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Noise Produced by Turbulent Flow Into a Rotor: Theory Manual for Atmospheric Turbulence Prediction and Mean Flow and Turbulence Contraction Prediction

(NASA-CR-181789) NOISE PRODUCED BY TURBULENT FLOW INTO A ROTOR: THEORY MANUAL FOR ATMOSPHERIC TURBULENCE PREDICTION AND MEAN FLOW AND TURBULENCE CONTRACTION PREDICTION Final Report (United

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J. C. Simonich

United Technologies Research Center
East Hartford, CT

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Langley Research Center
Hampton, Virginia 23665-5225

CONTENTS

INTRODUCTION

Turbulence ingestion noise is a significant part of the broadband noise produced by helicopters. This sound generation mechanism involves the interaction of the rotating blades and the unsteady upwash velocity vectors associated with the atmospheric turbulent eddies ingested by the rotor. The resulting noise exists in the presence of loading noise and thickness noise mechanisms. It is also additive to the rotor trailing edge noise and vortex interactions noise generation mechanisms which represent additional broadband acoustic sources.

This module incorporates three separate models: an atmospheric turbulence model, a rapid distortion turbulence contraction model, and a non-isotropic turbulent inflow acoustic source model. Together they determine the atmospheric turbulence ingestion noise produced by a helicopter in flight.

Inputs to the combined mean inflow and turbulence models are controlled by atmospheric wind characteristics and helicopter operating conditions.

LIST OF SYMBOLS AND NOMENCLATURE

A	Constant in geostrophic drag law
B	Constant in geostrophic drag law
C_T	Rotor thrust coefficient $= T/\rho\pi R^2(\Omega R)^2$
d	Zero plane displacement height, m, (ft)
$\underline{e}$	Unit vector along one of the three upstream or downstream axes
E(k)	Wavenumber energy spectrum $= \frac{1}{2}\Phi_{ii}(k)d\sigma$
f_c	Coriolis parameter, $2\omega \sin\theta$
g	Gravitational acceleration, m/s^2, (ft/s^2)
G	Geostrophic wind speed, m/s, (ft/s)
H	General rooftop level, m, (ft)
k	Wave number, radians/m, (radians/ft)
k	von Karman constant
$\underline{k}$	Wavevector of turbulence
k_E	Wave number defined by Equation 21
L	Monin-Obukhov length $= \frac{-TU_*^3}{gk\overline{w\tau}}$, m, (ft)
Lw^X	Integral length scale $= \int_0^\infty R_{ww}(r_x)dr_x$, m, (ft)
n	Direction of the principle normal to the streamline
p	Exponent in mean velocity power law
r_x	Displacement in x direction, m, (ft)

R	Rotor radius, m, (ft)
R_{ww}	Cross correlation coefficient $= \frac{w(x)w(x+r_x)}{w^2}$
R_i	Richardson number $= \frac{g(\partial\theta/\partial z)}{\theta(\partial u/\partial z)}$
T	Temperature, K, (R)
T	Thrust, N, (lbf)
u	Turbulence velocity fluctuation, m/s, (ft/s)
U	Local time mean velocity, m/s, (ft/s)
U_∞	Horizontal freestream velocity, m/s, (ft/s)
U_*	Friction velocity $= \sqrt{\tau_w/\rho}$, m/s, (ft/s)
V_∞	Vertical freestream velocity, m/s, (ft/s)
V_0	Rotor induced velocity $= \frac{C_T \Omega R}{2\sqrt{\lambda^2+\mu^2}}$, m/s, (ft/s)
w	Vertical velocity fluctuations, m/s, (ft/s)
$\sqrt{w^2}/U_\infty$	RMS turbulence intensity
x_i	Upstream Cartesian coordinate system
Z	Height above ground, m, (ft)
Z_0	Roughness length, m, (ft)
Z_T	Tropopause height, m, (ft)
α	Rotor tip path plane angle of attack, degrees
$\Gamma(\,)$	Gamma function
δ	Boundary layer thickness, m, (ft)

