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TASS Model Application for Testing the TDWAP Model

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TASS Model Application for Testing the TDWAP Model

By

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Table of Contents

1. Introduction

One of the operational modes of the Terminal Area Simulation System (TASS) model simulates the three-dimensional interaction of wake vortices within turbulent domains in the presence of thermal stratification. The model allows the investigation of turbulence and stratification on vortex transport and decay. The model simulations for this work all assumed fully-periodic boundary conditions to remove the effects from any surface interaction.

During the Base Period of this contract, NWRA completed generation of these datasets but only presented analysis for the neutral stratification runs of that set (Task 3.4.1). Phase 1 work began with the analysis of the remaining stratification datasets, and in the analysis we discovered discrepancies with the vortex time to link predictions. This finding necessitated investigating the source of the anomaly, and we found a problem with the background turbulence. Using the most up to date version TASS with some important defect fixes, we re-generated a larger turbulence domain, and verified the vortex time to link with a few cases before proceeding to regenerate the entire 25 case set (Task 3.4.2).

The effort of Phase 2 (Task 3.4.3) concentrated on analysis of several scenarios investigating the effects of closely spaced aircraft. The objective was to quantify the minimum aircraft separations necessary to avoid vortex interactions between neighboring aircraft. The results consist of spreadsheets of wake data and presentation figures prepared for NASA technical exchanges. For these formation cases, NASA carried out the actual TASS simulations and NWRA performed the analysis of the results by making animations, line plots, and other presentation figures. This report contains the description of the work performed during this final phase of the contract, the analysis procedures adopted, and sample plots of the results from the analysis performed.

2. Model Simulation Process

The TASS modeling of simultaneous counter-rotating vortex systems in the presence of both turbulence and stratification requires many preparation steps. The process starts with the selection of the desired aircraft parameters, which then dictate minimum domain sizes and resolutions required.

2.1 Initial Conditions

2.1.1 Vortex Parameters

The formation vortex systems chosen represent Boeing 737 and 747 aircraft flying at a constant velocity in straight and level flight. Table 1 shows the vortex parameters assumed for all cases used in this study.

Table 1. Initial vortex parameters assumed for the study.

Initial Vortex Parameters	Symbol	737	747
Horizontal Separation	b_0	27 m	50 m
Circulation	Γ_0	250 m^2/s	565 m^2/s

2.1.2 Domain Specification

The domain is a right handed Cartesian grid with X being along the vortex axis, Y being horizontal and perpendicular to the vortex axis, and Z being vertically up. Table 2 shows the values of domain size and resolution used for the investigation. The velocity components related to this system are U, V, and W for the X, Y, and Z directions, respectively.

Table 2. TASS multiple vortex model domain parameters

Domain Parameters	Physical Dimension	737 Vortex Spacing Units	747 Vortex Spacing Units
Axial Dimension (x)	1037 m	38.4 b_0	20.74 b_0
Lateral dimensions	750 m	27.8 b_0	15 b_0
Vertical dimensions	624 m	23.1 b_0	12.5 b_0
Axial grid spacing	3.6 m	0.13 b_0	0.07 b_0
Lateral and vertical grid spacing	2.6 m	0.09 b_0	0.05 b_0

2.1.3 Turbulence Generation

One of the big hurdles to the completion of any TASS turbulence simulation is the generation of the background turbulence. The turbulence generation in this study assumed the energy forcing method of Han et. al.[1]. The process adopted for this investigation also adopted grid refinement to accelerate the arrival at a quasi-steady state turbulence field. Once establishing a quasi-steady state energy spectrum, the saved three-dimensional velocity and pressure fields are the initial conditions within which a vortex system starts. However, it is not possible to predict beforehand what the turbulence intensity will be, and, thus, the initial turbulence field requires scaling to the desired level. Figure 1 shows the initial spectra resulting from the turbulence generation phase of this study.

A further measure of turbulence quality is the large eddy turnover rate given as:

$$L/\sigma,$$

Where L is the integral length scale of the energy spectra and σ is the standard deviation of the corresponding velocity component. The total turbulence simulation time should be long enough to allow for at least 5 large eddy turnover times of all the coordinate directions to insure adequate

mixing and homogeneity. The turbulence from the generation phase had eddy turnover times from 60 to 80 seconds and ran for 6 to 8 eddy turnover times (480 seconds).

