$ with blowing at $C_{p} = 0.0033$. Also, increased unsteadiness in the region of the vortex with the blowing blade was observed. A basis for future research has been established by showing potential reductions in blade vortex interaction effects using this technique.
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<td>$A_j$</td>
<td>Area of the jet port</td>
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<td>A/D</td>
<td>Analog to digital converter</td>
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<td>Jet blowing (momentum) coefficient $C_\mu = 2 m_j V_j / \rho S U^2$</td>
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<td>$m_j$</td>
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<td>Particle Image Velocimetry</td>
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<td>$R_{op}$</td>
<td>Operating resistance of the hot-film probe ($\Omega$)</td>
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<td>$R_{0\cdot100}$</td>
<td>Resistance per degree of the probe between 0 and 100 degrees Celsius</td>
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<td>$Re$</td>
<td>Reynolds number</td>
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<tr>
<td>rpm</td>
<td>Revolutions per minute</td>
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<tr>
<td>$S$</td>
<td>Planform area of rotor blade or wing</td>
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<tr>
<td>$St$</td>
<td>Strouhal number - $St = f_j c / V_{up}$</td>
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<td>$T_m$</td>
<td>Mean sensor temperature</td>
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<td>TE</td>
<td>Trailing edge of wing or blade</td>
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<td>Thermal Systems Incorporated</td>
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Vy  Local velocity in the y - direction
Vz  Local velocity in the z - direction (axial velocity)
V_{tip}  Rotor blade tip velocity
V_{eff}  Effective velocity as measured by the hot-film probe
V_r  Local radial velocity component
V_\theta  Local velocity in the \theta - direction (tangential velocity)
V_N  Local velocity normal to hot-film sensor, parallel to sensor supports
V_{BN}  Local velocity normal to hot-film sensor, perpendicular to sensor supports
V_T  Local velocity parallel to the hot-film sensor
\alpha  Angle of Attack
\delta_c  Distance between jet ports along chord line (axial distance)
\delta_v  Vertical distance of jet ports above or below chord line
\rho  Fluid density
\theta_{sweep}  Sweep angle of injected jet
\theta_{di}  Dihedral angle of injected jet
\mu  Fluid viscosity
CHAPTER I

INTRODUCTION

In applying fluid dynamics to solve problems, engineers are often confronted with flows whose vortical nature dominates the flow field. The ability to control or modify these flows for a specific application depends on our ability to control or modify flow vorticity. Much research has been performed in an effort to understand the nature of vortical flows and to determine the relationships between the generation, structure, strength, stability, and accelerated decay of vortices.

One fluids problem which can benefit from such research is flow over three dimensional wing surfaces which results in concentrated vortices formed at the wing tips. Tip vortices are an undesirable by-product of lift. These vortices are directly linked to reduced aerodynamic efficiency of three dimensional lifting bodies. This reduction in efficiency is manifested in the addition of 'induced drag' to the forces acting on the aircraft.

Also, interaction of these vortices with other structures results in undesirable noise and structural vibrations. Examples of such interactions include impulsive noise and vibration from helicopter rotors, and large unexpected rolling moments experienced by small aircraft that fly into the wakes of larger aircraft. This latter example has caused accidents and attests to the persistence and strength of tip vortices. Obviously, there is good reason to seek ways to modify and attenuate these vortices. Despite much research, unfortunately, the nature of vortex stability and breakdown is not yet well understood and there is no theoretical model which provides accurate predictions of a vortex's stability characteristics. Experimental, empirical, and theoretical analyses are needed to gain a greater understanding in this area. This will lead to better theoretical models and more efficient use or modification of vorticity in engineering applications.

This study is an experimental investigation into the effects of tip, small mass blowing, using discrete jets to accelerate the decay of tip vortices from wings. It is proposed that introducing small perturbations in the flow where the tip vortices are
formed will inhibit the formation of the vortices and decrease their coherence and stability. This research was designed to investigate two separate aspects of the wing tip flow with injection. The first is an investigation into the effects of pulsed injection on a fixed blade using flow visualization in a water tunnel study. The second is the application of tip blowing on a model rotor, using hot-film measurements to gauge the effectiveness of the technique. After a presentation of the background to this research in Chapter II, these two areas of study are presented separately, in Chapters III and IV respectively. Finally, conclusions and recommendations are provided in Chapter V.
CHAPTER II

BACKGROUND AND THEORETICAL CONSIDERATIONS

Literature Review and Theoretical Considerations

In preparation of this research, a review of existing work was done which revealed the extensive work that this field has commanded. Both experimental and theoretical studies provide an excellent basis for current efforts. First, the physics of wing tip vortex flows will be reviewed. Next, the motivation for attempting to minimize the tip vortex will be presented. Finally, a discussion of previous work related to the problem will be provided to form the basis of this work.

Vorticity and The Flow Field of Finite Wings

Vorticity is mathematically defined as the curl of the velocity vector:

\[ \Omega = \nabla \times V \]

In plain terms it is a measure of a fluid element's rotation about a given axis. Circulation is defined for any closed contour in a fluid as the line integral of the velocity vector around the curve:

\[ \Gamma = \oint_C V \cdot dl \]

The close relationship between circulation and vorticity can be seen by applying Stokes' theorem to the above expressions:

\[ \oint_C V \cdot dl = \iint_S (\nabla \times V) \cdot n\, dS = \iint_S \Omega \cdot n\, dS \]

This equation states that the circulation around any closed curve is equal to the outflow of vorticity through any surface bounded by the curve. In addition, applying the divergence theorem provides further insight into the nature of vorticity. Noting that 'div curl V' is zero by definition, the divergence theorem states that the net flux of vorticity of a homogeneous fluid through a fluid surface is zero:
\[ \int \int \int \mathbf{v} \cdot \mathbf{\Omega} \, dS = \int \int \mathbf{\Omega} \cdot \mathbf{n} \, dS = 0. \]

An implication of this statement is that a vortex cannot begin or end in a fluid. An argument for this statement can be formed as follows. If we define a vortex line as a line that is everywhere tangent to the local vorticity vector, and a vortex tube as the set of vortex lines that intersect the boundary of a simple surface in space, then by definition no vorticity crosses the surface of the tube. This is analogous to a stream tube. By the expression given by the divergence theorem, between any two imaginary cross-sectional surfaces of the tube, the net flux of vorticity across these surfaces must be zero. An implication of this is that the circulation around these two surfaces and, therefore, around any section of the tube is constant. This fact precludes a tube from starting or ending in a fluid. Vortex tubes must therefore form endless loops or they must start or terminate at a fluid boundary.

Adding to the above spatial characteristics of vorticity, the Helmholtz theorem addresses how vorticity in a fluid changes with time. The Helmholtz vorticity transport equation can be derived by taking the curl of the equation of motion for incompressible, constant viscosity, homogeneous fluid under the action of irrotational body forces [1]. Solving for the total derivative of vorticity gives:

\[
\frac{D\mathbf{\omega}}{Dt} = (\mathbf{\Omega} \cdot \nabla) \mathbf{v} + \mathbf{v} \cdot (\nabla^2 \mathbf{\Omega})
\]

This is the Helmholtz equation which states that for this flow regime, vorticity is conserved and must be convected along with the flow - dissipated only by viscous diffusion. Vorticity then, can only be altered through vortex stretching, viscous diffusion, interactions with other vortices (or free or solid surfaces), or flow instabilities.

