Chapter 1 . Introduction

Turbulent wakes have been of interest in many practical-engineering applications mainly due to the noise generated by such wakes. Aircraft and submarine components usually operate in or near a wake of another component. Consequently researchers have been attempting to understand and model such turbulent wakes.

The idea of self-preservation of wakes further in the downstream distance represents an important concept in turbulence theory. Self-preservation (or similarity) is said to occur when profiles of velocity or other quantities can be made to be self-similar when scaled by their local length and velocity scales. This concept essentially illustrates that the wake has reached a dynamical equilibrium. Significant research has been made to understand the mechanism and influencing factors that contribute to such turbulent wakes in dynamical equilibrium in the far wake region.

The reason for our study stems from the experimental results obtained by Devenport *et al*. (1996) in their experimental study of the tip vortex shed from a NACA 0012 wing. As the wake progresses downstream, this wake rolls into a continuously widening spiral with the thickness of the wake increasing and velocity fluctuations diminishing. Such wake can be see as having made up of two parts. Far from the vortex the wake is flat and almost identical to a two-dimensional wake. Around the vortex however the wake is much complex as it undergoes severe later stretching, skewing, and lateral curvature causing substantial variation in the turbulence levels and structure in the wake as it curls up around the vortex. Through the complex interplay of such factors, the turbulent field achieves a self-similar state. This illustrates that the turbulence is in equilibrium with the ever-increasing strain rates and lateral curvature of the wake with streamwise distance.

In order to study such complex interplay between the various factors, a simple ’canonical’ flows can be set up to study the dependence of the turbulent field on a single influence factors. Hence the objective of our study is to reveal the effect of lateral curvature on a turbulent wake. Such lateral curvature in a flow is introduced by means of a ring model of circular cross section under zero pressure gradient conditions. In order to compare such curved wake, a plane wake generated by a circular cylinder was used as control case.

There have been numerous experimental studies done on plane wakes from a cylinder. Early investigations concentrated on the near wake region. The idea of self-preservation of plane wakes has been analytically developed with an asymptotic approach as Reynolds number goes to infinity. Experimental results confirmed the length and velocity scales relation as a function of streamwise direction. Consequently the idea of a universality principle was born from an assumption that plane wakes are independent of initial conditions. This long held assumption would later be disproved by experimental results. The self-preservation of the mean axial velocity for different wakes was demonstrated from many experimental results. The other body of research in the far region has been the presence of large coherent structures and their roll in determining the overall character of the turbulent flow. This body of studies mainly concentrates on identifying such structures through different approaches. Examples include such as extracting eddy structure from flow visualization, use of correlation tensor, conditional ensemble averaging of velocity signals and defining a set of conditions to be met, and using methods like proper orthogonal decomposition and linear stochastic estimation. Such methods have come up with possible eddy structures from double rollers to horseshoe vortices and myriad of interconnections between adjacent structures with rib like structures high in vorticity.

Numerous studies have been done on the small-scale turbulence to investigate the Kolmogorov hypothesis of universality in scaling laws. It has been a long held view that turbulence at the smallest scales is essentially isotropic and with that assumption, the average dissipation rate has been inferred. Experimental results however do not support such local isotropy.

1.1 Plane wakes

1.1.1 Self-preservation of Plane wakes

The idea of self-preservation of free shear turbulent flows has its origins in the concept that turbulence is characterized by local invariance. This means that in the far wake region of the wake, the flow appears to be controlled by the local environment. This idea leads to the notion that the flow achieves a state of equilibrium and that the flow is dynamically similar if non-dimensionalized on local length and velocity scales. Consequently the governing equations of turbulent wakes reduce to ordinary differential equations. Thus self-preservation is an asymptotic state achieved once internal dynamical readjustment is complete where details of the initial conditions is smoothed out.