The eddy dissipation rate (EDR, ε), from the inertial sub-range of the velocity spectra from the initial turbulence undergoes a scaling from its initial value to any desired value by the following relationship[2],

$$(\varepsilon_{old})^{2/3} = \alpha(\varepsilon_{new})^{2/3},$$

where the units of EDR are m^2/s^3. Application of the scaling constant to the pressure and the velocity fields allows the one turbulent domain to represent the turbulence field of any desired turbulence intensity level.
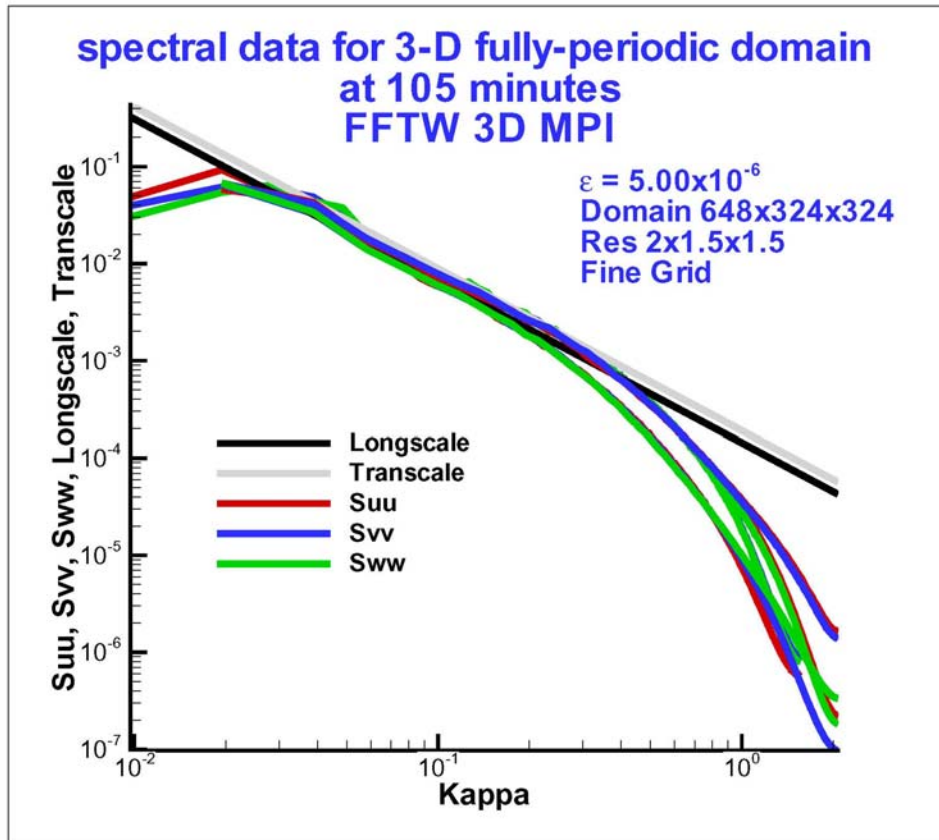

Figure 1. Initial spectra of the turbulent three-dimensional domain after 105 minutes simulation time at the finest grid level showing a dimensional eddy dissipation rate (ε) of 5.0e-6 m^2/s^3.

2.2 Vortex Injection Method

The vortex field consists of an axial plane representing a pair of counter-rotating vortices and a constant neutral stratification value throughout the domain. TASS introduces this plane to

the turbulence domain by superimposing the velocity, pressure, and temperature fields on each axial plane of the scaled turbulent domain. After the merging of the turbulence with the vortex system, TASS proceeds to march forward in time without energy forcing activated. This merging assumes that the time of decay of the turbulence is much longer than the vortex lifetime, and, therefore, the vortex evolution occurs in a nearly constant turbulent environment for the duration of the simulation.

2.2.1 Formation Flying Initialization

The simulation of multiple aircraft involved simultaneous injections of the vortices from all aircraft at the beginning of the simulation, thereby replicating the environment of aircraft flying abreast of each other (at the same height). The formation cases assumed both two and three aircraft scenarios. The limitations of domain size and ability to track multiple vortex systems prevented simulation of greater numbers of aircraft. Laterally centering the formation of planes coupled with symmetry assumptions enabled accurate vortex tracking. The formation simulations assumed out-of-ground (OGE) effect conditions.

2.3 Normalization Relationships

The basic parameters used in the study are length, time, turbulence intensity, and thermal stratification. Table 3 shows the relationships between dimensional and non-dimensional parameters.

