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Selection of a Realistic Viscous Vortex Tangential Velocity Profile for Computer Simulation of Vortex-Structure Interaction

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Running Title: Selection of a Realistic Viscous Vortex Tangential Velocity Profile

Abstract

Structure loading by vortices is a relevant phenomenon in numerous fields of engineering significance. Computer modelling is a powerful tool that can be used to study the loading produced on structures by impacting vortices. Realistic simulation of vortex-loading of structures necessitates the use of a realistic vortex tangential velocity profile (TVP). The present study compiles measured TVPs from various types of experimentally-produced vortices as well as real-world tornado and hurricane vortices. The measured TVPs are compared with commonly-used, analytical TVPs. Analytical TVPs that realistically represent the range of measured TVPs are identified and selected for use in future computer simulation studies.

Introduction

Viscous vortices are complex flow phenomenon that are studied for numerous engineering applications. The aerospace community seeks to mitigate interaction between shed vortices and rotors of helicopters which produces impulsive noise and vibration (Ramasamy and Leishman 2006). Also, wings of flapping micro-air vehicles are designed for thrust enhancement due to interaction between wing tip and leading edge vortices (Ellington 1999). The civil and structural design communities seek to develop accurate design loadings for tornado wind loads on buildings (Selvam and Millet (2003, 2005), Sengupta et al. (2008), Haan et al. (2010)). Finally, meteorologists seek to predict the growth and trajectory of hurricanes and tornados so that advance warning can be given to surrounding areas (Cao et al. 2011).

Most vortices of engineering interest are “intense” meaning the tangential velocity V_θ is much greater than the radial or axial velocity (Vatistas 1998). It is generally accepted that the cross section of the vortex consists of three regions (Figure 1a): (1) laminar inner

core, (2) transition region, and (3) turbulent exterior. Several typical radial tangential velocity profiles (TVPs), or $V_\theta(r)$, are illustrated in Figure 1b. $V_\theta(r)$ increases moving away from the vortex center ($r < r_c$) and reaches its maxima “ $V_{\theta,max}$ ” at the critical radius $r = r_c$. Subsequently, $V_\theta(r)$ decays with increasing radial distance from the vortex center ($r > r_c$).

Figure 1. (a) Schematic of the 3 cross-sectional regions of the vortex and (b) illustration of 3 analytical vortex TVPs.

Extensive research has focused on defining the correct TVP for real-world, viscous vortices. Vortices are typically classified using the vortex Reynolds number $Re_v = \Gamma_\infty/\nu$, where $\Gamma_\infty = V_{\theta,max} \cdot r_c \cdot 2\pi$ is the maximum circulation in the vortex and ν is kinematic viscosity. Vatistas (2006) studied rotor tip vortices and concluded that $V_\theta(r)$ should “flatten” as Re_v increases due to turbulent diffusion of the vortex; progressive flattening of TVPs is illustrated from TVP1 to TVP3 in Figure 1b. However, Kessler (1970) notes that the TVP may not just be a function of Re_v , as similar-sized tornados may have laminar or turbulent structure as illustrated in Figures 2a and 2b respectively. The Doppler on Wheels (DOW) group has recorded tornado TVPs since 1995, hence they are the primary source for field-measured tornado data. Even with advancements in radar capabilities, their lowest

Selection of a Realistic Viscous Vortex Tangential Velocity Profile

reported measurements of tornado TVPs are ≈ 40 m above ground level (Kosiba and Wurman 2010). As previously concluded in Wurman et al. (2007), the current understanding of near-ground tornado TVPs is at best an educated guess. Kepert (2010) reaches a similar conclusion for hurricanes, noting that $V_\theta(r)$ may vary from v- to u-shaped (TVP1 to TVP2 in Figure 1b) depending upon numerous environmental parameters.

(a) (b)

Figure 2. (a) Laminar (TornadoFacts, 2009) and (b) turbulent (Zimmerman, 2012) tornado vortex.