The treatment of self-preservation has been in the domain of theoretical analyses, for example Townsend (1956), Tennekes and Lumley (1972), and George (1989). The Townsend (1956) and Tennekes and Lumley (1972) approaches are similar in their assumptions in formulating the self-preservation of the governing equations. Following is the treatment used by Tennekes and Lumley (1972). They state that one of the characteristics of turbulence is that it is locally invariant, hence at some point in time appears to be controlled by the local environment. In general the velocity distribution in the wake is a functional form of

$$\frac{U_\infty - U}{U_o} = f\left(\frac{y}{L_0}, \frac{L_o}{L}, \frac{L_o U_o}{\upsilon}, \frac{U_o}{U_\infty}\right) \tag{1}$$

where U_∞ and U_o are the freestream and maximum deficit velocity respectively, L_o and L are the half width wake and stream wise distance from the bluff body, y is the coordinate denoting the width of the wake.

The dependence of the function f is reduced further by assuming $L_o/L \to 0$, $L_oU_o/\upsilon \to \infty$, $U_o/U_\infty \to 0$ in the far wake region hence,

$$\frac{U_\infty - U}{U_o} = f\left(\frac{y}{L_0}\right) \text{ , where } L_o = L(x) \tag{2}$$

Tennekes and Lumley further note that the turbulent intensity u is of the order U_o, thus the Reynolds stress can be described by

$$-\overline{uv} = U_o^2 g(y/L_o) \tag{3}$$

where g is the self similar profile function for the Reynolds shear stress.
These sets of equation (2) & (3) constitute the self-preservation hypothesis: where the velocity deficit and Reynolds stress are invariant when normalized in the local velocity and length scales U_o and L_o respectively.

In order to verify the equations of their feasibility to such hypothesis, the equations need to be substituted into equation of motion.

$$U\frac{\partial U}{\partial x} + \frac{\partial(\overline{uv})}{\partial y} = 0 \tag{4}$$

which is the reduced form of the streamwise momentum equation

$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + \frac{\partial(\overline{u^2} - \overline{v^2})}{\partial x} + \frac{\partial(\overline{uv})}{\partial y} = \upsilon\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) \tag{5}$$

on the assumption that the wake is far from the bluff body.

The second term is negligible compared to the first term in the far wake region since V ~ 0, the third term is dropped since turbulent intensities in the far wake region are of the order of the velocity defect which is negligible compared to the mean axial velocity, the last term is neglected assuming the flow is at sufficiently high Reynolds number and thus viscosity effects are small.

By substituting equations (2) & (3) into (4), and where $\eta = y / L_o$

$$\frac{\partial U}{\partial x} = -\frac{\partial U_o}{\partial x} + \frac{U_o}{L_o}\frac{\partial L_o}{\partial x}\eta f' \tag{6}$$

$\frac{\partial(\overline{uv})}{\partial y} = -\frac{U_o^2}{L_o} g'$, where the prime denotes differentiation with respect to η (7)

Now by substituting equations (6) & (7) into (4)

$$-\frac{U_\infty L_o}{U_o^2}\frac{\partial U_o}{\partial x} f + \frac{U_\infty}{U_o}\frac{\partial L_o}{\partial x}\eta f' = g' \tag{8}$$

If the wake is to be self-preserving, so that the shapes of f and g are the same for all x, then it is required that the coefficients of f and nf' be constant. Thus we have

$$\frac{L_o}{U_o^2}\frac{\partial U_o}{\partial x} = const.\,, \quad \frac{1}{U_o}\frac{\partial L_o}{\partial x} = const. \tag{9}$$

The general solution for both is $L_o \approx x^n$, $U_o \approx x^{n-1}$. However such solution is indeterminate, therefore another relation is needed, which is provided by rewriting the momentum integral as

$$U_\infty U_o L_o \int_{-\infty}^{\infty} f(\eta)d\eta - U_o^2 L_o \int_{-\infty}^{\infty} f^2(\eta)d\eta = -\frac{M}{\rho} \tag{10}$$

where M is the total momentum deficit flux.

The second term is of the order U_o/U_∞ in comparison with the 1st term. U_∞/U_o is of the order L_o/L for far wakes, so the second term can be neglected. Substituting M by $\rho U_\infty^2 \theta$, where θ is the momentum thickness we get

$$U_o L_o \int_{-\infty}^{\infty} f(\eta)d\eta = -U_\infty \theta \tag{11}$$

It is concluded that $U_o L_o$ must be independent of *x*. If $L_o \approx x^n$, $U_o \approx x^{n-1}$, and find that 2n-1 = 0, so that n = 1/2. Hence L_o and U_o can be given by

$$U_o = Ax^{-1/2} \ , \ L_o = Bx^{1/2} \tag{12}$$

where A and B are universal constants.