Table 3. Assumed normalizations for the vortex and environmental parameters

Quantity	Dimensional Symbol	Normalized Symbol	Relationship
Time	t	T	t/T_o
Length	l	L	x/b_0
Turbulence intensity	ε	ε^*	$(b_0\,\varepsilon)^{1/3}/V_o$
Stratification	N	N^*	$(b_0\,N)/V_0$

3. Specific Simulations Performed

3.1 Cases Chosen
This phase of the contract focused on the simulation of aircraft vortex interactions that may occur in closely spaced runway configurations.

3.1.2 Multiple Vortex Systems

The purpose of the multiple vortex system simulations is to examine the possible interaction of vortices from neighboring aircraft. To that end, a series of wake simulations at varying aircraft separations can indicate the likelihood of such interactions. Table 4 shows the range of separations and the aircraft types assumed for each simulation. Also, isolated 747 and

737 wake simulations served as base comparisons for ascertaining the effects of adjacent aircraft vortex interactions. The triple aircraft case of the mixed type assumed the 747 flanked by a 737 on each side.

Table 4. Matrix of specific 3-D wake vortex dataset cases used in OGE formation scenarios. The rows represent cases performed with specific characteristics shaded.

Aircraft Sep	747	747	747	737	737	Number of Aircraft
400 ft	■	■				2
500 ft	■	■				2
600 ft	■	■				2
750 ft	■	■				2
400 ft	■			■		2
400 ft	■	■	■			3
400 ft	■		■	■		3

3.3 TASS Model Vortex Processing

The process employed for multiple vortices remains essentially intact when switching to multiple vortices. Figure 2 displays a schematic for 2 aircraft flying abreast of each other. For 2 identical aircraft, the problem reduces to 2 counter-rotating vortices by assuming symmetry along a vertical plane midway between the two aircraft and analyzing only half of the domain. This technique transforms the traditional port and starboard vortices to inner and outer counter-rotating vortices. For identical aircraft in the absence of ambient winds, this is a reasonable assumption to facilitate vortex analysis.
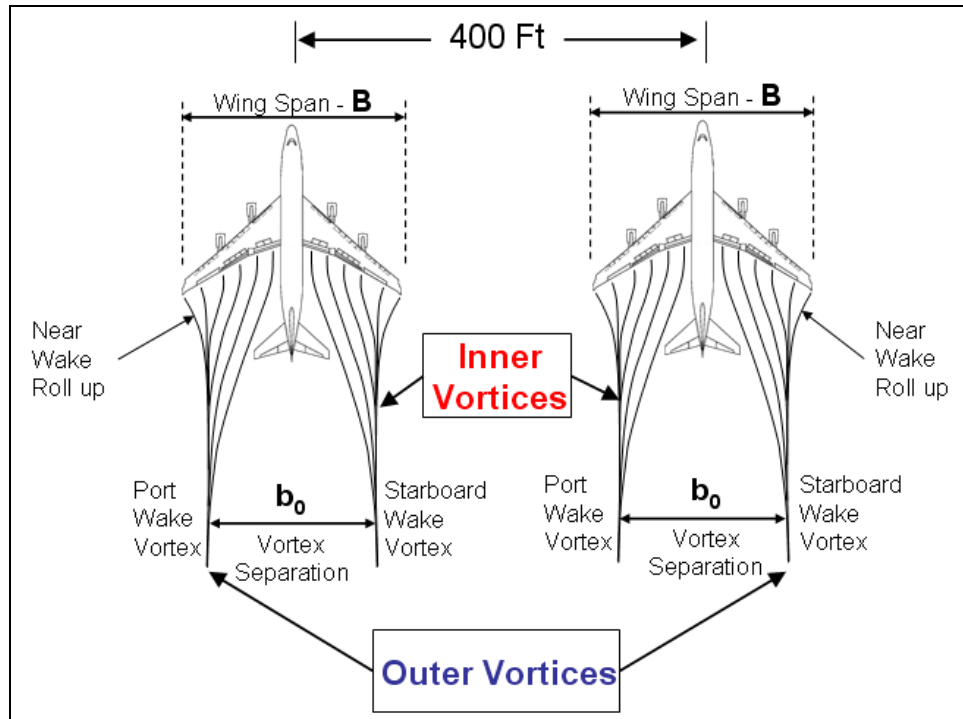
Figure 2. A schematic of the formation scenario for the purposes of explaining vortex tracking procedures.