Meaningful computer simulation of vortex-structure interaction, at both the rotor tip vortex and tornado vortex scales, necessitates the use of analytical TVPs that give realistic representation of real-world viscous vortices. The viscous vortex is an extremely complex phenomenon, the physics of which are clearly not well understood. However, the literature documents measured TVPs from both laboratory-generated and convection-driven vortices. The best approach to select analytical TVPs for computer simulations is to assimilate measured TVPs and identify the analytical TVPs that provide the best representation of the measured data.

The present work collects and compares viscous vortex TVPs reported in the literature. Measured TVPs are grouped into 6 categories by vortex and experiment type. Analytical TVPs are then introduced and compared with the measured TVPs. Analytical TVPs which best fit the measured TVPs are identified and recommended for use in computer simulation of vortex-structure interaction.

Measured Tangential Velocity Profiles

Vortex Chamber Experiments

Vortex chamber experiments are commonly used to investigate flows in vortex combustors and

separators (Vatistas et al. 1986). Generally stated, fluid is input at one end of the chamber as four tangential streams spaced at $\pi/2$ around the circumference of the chamber and extracted as a single axial stream at the opposite end of the chamber.

Pritchard (1970) employs a different experimental method than that used by the other four sources. A cylindrical bucket is filled with water seeded with reflective spheres. The water is then stirred, and streak photography is used to compute the TVP.

Parameters for the vortex chamber experiments are not well reported. Faler and Leibovich (1977) report a Reynolds number range of $3000 \leq Re \leq 6000$, but do not explain how they defined the Reynolds number. It is believed, however, that the vortex chamber vortices have lower Re_v compared with the tornado simulator profiles discussed subsequently. Summary of the measured TVPs is provided in Figure 3.

Figure 3. Measured TVPs from vortex chamber experiments.

The vortex chamber TVPs are all relatively well grouped. Pritchard's (1970) TVP falls below the TVPs; this is likely due to the inferior data collection method (streak photographs instead of pressure probes) that is used. Faler and Leibovich's (1977) TVP exhibits unrealistic, rapid decay for $r/r_c > 2.5$. It is postulated that they report measurements taken too closely to the walls of the chamber, hence the vortex is damped by the confining walls.

Tornado Simulator Experiments

Tornado simulators are used to study both the structure of tornados (Church and Snow 1993) and the

structure loading they produce (Haan et al. 2010). Generally stated, a large blower or fan is mounted at the top of a hood, and fluid is pulled into the hood through many angled vanes spaced around the circumference of the hood. The hood may be stationary (Wilkins (1964), Wan and Chang (1972)) or may translate (Kuai et al. (2008), Haan et al. (2010)).

The translating tornado simulator at Iowa State University is the current standard for tornado simulators. Haan et al. (2008) provide further details of the design and testing of the Iowa State tornado simulator. Measured TVPs from tornado simulators are summarized in Figure 4.

Figure 4. Measured TVPs from tornado simulator experiments.

Tornado simulator experiments are compared using the previously-defined Re_v . Some in the literature prefer to discuss experimental vortices in terms of the swirl ratio S , which is the ratio of the tangential velocity to the axial (or vertical) velocity of the vortex. Given the swirl ratio and volumetric flow rate Q through the fan, the total circulation is defined as $\Gamma_\infty = 2 \cdot S \cdot Q \cdot r_c^{-1}$. Summary of Re_v for the tornado simulator experiments is provided in Table 1.

Table 1. Re_v range for tornado simulator experiments

Source	Re_v
Wilkins (1964)	205,000
Wan and Chang (1972)	710,000 to 1,300,000
Kuai et al. (2008)	1,798,000 to 2,062,000
Haan et al. (2010)	1,800,000 to 4,165,000

The tornado simulator experiments represent a wide range of Re_v . There is some scatter in the data, but all sets exhibit the same trend. An interesting observation is that the TVP decays more sharply in the tornado simulator experiments than the TVP decays in the vortex chamber experiments. This seems to disagree with the view that the TVP should flatten with increasing Re_v (Vatistas 2006).