The phenomenon of the wing tip vortex is well documented and has been studied for some time. As such, only a brief review of the physics regarding this flow condition will be presented here. Readers interested in pursuing this topic in greater detail are directed to Green's review [2]. The circulation theory of lift states that the source of lift on a body submerged in a moving fluid is circulation around the surface of the body. On a two dimensional body, this circulation can be represented as a bound vortex of constant strength. If we ignore the effects of viscosity, in order to preserve the total
circulation or vorticity in a control volume encompassing the airfoil (as required by Helmholtz theorem), there must be vorticity shed along the span of the airfoil such that the total circulation is conserved. This shed vorticity can be envisioned as a trailing sheet of vorticity. On a finite wing, because there can be no discontinuities in velocity or pressure at the tips, the lift force and hence the circulation must go to zero at the tips. Unlike the two dimensional case, this implies that the circulation (and shed vorticity) varies along the span of the wing. The strength and distribution of the vorticity in the trailing sheet is a function of the lift distribution across the wing and is strongest at the tips. Figure 2-1\(^1\) provides a graphical summary of these statements. An important characteristic of the vortex sheet is that the inherent instability of the sheet results in the vorticity ‘rolling - up’ into two concentrated vortices of opposite sign near the tips. A simplified representation of this is shown in Figure 2-2. It is estimated [2] that all the vorticity in the wake rolls-up into the two concentrated tip vortices within a couple of chord lengths.

A physical argument on the formation of the tip vortices can also be made. Because the flow seeks to reach equilibrium, the higher pressure air on the underside of the airfoil seeks out the region of lower pressure on the airfoil’s top side. With the physical barrier (the surface itself) removed at the tip, the flow is free to wrap around the tip. The circular flow around the tip superimposed on the freestream, results in the helical flow pattern characteristic of tip vortex flow.

Motivation to minimize the tip vortex

The generation of vorticity due to a lifting surface in a fluid is inevitable and it will therefore exist in the flow aft of a wing. However, changing the distribution of the vorticity or the structure and stability characteristics of the vortices can have a tremendous impact on the performance of the wing and on other aspects of modern flight.

There are at least two motivations for attempting to minimize the tip vortices from wings. The first motivation is to increase the aerodynamic efficiency of the lifting surface. The primary adverse effect of lift-generating circulation on a wing is the resulting

\(^1\) All figures are provided in Appendix A.
downwash and the formation of concentrated tip vortices in the wake. The effect of downwash is summarized in Figure 2-3. Since the local lift is defined as the force perpendicular to the local freestream, one sees from the figure that the downwash tilts the local lift vector slightly aft. The component of the local lift vector in the direction opposite to the motion of the body is known as induced drag - the drag due to lift. Note that apart from producing drag, the downwash also decreases the effective vertical force on the body. This suggests one motivation to minimize the strength of the vortex: to reduce the induced drag and improve the aerodynamic efficiency of the wing at a given flight condition. Induced drag often makes up a significant percentage of the total drag experienced by a lifting body which translates into millions of dollars every year in fuel - not to mention the added environmental toll paid to burn the fuel to overcome this drag force.

A second motivation for minimizing tip vortices is related to vortex interactions with other structures whether in the far or near field case. The strength and persistence of tip vortices is well documented [3,4], making vortex interactions thousands of chord lengths aft of the lifting surfaces of today’s large aircraft potentially catastrophic for smaller aircraft. Even miles behind a large aircraft, a small aircraft can experience large rolling moments due to the tip vortex flow field of the preceding aircraft. These rolling moments can be strong enough to render the flight controls of smaller aircraft useless in trying to overcome the forces resulting from such an interaction. This is especially true on take-off and landing where wing loading and hence tip vortex strength is greatest. Moreover, with little room to recover from uncontrolled flight, the consequences for smaller aircraft are deadly. A number of accidents attributed to these factors forced the FAA to adopt increased separation distances between aircraft to avoid this problem. The result is that fewer aircraft are able to takeoff and land in a given time period. One study claims that the addition of one extra takeoff per hour at a medium sized airport could save millions of dollars over a one year period [4].

Interactions of vortices and structures in the near field also cause problems in modern aviation. In-flight refueling is made difficult and more hazardous since the receiving aircraft is generally flying near a tip vortex of the supply aircraft. Another
problem is vortex interactions with other aircraft surfaces causing accelerated structural fatigue or control problems. Such problems are not isolated to the fixed wing community. One of the greatest sources of impulsive noise from rotorcraft is caused by the interaction between rotor blades and tip vortices from preceding blades. The high velocity gradients across a vortex result in a rapid change in the local angle of attack of the following blade. The resulting pressure spike on the following blade is manifested as an objectionable ‘blade slap’ noise and structural vibration on the blade. This phenomenon is called Blade-Vortex Interaction (BVI) and it is a source of unwanted noise, vibration, and unsteady blade loading (Figure 2-4).

BVI is typically found in certain flight regimes where the helicopter’s rotor is flying through its own wake. Unfortunately, one of the flight regimes where this phenomenon is most common is slow descending flight, which is typical on approach for landing when the helicopter is near the ground and when the noise becomes most obtuse. The helicopter’s advantage of VTOL will not be fully realized if the aircraft cannot meet increasingly tough noise restrictions. Moreover, the military’s desire for stealthy aircraft makes the reduction of this type of noise of value to the Armed Forces. As a result, the application of vortex attenuation to reduce helicopter noise has received a lot of attention in the last 15 years [5,6,7,8,9,10].

Due to the unsteady three dimensional nature of the flow field, the BVI phenomenon is complicated and is difficult to measure as well as to model theoretically. However, experiments have been successfully carried out on both full scale and model tests [11] and advances in mathematically modeling the rotor wake have been made. Factors in the severity of BVI include the vortex strength and structure, the miss distance (between the vortex and the following blade), and the blade geometry and loading. This suggests that reducing the strength and coherence of the vortex or increasing the miss distance between the blade and the vortex are potential solutions to this problem.

In attempting to decrease the vortex strength or stability, the most obvious place to start is to consider mechanisms of vortex decay which occur naturally. There are three known categories of vortex decay. The first is viscous diffusion. This is a weak means of natural vortex decay which relies upon the effect of friction between fluid
particles to slow the rotational velocities of the vortex to the point where they are no longer strong enough to overcome ambient disturbances. The strength and persistence of tip vortices means that viscous diffusion can take miles to dissipate tip vortices produced by large passenger aircraft assuming other flow instabilities do not accelerate the decay process. It is generally far too slow to be much use from an engineering standpoint.

The second natural decay process is referred to as vortex bursting. It is characterized by a violent change to the vortex structure and tremendous deceleration of fluid particles which results in an almost instantaneous dispersion of the vortex. This phenomenon occurs under certain specific conditions - the various combinations of which are not entirely understood. A number of factors are known to influence the likelihood of vortex bursting. These include axial pressure gradient, Reynolds number, circulation number, geometry of the body, turbulence in the flow and the specific velocity field in question (see Sarpkaya [12]). This phenomenon has received most attention from aerodynamicists interested in the lift on delta wings at high angles of attack. It is unlikely to be used for control of tip vortex alleviation due to the absence of the required conditions in the natural flow field and the difficulties to produce these conditions artificially.

The third means of vortex decay is a flow instability known as Crow instability. This is a long wave process characterized by a sinusoidal instability of typically two line vortices which eventually merge, forming a single line of vortex rings [3,4,13]. This process is also rather slow and requires certain conditions for initiation.

