PAPER Nr. : 17

A THEORETICAL ANALYSIS OF THE EFFECT OF THRUST RELATED TURBULENCE DISTORTION ON HELICOPTER ROTOR LOW FREQUENCY BROADBAND NOISE

BY

M. Williams, GRADUATE RESEARCH ASSISTANT

W.L. HARRIS, PROFESSOR

HELICOPTER ROTOR ACOUSTICS GROUP
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139 USA

TENTH EUROPEAN ROTORCRAFT FORUM

AUGUST 28 – 31, 1984 – THE HAGUE, THE NETHERLANDS

A THEORETICAL ANALYSIS OF THE EFFECT OF THRUST RELATED TURBULENCE DISTORTION ON HELICOPTER ROTOR LOW FREQUENCY BROADBAND NOISE

Morgan Williams
Graduate Research Assistant

and

Wesley L. Harris
Professor
Helicopter Rotor Acoustics Group
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA

Abstract

The purpose of the analysis is to determine if inflow turbulence distortion may be a cause of experimentally observed changes in sound pressure levels when the rotor mean loading is varied. The effect of helicopter rotor mean aerodynamics on inflow turbulence is studied within the framework of the turbulence rapid distortion theory as developed by Pearson [1] and Deissler [2]. The distorted inflow turbulence is related to the resultant noise by conventional broadband noise theory. A comparison of the distortion model with experimental data shows that the theoretical model is unable to totally explain observed increases in model rotor sound pressures with increased rotor mean thrust. Comparison of full scale rotor data with the theoretical model shows that a shear type distortion may explain decreasing sound pressure levels with increasing thrust.

Notation

Symbol	Description
c	airfoil chord
C_T/σ	rotor mean loading, C_T is the thrust coefficient and σ is the rotor solidity
$E(k)$	turbulence energy spectrum function
k_i or k_x, k_y, k_z	turbulence wave number, $i = 1, 2, 3$
$\vec{k}$	wave number vector
$\lvert K(k_x, k_z)\rvert^2$	magnitude of gust lift transfer function
L	turbulence integral length scale in the longitudinal direction
$R_{ij} = \int \Phi_{ij}(\vec{k}) e^{i\vec{k}\cdot\vec{x}} d\vec{k}$	turbulence correlation tensor
$S_{pp}^{(d)}$	sound pressure spectrum for distorted inflow turbulence
$S_{pp}^{(o)}$	sound pressure spectrum for isotropic inflow turbulence
Δt	duration of turbulence distortion
$\sqrt{u'^2}$	turbulence intensity or root mean squared turbulence velocity
$\bar{U}$	longitudinal component of mean flow velocity
x_1, x_2, x_3	Cartesian coordinates
x, y, z	airfoil attached Cartesian coordinates
$\beta(k_x)$	$S_{pp}^{(d)}/S_{pp}^{(o)}$
γ_{ij}	mean shear tensor
$\Phi_{ij} = \frac{1}{8\pi^3} \int R_{ij}(\vec{x}) e^{-i\vec{k}\cdot\vec{x}} dx$	turbulence energy spectral density tensor
Φ_{vv}	turbulence upwash component of the energy spectral density tensor

Introduction

The present work deals with the non-impulsive component of helicopter rotor noise known as low frequency broadband noise. A mechanism responsible for the generation of this type of noise is unsteady rotor blade forces induced by a turbulent velocity field. Previous theoretical work related the turbulent flow field to the radiated acoustics using unsteady aerodynamics and dipole source representation, e.g., Homicz and George [3], George and Kim [4], and Amiet [5]. In all these methods, the incident blade velocity fluctuation is expressed in terms of a component of inflow turbulence energy spectral density tensor corresponding to transverse velocity fluctuations, i.e., Φ_{VV}. The majority of the analyses to date have utilized the isotropic spectrum formulae in their noise prediction schemes because of the unknown spectral nature of the turbulent flow field which the rotor blade encounters. The above cited analyses have been fairly successful, i.e., George and Chou [6]. However, they do not allow for rotor mean aerodynamic effects on the inflow turbulence.

To relate the rotor mean aerodynamics to the modification of inflow turbulence, the concept and theory of turbulence distortion are necessary. The properties of an initially turbulent flow field (e.g., isotropic turbulence) can be altered by imposing mean flow variations and blockage on the flow. The distortion occurs through the stretching and rotating of vortex elements.