Fixed Wing Experiments

Vortices produced by fixed wings are typically studied in the aerospace community to evaluate air loads on trailing aerospace vehicles due to vortices shed from leading aerospace vehicles (Dosanjh et al. 1962). The fixed wing configuration is also used as a less complex alternative to rotor experiments. Generally stated, a wing or air foil is rigidly fixed and a stream of fluid is circulated over it. Vortices are “tripped” by movement of the wing or by some other mechanism. Measured TVPs from fixed wing experiments are summarized in Figure 5.

Figure 5. Measured TVPs from fixed wing experiments.

Fixed wing experiments are classified using the chord Reynolds number $Re_c = c \cdot U_\infty / \nu$, where c is the chord of the wing and U_∞ is the free stream velocity. Summary of Re_c for the fixed wing TVP experiments is provided in Table 2.

The fixed wing experiments span a relatively wide range of Re_c . All data are well grouped for $r \leq r_c$, but the TVP of Dosanjh et al. (1962) increasingly deviates from the other data sets for $r > r_c$. This could be partially due to the fact that Re_c of Dosanjh et al.

Selection of a Realistic Viscous Vortex Tangential Velocity Profile

(1962) is much lower than Re_c used in the other works. It is also noted that the fixed wing TVPs resemble the vortex chamber TVPs much more so than the tornado simulator TVPs.

Table 2. Re_c for fixed wing experiments

Source	Re_c
Dosanjh et al. (1962)	10,000
Lee and Bershader (1994)	900,000 to 1,300,000
Devenport et al. (1996)	318,000 to 742,000
Porter et al. (2010)	830,000

Rotor Tip Experiments

Vortices produced by rotors are primarily studied in the aerospace community to reduce vibration in, and noise produced by helicopters (Ramasamy and Leishman 2004). In general, a single- or dual rotor is driven by a motor, and vortices are tracked in the rotor wake. The single-rotor configuration is the most commonly-observed configuration. Summary of measured rotor tip TVPs is provided in Figure 6.

Figure 6. Measured TVPs from rotor tip experiments.

Rotor tip vortices are characterized using Re_c , which is previously defined for fixed wing experiments. Summary of Re_c for the rotor tip experiments is provided in Table 3. Note that all of the reported rotor tip experiments are performed by JG Leishman's group at the University of Maryland using the same experiment configuration.

Table 3. Re_c for rotor tip experiments

Source	Re_c
Bhagwat and Leishman (2000)	270,000
Martin et al. (2003)	272,000
Ramasamy and Leishman (2006)	272,000

Within measurement error, it can be assumed that all of the rotor tip experiments are conducted for the same Re_c . Ramasamy and Leishman (2004) define the vortex Reynolds number for their experiment to be $Re_v = 48,000$. This implies that the vortices produced by the tornado simulator ($205,000 \leq Re_v \leq 4,165,000$) are much more turbulent, hence their TVPs should be much flatter than fixed wing and rotor tip TVPs (Vatistas, 2006). However, the measured TVPs surveyed up to this point suggest that there may not be such a direct relationship between TVP shape and Re_v .

Measured Tornado

Tornado vortices are studied to better understand the loading that they place on structures. Physical measurement of wind fields within a tornado is very hazardous, in addition to the fact that it is difficult to know when and where a tornado will occur. Early measurements of TVPs in tornados (Hoecker 1960) and water spouts (Golden 1974) use successive, timed photographs debris in funnel clouds to compute approximate wind speeds. The current standard in tornado TVP measurement is high resolution, mobile W-band Doppler radar ($\lambda = 3 \text{ mm}$, $f = 95 \text{ Hz}$), which is used in the other four works. A summary of measured tornado TVPs is provided in Figure 7.