Previous Work On Tip Vortex Alleviation

It is clear that there are great benefits to be realized if techniques can be found to redistribute the vorticity in the wake or accelerate the decay of the tip vortices. Efforts to modify the tip vortices from wings started almost 75 years ago when end plates were used in an attempt to prevent the formation of tip vortices [14]. Endplates continued to receive a lot of attention into the early 1950s and met with some success. However, the benefits realized from endplates were tempered by the drag penalty they imposed. The last thirty years has seen a great deal of research conducted on reducing or controlling tip
vortices. Any new technique must be evaluated on two counts: the effectiveness of the technique and the viability of the concept for implementation on real aircraft.

A concept that grew out of endplate research that has achieved some success is the winglet. Different from endplates, winglets are small lifting surfaces which, when properly designed and positioned on the wing tip, produce a sideforce which not only serves to inhibit tip vortex formation, but also provides a small force component opposing drag. Two problems exist with winglets - they have been unable to reduce rolling moments downstream of the lifting surface and they are designed for one flight condition - typically cruise. Other non-planar tip geometries have been attempted for use on both fixed wing and helicopter blades with limited success [15, 10].

Mass injection is another area that has received attention. Lee et al [16, 17, 18] have used a tip modified with a long single slot in the tip to produce a spanwise jet sheet. The effect of this sheet appears to be a modification to the lift distribution similar to that produced by a increase in aspect ratio. Unfortunately, the fundamental nature of the tip vortex for the wing does not appear to be altered significantly. More recently, Jacob [4] studied the use of rearward (axial) blowing near the tips which reduced tangential velocities in the vortices but did not significantly accelerate their decay.

Another technique that has been examined is active excitation of Crow instabilities through external forcing. One such studied [3] used oscillating flight surfaces at specific frequencies to excite long wave instabilities. Surprisingly, vortex breakdown occurred before the breakdown mode associated with Crow instabilities was observed. Although promising, these methods suffer from having to involve oscillating surfaces typically integral to the operation of the aircraft. This could adversely affect the structure of the airframe and the handling qualities of the aircraft. However, it does point out the potential of using forced excitation of flow instabilities to accelerate decay. Other means of introducing small perturbations to the flow to affect the vortex stability may be possible.
Basis for Current Research

The foundation for this study rests on work directed by Drs. Wu and Vakili of the University of Tennessee Space Institute. Studies [3,19,20,21,22] have shown that the concept of discrete jets has the potential to effectively disperse the vorticity present in the coherent tip vortices. Initial work [3] concentrated on water tunnel tests for flow visualization in order to observe the effects of the jets. The results were visually dramatic. Blowing with discrete jets clearly dispersed the tip vortex. Figure 2-5 is typical of the results and shows the effect of blowing during a water tunnel test of a wing model using dye injection for flow visualization. The mechanism for the change appeared to be the formation of multiple auxiliary vortices which decreased the tip vortex strength and increased instability introduced into the flow field. Further studies were done in the UTSI low speed wind tunnel [21]. These tests confirmed the initial results and revealed that the entire flow over the wing was effected. Discrete jets altered the three dimensional flow field and the lift distribution across the wing.

As a continuation to this work, the current study proposed the use of discrete jets in two new ways. First, on a fixed wing model, pulsating discrete jets were used to introduce small perturbations to the flow with the objective of destabilizing the concentrated tip vortex. Because of the complexity of the flow condition, a water tunnel study with pulsing jets will provide insight into the flow physics so that a better understanding of what is happening can be realized. Flow visualization also provides a qualitative means of evaluating the potential of this technique to affect the tip vortex - providing some direction for future studies. Secondly, in light of the problem of BVI, the technique of steady blowing will be applied to a model rotor for the second part of this study. A quantitative experimental investigation will indicate the potential of this technique for use on rotors.

Experimental Considerations - Dimensional Analysis / Similitude

For many years, fluid dynamicists have relied on experiments to gain insight into fluids problems that lack an analytical solution. Experiments are typically performed on full-scale models (prototypes) or scaled versions of a prototype (models). In the field
of aerodynamics, models are typically used because of the expense and difficulties in working with prototypes. In order that experimental results accurately reflect the performance of full-scale flows, the model must be geometrically similar to the prototype and the flow must be dynamically similar to the full-scale flow. All the variables that may influence a particular flow situation can be numerous and deciding how to report the effect of all the possible variables on the results can also be a problem. These issues are addressed by the concepts of similitude (the theory of models) and dimensional analysis.

In complex flows such as the one under study in this research, the equations of motion that govern the flow are time varying and non-linear. The solutions to these equations are not available with current methods however, they can be treated numerically in some cases. By non-dimensionalizing the equations of motion such that the equations exactly describe the given flow situation, data obtained by models are transferable to the prototype case by equating the non-dimensional groups. Dimensional analysis is the process of identifying these groups. In so doing, an ordered and efficient approach can be used to study the effects of one group of variables on the flow and results of experiments of entirely different scales can be compared. The Buckingham Pi theorem provides a means to order our variables in this way. The variables relevant to this research are as follows: b, c, f, fj, m, pj, Vj, Vtip or U, δc, δs, L, d, p, p, θsweep, θdi, μ. The problem is one of 17 variables in 3 dimensions: M, L, t. Therefore, 14 dimensionless variables are expected. Dimensionless groupings are obtained by grouping each variable with a set of selected repeating variables that cover the three dimensions. Each one of these groupings can be solved for exponents required to make the group dimensionless. For example, select ρ, Vtip, c, and as the repeating variables (for the fixed wing case, the freestream velocity, U, would be used as the reference). Now, let the first grouping be

\[ \Pi_1 = \rho^a V_{tip}^b c^c (\mu) = M^0 L^0 t^0 \]

\[ M^a L^{-3a} L^b t^b L^c (M L^{-1} t^{-1}) = M^0 L^0 t^0 \]

Solving the resulting equations gives;

\[ \Pi_1 = \mu / \rho V_{tip} c \]
This familiar result is a form of the Reynolds number (inverted) - which is one of the most important non-dimensional parameters in the study of viscous fluid dynamics. The other non-dimensional parameters are summarized below:

\[ \Pi_2 = \frac{V_j}{V_{tip}} \text{ (rotor)} \] - jet velocity ratio
\[ \Pi_3 = \frac{\rho_j}{\rho} \] - jet density ratio
\[ \Pi_4 = \frac{b}{c} \] - wing span to chord ratio (Aspect Ratio)
\[ \Pi_5 = 2m_j \frac{V_j}{\rho V_{tip}^2 S} \] - momentum coefficient
\[ \Pi_6 = \frac{\delta_j}{c} \] - jet slot axial position ratio
\[ \Pi_7 = \frac{\delta_v}{c} \] - jet slot vertical position ratio
\[ \Pi_8 = \frac{L_s}{c} \] - slot length parameter
\[ \Pi_9 = \frac{d_s}{c} \] - slot width parameter
\[ \Pi_{10} = \frac{f_j c}{V_{tip}} \] - Strouhal number
\[ \Pi_{11} = \frac{f_r c}{V_{tip}} \] - rotor speed parameter
\[ \Pi_{12} = \theta_{sweep} \] - jet sweep angle
\[ \Pi_{13} = \theta_{di} \] - jet dihedral
\[ \Pi_{14} = \frac{P_j}{\rho V_{tip}^2} \] - jet pressure coefficient (Euler Number)