ϵ_{ijk}	Alternating tensor
Θ	Geographic latitude, degrees
Θ	Potential temperature, K, (R)
λ	Wavelength of Fourier component of turbulence, m, (ft)
λ	Rotor inflow ratio, $= \frac{U_\infty \sin\alpha - V_0}{\Omega R}$
μ	Rotor advance ratio $= \frac{U_\infty \cos\alpha}{\Omega R}$
ρ	Density, kg/m^3, (lbm/ft^3)
Σ_i	Downstream Cartesian coordinate system
τ	Temperature fluctuations, K, (R)
τ_w	Wall shear stress, N/m^2, (lbf/ft^2)
Φ_m	Nondimensional wind speed gradient $= \frac{kZ}{U_*}\frac{dU}{dz}$
$\Phi_{ii}(k)$	Spectrum tensor $= \frac{1}{(2\pi)^3}\int_{-\infty}^{\infty} \exp(-ik\cdot r)R_{ii}(r)dr$
X	Wake skew angle = arctan $\left[\frac{-U_\infty \cos\alpha}{U_\infty \sin\alpha - V_0}\right]$, degrees
Ω, ω	Rotation rate, radians/s
$\underline{\omega}, \underline{\Omega}$	Vorticity field and magnitude of a Fourier component of turbulence. See Equations 24 and 25.

Superscripts

U and D	Specify the upstream or downstream location

Subscripts

i,j,k	Specify either a vector (such as one of the vectors $\underline{e_1}, \underline{e_2}, \underline{e_3}$) or a component of a vector (such as the first Cartesian component of the vector $\underline{e_2}$)

ATMOSPHERIC TURBULENCE PROPERTIES

Input

Name	Description
G	Geostrophic wind speed (m/s)
L	Monin-Obukhov stability length (m)
	(note: for neutral conditions, input 0.0)
Θ	Geographic latitude (degrees)
Z_0	Roughness height (m)
Z	Height above ground (m)

Output

Name	Description
G	Geostrophic wind speed (m/s)
${L_W}^X$	Correlation length scale (m)
$\sqrt{w^2}/U_\infty$	Vertical component of the rms turbulence normalized by the free stream velocity

Method

The atmospheric boundary layer is a fully three dimensional flow with boundary conditions which change in both space and time. Heat transfer is important as are the Coriolis forces due to the earth's rotation. The complexity of the flow renders a complete analytic description of the flow impossible. For these reasons, the description of atmospheric turbulence is still basically empirical.

The model presented below was chosen after a review of the current literature on the topic and is viewed as representative of the present state-of-the-art in atmospheric turbulence prediction. Most of the correlations are from Snyder [1]. These were chosen since they were the only ones found which included non-adiabatic effects (i.e. a non-neutral atmosphere where heat transfer is important).

In order to render the problem tractable, the following simplifying assumptions are made:

1) The flow is stationary.

2) The flow is homogeneous in any horizontal plane.

3) The flow is isotropic.

For neutral conditions, the boundary layer thickness is assumed to be constant at 600 m. For unstable conditions the boundary layer varies from 1 to 2 km during the course of a day. It is assumed here to be constant at 1500 m. For stable conditions, the boundary layer thickness is given by the following two equations:

$$\delta = \left[\frac{1}{30L} + \frac{f_c}{.25U_*} + \frac{1}{Z_T} \right]^{-1} \tag{1}$$

Equation (1) must be solved iteratively in conjunction with Equation (2) below to determine δ.

The friction velocity, U_*, is described by the "geostrophic drag law":

$$\ln\left(\frac{G}{f_c Z_0}\right) = A + \ln\left(\frac{G}{U_*}\right) + \sqrt{\frac{k^2 G^2}{U_*^2} - B^2} \tag{2}$$

G, the geostrophic wind speed, is a horizontal equilibrium wind which blows parallel to atmospheric isobars. It represents an exact balance between the horizontal pressure gradient force and the horizontal component of the coriolis force. Geostrophic wind scales give a good approximation to the actual wind in the free atmosphere. The magnitude of G is given by:

$$G = \left| \frac{1}{f_c \rho} \nabla_H p \right|$$

where f_c is the coriolis parameter $= 2\,\omega \sin\theta$ and $\nabla_H p$ is the horizontal pressure gradient.

A and B are described by "constants" which are a function of the stability condition of the atmosphere:

1) *Neutral Conditions*

$$A = 1.7$$

$$B = 4.7 \tag{3}$$

2) *Stable Conditions*

$$A = \ln(\delta/L) - .96(\delta/L) + 2.5$$

$$B = 1.15(\delta/L) + 1.1 \tag{4}$$

3) *Unstable Conditions*

$$A = \ln(-\delta/L) + (f_c\delta/U_*) + 1.5$$

$$B = \frac{k}{f_c\delta/U_*} + 1.8(f_c\delta/U_*)\exp(.2\delta/L) \tag{5}$$

Within the atmospheric boundary layer, there exists a sublayer, called the surface layer, where stresses and fluxes are nearly constant. This layer can be as thick as 150 m in neutral and unstable conditions, but can be as thin as 10 - 20 m under stable conditions.