The particular problem of interest is the effect of rotor mean thrust on the inflow turbulence and the broadband noise. Experiments have shown (Refs. 7,8,9) that rotor mean thrust variations significantly affect the observed sound pressure levels.

There is, of course, the Gutin type contribution to the radiated noise by virtue of the mean loading changes. This contribution has been shown to vary as the square of the rotor steady loading (e.g., Ref. 10). In addition, the unsteady gust response of the blades is altered by the mean angle of attack (α) changes, but this is a second order (α^2) effect on the lift. There are other explanations describing how the rotor mean loading effects the rotor acoustics (Ref. 8). However, the viewpoint taken here is that the inflow turbulence is altered by the rotor mean loading, leading to changes in the noise levels with changes in mean loading.

For acoustic calculations, the effect of the rotor flow field on the inflow turbulence has been largely ignored. Paterson and Amiet [11] did try to account for turbulence length scale modification by a rotor in hover. Their model gives the same turbulence upwash velocity intensity in both the isotropic and distorted cases, but the length scale of the distorted turbulence is increased by streamtube contraction.

Classical turbulence distortion theory and broadband noise theory were combined in Ref. 12 in an attempt to explain rotor thrust related changes in broadband noise levels. The calculation of the amount of distortion was entirely empirical. Comparison of the theoretical results with model rotor experimental data indicated that inflow turbulence distortion couldn't totally explain the broadband noise level variation with rotor mean thrust.

In this paper, inflow turbulence distortion is again considered in an attempt to explain rotor mean thrust related changes in broadband noise. The amount of distortion is estimated by an order of magnitude analysis. The theoretical results will be compared to some model experimental data, Refs. 8 and 9, and some full scale data, Ref. 7.

Inflow Turbulence Distortion Model

In the construction of a single model of turbulence distortion due to the mean aerodynamics of a helicopter rotor, several assumptions are made. They are: changes in rotor mean thrust is accomplished by blade pitch (angle of attack) changes and the rotor centerline is parallel to the x_3 axis; the dominant turbulence distortion is due to a homogeneous mean shear induced by blade incidence; and, the turbulence distortion is rapid enough so that turbulence inertia and viscous forces can be neglected.

The first assumption is made so that the blade upwash turbulence spectrum Φ_{vv} is identically Φ_{22}, where Φ_{22} is the vertical velocity turbulence energy spectral density measured or calculated in a x_1, x_2, x_3 Cartesian frame. In the general case, all nine components of the turbulence energy tensor, Φ_{ij}, are required to calculate, by tensor transformation rules, the blade upwash spectrum.

The homogeneous mean motion induced by the blade incidence is assumed to be of the form,

$$U = \gamma_{12} X_z \tag{1}$$

where γ_{12} is a constant which indicates the amount of shear. The qualification that the turbulence distortion be homogeneous facilitates the construction of a turbulence distortion theory (see Refs. 1 and 2) and is a necessary assumption if the resultant upwash spectrum is to be used in conventional noise prediction schemes. It can be shown that the turbulence distortion caused by a bluff body is inhomogeneous (Ref. 13) so the above assumption is artificial.

The remaining assumptions are related to turbulence distortion theory itself. For the case of weak, homogeneous turbulence, subjected to a uniform mean velocity gradient in the x_1 - x_2 plane, the upwash energy spectral dynamics are goverened by the linear partial differential equation,

$$\frac{1}{\gamma_{12} k_1} \quad \frac{\partial \Phi_{22}}{\partial t} - \frac{\partial}{\partial k_2} \quad \Phi_{22} = \frac{4k_2}{k^2} \quad \Phi_{22} \tag{2}$$

where, $k^2 = k_1^2 + k_2^2 + k_3^2$,

k_1, k_2, k_3 are wave numbers. For the derivation of this equation see Refs. 1 and 2.

Equation (2) is valid provided the turbulence is weak,

$$\sqrt{\overline{u'^2}} / \bar{U} < 1 \tag{3}$$

and the distortion is rapid,

$$\Delta t < \frac{L}{\sqrt{\overline{u'^2}}} \tag{4}$$

where, $\sqrt{\overline{u'^2}}$ is the intensity of the longitudinal component of the turbulence, $\bar{U}$ is the mean velocity of the flow, L is the turbulence integral length scale, and Δt is the duration of the distortion process. Equation (3) states that the turbulence must be weak so that the distortion is a result of mean flow changes and not from the turbulence itself. Equation (4) states a condition for which the neglect of viscous decay effects on the turbulence is valid. The turbulence is distorted by the stretching (rotating) of vortex filaments and not by the nonlinear inertial or internal viscous forces of the turbulence.