Many of these parameters relate to the geometry of the components and involve geometric similitude. These include the wing or blade sizing, jet slot position ratios, injection angles etc. Other parameters such as the blowing momentum coefficient, the Reynolds and Strouhal numbers relate to the dynamics of the flow. It should be noted that the above analysis provides no information into the relative importance of each of these parameters. This information comes from a combination of engineering judgment, experimentation and analysis of the non-dimensional equations of motion. In this study, the objective was not to match the results to a full scale flow situation. Other studies [11] have successfully modeled full scale helicopter rotor noise tests identifying other important non-dimensional parameters including advance ratio, tip Mach number, and tip path angle. This study was concerned with comparing the coherence of tip vortices.
between a baseline and a test condition. The dimensionless values are no less important in this case since they define the flow conditions for the tests. In studying the effects of changing any of the variables, the dimensionless parameters actually become the variables to be altered. This is the most effective means to achieve a parametric study.
CHAPTER III

WATER TUNNEL TESTS

Experimental Objectives

The objective of the water tunnel tests was to qualitatively study the effect of steady and pulsed injection on tip vortex attenuation using discrete jets at the tip of a wing. Due to the complex and unsteady nature of the flow field with pulsed injection, flow visualization was deemed a useful means to gain insight into the flow physics and provide information on spatial and structural changes to the region around the tip vortex flow field.

Experimental Set-up and Method

The Test Facility

All tests were performed at the University of Tennessee Space Institute (UTSI) Water Tunnel. The UTSI Water Tunnel is a closed circuit continuous flow facility powered by a 1 Hp electric motor which drives a 10" diameter two blade propeller. The test section is 12" x 18" x 60" with Plexiglas walls to permit full viewing of the flow. Attainable velocities range from 1 to 20 in/s. The tunnel layout is shown in Figure 3-1. The tunnel has a low turbulence characteristic attributable to the tunnel layout design, stilling chamber, and flow straighteners.

The Test Wing

The test model used was a rectangular wing featuring a NACA 0012-64 airfoil section. The wing has a semi-span of 10" and a 6.375" chord, resulting in an AR of 1.56. The model was milled from a solid piece of aluminum and fitted with a separate rounded tip featuring three rectangular slots with tip reservoirs milled inside the tip. A schematic diagram and pictures of the model are shown in Figures 3-2 and 3-3. The root of the
wing was fitted with a shaft that extended through the side wall of the tunnel to secure the wing at the desired angle of attack. All tests for this experiment were conducted at 8 degrees angle of attack. The wing was placed 12" from the front of the test section and the tip extended into the tunnel section to 60% of the tunnel width. Internal holes along the span permitted the placement of the water supply tubes to the tip reservoirs. These supply tubes were also passed through the tunnel wall, permitting the wing root to be mounted flush against the tunnel wall.

The Experimental Set-up

In order to be able to pulse the flow, the main water supply was branched through three controllable flow meters, then to three separate solenoid valves, and finally to the individual ports inside the wing. The valves were operated with a duty cycle of 0.5, meaning the valves were open for half of the cycle and closed for the other half. Three function generators were used to control the frequency of the flow injection.

The technique used for flow visualization was hydrogen bubbles. A DC power supply was connected at the cathode to a small wire placed in the flow, while the anode was connected to a conducting plate submerged in the water. The wire was supported by a bar placed across the top of the tunnel and a suction cup attached to the tunnel floor. This allowed easy movement of the wire to the desired locations. When the power supply was turned on electrolysis took place with hydrogen bubbles emanating from the wire and being carried away with the moving fluid. The hydrogen bubbles exhibited nearly neutral buoyancy since the bubbles traveled the length of the tunnel with no tendency to rise or fall. This method was chosen over dye because dye visualization suffers from providing information on the flow only where dye particles have been injected or migrated. The hydrogen bubbles provided a more global visualization of the flow behind the wing - revealing concentrated vorticity in the wake regardless of its position. A schematic diagram of the layout is provided in Figure 3-4.

In an effort to minimize errors associated with excessive tunnel blockage and side wall interference, the dimensions of the test airfoil section were limited. The aspect ratio of the test model was 1.56. Clearly, this is not typical for the wings of most aircraft
which typically have aspect ratios between 5 and 12. Rotor blades on helicopters have even larger aspect ratios. Wings with smaller aspect ratios carrying the same load suffer more from three dimensional effects due to the increased circulation required for the same lift. The Reynolds number for the tests was in the area of 22,000 which is low when compared to the flow over an actual aircraft wing in flight. However, the Reynolds number is high enough to avoid entering an entirely different flow regime and therefore while matching these parameters was not possible, the tests still capture the essence of the flow. Moreover, the nature of the test was qualitative and the results were compared only to a tested baseline and not to a particular full scale flow. The results are valid in the context of the trends and the nature of the flow alterations observed.

Test Conditions

With the geometries of the test components fixed, the tests were designed to study the effects of varying the momentum coefficient and pulsing frequency (Strouhal number) on the coherence of the tip vortex. Test configurations included testing individual ports and combinations of ports at various momentum coefficients and frequencies. The momentum coefficient is defined for this flow as:

\[ C_\mu = \frac{2 m_i \sqrt{V_i}}{\rho S U^2} \]

Momentum coefficients for individual ports ranged from 0.003 to 0.016 with coefficients for multiple port configurations reaching 0.0396. Injection frequencies were varied incrementally between 0 Hz (steady injection) to 10 Hz (corresponding to a St number range of 0.035 to 1.4). Changing the injection phase for multi-port blowing was also investigated in a preliminary manner. The wing was set at 8 degrees angle of attack and the flow was consistently set around 5.5 in/sec (Re = 22,000). For each configuration tested, the hydrogen bubble wire was placed at 1 chord and 5 chords aft of the wing’s trailing edge.
Water Tunnel Study - Results and Discussion

The hydrogen bubble technique was very effective in capturing the nature of the flow behind the wing. The wire could be placed anywhere downstream of the tip and capture regions of coherent, concentrated vorticity associated with tip vortices. However, proper viewing of the bubbles was highly dependent on the position of the light source. A better arrangement would have been to use a light sheet to illuminate a plane perpendicular to the tunnel walls and the freestream.

Before discussing specific results on pulsed jets, some general remarks are offered. The results of previous tests using steady injection and dye for flow visualization were generally confirmed during this study. The effect of the discrete jets increased with blowing coefficient. Yet only small coefficients were needed to observe significant changes in the coherence of the tip vortex, due to the non-linear nature of the flow. Blowing coefficients of 0.0035 were sufficient to observe such changes.

Along with confirming previous test results, additional information was gained on steady injection. Different ports seemed to be responsible for shifting the tip vortex from the baseline position in different ways. One chord aft of the trailing edge, steady injection with port #3 typically caused the vortex to shift outboard. By 5 chords downstream, the vortex shifted up and inboard of the baseline. In contrast to this, injection from port #2 shifted the vortex initially up (1 chord aft) then inboard and only slightly up 5 chords downstream. The #1 port was generally less effective than the other two ports. This is believed to be in part due to a misalignment of the supply tube with the port itself which was discovered after testing was complete. The movement of the vortex was a direct function of the strength of the blowing (increasing momentum coefficient). The vortex core was shifted a maximum of 0.15c outboard and 0.30c vertically from the baseline position. Increased unsteadiness in the flow with steady blowing resulted in a less coherent vortex with variability with time in core shape and core size being observed. As shown in Figures 3-5 and 3-6, steady injection affected the strength of the tip vortex. Reduced tangential velocities and an increase in the size of the hydrogen bubble void near the apparent center of the vortex suggested a weaker vortex. Although both ports were
effective, port #3 was the most effective followed by port #2.