In the surface layer, the log law is valid and a description of the mean velocity profile is given by the following equations for neutral, stable, and unstable conditions respectively:

1) *Neutral Conditions*

$$\frac{U}{U_*} = \frac{1}{k}\ln\left(\frac{Z-d}{Z_0}\right) \tag{6}$$

where $d = 0 \ for \ Z_0 < .2 \ m$

and $d = H - Z_0/k \ for \ Z_0 > .2 \ m$

2) *Stable Conditions*

$$\frac{U}{U_*} = \frac{1}{k}\left[\ln\left(\frac{Z}{Z_0}\right) + \frac{5Z}{L}\right] \tag{7}$$

3) *Unstable Conditions*

$$\frac{U}{U_*} = \frac{1}{k}\left\{\ln\left(\frac{Z}{Z_0}\right) - 2\ln\left(\frac{1+1/\Phi_M}{2}\right) - \ln\left(\frac{1+1/{\Phi_M}^2}{2}\right) + 2\arctan\left(\frac{1}{\Phi_M}\right) - \frac{\pi}{2}\right\} \tag{8}$$

where $\Phi_M = \left[1 - 15\frac{Z}{L}\right]^{-\frac{1}{4}}$

Equations (6), (7), and (8) are undefined if Z_0 is zero. For an actual atmospheric boundary layer, the surface roughness is never zero. Typical values of surface roughness length vary from .01 cm for sand to 100 cm for a pine forest [1].

For neutral conditions, the integral length scale is a function of height only and is given by:

$$L_w{}^z = .4Z \tag{9}$$

For stable atmospheric conditions, the following equation from Kaimal [2] is used:

$$L_w{}^z = .015\frac{Z}{R_i} \quad for\ .05 < R_i < .2 \tag{10}$$

$$\begin{aligned} where\ R_i &= \ Richardson\ number \\ &= \frac{Z/L}{1+5Z/L} \qquad for\ Z/L > 0 \qquad (11) \\ &= Z/L \qquad for\ Z/L < 0 \qquad (12) \end{aligned}$$

For unstable conditions, no correlation is available which takes into account stability parameters. Therefore, Equation 9 for neutral conditions is suggested. Strictly, the models for the integral length scale are valid only for the surface layer, typically the lower 10 to 20 percent of the boundary layer.

Under the assumption of isotropic turbulence, all longitudinal integral scales are equal to each other, as are the lateral integral scales, i.e.

$$L_U{}^X = L_V{}^Y = L_W{}^Z = L_U \tag{13}$$

and

$$L_U{}^Y = L_U{}^Z = L_V{}^X = L_V{}^Z = L_W{}^X = L_W{}^Y = L_V \tag{14}$$

Teunissen [3] has shown since all longitudinal correlations are equal and all lateral correlations are equal, and by the use of the continuity equation that:

$$L_U = 2L_V$$

so that

$$L_U{}^X = 2L_V{}^X = 2L_W{}^X \tag{15}$$

The vertical component of the rms turbulence intensity is given for neutral, stable and unstable conditions respectively by the following equations:

1) *Neutral Conditions*

$$\frac{\sqrt{w^2}}{U_\infty} = .5p\frac{\ln(30/Z_0)}{\ln(Z/Z_0)} \tag{16}$$

$$where\ p = .24 + .096\log_{10} Z_0 + .016(\log_{10} Z_0)^2$$

2) *Stable Conditions (and Neutral)*

$$\sqrt{w^2} = 1.25U_* \quad for\ Z/L > -.3 \tag{17}$$

3) *Unstable Conditions*

$$\sqrt{w^2} = 1.9\left(\frac{-Z}{L}\right)^{\frac{1}{3}}U_* \quad for\ Z/L < -1 \tag{18}$$

Since these correlations are strictly valid only for the surface layer, following Counihan's [4] suggestion a linear interpolation is used between the value at the top of the surface layer (assumed to be 15% of the boundary layer thickness) to a value of .01 at the top of the boundary layer.