Because of the nature of the governing partial differential equation and the solution technique (characteristics), imposing blade surface velocity boundary conditions don't give a well posed problem. The only auxiliary information needed to solve Eq. (2) is the initial condition for Φ_{22}. It is assumed at a time t_o the turbulence is isotropic, so (Ref. 14)

$$\Phi_{22}(k, t_o) = \frac{E(k)}{4\pi k^4} (k_1^2 + k_3^2) \tag{5}$$

where E(k) is the turbulence energy spectrum function.

The solution to Eq. (2) is,

$$\Phi_{22}^{(d)} = \frac{(k_1^2 + k_3^2)}{4\pi k^4} E(k') \tag{6}$$

where the superscript (d) indicates the distorted turbulence spectrum, and $k'^2 = k_1^2 + (k_2 + \gamma_{12}\Delta t k_1)^2 + k_3^2$.

A simple order of magnitude analysis shows that,

$$\gamma_{12} \sim \alpha U/\tau$$

$$\Delta t \sim c/\bar{U}$$

so,

$$\gamma_{12}\Delta t \sim \alpha/\tau \tag{7}$$

where α indicates the amount of blade incidence, τ is the blade thickness ratio, and $\bar{U}$ is the convection velocity.

Calculation of Broadband Noise Due to Distorted Inflow Turbulence

To determine the effect of turbulence distortion on the low frequency broadband noise due to turbulence, the following parameter is computed,

$$\beta(k_x) = \frac{S_{pp}^{(d)}}{S_{pp}^{(o)}} = \frac{\iint_{-\infty}^{\infty} dk_y dk_z |K(k_x,k_z)|^2 \Phi_{vv}^{(d)}}{\iint_{-\infty}^{\infty} dk_y dk_z |K(k_x,k_z)|^2 \Phi_{vv}^{(o)}} \tag{8}$$

where $|K|^2$ is the magnitude of an unsteady lift transfer function. The notation in Eq. (8) refers to a blade local (x,y,z) coordinate system. The superscript (o) refers to the undistorted case (isotropic inflow turbulence).

The double integral of the product of the turbulence spectrum and unsteady lift transfer function is directly proportional to the radiated sound pressure power spectral density, S_{pp} (e.g., see Ref. 3).

To perform calculations, it is assumed that,

$$|K|^2 \sim \left(k_x^2 + k_z^2 + \frac{8}{\pi^2 c^2}\right)^{-1} \tag{9}$$

Constants of proportionality have been omitted. Equation (9) is part of Mugridge's [15] strip theory correction factor for a three-dimensional gust convected past a two-dimensional airfoil. For the initial turbulence an exponential correlation function is assumed so (Ref. 14),

$$E(k) \sim k^4(k^2 + L^{-2})^{-3} \tag{10}$$

and,

$$\Phi_{vv}^{(o)} \sim (k_x^2 + k_z^2)(k^2 + L^{-2})^{-3} \quad (11)$$

From Eqs. (6) and (10),

$$\Phi_{vv}^{(d)} \sim \frac{k'^4}{k^4} (k_x^2 + k_x^2)(k'^2 + L^{-2})^{-3} \quad (12)$$

where, $k^2 = k_x^2 + k_y^2 + k_z^2$,

$$k'^2 = k_x^2 + (k_y + k_x \gamma_{12} \Delta t)^2 + k_z^2$$

For calculation pueposes, the infinite integrals in Eq. (8) where transformed to a finite domain by trignometric substitutions, and then numerically evaluated.

Comparison of Results with Experiment

To compare this distortion model with experiment, model helicopter data (Refs. 8,9) and some full scale data (Ref. 7) are used. Pertinent data is listed in Table 1. For the model data (Ref. 9) the turbulence was initially nonisotropic and was generated by an airfoil placed upstream of the rotor. The model data (Ref. 8) is for wind tunnel ambient inflow turbulence conditions. The full scale data is for atmospheric turbulence conditions. For all the experimental cases the criteria expressed by Eqs. (3) and (4) are satisfied.