Therefore, the hypothesis states that self-preserving solution, independent of initial conditions, is only possible if the velocity and length scales behave as equation (12). The universality of the wake implies that all plane wakes irrespective of the wake generator grow at the same rate. However such universality of the length scales was not supported experimentally. This idea of non-universality was supported later on by George (1989) from theoretical approach without the assumption that such turbulent flows are independent of their initial condition. He was able to show that even though different wakes grow at different rates, the scaled mean velocity profiles have the same shape for all. However the profiles for the Reynolds stresses would differ from wake to wake by a factor even though each wake is self-preserving. Experimental studies done by Wygnanski *et al* (1986), Zhou *et al*. (1995), Kopp *et al*. (1996), and Ghosal (1997), Moser *et al*. (1998) among others support the non-universality of self-preserving flows. Among issues investigated studied in such studies was on the growth of the wake and to ascertain whether such flows ever reach self-preserving status in the mean and turbulent flow. Another issue is the dependence of the wake on the initial conditions and whether the often-made assumption that "turbulence forgets its initial conditions" far away from the body holds and the uncertainty involved in the boundary conditions. The other issue investigated was the Reynolds number dependence on the self-preservation of plane wakes.

Wygnanski *et al*. (1986) investigated two-dimensional, small deficit wakes to study their structure and whether the self-preservation is universal. The experiments were done on an array of different bodies (circular cylinders, symmetrical airfoil, a flat plate, and different types of screens with varying solidity) with identical drag coefficients and momentum thickness. The Reynolds number ranged from 680-3200 and Reynolds number based on the momentum thickness was about 2000. The study confirms the theoretical dependence of the length and velocity scales as described in equation 12. The study reveals that the normalized mean velocity profile is independent on the initial conditions, and that is universal for all the wake generators. The universality of the Reynolds stresses however is not shown, nor are the velocity and length scales universal, showing dependence on the type of wake generators.

Zhou *et al*. (1995) investigated the memory effects for different wake generators (circular, triangular, square cylinders, and a screen with 50% solidity) using orthogonal arrays of X - wires. Measurements were done in range 20 to 820 momentum thickness for Re_d = 5600. The near wake structure is compared to the far wake region to investigate the qualitative and quantitative differences. Results show that the mean velocity profiles are identical for all the wake generators, whereas the Reynolds stress, spectra and r.m.s. vorticity distributions are not universally self preserving, showing a dependence on the initial conditions.

Ghosal (1997) used large-eddy simulation (LES) to investigate whether turbulent plane wakes achieve universal self-similarity. The Reynolds number based on the maximum velocity deficit and half wake width, $R_e = U_o L_o / \upsilon$, was 2000. Their study is significant in that many uncontrolled factors concerning the initial conditions are eliminated. Their results are in agreement with many experiments and the theoretical arguments of George (1989), that depending on initial conditions, turbulent wakes relax to self-similar states that are not universal but dependent upon their initial condition.

Further evidence of the non-universality in the self-preservation of the wake is noted by Moser *et al*. (1998), in their DNS study of flat plate wakes with three different initial conditions. The mass flux Reynolds number (which is equivalent to the Reynolds number based on the momentum thickness in a spatially developing wake) was 2000, which was enough to show the characteristic slope of -5/3 in the subrange of velocity spectra. The first flow was unforced while the other two flows had their initial conditions changed by varying forcing levels to the *u* and *v* fluctuating velocity components. In their study they present a theoretical similarity analysis that retains the viscous terms in the momentum equation whish is different that what Tennekes & Lumley (1972) presented. The result shows that mean velocity deficit profile is indeed universal for all three plane wakes investigated. The Reynolds stress profiles however are not universal as has been evidenced by other experimental researchers. They also introduce a scaling factor for the Reynolds stress profiles by normalizing it with $U_o^2\beta$, where β is a non-dimensional number that represents the growth rate of the wake and is expressed as $\beta = \frac{U_\infty}{U_o}\frac{dL_o}{dx}$, in order to improve the collapse of the Reynolds stresses profiles for the three types of flows.