For neutral conditions, the longitudinal and lateral turbulence intensities are approximately:

$$\sqrt{u^2} = 2\sqrt{w^2}$$

and

$$\sqrt{v^2} = 1.5\sqrt{w^2}$$

For nonadiabatic atmospheric boundary layers, the horizontal velocity components do not obey Monin-Obukhov similarity (as the vertical velocity fluctuations do) and no simple formula to describe them exists at the present.

The von Karman model is used to describe the energy spectrum for isotropic turbulence:

$$E(k) = \frac{Ik^4}{\left[1 + \left(\frac{k}{k_E}\right)^2\right]^{\frac{17}{6}}} \tag{19}$$

where

$$I = \frac{55}{9\sqrt{\pi}} \frac{\Gamma(5/6)}{\Gamma(1/3)} \frac{u^2}{{k_E}^5} = 6.25278u^2L^5 \tag{20}$$

and

$$k_E = \frac{\sqrt{\pi}}{L} \frac{\Gamma(5/6)}{\Gamma(1/3)} = \frac{.746834}{L} \tag{21}$$

DISTORTION TENSOR CALCULATION

Input

Note that either meters or feet can be used for input as long as the user is consistent throughout.

NAME	FUNCTION
NSS	Relative time step resolution (s)
NISO	Number of streamlines to compute
ISTR	Flag for outputing a streamline for plotting 0 for no output file 1 for streamline file
ITIME	Flag for outputing a deformation file 0 for no output file 1 for deformation tensor file (Note: either ISTR or ITIME can be 1 but not both at the same time)
XMIN	Minimum streamline domain limit in X direction (program will stop if it attempts to compute outside of this domain)
XMAX	Maximum streamline domain limit in X direction, radii
YMIN	Minimum streamline domain limit in Y direction, radii
YMAX	Maximum streamline domain limit in Y direction, radii
ZMIN	Minimum streamline domain limit in Z direction, radii
ZMAX	Maximum streamline domain limit in Z direction, radii
μ	Rotor advance ratio
ΩR	Rotor tip speed (rotational frequency time radius)
α	Rotor tip path plane angle of attack, degrees
V_0	Induced velocity at the rotor, m/s, (ft/s)
R	Rotor radius, m, (ft)
V_∞	V component velocity to be added to the hover case to simulate vertical ascent or descent, m/s, (ft/s)
RERROR	Relative error allowed in ODE solver (recommended value = 1.0E-10)
AERROR	Absolute error allowed in ODE solver (recommended value = 1.0E-10)
dS	Delta distance between streamlines used to compute the deformation tensor, radii (recommended value = 1.0E-4)

RECPOL	Coordinate specification trigger 'P' for polar specification of streamline starting coordinates 'C' for cartesian specification of streamline starting coordinates
NX	Number of X coordinate specification points
NY	Number of Y coordinate specification points
NZ	Number of Z coordinate specification points
X1	Minimum X for cartesian specification, radii
X2	Maximum X for cartesian specification, radii
Y1	Minimum Y for cartesian specification, radii
Y2	Maximum Y for cartesian specification, radii
Z1	Minimum Z for cartesian specification, radii
Z2	Maximum Z for cartesian specification, radii
NR	Number of radial specification points
NT	Number of angular specification points
R2	Maximum radius for polar specification
Θ_1	Mimimum angle for polar specification, degrees
Θ_2	Maximum angle for polar specification, degrees

Output

NAME	FUNCTION
TITLE	60 character alphanumeric title
NR	Number of radial specification points
NT	Number of angular specification points
IH	Code for selection of nonhomogeneous case
Γ	Vortex circulation strength, m^2/s, (ft^2/s)
TSAV	Streamline drift time, s (time for fluid particle to travel from upstream to rotor)
U	Velocity component in x direction, radii/sec
V	Velocity component in y direction, radii/sec
W	Velocity component in z direction, radii/sec
XTSAV	Downstream X coordinate of streamline in rotor plane, radii
YTSAV	Downstream Y coordinate of streamline in rotor plane, radii
ZTSAV	Downstream Z coordinate of streamline in rotor plane, radii
XSL1	Downstream X coordinate of streamline in standard cartesian coordinate system, radii (standard coordinate system has x,y plane parallel to horizon with x axis in flight direct
YSL1	Downstream Y coordinate of streamline in standard cartesian coordinate system, radii

ZL1	Downstream Z coordinate of streamline in standard cartesian coordinate system, radii
XSL2	Upstream X coordinate of streamline in standard cartesian coordinate system, radii
YSL2	Upstream Y coordinate of streamline in standard cartesian coordinate system, radii
ZSL2	Upstream Z coordinate of streamline in standard cartesian coordinate system, radii
USAV	Upstream U velocity component, radii/sec
VSAV	Upstream V velocity component, radii/sec
WSAV	Upstream W velocity component, radii/sec
X1A1, ETC	Deformation tensor

If ISTR = 1, a file is created named SFILE which contains the coordinate specifications of the streamlines

The output parameters are described below.