Figures 1 and 2 show schematically how the observed sound pressure spectral density changes for different levels of rotor loading for a model rotor. Note that the peak sound pressure level occurs in the low frequency range and that for the increased loading cases, the spectra amplitudes are correspondingly increased except at the highest frequencies.

For the experimental cases conducted in References 8 and 9 the low frequency broadband noise peak SPL occurs at approximately 200 Hz ($k_x \sim 7$).

Since the amount of distortion hasn't been rigorously linked to the rotor blade incidence i.e., rotor mean aerodynamics, it is only possible to estimate the size of the terms indicated in Eq. 7. Typical numbers for $\gamma_{12}\Delta t$ are assumed to be 1-2 based on the fact that the rotor blade incidence changes were approximately 8 degrees from the low load to the high load cases for the model rotor.

Figures 3 and 4 indicate how the distorted inflow turbulence changes the noise spectrum calculated with an isotropic inflow turbulence model. Recalling that a factor of two represents 3 dB and comparing Figs. 1 and 2 with Figs. 3 and 4, it is clear that the inflow distortion model can't totally account for the increases in peak SPL with rotor thrust.

Figure 5 shows that under certain conditions, the peak SPL (which occurs at approximately $k_x \sim 2$) of the low frequency broadband noise of a full scale rotor (Ref. 7), decreases with increasing thrust. Figure 6 shows that an inflow turbulence distortion which increase with thrust can explain the trend shown in Fig. 5. However, if turbulence induced noise is the dominant broadband noise source for a range of frequencies, then the reduction of noise levels at high k_x predicted by the distortion model isn't consistent with experimental spectra.

Conclusions

Conceptually, the idea of inflow turbulence distortion is an attractive one, since in real rotor flows the turbulence is constantly being distorted. The distortion model presented in this paper was not able to totally explain experimentally observed changes in sound pressure levels with rotor mean thrust. Other, more robust phenomena occur when the rotor mean thrust changes, e.g., the blade flapping velocities and acceleration changes, rotor inflow velocity changes, and the Gutin type noise varies.

The distortion model presented linked inflow turbulence modification to the rotor mean aerodynamics, albeit in a simple fashion. What is needed is a model which rigorously links the amount of turbulence distortion to the rotor mean aerodynamics. This is required because clearly the distortion is not homogeneous, nor does it proceed by virtue of a lone mean velocity shear, as was assumed in the present model.

Acknowledgements

This research was supported in part by the NASA Langley Research Center under Grant No. NSG-1583.

References

1) J.R.A. Pearson, The Effect of Uniform Distortion on Weak Homogeneous Turbulence, JFM, 5, 1959.

2) R.G. Deissler, Effects of Inhomogeneity and of Shear Flow in Weak Turbulent Fields, Physics of Fluids, 4, 1961.

3) G.F. Homicz and A.R. George, Broadband and Discrete Frequency Radiation from Subsonic Rotors, J. Sound and Vib., 36, 1974.

4) A.R. George and Y.N. Kim, High Frequency Broadband Rotor Noise, AIAA J., 15, 1977.

5) R.K. Amiet, Noise Produced by Turbulent Flow into a Propeller or Helicopter Rotor, AIAA J, 15, 1977.

6) A.R. George and S.T. Chou, Comparison of Broadband Noise Mechanisms, Analyses, and Experiments on Helicopters, Propellers, and Wind Turbines, AIAA Paper 83-0690.

7) J.W. Leverton and J.S. Pollard, Comparison of the Overall and Broadband Noise Characteristics of Full Scale and Model Helicopter Rotors, J. Sound and Vib., 30(2), 1973.

8) N.G. Humbad and W.L. Harris, Effects of Tip Geometry on Model Helicopter Rotor Low Frequency Broadband Noise, M.I.T. FDRL Report No. 81-2.

9) M. Williams, SM Thesis, M.I.T., Cambridge, MA, 1984.

10) A.D. Pierce, Acoustics, McGraw-Hill, 1981.

11) R.W. Paterson and R.K. Amiet, Noise of a Model Helicopter Rotor due to ingestion of Turbulence, NASA CR-3213, 1979.

12) M. Williams and W.L. Harris, Application of a Turbulence Distortion Theory to Predict Helicopter Broadband Noise due to Inflow Turbulence as a Function of Rotor Thrust, Proceedings of the 40th Annual Forum of the American Helicopter Society, Paper Number A-84-40-02-0000, 1984.