Kopp *et al*. (1996) used a pattern recognition technique to study uniformly distorted wakes one from a solid mesh and the second from a flat plate. The study is to ascertain as to the similarity of such wakes in the far wake region. It is seen that their mean velocity profiles are identical, however the far wake structures are markedly different. This was noted by Wygnanski *et al.* (1986) in which there were puzzled by the difference in structures since instability in the mean velocity was the major reason for the development in these structures. The authors conclude that these structures develop independently of the mean profiles.

1.1.2 Turbulence Structure in the Far Plane wake

The structure and evolution of the large-scale coherent structures has been of great interest and study (e.g. Grant (1958), Mumford (1983), Antonia *et al*. (1987), Hayakawa *et al*. (1989), Bisset *et al*. (1990), Ferre *et al*. (1990), and Z. Huang *et al*. (1995)). Townsend *et al*. (1956) first proposed the existence of such structures, in a fully developed wake. Based on velocity-correlation measurements Grant (1958), suggested two possible types of structures i.e. the "double-roller" eddies and the "mixing jets" or entraining eddies. The former type have vorticity in the (x,z)-plane, while the latter consist of span wise vortices. Further detailed properties of these eddies was given by Townsend (1979). The use of velocity-correlation to extract structure was found to be not satisfactory by Lumley (1967) and proposed instead the use of proper orthogonal decomposition which requires that the eddies be identified by the eigenfunctions of the correlation function. Such methodology was applied to Grant's data described by Payne & Lumley (1967), in which they deduced the existence of the double roller type structure similar to Grant's, however significantly differing in the orientation and sense of circulation of such eddies. While Grant described the double roller eddies as being aligned 45° to the vertical (x,z)-plane, Payne & Lumley describe them normal to the vertical (x,z)-plane and their rotation opposite to that of Grant's.

Mumford (1983) used a new approach to investigate the existence of such large eddies by using a pattern recognition pattern method of a circular cylinder. He used a computer code to extract repetitive signals from the turbulent signal using a set of anemometers. The measurement was done at x/d = 178 and at Reynolds number based on the cylinder Re_d = 7000. Mumford was in agreement by the hypothesis advanced by Grant of the existence of double roller-like counter-rotating vortices on either side of the wake centerline and inclined 45° to the streamwise x-axis. This alignment is approximately in the same direction of the strain rate associated with the mean velocity gradient. He also suggested the possible inter-connection between the span wise vortices and the double roller eddies. The existence of such horseshoe structure in an intermediate region of the wake has been studied (e.g. Hussain *et al.*1987, and Hayakawa *et al.* (1989)).

The three dimensional nature of coherent structures in the nominally two-dimensional wake was studied by Hayakawa *et al*. (1989). Although their study is in the intermediate region (10d ≤ x ≤ 40d), it points out the three dimensionality of the structures. In their investigation, they describe the description of the topology of the coherent structures in a turbulent plane wake. The detection of such structures was achieved using certain criteria to define them from the instantaneous vorticity measurements. This investigation is carried out at the intermediate wake region (10d ≤ x ≤ 40d) for a circular cylinder d = 2.7cm., and Re_d = 13,000. The advection velocity increases rapidly up to x/d = 6, and then gradually increases modestly. Further downstream, the peak vorticity decreases rapidly, while the vortex spacing ratio (lateral/longitudinal) is not much affected. It is noted that, the coherent structures are closer to the center wake than to the wake half width. The transverse vorticity has strength comparable to the spanwise vortices. They also point out the presence of horseshoe vortex structure in the transverse direction. The structure is oriented 30 degrees from the y-axis and is able to maintain itself in that position from the opposing effects of self-induction of the vortex, and tilting due to the mean-strain. The three dimensionality of the wake is attributed due to longitudinal rib like structure. However, they caution about identifying between rolls and ribs structures and the necessity of further studies.