As might be expected, the field-measured tornado TVPs exhibit much greater variation than any of the previously-considered experimental data sets. The early TVP measurements (Hoecker 1960, Golden 1974) computed from photographs of debris employ excessive estimation, hence it seems reasonable that these measurements should differ from the later and more accurate radar measurements. However, there is even considerable scatter within the radar-measured TVPs. A summary of the details of the radar-measured TVPs is provided in Table 4.

Radar measurements lose accuracy due to two primary factors: attenuation of the emitted signal and increased observation distance. Signal attenuation occurs due to absorption and scattering, both of which are enhanced by moisture and contaminants in the air. As the observation distance increases, the area covered

Figure 7. Measured TVPs for tornado field data.

Table 4. Measurement details for field-measured tornados

Source	Measurement	
	Height (m)	Distance (km)
Bluestein et al. (2003)	N/A	2.3 - 7.0
Tanamachi et al. (2007)	70 - 155	4.5 - 6.8
Kuai et al. (2008)	20 - 660	1.7 - 12.9
Kosiba and Wurman (2010)	≈ 40	1.7 - 6.5

by the emitted pulse increases, hence resolution of the radar image decreases. Furthermore, the signal must travel over a greater distance leading to greater attenuation of the signal. The high-frequency W-band is used because it is able to provide high temporal resolution of the tornado structure. However, as the wavelength of a signal shortens, it is attenuated much more rapidly. In short, although the radar-measured TVPs are measured at similar distance and with the same radar technology, many factors can influence and distort the measured TVP. Different levels of moisture and or dust in the air surrounding the vortex may substantially influence the measured TVP and is likely the cause of the substantial deviation in the measured tornado TVPs.

Measured Hurricane

Hurricane TVPs are primarily studied to allow forecasting of their size and trajectory (Cao et al. 2011). Because hurricanes are large and slow-moving,

they can be tracked for days or even weeks before making landfall. Early measurements of hurricane TVPs were made by manned flights through the eyewall of the hurricane as summarized in Willoughby (1990). Manned flight through a hurricane is hazardous to human life, hence alternative measurement procedures have been developed. The current standard in measurement of hurricane properties is via dropsonde. Specifically, manned or unmanned aircraft fly above the hurricane and seed it with numerous data-acquisition dropsondes. These are equipped with GPS and report local velocity and pressure at specified heights. Summary of measured hurricane TVPs is provided in Figure 8.

Figure 8. Measured TVPs for hurricanes.

Generally, the hurricane TVPs are well grouped with no significant outlying data. Keppert reports TVPs measured at 500, 1000, and 2000 m for two separate hurricanes. His first study shows that the TVP remains relatively constant with increased elevation (Keppert 2006a). His subsequent study, however, shows that the TVP decays more slowly with increasing elevation (Keppert 2006b).

Analytical Tangential Velocity Profiles

Numerous analytical TVPs for viscous vortices are discussed in the literature. Bhagwat and Leishman (2002) survey TVPs for rotor tip and fixed wing applications and more recently in Wood and White (2011) survey TVPs for tornados and hurricanes. The present study is only concerned with comparing the analytical TVPs with the measured TVPs, hence the

Selection of a Realistic Viscous Vortex Tangential Velocity Profile

assumptions and derivations of the analytical models shall not be discussed. However, the interested reader can find these details in the cited works.

First, analytical TVPs derived from the Navier Stokes equations are introduced. It is important to include the original names of these profiles, as these names are primarily used in the literature. Subsequently, two algebraic TVPs which are used to reproduce the derived TVPs are introduced and discussed. The capability of the algebraic profiles to reproduce the derived TVPs is then demonstrated.