13) J.C.R. Hunt, A Theory of Turbulenct Flow Round Two-Dimensional Bluff Bodies, JFM, 61, 1973.

14) G.K. Batchelor, The Theory of Homogeneous Turbulence, Cambridge University Press, N.Y., 1953.

15) B.D. Mugridge, Gust Loading on a Thin Airfoil, Aero. Quart., 22, 1971.

Table 1

Rotor Data

Model Helicopter Rotor Characteristics (Refs. 8,9)

Radius	0.635m
Chord	0.0508m
Number of Blades	2
Section	NACA 0012
Twist	8 degrees
Microphone Location	1.1m above rotor, on axis (Ref. 8)
	1.3m above rotor, on axis (Ref. 9)

Full Scale Rotor Characteristics (Ref. 7)

Radius	8.5m
Chord	.417m
Number of Blades	2
Section	NACA 0012
Twist	8 degrees
Microphone Location	11.5 degrees below disc at 76m radius

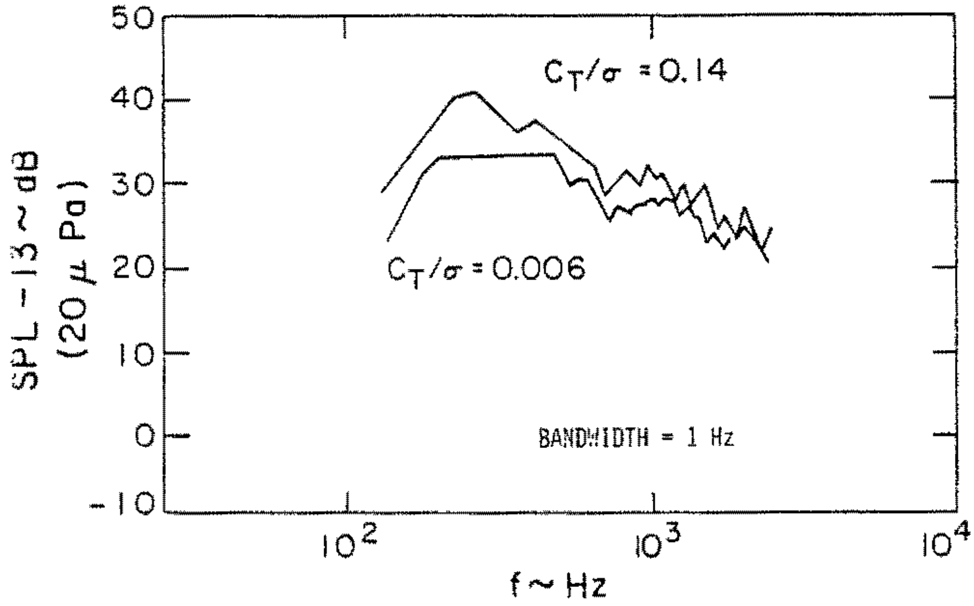


Figure 1 Experiment data showing the effect of rotor mean loading on the sound pressure power spectral density for a model rotor, rpm= 810, L =0.16cm, C = 5.1cm, μ = 0.3