Other studies at the far wake region of the wake also have tried to provide an insight of the connection between the spanwise and roller type eddies. Antonia *et al*. (1987) made measurements using multiple cold wires and X-hot-wire probes at x/d = 420 downstream of a circular cylinder at Re_d = 1200, slightly heated. Cold-wires, placed spanwise across the wake near its outer edge (y/L = -1.42) used to provide signals to conditionally average X wire measurements. Results show antisymmetric train of large spanwise eddies with high production and dissipation of turbulence are found in the regions of high strain rate between eddies rather than in the eddies themselves. Measurements reveal little, if anything of the 3D structure which the authors try to put back with some low Reynolds number water tunnel flow visualization. They use this to suggest that spanwise structures they observe, + ‘streamwise’ structures aligned (at 45 degrees) with the strain rate, are connected (like horseshoes).

Antonia *et al*. (1989) investigated the organized motion in the self preserving wake of a cylinder at x/d = 420, Re_d = 1170, by using the dominant lateral velocity spectrum v to describe the large structures, similar as phase-averaging has been used to study the organized motion in the near-wake. Spectral density results show a clear peak for v-fluctuations, which they associate with passage of organized structure. There is no corresponding peak is shown in the u-fluctuations. The use of phase averaging based on filtered v signals show similar flow pattern comparable to other methods used in the eduction structural patterns.

Bisset *et al*. (1990) used an array of x-probes aligned with the plane of the mean shear in a turbulent far wake of cylinder of d = 2.67mm, at Re_d = 1170, to obtain instantaneous velocity vector patterns. The measurements were carried out at x/d = 420, where the mean velocity half width L was 12.3mm. Stream functions were calculated using an iterative procedure from the velocity measurements to help visualize the organized structures. From these sectional stream functions, occurrence of alternating opposing modes of structures were identified. It is shown that the alternating modes contribute more strongly to the coherent v^2 than to the u^2, while contribution to uv is at an intermediate level. Kinematic numerical modeling (2-D Rankine line vortex) of the turbulent flow is presented to determine the condition under which large-scale organized motion could be largely responsible for the observed mean velocity and Reynolds stress profiles. Their modified Rankine models of alternating and opposing modes reproduce many of the flow properties quite well. Their model also illustrates existence of quasi-three dimensional flow structure, implying that spanwise and double roller vortices observed in experiments might be two views of the same structure.

The relation between the structures in the far wake and their roll in the entrainment process were studied Ferre *et al*. (1989). They investigated a wake from a heated a cylinder d = 12mm, at free stream velocity of 11.3m/s, for Reynolds number of 9000. Conditional pattern recognition method was used to educe the structure involved in the turbulent wake at x/d = 140. The measurement was done at two perpendicular planes where the horizontal plane is at y = $0.6L_o$, where L_o is the half width wake and L_o = 3.3D. The study shows the existence of double rollers, some of them spanning the whole width of the wake and some on either side of the wake. The point put that these structures have a front edge that forms the bulge of the turbulent/non turbulent inter-phase. These structures have a preferred sense of rotation, characterized by a back flow to the center and are connected at the external edge forming a horseshoe like vortex lines. The entrainment process is controlled by these structures by bringing in potential flow from the edges to the center of the wake. Thus they inferred that the transfer of energy might be controlled by those structures.

1.1.3 Small Scale Turbulence in the far wake

The nature of small-scale turbulence of the far wake has been of interest for many researchers including Comte-Bellot *et.al* (1971), Champagne (1978), Browne *et al*. (1987), Aronson *et al*. (1994), Antonia *et al*. (1996) among others. The early assumption has been that small scales in the self-preserving region are isotropic, hence the dissipation in the turbulent kinetic energy has been obtained under this assumption. The reason for this assumption lies in the difficulty of measuring dissipation and also the hypothesis of Kolmogorov that small eddies behave as isotropic turbulence. Kolmogorov's first similarity hypothesis states that there are a range of small scale eddies whose average property is only determined by the rate of dissipation ε. Hence as a consequence determining the length and velocity scales for such fine scale turbulence. His universality hypothesis that at high Reynolds numbers, small-scale turbulence scaled according to Kolmogorov's length scale $\eta = (\nu^3/\varepsilon)^{1/4}$ reduces the probability density functions describing the small scales to universal similar forms. However George (1989) counters from experimental evidence of Comte-Bellot and Corrsin (1971), where they used the Taylor microscale and velocity scale determined from the energy to show the self-preservation of the spectrum in a fully developed turbulent channel flow, that the self-preservation occurs in all scales using only one length scale, consequently the Kolmogorov's theories for the universal equilibrium range could be shown to be incorrect for self-preserving wakes. Other experimental evidence that counters the universality at high wavenumbers is that of Champagne (1978). In their experiment of different flows (wakes, jets, and atmospheric boundary layer), the spectral result illustrates that the energy spectrum did not collapse into a single curve at the higher wave numbers, when normalized with Kolmogorov's scale, which they attribute to Reynolds number dependence.