In the case of triple aircraft, the symmetry approach still leaves 3 vortices to track with logic designed for 2. In this scenario the outermost vortex of the aircraft on the edge and the closest vortex of the center aircraft have the same rotation. Using a centroid approach to the vortex center will give the location mid-way between the two vortices. The method adopted to track the strongest of these used the peak rather than the centroid of the weighting function for the vortex position. In this manner, the resulting location would be either one or the other. The difficulty with this method is the switching early on between the two vortices when using different aircraft (i.e., 747 flanked by 737). The inner vortex of the outer aircraft posed no problems in this situation.

The final situation requiring special consideration is the mixed pair of 747 and 737 aircraft. The circulation strength of the 747 far exceeds the 737, so the approach in this scenario followed that of the triple aircraft. The effect is to track the 747 as the 737 affects its position and circulation.

The analysis for all vortices once located assumed the same restrictions as in phase 2 of this contract, that is, a 30° angle deviation limit from along the x axis, and a minimum pressure of 6.5 Pa in each x-station plane. The vortex location assumed the first moment of the following centering function,

$$F(\xi_x, \Delta P) = \xi_x^5 \Delta P^2 \,,$$

where ξ_x is the vorticity in the axial direction at a given point, and ΔP is the pressure deficit.

The final step combined the above results for position and circulation at each axial plane to provide a single value representative of each vortex in the domain at a given time. This final step resulted in the accompanying spreadsheet and figures delivered with this report.

3.3.1 Resulting Vortex Parameters

The above processed results, delivered as a spreadsheet, consist of 5 variables: height, lateral position, 90th percentile of the circulation values, 50 meter axial averaged circulation, and mean value of circulation. At each analysis time, there are 3 sets of these 5 parameters representing the starboard vortex, port vortex, and the average of the two vortices. A value of -9999 indicates the absence of valid parameters at any given time. The last column of the spreadsheet contains a vortex link factor based upon lateral vortex separations in all planes given by the following relationship:

$$\frac{b_{max} - b_{min}}{b_{max} + b_{min}},$$

where b_{max} and b_{min} represent the maximum and minimum separation at a given time, and values of this factor greater than 0.85 indicate the presence of vortex linking. The spreadsheet has a total of 17 columns of data as follows: time, 5 each for port, starboard, and average quantities, and vortex linking factor.

TASS Model Vortex Analysis

4.1   Out of Ground Effect Formation Results

The results from the OGE simulations show that for aircraft separations less than 600 ft, the inner vortices interact to create a delay in the decay of the outer vortices. Figure 3 and Figure 4 show the comparisons of the 747 paired aircraft runs to the isolated 747 simulation. The deviation from the isolated data shows the effect of the interacting influence upon the vortex systems. At separations less than 600 ft, the inner vortices interact and dissipate quickly, thereby leaving the 2 outer vortices to interact as a single system. This behavior diminishes as the separation increases due to the reduction in time that the inner vortices act to decay the outer vortices prior to their dissipation.