The effect of using multiple ports for steady blowing appeared to be somewhat similar to the effects of the individual ports. At 1 chord aft of the trailing edge, injection from ports #2 and #3 together for the same individual blowing coefficients resulted in displacement of the vortex up and outboard of the baseline position. Five chords downstream, the vortex moved back toward the vertical baseline position and inboard of the baseline. It should be noted that the vortex for these tests became increasingly difficult to identify due to decreased coherence in the vortex, however, a void associated with a vortex core could generally still be identified. As expected all three ports blowing resulted in the greatest effect relative to the baseline, however the effect was not much different from the combination of ports #2 and #3 which was the best two port configuration.

The effects of pulsing the flow were consistent regardless of the port configuration tested. The effects are divided by injection frequency. Below 0.75 Hz (St = f/c / U = 0.010), the flow appeared to follow a periodic pattern that was a function of the injection frequency. The flow would vary between a vortex at the baseline position and the steady blowing position, following a specific path between these two locations. At the onset of the injection, the vortex would shift laterally to an outboard position and then move up and inboard to the steady blowing position. At the end of the injection cycle, the vortex would then return to the baseline position. This process is shown in Figure 3-7.

The explanation for this behaviour is that, given time, the flow will go to the baseline position during the off cycle of the pulsed injection. With the impulse at the start of the injection cycle, the interactions due to the jet shifts the flow initially outboard, until the jet stabilizes and the vortex moves to the steady blowing position. This phenomenon is likely due to a combination of factors, including entrainment of the flow with the laterally injected jet, changes in the stability of the vortex due to the perturbations introduced to the flow, as well as interactions of the tip vortex with auxiliary vortices formed by the jets themselves [3]. It should be noted that the structure of the vortex changes through this cycle from the very coherent baseline vortex, to a more diffused and weakened vortex associated with steady injection.
Between 0.75 and 1.0 Hz (corresponding St = 0.010 to 0.014) the process described above continued at a faster rate and the flow was more turbulent with significantly less coherent vorticity. Occasionally, a vortex core could be identified. This typically occurred at one of the three positions described above: steady blowing, baseline or the transient outboard location. Despite this, however, the flow was generally unsteady with no identifiable void, indicating that the vorticity distribution in the wake had been fundamentally altered. More importantly, in viewing the flow 5 chords downstream, the flow showed no tendency to reform an area of coherent vorticity, suggesting that the pulsed injection affected the stability characteristics of the tip vortex. Figure 3-8 shows a typical flow field for pulsed injection at these frequencies.

Above 1.0 Hz (St > 0.014) the flow began to appear more and more like the steady injection case. Above 5 Hz it was difficult to tell the difference between pulsed and steady injection apart from some minor fluctuations in the flow. This indicates that the stability of the tip vortex was susceptible to perturbations at certain frequencies.

An attempt was made to investigate the effect of uncoupling the phase of pulsed injection in multi-port injection configurations. However, it was quickly evident that little could be learned with the existing test set-up. The flow for tests using ports pulsed at different frequencies and out of phase (ports not synchronized) were not significantly different from the results of synchronized pulsed injection between 0.75 Hz and 1.0 Hz. Unsteadiness dominated these flows and more sophisticated instrumentation would be required to ascertain differences in the flows for these configurations.

It is possible that increasing the number of small perturbations introduced to the flow at various locations at the proper frequency and phase could attack the stability of the vortex, redistributing the vorticity in a manner more suitable for our applications. It should be noted that steady injection seems to be related as much to a displacement of the tip vortex as it is on the vortex structure and stability. While also affecting its coherence and strength, increasing the blowing coefficient primarily tended to displace the vortex. On the other hand, adjusting the injection frequency of the discrete jets tended to affect the coherence of the tip vortex, redistributing the vorticity in the wake and attacking the stability of the vortex.
CHAPTER IV

STATIC ROTOR TESTS

Experimental Objectives

The objectives of this part of the study included design and manufacture of a static rotor test stand (non-articulating) and a quantitative assessment of steady blowing using discrete jets on the tip vortices of a rotor blade in rotation.

Experimental Equipment, Set-up, and Method

Design and Manufacture of Test Stand

The first task in this phase of the research was the design and construction of a static, non-articulating rotor test stand. The support structure was made from steel angle iron to provide a solid base for a large model rotor. The horizontal platform of the support structure provided the main support for the motor and bearings. The platform is 72" off the ground providing suitable clearance for a rotor semi-span of 36". A 1 Hp motor was secured to the test stand platform and a motor controller provided speed control from zero to 1700 rpm.

Air Supply Adaptor Assembly

In order to get air to the tips of the rotating blades, a special supply adaptor was designed. The adaptor is shown in Figures 4-1 and 4-2. Compressed shop air is supplied through a stationary center piece to two concentric cylinders via a slot around the circumference of the outer cylinder. The ‘barbell’ shape of the inner cylinder provides an axial path for the air to follow to the end of the cylinders. There, tubes connected to two ports off the outer cylinder carry the air to the blade tips. The concentric cylinders which are keyed to the rotating shaft are sealed together to prevent leaks. Leaks between the stationary center piece and the rotating cylinders are minimized by ‘sandwiching’ the
center piece between two heavy flange bearings. These bearings also support the shaft (through the cylinders) and carry the shaft load near the blades. The adaptor worked well up to supply pressures of 10 psig beyond which leaks through the bearings were apparent. Pressures at 5 psig allowed momentum coefficients in the desired range without noticeable leaks. The leaks through the supply adaptor were not quantified because of the difficulties of measuring small air flow rates at the rotating tips. Instead, the error associated with this leakage means that the reported momentum coefficients are conservative values since the actual coefficients were reduced by leakage through the assembly.

The Rotor Blades

The blades were made by a hand lay-up of fiberglass over a styrofoam and aluminum skeletal form. The aluminum bar that runs through each blade span was connected to a flange at the blade root, allowing attachment of the blade assembly to the hub flange assembly. Because the blades were made by hand and not machined there is some variation in the corresponding dimensions of the two blades. The surfaces of the blades are considered accurate to ± 0.0625". As in previous tests, the NACA 0012-64 airfoil section was used. The tips were machined from solid aluminum blocks and attached to the main blade with screws. One blade was fitted with a modified tip similar to the one used in the water tunnel experiments. The salient features of the modified tip and orientation of the slots for the experimental blade are shown in Figures 4-3 and 4-4. The blades measured 25.25" (semi-span) by 7" resulting in an aspect ratio of 3.61.

The angle of attack of the blades was set using position pins between the blade roots and shaft hub flange assemblies. Slots in these flange assemblies allowed rotation between the blade and hub for angle of attack adjustments. Three position pin holes in each flange mated at angles of zero, five, and ten degrees. Once the position pin was in place, the hub and blade roots were bolted together. The blades were set at ten degrees for all tests in this study. While the blades were successfully tested to over 600 rpm, all tests were conducted at about 285 rpm to allow momentum coefficients to reach desired levels without excessive line pressure which caused leaks through the supply adaptor.
Experimental Approach and Instrumentation

The approach for this study was to compare the effective velocities in the wake of the rotor while applying steady injection using discrete jets, to the effective velocities with no blowing (baseline condition). Resource limitations precluded a detailed wake survey or resolution of the velocity field in the wake in three dimensions. Instead, hot-film measurements at various locations were used to measure the velocities associated with the tip vortices off the blade tips. All testing was performed at the Applied Fluid Dynamics Group main propulsion lab which afforded the largest room to minimize interference and recirculation effects.