Derived Tangential Velocity Profiles

The most commonly-used analytical TVPs for fixed-wing and rotor-tip vortices are the Lamb-Oseen (L-O) (Ramasamy and Leishman 2006) and Scully-Kaufmann (S-K) (Vatistas 2006) profiles defined by equation (1) and equations (2-3) respectively.

$$V_{\theta,S-K}(r) = r \cdot r_c \cdot (r^2 + r_c^2)^{-1} \quad (1)$$

$$V_{\theta,L-O}(r) = r_c / r \cdot [1 - \exp(-\alpha \cdot r^2 / r_c^2)] \quad (2)$$

$$r_c(t) = (4 \cdot \alpha \cdot v \cdot t)^{0.5} \quad (3)$$

The Oseen constant in equations (2-3) is $\alpha = 1.25643$. Also note that the L-O vortex stretches in time due to the viscosity of the fluid. The present work is concerned only with the profile shape, hence r_c is fixed. When r_c is fixed in equation (2), the L-O profile is identical to the Burgers-Rott profile.

TVPs of atmospheric vortices are most commonly modeled using the modified Rankine (MRCVM), Burgers-Rott (B-R), or Sullivan (S) profiles (Wood and White 2011). The MRCVM is a bi-regional profile defined using equations (4-5). The value of the exponent in equation (5) ($r > r_c$) varies in the literature from $0.4 \leq x \leq 1.0$ (Kosiba and Wurman, 2010).

$$V_{\theta,MRCVM}(r) = r / r_c \quad 0 \leq r / r_c \leq 1.0 \quad (4)$$

$$V_{\theta,MRCVM}(r) = (r_c / r)^x \quad r / r_c > 1.0 \quad (5)$$

The B-R TVP is identical to equation (2) when r_c is constant, hence re-definition is not necessary. The original Sullivan TVP is simplified by Vatistas (1998) and reported in the simplified form in equations (6-7). Note that constants $\beta = 6.238$ and $\Phi = 37.9043$.

$$V_{\theta,S}(r) = r_c / r \cdot [H(\beta \cdot (r / r_c)^2) / \Phi] \quad (6)$$

$$H(x) = \int_{0-x} \exp\{-\tau + 3 \cdot \int_{0-\tau} [(1 - \exp(-\tau)) / \tau] d\tau\} d\tau \quad (7)$$

Computation of $V_{\theta,S}(r)$ requires numerical integration of equation (7) for each radial ordinate, making the Sullivan profile cumbersome to define. Furthermore, the tornado model used by Selvam's group introduces the vortex into the domain through boundary conditions. Computation of the Sullivan profile for each boundary node via numerical integration at each time step would be very computationally expensive, hence it is not a viable option. Fortunately algebraic approximations have been developed as shall be discussed subsequently.

Algebraic Tangential Velocity Profiles

Vatistas et al. (1991) introduce the "n-family" of TVPs defined in equation (8). The exponent "n" is varied to duplicate the previously-defined analytical TVPs: S-K ($n = 1$), L-O/B-R ($n = 2$), and MRCVM ($n = 100$ for $x = 1$). This profile is robust and particularly useful in computer simulations, because a single TVP model can be incorporated and easily modified to study vortices having a range of TVP structures.

$$V_{\theta,V}(r) = r \cdot r_c \cdot ((r^{2n} + r_c^{2n})^{1/n})^{-1} \quad (8)$$

Wood and White (2011) modify the Vatistas et al. (1991) profile, adding two additional exponents to allow greater control of the TVP. One noted benefit of the Wood-White (W-W) profile is the capability to produce inner curvature in the region $r < r_c$. Consequently, the W-W profile can be used to reproduce the Sullivan TVP without requiring the numerical integration of equation (7). The W-W profile is defined in equation (9), and exponent values that reproduce the previously-defined, derived TVPs are summarized in Table 5.

$$V_{\theta,W-W}(r) = (r \cdot r_c)^{\kappa} \cdot [1 + \kappa / \eta \cdot ((r / r_c)^{\kappa / \psi} - 1)]^{-1} \quad (9)$$