Another assumption that has been countered experimentally has been the idea that small-scale turbulence locally is isotropic. This assumption has led to estimating the average dissipation rate $\bar{\varepsilon} = 15\nu\overline{(\partial u / \partial x)^2}$. Experimental evidence of such an assumption however is not supported for example Browne et al. (1987) and Aronson et al. (1994) show that such assumption under predicts the dissipation rate.

Browne *et al*. (1987) measured the nine major terms that make up the total dissipation in the self-preserving region of a cylinder wake of 2.67 mm diameter at free stream velocity of 6.7 m/s, giving Re_d of 1170. Their result indicates that local isotropy is not satisfied, and that dissipation assuming isotropy underestimates the dissipation by about 45% at the wake centerline and by about 80% near the edge of the wake.

Aronson *et al*. (1994) made measurements of dissipation and, by difference, pressure diffusion and pressure strain terms in a cylinder wake at Re_d = 1840 and x/d = 420 using pairs of probes separated by up to 3.4 Kolmogorov length scales. Dissipation found to be substantially anisotropic - the isotropic value underestimating the actual dissipation by 20% on the wake axis and 40% near its edge.

1.1.4 Higher Order Turbulent statistics

The third order turbulent quantities play a role in the transport equation of turbulent kinetic energy by way of the derivative of the nine correlation terms $\overline{u_i u_j^2}$. No detailed measurements of all the terms were made until Fabris (1983) used conditional sampling technique to investigate the transport mechanism of a slightly heated circular cylinder, using a four-wire probe made by himself. He was able to measure second and third order transport correlations. The measurements were done at x/d = 200 and 400 although only the results at x/d of 400 were presented. All important third-order correlations of *u*, *v*, and *w* are presented also the mechanism of temperature transport is also presented. The author points out to interesting results that lateral transport of u^2 and v^2 fluctuations is three times as intense as that of w^2, whereas the streamwise transport of u^2 is only twice as intense as that of v^2 and w^2. The thermal kinetic energy shows it being transported by the large scales towards the edge of the wake laterally resembling that of turbulent kinetic energy.

1.2 Axisymmetric wakes

Similar to the analysis applied to the plane wake, Tennekes and Lumley show that for the axisymmetric flows, the velocity and length scales should behave as $U_o \sim x^{-2/3}$ and $L_o \sim x^{1/3}$. George (1989) in his analytical treatment of the governing equations shows that in contrast to plane wakes were the turbulent Reynolds number is constant (i.e. once plane wake is turbulent it remains turbulent), axisymmetric wakes do not evolve at constant Reynolds number. The Reynolds number, which governs the downstream evolution, is given by $U_o L_o / \nu \approx \left[\frac{U_\infty \theta}{\nu}\right]\left[\frac{\theta}{x}\right]^{1/3} \approx$ *constant*, thus decreasing with downstream distance. He also shows is his analysis for full self-preservation of such wakes (i.e. examining the governing equation for the kinetic energy equation) that there are two possible cases where the flow can achieve equilibrium. One case is the classic result described by Tennekes and Lumley, while the other case is scales $L_o \sim x^{1/2}$ and $U_o \sim 1/x$, thus the wake allowing both regimes of growth during its evolution. He also shows that the Reynolds number governing downstream development, given by $U_o L_o / \nu \approx \left[\frac{U_\infty \theta}{\nu}\right]^{3/2}\left[\frac{\theta}{x}\right]^{2} \approx$ *constant*, decreases even faster than the first case. He contends in his analysis that, for high Reynolds number axisymmetric wake, both regimes of growth should be observed in succession. Tennekes and Lumley observe that for a wake to be self-preserving the time scale of the turbulence has to keep pace with the time scale of the flow. They show that in axisymmetric wakes, the time scale of turbulence to that of the flow is 1/2 using dimensional analysis contend that such flows can never be in equilibrium.