The hot-film anemometer was located behind the rotor tip path plane for measurements in the wake of the rotor flow. The support structure for the probe assembly consisted of a heavy tripod which permitted vertical positioning of the probe (movement inboard toward the hub). Axial positioning (movement perpendicular to the tip path plane) was provided by a traversing mechanism secured to the top of the tripod (Figure 4-5). To set the angle of the probe, the probe housing passed through the center of a rotating vernier scale which permitted the probe to be rotated in a plane parallel to the tip path plane. Laterally, the probe support stand was positioned so that the probe sensor was in line with the leading edge of the blades as the blades passed through the vertical axis.

To acquire blade phase information, a photo-interrupter module was used to trigger a square wave signal to indicate the position of the blades. The signal was triggered by interrupting the photo-module circuit once per revolution with a small metal plate fixed to a collar around the flexible coupling (see Figure 4-6). The position and size of the metal plate were set to correspond to passage of the blade through the plane defined by the vertical leading edge of the blowing blade. The acquisition and processing of the hot-film signal was provide by a TSI IFA300. The conditioned hot-film signal and the phase signal from the photo interrupter module were sent into a PC through the IFA300 A/D board. An IBM compatible 133 MHz pentium PC was used during the tests. The IFA300 software was used to process the data based on the stored calibration files, producing results in velocity vs time in almost real time. All tests runs were conducted at a sampling rate of 4000 Hz over a 2.048 second sampling time. At the pre-determined
rpm, this sampling rate gave a resolution of better than half of one degree per sampled point.

The calibration of the hot-film probes was made easier with the help of the IFA300 software. Two separate sensors were used during the tests (models TSI FN19 and FN21) and both exhibited the same characteristics. The calibrations were repeated before and after testing and the calibrations showed excellent repeatability. The errors of the calibration points from the resulting curve fit for velocities greater than 4 m/s were excellent - varying only by an average of $\pm 1\%$. Below 4 m/s, (which for these tests corresponds to about $0.25V_{tip}$) larger errors resulted (around $\pm 4\%$) due to the non-linearity of the curve. It should be noted that due to limits on the calibrator, the sensors were calibrated in only one orientation and correction factors were not determined for flows perpendicular to the sensor and the probe supports. This means that the effective velocities measured by the probes were not corrected for flow orientation and extracting velocity components from the hot-film data was not possible. However, because of the comparative nature of the test, absolute velocities were not required. Issues regarding the hot-film calibrations are provided in Appendix B.

Test Planning and Conditions

The approach for the tests was to take effective velocity measurements at various points in the rotor wake in an attempt to quantify the velocities associated with the tip vortices for the baseline (no blowing) and experimental (one blade blowing) configurations. A matrix of data points behind the rotor plane was selected initially for sampling. These points were adjusted during the tests based on preliminary results. Points were sampled by moving the probe axially (fore and aft of the rotor plane) and vertically (inboard from the blade tip toward the hub). With the lateral position of the probe fixed, the data could provide the third spatial variable by using the blade phase information. A summary of the test points is shown in Figure 4-7. The probe was oriented at two complementary angles for each test point to ensure data was not being missed by probe orientation.

Two injection configurations were tested. The first series ("X" series) used
blowing from ports #2 and #3. The other two series ("Y" and "A" series) directed both supply tubes to port #3 to increase the momentum coefficient from a single port. An attempt was made to examine the effect of increasing the momentum coefficient in the first series of tests, however, because of the size of the tubing used to supply the ports, excessive line pressure was needed to increase the blowing coefficient which simply caused leakage from the supply adaptor assembly. The momentum coefficient is defined as:

\[ C_\mu = \frac{2 m_j V_j}{\rho S V_{tip}^2} \]

The momentum coefficient for ports #2 and #3 in the first test series was \( C_\mu = 0.00163 \) for a total of \( C_\mu = 0.0033 \). In the other tests, both supply ducts were directed to port #3, resulting in \( C_\mu = 0.0033 \). All tests were run at approximately 285 rpm which gives a Reynolds number based on the tip speed and chord length of approximately \( 0.4 \times 10^6 \). The final test set-up is shown in Figures 4-8 and 4-9.

**Rotor Test Stand Study - Results and Discussion**

Three sets of data and over 500 test runs were conducted over a period of 5 days. Each data set was run at approximately 285 rpm. Samples of the measured velocity field points (non-dimensionalized plots of effective velocity versus time) are provided in Figures 4-10 through 4-17.

Measurements from the baseline tests (no blowing) show the classic shape associated with vortex flow. In some cases (Figures 4-13 and 4-15), the velocity traces reveal a "V" shape indicating that the vortex core passed over the probe. As shown in the figures, the maximum effective velocity for the baseline tests reached between \( 0.4V_{tip} \) and \( 0.55V_{tip} \). The shape of the curves and the maximum values are consistent with previous research. McAlister et al [23] compiled a list of the maximum circulatory velocities measured in the wake of a rotor from 6 different studies. The results range from 0.12 to \( 0.77 V_{tip} \). While resolving the circulatory component from the current study is not possible, the maximum effective velocities measured, indicate the results are consistent.
with the results of other studies.

In comparing the results of the experimental blade with blowing against the baseline blade - the results are striking. Even with the low momentum coefficients used in this study, the maximum velocities in some cases are reduced by 50%. Figure 4-11 indicates reductions of the maximum velocities from $0.475V_{tip}$ to only $0.20V_{tip}$ (note: rectangular pulse in the figures indicates passage of experimental blade). The shape of the velocity trace has also changed from a steep smooth curve for the baseline blade to a broad unsteady trace for the experimental blade. Replacing the steep gradients associated with the baseline curves with those of the experimental blade would result in a more gradual gradient in the tip flow. This would improve BVI characteristics.

As observed in previous testing [3], and in the water tunnel tests of this study, steady blowing has the effect of displacing the concentrated vorticity as well as reducing its strength. It was expected that in some cases, the probe may be capturing the vortex of the baseline blade but not that of the experimental blade. In an effort to ensure that a maximum velocity associated with a concentration of vorticity was not simply relocated, each axial position was scanned vertically in the blowing configuration. No maximum velocities similar to the baseline configuration were found. In some cases, the experimental blade velocities show the classic "V" spike associated with the center of the vortex passing over the probe (Figures 4-13 and 4-17). These velocity traces show dramatic reductions in maximum velocities across the vortex.

Because the experimental blade using steady blowing may shift the position of vortex flow, generally, the maximum velocity associated with this blade will not be in the same location as the maximums for the baseline blade. However, despite scanning the flow field, no maximums associated with the blowing blade were found that approached the maximums from the baseline blade. Instead of a maximum of $0.55V_{tip}$, the maximum with blowing would be around $0.3V_{tip}$ in a different location. Blowing clearly had a positive effect on the concentrated vorticity from the blade tips. A sample of results from various runs is provided in Appendix C.

The effect of increased momentum coefficient was not successfully demonstrated during these tests. As mentioned, in the first series of tests, an attempt was
made to increase the momentum coefficient. The results of these test were inconclusive, in fact, the two blowing rates produced very similar results. This was most likely due to the fact that in order to get the increased flow rate the line pressure in the supply tubes had to be increased which resulted in excessive leakage through the air supply adaptor. The increased flow rate was likely lost through the adaptor, resulting in no effectual increase at the blade tips.