Table 5. W-W exponents to approximate derived TVPs

Profile	κ	η	ψ
S-K	0.850	1.700	0.700
L-O/B-R	1.000	2.265	0.830
Sullivan	2.401	3.433	0.435
MRCVM ($x = 1$)	1.000	2.000	0.010

Profile Normalization and Comparison

All of the analytical vortex profiles defined previously reach maximum tangential velocity at the critical radius, restated $V_{\theta}(r_c) = V_{\theta,max}$. However, not all

of the analytical profiles reach the same value of $V_{\theta, \max}$. For meaningful comparison of the analytical profiles, as well as comparison of the analytical and measured profiles, it is necessary to normalize the analytical profiles such that $V_{\theta}(r_c) = 1$.

The MRCVM profile (equations (4-5)) and the W-W profile (equation (9)) are already normalized. However, the S-K, L-O, and Vatistas profiles need to be normalized. Equations (1), (2), and (8) are evaluated at $r = r_c$, and the results summarized in equations (10-12).

$$V_{\theta, S-K}(r_c) = 0.5 \quad (10)$$

$$V_{\theta, L-O}(r_c) = 1 - \exp(-\alpha) \quad (11)$$

$$V_{\theta, V}(r_c) = 2^{-1/n} \quad (12)$$

Now the respective S-K, L-O, and Vatistas TVPs are normalized by dividing the original profile definitions by equations (10-12) respectively. The resulting TVPs, equations (13-15) are marked by an asterisk indicating that $V_{\theta}(r_c) = V_{\theta, \max} = 1$.

$$V_{\theta, S-K}^*(r) = 2 \cdot r \cdot r_c \cdot (r^2 + r_c^2)^{-1} \quad (13)$$

$$V_{\theta, L-O}^*(r) = (1 - \exp(-\alpha))^{-1} \cdot r_c / r \cdot [1 - \exp(-\alpha \cdot r^2 / r_c^2)] \quad (14)$$

$$V_{\theta, V}^*(r) = r \cdot r_c \cdot (2 / (r^{2n} + r_c^{2n}))^{1/n} \quad (15)$$

The normalized TVPs are compared with approximations by the algebraic profiles in Figures 9a and 9b. The W-W approximation of Sullivan's profile is plotted as well. The exact solution to equation (6) is not provided for comparison, but Wood and White (2011) show that their approximation has RMS error of only 0.0005.

Both algebraic TVPs accurately approximate the derived TVPs. The W-W profile provides slightly better approximation of the L-O profile for $r < r_c$, but Vatistas' profile better approximates both the L-O and S-K profiles for $r > r_c$. Moving forward, Vatistas' approximations of the derived TVPs shall be considered save two exceptions. The Sullivan vortex shall be represented by the W-W approximation. Also, equations (4-5) shall be used for the MRCVM for $x \neq 1$.

Omitted Measured Tangential Velocity Profiles

Several measured TVPs are excluded from the comparison because they outlie the majority of the

other collected TVPs within their categories. It is therefore believed that the measurements were somehow flawed.

From the vortex chamber experiments, the data of Faler and Leibovich (1977) is omitted. Their measured TVP shows unrealistically-rapid decay for $r/r_c > 2.5$. It is likely that they report measurements taken too closely to the wall of their experimental system, hence the confining walls force the decay of the vortex.

(a)

(b)

Figure 9. Comparison of derived analytical TVPs with approximations by (a) Vatistas and (b) Wood and White's TVPs.

Selection of a Realistic Viscous Vortex Tangential Velocity Profile

From the tornado measurements, the data of Hoecker (1960) and Golden (1974) is omitted. There measured TVPs are derived by tracking debris movement between successive photographs; this procedure gives at best qualitative results which deviate substantially for $r/r_c > 1$ from the more recent radar measurements.

Lastly and also from the tornado measurements, the data of Bluestein et al. (2003) are omitted. Their measurements are conducted using the same radar technology and similar measurement distances as the other radar data sources. However, unrealistically-rapid decay of the TVP occurs for $r/r_c > 1.5$.