TITLE	60 character alphanumeric title
NISO	Number of streamlines computed
NSS	Relative time step resolution
XMIN	Minimum X streamline domain limit, radii
XMAX	Maximum X streamline domain limit, radii
YMIN	Minimum Y streamline domain limit, radii
YMAX	Maximum Y streamline domain limit, radii
ZMIN	Minimum Z streamline domain limit, radii
XPLOT	X streamline coordinate, radii
YPLOT	Y streamline coordinate, radii
ZPLOT	Z streamline coordinate, radii

Method

Mean Flow Model

To calculate the distortion of the atmospheric turbulence field as it convects towards the helicopter rotor, it is first necessary to describe the flow into the rotor. The mean flow field is needed to define the streamlines (particle paths), and these in turn are used in computing the change in vorticity and wavenumber between far upstream and the rotor disk. A necessary part of the mean flow model is thus a procedure for computing these particle paths.

The method chosen to calculate the mean flow into the helicopter rotor is to model the helicopter wake by a series of ring vortices. A graphical representation of the model is shown in Figure 1. The overall flow is made up of the velocity field due to the superposition of twenty ring vortices plus an ambient velocity. The spacing is varied so that the vortices are placed closer together near the rotor disk (see Figure 1), with the circulation per unit length (along the wake) constant. The vortices extend to approximately ten rotor diameters along the line of the wake.

The wake skew angle, X, (the angle between the normal to the rotor disk and the wake boundary) is defined by :

$$X = arctan\left[\frac{-V\cos\alpha}{V\sin\alpha - V_0}\right] \tag{22}$$

The strength of the vortices is found by matching the predicted induced velocity at the rotor face with the input value.

From momentum theory for helicopter aerodynamics, the rotor induced velocity is:

$$V_0 = \frac{\Omega R C_T}{2\sqrt{\mu^2 + \lambda^2}} \tag{23}$$

where

$$\mu = Rotor\ advance\ ratio = \frac{U_\infty \cos\alpha}{\Omega R}$$

and

$$\lambda = Rotor\ inflow\ ratio = \frac{U_\infty \sin\alpha - V_0}{\Omega R}$$

As stated, the rotor wake is described by a series of twenty ring vortices, along the skewed centerline of the wake. The velocity field at any point is found from the summation of the velocity field due to the individual vortices. The potential velocity for a ring vortex is given by Kuchemann and Weber [5] and by Castles and De Leeuw [6]. The axial and radial velocity at any point may be expressed by:

$$V_z = \frac{\Gamma}{2\pi x R}(AB + CDF)$$

$$V_R = \frac{-\Gamma}{2\pi x R}(A\acute{B} + CD\acute{F})$$

where

$$A = K(\tau) - E(\tau)$$

$$B = \frac{x-1}{d_1} + \frac{x+1}{d_2}$$

$$C = d_1 + d_2$$

$$D = \frac{\tau E(\tau)}{1-\tau^2}$$

$$F = 1 - \frac{1 + x^2 + z^2 - d_1 d_2}{2x^2} - \frac{(1+x){d_1}^2 - (1-x){d_2}^2}{2x d_1 d_2}$$

$$\acute{B} = z\left(\frac{1}{d_1} + \frac{1}{d_2}\right)$$

$$\acute{F} = \frac{z}{x}\left(1 - \frac{1 + x^2 + z^2}{d_1 d_2}\right)$$

$$d_1 = \sqrt{z^2 + (x-1)^2}$$

$$d_2 = \sqrt{z^2 + (x+1)^2}$$

$$\tau = \frac{d_2 - d_1}{d_2 + d_1}$$

x = radial distance from the axis of the vortex ring nondimensionalized by the ring radius

z = axial distance from the plane of the vortex ring nondimensionalized by the ring radius

$$\begin{aligned} K(\tau) &= \textit{complete eliptic integral of the first kind} \\ &= \int_0^{\pi/2} \frac{1}{\sqrt{1-\tau^2 \sin^2\alpha}} d\alpha \end{aligned}$$

$$\begin{aligned} E(\tau) &= \textit{complete eliptic integral of the second kind} \\ &= \int_0^{\pi/2} \sqrt{1-\tau^2 \sin^2\alpha}\, d\alpha \end{aligned}$$