The blowing configuration was changed from ports #2 and #3 to blowing with only port #3. The total momentum coefficient for these two blowing configurations remained the same \( C_\mu = 0.0033 \). Similar results were obtained for both configurations (see results in Appendix C). A more detailed comparison between these two configurations with the existing data would be of little value because of the variability of the measured flow with small changes in rpm or probe placement. Therefore, only results from the same test series were compared in the analysis.

The results indicate that introducing perturbations to the flow using discrete jets directly affects the stability of the blade tip vortices - reducing the tip vortex strength (as measured by the reduced effective velocity ratio) and shifting the location of the vortex. It is postulated that the stability of the tip vortices has been affected since such major changes in the flow field would not otherwise result from such small levels of blowing \( C_\mu = 0.0033 \). Small perturbations can affect the flow in this manner because of the non-linear nature of the flow field.

**Limitations of the Study**

A number of limitations in this study were evident during testing and upon review of the results. There were often differences between the maximum velocities of the two blades in the baseline configuration. The maximum effective velocities of the experimental blade with no blowing were typically less than those of the baseline blade, particularly in regions with steep velocity gradients associated with vortex flow. The source of this discrepancy is likely the experimental set-up itself. Differences between the two blades and, in particular, differences in the axial distance from the trailing edge of each blade to the probe, are the most likely sources of this error. There was a difference of
0.125" between the axial distances of the two blades. Despite this, the two blades produced velocity traces with the same characteristics - if not the exact same amplitudes in the baseline runs.

Despite clear and unmistakable trends in the data, there was variability in the results even within a given test run. This was less common in the baseline tests suggesting that the variability was in part due to unsteadiness introduced by blowing. Other sources of variability are described below.

Despite the large size of the test area, there was some recirculation which likely affected the variability of the results. The meandering of the vortex location in rotor wakes is a known phenomenon [2, 3, 4, 23] and is another possible source for such observations. It was also found during testing that the flow behind the rotor and the location of the maximum velocities associated with the tip vortices were sensitive to small changes in rpm. While the motor speed for a given test run was quite stable (± 1%), it is possible that small rpm changes from run to run and resulting flow variations affected the results. In the case of tests with blowing, previous testing [3], including the water tunnel testing done in this research, has shown that there is increased unsteadiness and turbulence in the flow - even when steady blowing is used. This is consistent with the fact that jet instabilities are not stationary in time or space. As such, variability in the results was expected.
CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

An experimental study of the effects of destabilizing the tip vortices from a model wing and a model rotor using perturbations introduced by discrete jets located at the tips was conducted. Experiments on a fixed wing were conducted in a water tunnel using hydrogen bubbles for flow visualization. Also, hot-film measurements in the wake of a ‘hovering’ rotor model were taken to quantify the effects of blowing on velocities associated with rotor blade tip vortices.

The following conclusions are identified:

a) Discrete jets were utilized to reduce the coherence of the vortex near the wing tips;

b) Steady flow injection using discrete jets displaced the center of the tip vortex and reduced the strength and coherence of tip vortices;

c) Pulsed injection below a Strouhal number of 0.010 (St = f \cdot c / U) produced a pattern of flow that alternated between the baseline vortex and the weakened and displaced vortex flow associated with steady injection;

d) The frequency for optimum dispersion of the tip vortex and unsteadiness in the flow field corresponded to a range of Strouhal numbers between 0.010 and 0.014. Increasing the frequency above this value resulted in a flow field which resembles that of steady injection;

e) Rotor flow field measurements produced baseline results consistent with previous studies; and,

f) Steady injection using discrete jets on a ‘hovering’ rotor effectively reduced the strength of tip vortices as measured by the effective velocities in the wake.
The following recommendations are made:

a) A detailed study of the effects of discrete jets on helicopter rotor induced BVI should be undertaken to further explore these preliminary findings;

b) Parametric optimization studies of both fixed wing and rotors using discrete jets should be performed to identify configurations of greatest effectiveness; and,

c) Improvements in the test set-up be initiated to reduce any limitations on the results, including the use of PIV measurements and an improved air supply adapter assembly using larger supply tubes to the blades.
LIST OF REFERENCES


APPENDICES
APPENDIX A

FIGURES
Figure 2-1. Circulation, Lift Distribution, and Tip Vortices. Representation of bound circulation and resulting shed circulation distribution (calculated in discrete increments) across a rectangular planform. (Adapted from Green (1996))
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b) Induced drag resulting from downwash.

Figure 2-3. The Effect of Downwash on Finite Lifting Surfaces. Velocity distribution in the wake of a wing and its effect on the lift vector.
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Jet Port #1: 7/8" x 5/64"
Jet Port #2: 1/2" x 5/64"
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(No sweep or dihedral)

Figure 3-2. Schematic Diagram of NACA 0012-64 Model Wing.
Figure 3-3. Model Wing - NACA 0012 - 64 With Discrete Jets.
Figure 3-4. Schematic Diagram of the Experimental Set-up.
Figure 3-5. Hydrogen Bubble Visualization - Baseline (No Blowing).

$U = 5.5\text{ in/sec (Re = 22,000)}, \alpha = 8\text{ degrees},\text{ Wire 5 chords aft of trailing edge. Note tight, coherent vortex for baseline configuration.}$
Figure 3-6. Hydrogen Bubble Visualization - Steady Injection.

$U=5.5 \text{ in/sec (Re = 22,000)}, \ C_\mu = 0.014$, wire 5 chords aft of trailing edge.

Note change in vortex coherence and structure from baseline.
Figure 3-7. Hydrogen Bubble Visualization - Stages of Pulsed Injection.

$U=5.5\text{ in/sec (Re = 22,000)}, \ C_{\mu}=0.016, \ f_{j} = 0.5\text{ Hz (St = 0.0058)},$ wire 5 chords aft of trailing edge. Vortex shifts outboard (frame 2), then up to steady blowing position (frame 4).
Figure 3-8. Hydrogen Bubble Visualization - Pulsed Injection.

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Figure 4-2. Air Supply Adapter and Shaft Support Assembly. Two views of the assembly that gets air to the rotating blades and supports the rotor shaft.
Figure 4-3. The Rotor Blades - NACA 0012-64 With Discrete Jets.
Blade Data:
Fiberglass skin over foam/aluminum frame with solid aluminum tips
Dimensions: 25 1/4" semi-span, 7" chord
Jet Ports:
#1: 1" x 5/64" (A_j = .078 sq in), starts 3 11/16" from TE
#2: 11/16" x 5/64" (A_j = 0.0537 sq in), starts 2 3/16" from TE
#3: 11/16" x 5/64" (A_j = 0.0537 sq in), starts 3/4" from TE
(#2 directed 30 degree aft (sweep)),
(#3 directed 30 degrees aft (sweep) and 30 degrees down (anhedral))

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Figure 4-5. The Hot-film Support Stand. The stand provides accurate axial, vertical, and angular positioning of the hot-film sensor.
Figure 4-6. The Test Stand Motor and Photo-Interrupter Module. Two views of the motor and the photo interrupter module that provides a square wave once per revolution for blade position information.
Blowing Configurations:

1) Port #3
2) Ports #2 and #3

RPM = 285
C_μ = .0033
Re = 0.4 \times 10^6
Sample Rate = 4000 Hz

Figure 4-7. The Hot-film Probe Positions for Testing. Test matrix of positions of probe for tests. Others were added based on initial results. Test positions defined by vertical distance inboard of the tip and axial distance behind trailing edge (TE) plane. Hot-film was rotated $Ψ = ± 45$ degrees in the plane of the rotor for each probe location.
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APPENDIX B