Comparison of Measured and Analytical Profiles

The measured TVPs are compiled and compared with the analytical TVPs in Figures 10a and 10b. The six defined groups of measured TVPs are plotted as two data sets to avoid excessive overlap and saturation of the data.

Beginning with Figure 10a, Vatistas' $n = 1$ and $n = 2$ profiles are excellent fits to the measured vortex chamber, fixed wing, and rotor tip TVPs for $r/r_c \leq 1$. For $r/r_c > 1$, the $n = 1$ profile is effectively an upper boundary for the measured TVPs. The $n = 2$ profile falls from the middle of the measured profiles at $r/r_c > 1$ to effectively become a lower boundary for the measured TVPs at $r/r_c = 4$. The MRCVM and W-W (Sullivan) profiles deviate substantially from the measured TVPs for $r/r_c < 1$. The MRCVM $x = 0.6$ profile gives a fair approximation of the measured TVPs for $r/r_c > 1.5$, but the MRCVM $x = 1.0$ and $x = 0.4$ models consistently under- and over-estimate the measured TVPs respectively.

Now moving to Figure 10b, W-W's Sullivan profile is an effective lower boundary to the simulated tornado, tornado, and hurricane TVPs. Vatistas' $n = 1$ profile is an effective upper boundary for $r/r_c \leq 1.5$, but falls within the measured hurricane TVPs when $r/r_c > 1.5$. The MRCVM $x = 0.6$ profile provides a higher upper bound for $r/r_c > 2.5$, but is a poor fit to the measured TVPs for $0.5 \leq r/r_c \leq 1.5$.

Summary and Conclusions

Realistic computer simulation of vortex-loading of structures necessitates the use of a realistic vortex tangential velocity profile (TVP). The physics that govern vortex structure are not well understood, hence the best approach for selecting a realistic vortex TVP for integration in a computer model is to find the analytical TVP which best represents measured TVPs

in experimental and naturally-occurring vortices.

(a)

(b)

Figure 10. Comparison of measured and analytical TVPs.

An extensive survey of measured TVPs is conducted, and TVPs from various experimentally-produced vortices as well as tornado and hurricane vortices are compiled. Subsequently, analytical TVPs are compiled and normalized for comparison with the measured vortex TVPs. Based upon the content presented in this work, the conclusions outlined below have been reached.

1. Vatistas $n = 1$ analytical profile (the

normalized S-K vortex) is an effective upper boundary to most of the measured TVPs.

2. Vatistas $n = 2$ analytical profile (the normalized L-O/B-R vortex) bisects most of the measured TVPs, hence it represents the “typical” vortex.

3. The W-W (Sullivan) analytical profile provides the best lower boundary to the data. It is an excellent lower boundary for the following categories of measured TVPs: experimental tornado, measured tornado, and measured hurricane. However, it deviates greatly from the measured vortex chamber, fixed wing, and rotor time vortex TVPs for $r < r_c$.

4. The analytical MRCVM profile deviates greatly from the measured TVPs for $0.75 \leq r/r_c \leq 1.25$ due to the peaked profile near $r = r_c$. The MRCVM with $x = 0.6$ fits the measured TVPs for $r/r_c > 1.25$.

Vatistas' $n = 2$ profile best approximates the typical, measured TVP, hence it shall be applied in subsequent computer simulations. It is stressed, however, that no single TVP defines all vortices. Therefore, studies need to be conducted to evaluate the influence of the vortex's TVP on structure loading that it produces.

Future Work

A range of possible vortex TVPs has been identified. Although the “typical” vortex profile has been suggested for general computer simulations, it is necessary to determine the influence of vortex profile on structure loading. Computer modeling is currently being used to study the influence of vortex TVP on maximum structure loading and dynamic amplification of structure loading.

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Selection of a Realistic Viscous Vortex Tangential Velocity Profile

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