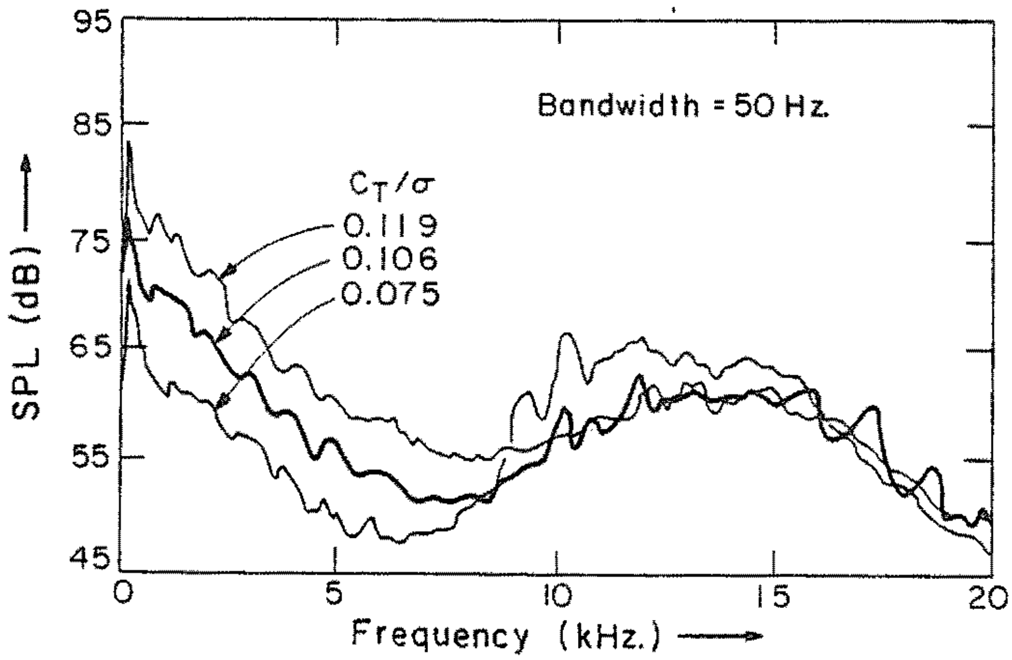
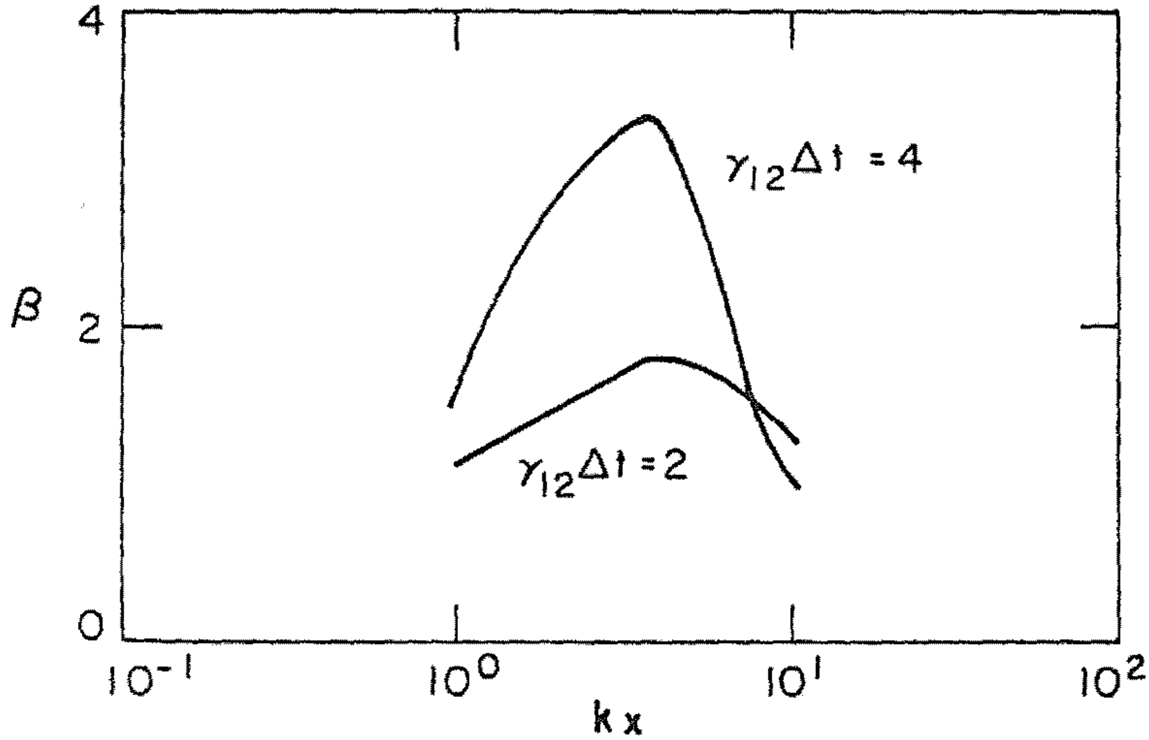


Figure 2 Effect of blade loading, no grid, square tip (Taken from ref. 8)



(a) L = 1.9 cm, C = 5.1 cm

Figure 3 The effect of a shear type distortion on the parameter β for the model rotor (ref. 9)