The interaction of the aircraft vortex systems serves to tilt each aircraft vortex pair upward at the center, because the initial descent of the inner vortices is less than the descent of the outer vortices. Figure 5 shows this condition after substantial tilting occurs. The net effect is the inner vortices reduce separation and increase their vertical ascent, while the outer vortices also reduce their separation but not nearly as rapidly. Once the separation of the inner vortices reaches a critical distance, they rapidly interact to dissipate each other, thereby leaving the outer vortices to act as an isolated pair. The net effect is a substantial increase in the effective wingspan on the decay and transport of the remaining system. With an increased separation, the remaining vortices last longer and descend slower.
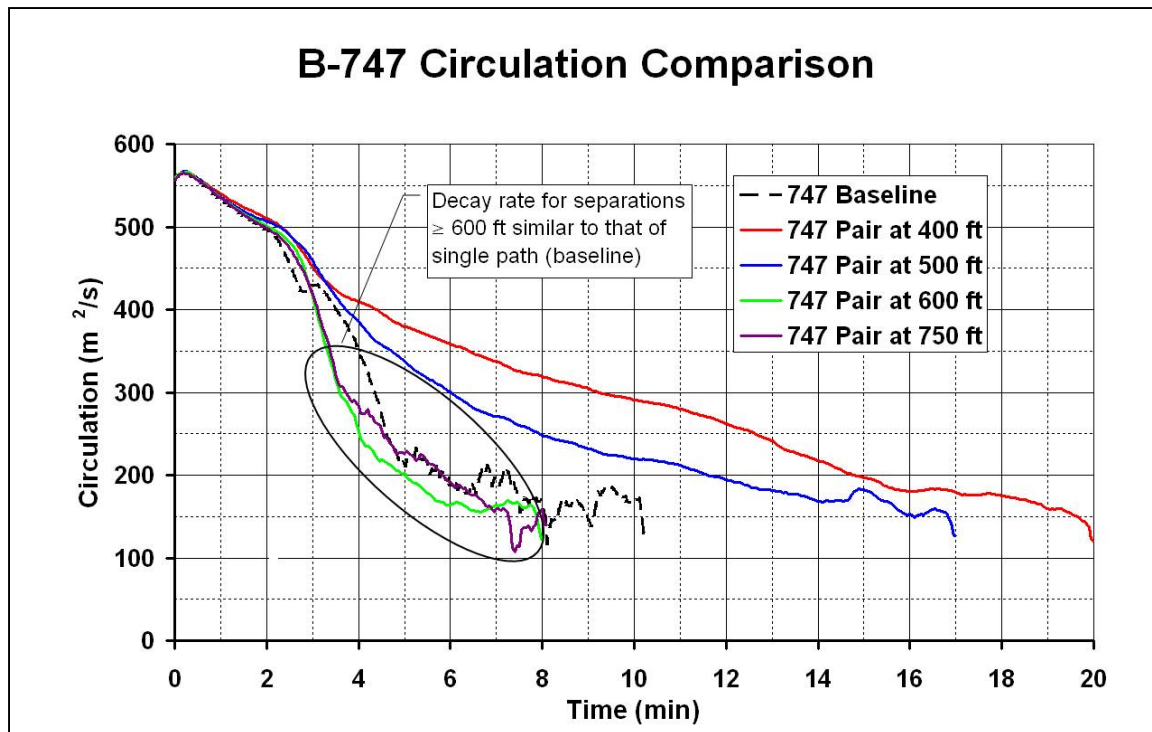