1.2.1 Curved Wakes

The literature on the wake of ring models is not as widely investigated as that of the cylinder wake. There is less literature on the effect of lateral curvature and especially on ring wakes which is pertinent to our studies. Early studies on the Toroid ring involved mainly about the drag of such models. The interest mainly stems from the fact that many micromolecules and microorganisms, the fluid particles of agglomerates and micelles have such curved Tori shape. Monson (1981) studied effect of transverse curvature on the drag and vortex shedding. Monson found that the reduction of drug by as much as 13% from it's linear counter part. He also conducted flow visualization of Re_d ranging from 55 to 2940 for varying curvature Tori sets. Two patterns of vortex shedding were observed one with alternating ring vortices or a less common but more stable counterrotating helical vortex pair. Wake pattern at Re_d = 2940 shows periodic turbulent annular puffs.

Adomaitis (1980) investigated the effect of lateral curvature of cylinder in longitudinal flow and of the external flow turbulence on the boundary layer thickness parameters. They used an annular test section, measuring the boundary layer in the inner cylinder at different streamwise stations. The Reynolds number based on the streamwise distance from cylinder, Re_x ranged from 3 x 10^5 - 3 x 10^7. The effect of curvature increases with parameter δ / r_o where δ and r_o are thickness of boundary layer and radius of the cylinder respectively. The effect was a more steeper velocity profiles, and reduced the δ, δ^*, and wall friction τ_w.

Leweke *et al*. (1995) investigated the flow behind rings, without the influence of end effects at low Re_d = 150. Flow visualization showed different shedding modes. Depending on the initial conditions, parallel vortex rings or oblique helical vortices were formed. The phenomenological Ginzburg-Landau model is used to describe qualitatively and quantitatively observations in a large Reynolds number interval.

The authors contend that the continuum oblique shedding angles present in wakes with end effects are not present in rings. That is there are only discrete modes of oblique shedding. Consequently end effects do have a great influence on the type of shedding of wakes. Transition to instability in the shedding frequencies is also studied, including secondary instabilities. The inclined shedding is shown to be stable compared to the parallel shedding of the wake.

1.3 Context of the present study

The present study is a follow up to Devenport *et al*. (1996) study on results obtained in their experimental study of the tip vortex shed from a NACA 0012 wing. Results showed that contours of axial turbulence normal stress when normalized on scale of the spiral and the axial deficit velocity in the two dimensional part of the wake, achieve a self-similar state from x/c = 10 onwards. Given the fact that the turbulence surrounding the vortex core is undergoing severe stretching, skewing and later curvature effects, it was surprising such a complex flow would achieve some sort of equilibrium state. The objective of the present study is to understand the functional dependence of the turbulence upon lateral curvature on a turbulent wake. Such understanding would be valuable in modeling curved or spiral wakes. Our approach was to set a simple ’canonical’ flow to study the dependence of the turbulence upon lateral curvature. A toroid ring served to generate such laterally curved wake, and a plane wake generated by a straight cylinder was used to serve as a control case for comparison.

In order to understand such dependence upon lateral curvature, it was necessary to investigate in detail the evolution of the turbulence field into the far wake region. Mean velocity, second and third order turbulent quantities, and spectra were obtained throughout the whole measurement regime at 20 downstream stations covering the intermediate and far wake region. In order to understand more of the turbulence structure, two-point measurement was taken one in the intermediate and the other at the far wake region.

This report presents a comprehensive investigation on the evolution and effect of laterally curved wakes into the far wake region. Chapter 2 describes the apparatus and measurement techniques used in the study. Chapter 3 presents the results of the mean velocity, turbulence quantities, spectral, and two-point measurements that were conducted. Chapter 4 presents the conclusion.