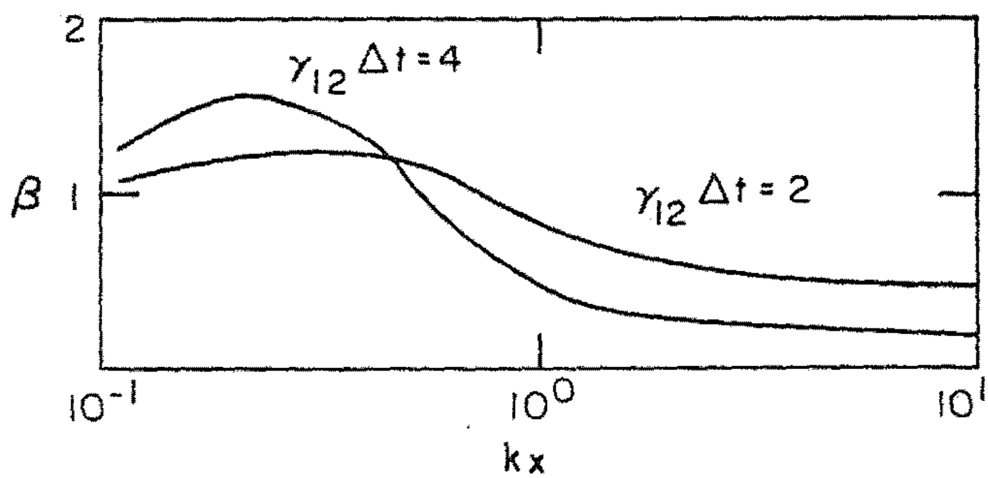


Figure 4 The effect of a shear type distortion on the parameter β for the model rotor (ref. 8)

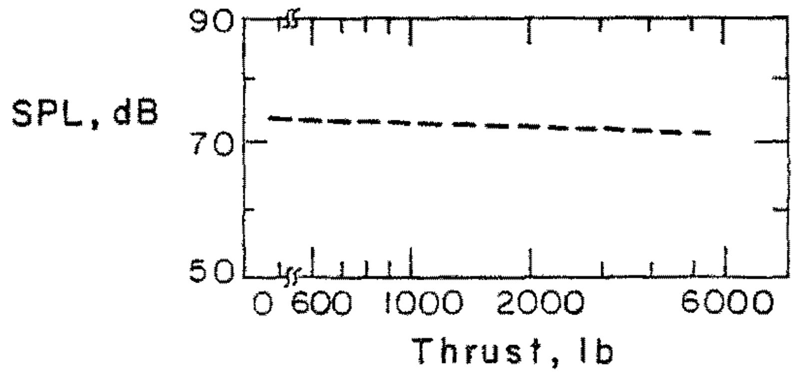


Figure 5 Full-scale rotor data showing decreasing SPL for increasing thrust (data from ref. 7)

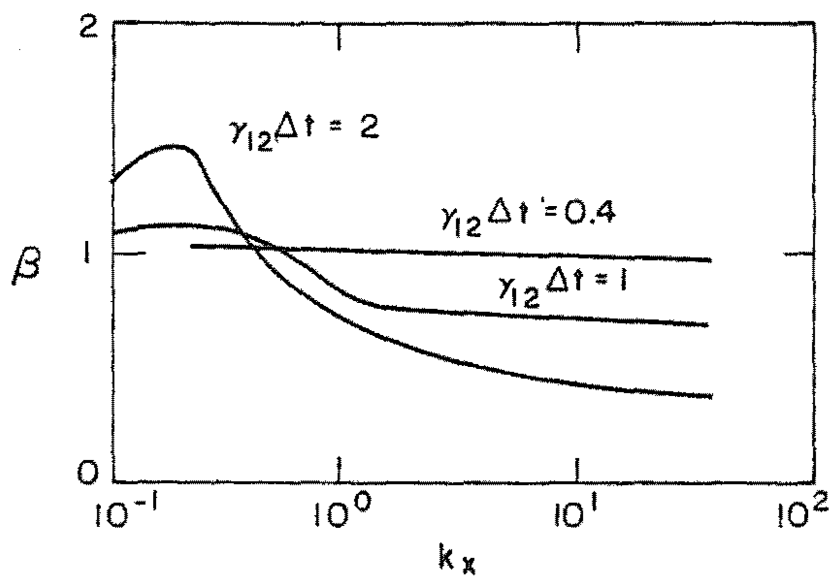


Figure 6 The effect of a shear type distortion for a full scale rotor, L = 57cm, c = 43cm