Figure 3. A plot of circulation comparisons among aircraft pairs at varying separation distances. The dashed line represents an isolated 747 wake vortex history.
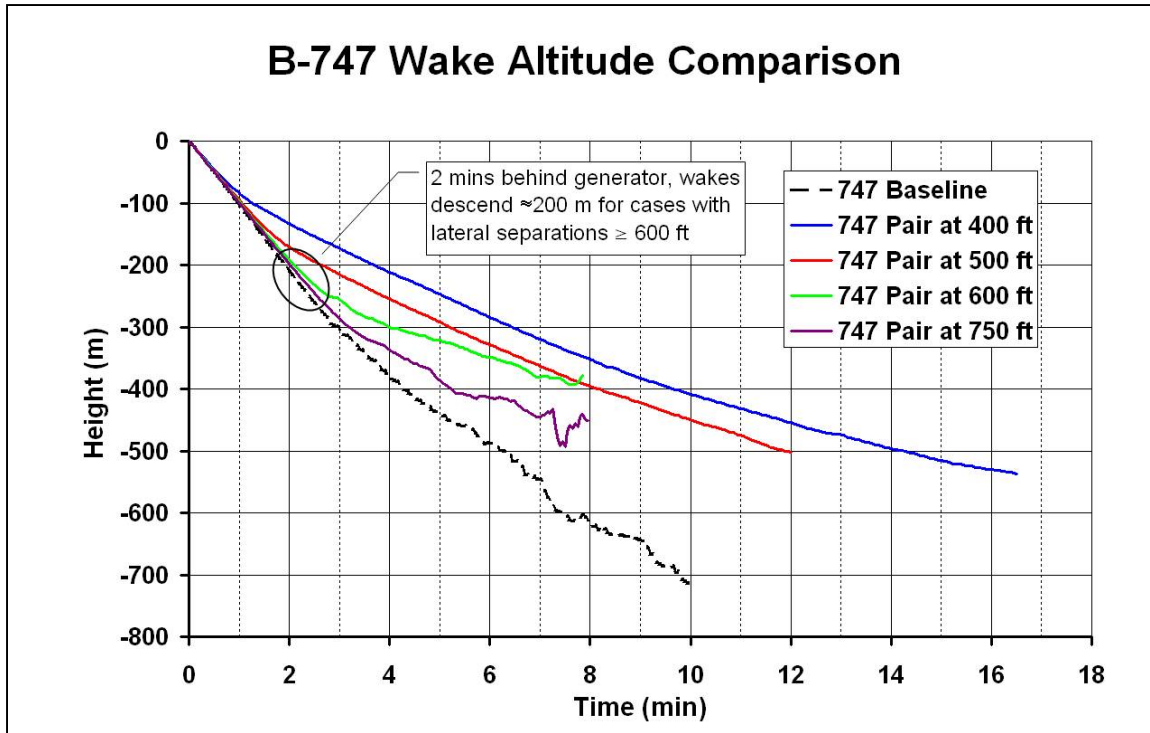
Figure 4. Same as Figure 3 except the data is of the vortex elevation of the outer vortex.
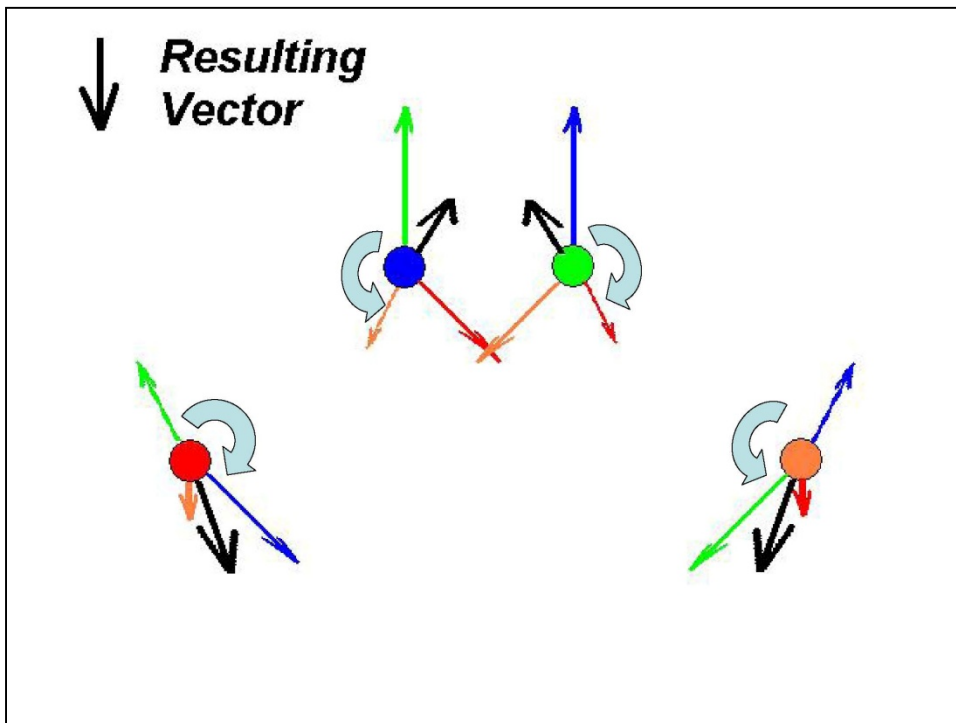

Figure 5. A schematic of the mutual vortices interaction later in the simulation. The two vortices on the left are from one aircraft, and the two vortices on the right are from a second aircraft. Each vortex has three colored vectors representing the velocity from the other vortices, and the black vector represents the net induced velocity.

9

5. Dataset Related Deliverables

The deliverables for this study consist of processed spreadsheets of position and circulation, plots of the spreadsheet results, and animations of 3 view isometric projections of the three-dimensional simulations. The animations rely upon the visualizations of the isosurface of the Eigen value for vortex signatures[2]. The deliverables of processed spreadsheets all reside in Microsoft Excel and accompany this final report. The animations of the vortex systems require the use of the freely available Swiff Player for Windows from www.globfx.com.

References

[1] Han, Jongil; Lin, Yuh-Lang; Schowalter, David G.; Arya, S. Pal, 2000. Large Eddy Simulations of Aircraft Wake Vortices within Homogeneous Turbulence: Crow Instability. AIAA Journal, Vol. 38, No. 2, pp. 292-300.

[2] Jeong, J., and Hussain F., 1995. "On the Identification of a Vortex." Journal of Fluid Mech., Vol. 285, pp. 69-94.