Hot-Film Calibration
Hot-Film Calibration

Thermal anemometers utilize a small electrically heated wire to sense changes in heat transfer due to a moving fluid and correlate these changes to fluid velocity. This is done by continually adjusting the bridge voltage to maintain the sensor at a specific reference temperature. The changes in bridge voltage result in resistance changes in the small wire such that the sensor temperature remains constant. Normally, a linear relationship between the sensor resistance and temperature is assumed:

\[ R_{op} = \left( \frac{R_{100} - R_0}{100} \right) T_m + R_0 \]

The constant temperature hot-film has a frequency response of the order of 100KHz. Advantages of thermal anemometers include their relatively low cost, accuracy, resolution, ease of use, and small size. The main disadvantage is the intrusive nature of the probe. There are two general types of thermal anemometer: hot-wire and hot-film probes. All tests in this study were performed with a hot-film. The relationship between output voltage of the hot-film sensor and fluid velocity is determined prior to testing through a calibration process. The accuracy of the probe is in part a function of how closely the calibration conditions match the test conditions. The two main characteristics of a typical calibration curve are its non-linear nature and apparent decreasing sensitivity at higher velocities. In calibrating the probes used in the rotor tests, a calibrator specifically designed for thermal anemometers was used (TSI Calibrator Model 1125). Also, all calibrations were performed at the test site before and after testing to ensure repeatability. The calibrator is equipped with flow controls and different nozzle sections to allow calibrations through different velocity ranges. The flow velocity was set at known values using the flow controls and the velocity and output of the hot-film was fed into the IFA300. With the atmospheric pressure manually entered and the temperature recorded automatically, corrections to standard conditions were calculated by the calibration software. Seventeen points were used in the calibrations with points being taken with velocities increasing and decreasing. Over the 5 day period of testing, four calibrations on two probes were performed. The calibration curves are shown in Figures...
B-1 and B-2. A fourth order polynomial curve fit was applied to the data. The graphs indicate the small error associated with each point. The errors are particularly small at the higher velocities. The curves also show excellent repeatability.

**Angle Sensitivity and Support Interference**

Typically, for a single sensor probe, the hot-film is positioned such that the flow is normal to the sensor and parallel to the supports (see Figure B-3). When the flow direction approaches the sensor from an angle, the theoretical velocity measured by the probe or the effective velocity, \( V_{\text{eff}} \), is given by

\[
V_{\text{eff}} = V \cos \theta
\]

This assumes that the component of velocity tangent to the sensor (\( V_T \)) does not influence the heat transfer at the sensor. However, there is some effect due to that component and it is accounted for by including part of the tangential velocity component in the expression for the effective velocity:

\[
V_{\text{eff}} = V \sqrt{\cos^2 \theta + K_T^2 \sin^2 \theta}
\]

Normally, \( K_T \) can be considered a constant value for angles up to 60 degrees. This value is typically between zero and 0.2 depending on the probe being used [24]. Flow that approaches the probe normal to the sensor but also normal to the supports (\( V_{BN} \)) is subject to support interference and another constant is used to account for this component:

\[
V_{\text{eff}} = V_{BN} \sqrt{V_N^2 + K_T^2 V_T^2 + K_N^2 V_{BN}^2}
\]

If \( K_{BN} = 1 \), the probe is said to have zero pitch correction or rotational symmetry. Again values of \( K_{BN} \) depend on the flow orientation and specific probe characteristics, but typical values range from 1 to 1.2 [24]. These constants are normally determined through calibration. This was not done in this study because the velocity range for the rotor tests required calibrations in an internal nozzle in the calibrator where angle adjustments of the probe were not possible. Resolution of an arbitrary velocity using the above components...
is shown in Figure B-3. It should be noted that a single sensor probe can be used to
determine the velocity components of a two dimensional flow by placing the probe in the
flow at two complimentary angles and solving the resulting two equations in two
unknowns. Because of the three dimensional nature of the flow, and the inability to
determine correction factors, using complimentary angles for the test runs did not permit
resolution of the velocity components. However, it did ensure that if the orientation of the
vortex was such that the circulatory component ($V_\theta$) was parallel to the sensor at one
angle, it would be captured at the complimentary angle (the probe was positioned so that
the axial component of the flow would always be captured). In fact missing the
circulatory component at one angle rarely happened during this study. There were a few
test runs where the effective velocity at the first probe angle showed a low maximum (ie:
minimal tangential component) while the second angle showed a peak indicative of both
the axial and a circulatory component associated with vortical flow. Typically, there were
minor differences in the data taken at the two angles suggesting that both probe angles
were capturing part of the circulatory component.
Figure B-1. Hot-film Calibration Curves - Probe FN19.
Figure B-2. Hot-film Calibration Curves - Probe FN21.
Figure B-3. Hot-film Probe Velocity Components.
APPENDIX C

SAMPLE HOT-FILM RESULTS
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Figure C-2. Plot of Velocity Ratio vs Time for Test X05 - Runs 01 and 05. Probe 2" inboard of tip, 0.5" aft of TE, Rpm = 285, $C_x = 0.0033$ (port #2 and #3).
Test X05 - Run11 (Baseline)

Test X05 - Run09 (Blowing)

Figure C-3. Plot of Velocity Ratio vs Time for Test X05 - Runs 11 and 09. Probe 2" inboard of blade tip, 0.5" aft of TE, Rpm = 285, Cμ = .0033 (port #2 and #3).
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Figure C-5. Plot of Velocity Ratio vs Time for Test X10 - Runs 11 and 08. Probe 2" inboard of tip, 1.5" aft of TE. Rpm = 285, Cμ = 0.0033 (port #2 and #3).
Figure C-6. Plot of Velocity Ratio vs Time for Test X12 - Runs 11 and 09. Probe 3" inboard of tip, 2.5" aft of TE, Rpm = 285, Cμ = 0.0033 (port #2 and #3).
Figure C-7. Plot of Velocity Ratio vs Time for Test X14 - Runs 11 and 09. Probe 2.5" inboard of tip, 2.5" aft of TE, Rpm = 285, C_μ = 0.0033 (port #2 and #3).
Figure C-8. Plot of Velocity Ratio vs Time for Test Y18 - Runs 02 and 04. Probe 4.17" inboard of blade tip, 4" aft of TE, Rpm = 285, Cμ = 0.0033 (port #3).
Figure C-9. Plot of Velocity Ratio vs Time for Test A00 - Runs 32 and 31. Probe 3" inboard of blade tip, 0.5" aft of TE, Rpm = 285, Cμ = .0033. Result of vertical scan to find maximum velocities for blowing blade. Results much lower than baseline maximums.

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VITA

Charles Scott Matthewson was born on 17 March, 1966, in Windsor, Ontario Canada. After attending public schools in both Windsor and Hamilton, Ontario, he graduated from Sir Allan MacNab High School in June, 1983. In 1989 he graduated from the University of Western Ontario with a degree in Engineering Science. Upon graduation, he enrolled as a direct entry officer in the Canadian Armed Forces. After completion of general and occupational training, he was posted to CFB Cold Lake to work at the Aerospace Engineering Test Establishment. Two years later, he was selected by the Armed Forces to attend the University of Tennessee Space Institute to obtain a Master's degree in Aerospace Engineering which he completed in December 1996.