Given the helicopter operating parameters, the procedure described above can be used to compute the velocity at any station in the flow field. A streamline can then be computed by integrating the streamline equations:

$$dx = U dt$$

$$dy = V dt$$

$$dz = W dt$$

where U, V, and W are the local time mean velocities in the x, y, and z directions.

These are three, coupled, ordinary differential equations. Starting at a given station, these expressions can be integrated forward or backward in the time domain to predict the next streamline position. A computer subroutine, written by Shampine and Gordon [7] was used for numerical integration. This method uses a modified divided difference form of the Adams - Pece formulas and local extrapolation. It adjusts the order and step size to control the local error per unit step in a generalized sense.

Turbulence Contraction Model

A "Rapid Distortion Theory" approach has been adopted for calculating the evolution of the turbulent flow. Basically the analysis models the flow field in terms of a primary flow, induced by the rotor, which convects (and distorts) the vortex filaments which are used to represent the turbulence. The rapid distortion approach thus accounts for the inherently three-dimensional processes of vortex stretching and tilting, which can change both the frequency distribution and the intensity of the turbulence.

The assumptions inherent in this approach are: 1) the turbulence intensity is small, 2) the overturning time for a turbulent eddy is much larger than the time for the distortion of the mean flow, and 3) the Reynolds' number associated with the turbulence is large.

The basic concept of the Rapid Distortion Theory is to relate the components of the vorticity at given locations along a streamline. In a linearized rapid distortion analysis, these streamlines (along which the fluid particles are tracked) are streamlines associated with the mean flow. Thus the vortex filaments are regarded as being convected by the mean flow. The velocities induced by the perturbation vorticity are therefore neglected in considering the deformation of the vortex filaments.

A general turbulent velocity field for incompressible flow can be expressed as a distribution of vorticity superimposed on a potential flow field. For an inviscid constant density flow, vortex lines move with the fluid in which they are embedded. Thus any deformation of the fluid will distort the vortex lines and in a contracting stream, the vortex filaments will be stretched and tilted, affecting the velocities induced by the vorticity.

The distortion of the vortex lines from one point on a streamline to another can be described by a deformation tensor. This deformation can be decomposed into a fluid rotation (3 quantities), the directions of the principal axes (3 quantities), and the amount of contraction or extension along each axis (3 quantities). Denoting the upstream coordinates by x_i and the downstream coordinates by ξ_j, the deformation tensor is denoted by $\partial x_i/\partial \xi_j$.

The basic equation for the vorticity at any location in terms of the initial vorticity contained by a given fluid particle is:

$$\Omega_i{}^U = \Omega_j{}^D \frac{\partial x_i}{\partial \xi_j} \tag{24}$$

or

$$\Omega_i{}^D = \Omega_j{}^U \frac{\partial \xi_i}{\partial x_j} \tag{25}$$

The deformation tensor is calculated using the streamline tracing procedure described above. Starting at a given point on the rotor face the equations describing the streamline coordinates are numerically integrated to trace a streamline from the rotor face to a far upstream location, usually taken as three radii from the rotor hub. A second streamline starting a distance $d\xi_1$ from the first is then also traced for the same length of time as the first. At the upstream end of these streamlines a vector is drawn from the end of the first streamline to the end of the second. This vector determines three of the nine components of the deformation tensor: $\partial x_1/\partial \xi_1$, $\partial x_2/\partial \xi_1$, $\partial x_3/\partial \xi_1$. The process is repeated for two other streamlines displaced a distance $d\xi_2$ and $d\xi_3$ respectively from the initial one, to yield the other six components of the distortion tensor.

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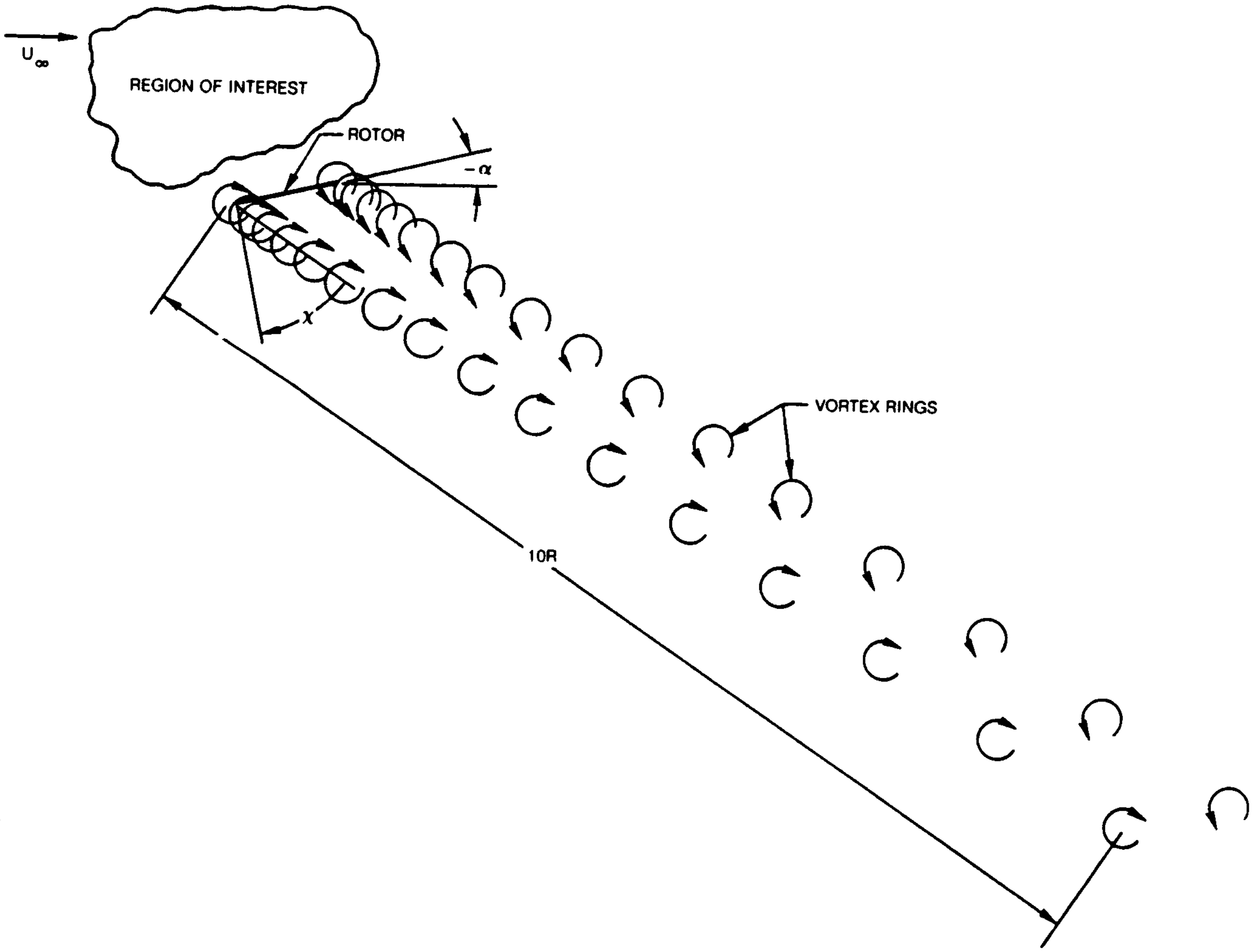

Figure 1: Schematic Diagram of Wake Model

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16. Abstract

An analytic study has been carried out to predict helicopter main rotor noise due to ingestion of atmospheric turbulence. The analysis combines several different models that describe the fluid mechanics of the turbulence and the ingestion process. This report covers two models, atmospheric turbulence, and mean flow and turbulence contraction. The third model, covered in a separate report, describes the rotor acoustic model. The method incorporates the atmospheric turbulence model and a rapid distortion turbulence contraction description to determine the statistics of the anisotropic turbulence at the rotor plane. This study provides the analytical basis for a module which has been incorporated in NASA's ROTONET helicopter noise prediction program.

The mean flow and turbulence statistics associated with the atmospheric boundary layer have been modeled including effects of atmospheric stability length, wind speed, and altitude. The turbulence distortion process is modeled as a deformation of vortex filaments (which represent the turbulence field) by a mean flow field due to the rotor inflow.

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