FIFTH AUSTRALASIAN CONFERENCE

on

HYDRAULICS AND FLUID MECHANICS

at

University of Canterbury, Christchurch, New Zealand

1974 December 9 to December 13

RESPONSE OF A SLENDER TOWER TO WIND ACTION

by

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SUMMARY

The aerodynamic design philosophy used in the development of a design for a 19ft (5.8m) square 385ft (118m) high tower is described. Basically it was required to reduce the crosswind motion of the tower which was achieved with the use of a porous shroud over the top half of the tower.

Wind tunnel tests were made on a 1/150 scale aeroelastic model of the tower in a turbulent shear flow model of the natural wind. The model scaling criteria are developed.

A vortex "lock-in" phenomenon was encountered at low values of structural damping and this is discussed along with some hot wire measurements in the wake to establish whether the wake has any dependency on the motion of the tower. The porous shroud was shown to reduce the oscillatory motions to between half and a third that for the configuration without a shroud. Probability distributions of the response and the effect of damping are also presented.

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1. INTRODUCTION

The design of a tall slender tower in which high speed elevator systems could be tested is being undertaken by Johns and Waygood in Melbourne. To establish the effective wind loading and response of several of the proposed, steel frame, configurations a series of wind tunnel tests was undertaken. The aeroelastic model tests were conducted in a natural wind model generated in the 4 x 3m wind tunnel at Monash University during 1972. Because some of the results of these tests are of general and research interest, permission to publish them has been given by Johns and Waygood Ltd.

2. AERODYNAMIC DESIGN OF THE TOWER

The tower was required to house two elevator shafts and a staircase in a 19ft (5.8m) square section, initially to a height of 385ft (118m), with a machine house on the top. Early tests showed that a tower with a square cross-section, stiff enough to resist the wind loading in the along-wind (drag) direction, exhibited a cross-wind motion far in excess of what could even be tolerated structurally. The mechanism of the cross-wind excitation was a combination of wake excitation, due to the periodic shedding of vortices, and possibly some galloping excitation due to the characteristics of the basic square section which has a negative lift curve slope with the wind direction near normal to a face.

In terms of design philosophy a design was sought in which critical velocity effects due to resonant wake excitation would be eliminated and the cross-wind motion was to be no more than the along-wind motion due to incident freestream turbulence. To achieve this an aerodynamic design incorporating a porous circular shroud over the top half of the tower was proposed. The purpose of the porous shroud was:

(a) to remove the adverse negative lift curve characteristics of the basic square section,
(b) to use the porosity to reduce the peak (resonant) wake energy caused by the shedding of alternate (periodic) vortices, and
(c) to reduce the overall drag of the basic square section.

The full scale dimensions and structural parameters of the configurations tested are given in Figure 1. and a photograph of the model in particular showing the circular porous shroud is given in Figure 2. The porosity of the shroud is defined as the percentage of open area over the total surface area of the shroud.

Initial information about the use of porous shrouds was obtained from Price[1] and Wooten[2].

3. THE MODELS

3.1. Model Scaling Requirements

The modelling of wind effects on structures first requires tha a satisfactory model of the natural wind be produced and then that a similarly scaled structural model be tested in this model wind environment. One rational approach to the determination of scaling or similarity requirements for a model test is to assemble all the criteria through dimensional or similarity arguments than from a physical understanding of each criteria to enable their relative significance to be established. To this end the following list of variables on which the behaviour of a structure under wind loading could be expected to depend has been set down,

$$\bar{u}_g, \bar{u}_z, u', v', w', L_{bl}, n, Su(n), Sv(n), Sw(n), \rho, \mu, p, L_s, n_s, \rho_s, E, g, \delta$$

where

$\bar{u}_g$	mean freestream longitudinal velocity at the gradient height
$\bar{u}_z$	mean longitudinal velocity at height z
u', v', w'	fluctuating velocity components in the longitudinal, lateral and vertical directions respectively (i.e. meteorological convention)
L_{bl}	length associated with the boundary layer flow
n	frequency associated with the boundary layer flow
$S_u(n), Sv(n), Sw(n)$	power spectral density of the respective velocity components
ρ	air density
μ	air viscosity
p	pressure
L_s	length associated with the structure
n_s	frequency associated with the structure
ρ_s	density of the structure
E	stiffness modulus of the structure
g	acceleration due to gravity
δ	damping ratio for the structure

By using either dimensional analysis or similarity arguments it can be shown that dynamic similarity with respect to these nineteen variables can be achieved if the sixteen following non-dimensional groups are maintained constant between model and full scale.

NON-DIMENSIONAL GROUP	NAME (IF IN COMMON USAGE)	PHYSICAL MEANING
$\bar{u}_z/\bar{u}_g$	Velocity profile	Velocity ratio which defines the vertical velocity profile
$\frac{\sqrt{\overline{u'^2}}}{\bar{u}_z}, \frac{\sqrt{\overline{v'^2}}}{\bar{u}_z}, \frac{\sqrt{\overline{w'^2}}}{\bar{u}_z}$	Turbulence intensity Alt. $I_u = \frac{\sigma_u}{\bar{u}_z}, I_v = \frac{\sigma_v}{\bar{u}_z}, I_w = \frac{\sigma_w}{\bar{u}_z}$	Expression relating total energy of the fluctuating components
$\frac{nSu(n)}{\sigma_u^2}, \frac{nSu(n)}{\sigma_u^2}, \frac{nSw(n)}{\sigma_u^2}$	Normalized power spectral density	Expression giving turbulent energy distribution with respect to frequency
$\frac{n\,L}{\bar{u}}$ (L is any related length)	Strouhal Number or reduced frequency (or inverse of reduced velocity)	Time scale
$\frac{\rho\,\bar{u}\,L}{\mu}$ (L is any related length)	Reynolds Number	$\frac{\text{Inertia Force (Fluid)}}{\text{Viscous Force}}$
$\frac{p}{1/2\rho\bar{u}^2}$	Pressure Coefficient	$\frac{\text{Pressure Force (Fluid)}}{\text{Inertia Force (Fluid)}}$
$\frac{L_{bl}}{L_s}$	Length Ratio	Ratio of lengths in boundary layer and structure
$\frac{n}{n_s}$	Frequency Ratio	Ratio of frequency or time in boundary layer and structure
$\frac{\rho}{\rho_s}$	Density Ratio	$\frac{\text{Inertia Force (Structure)}}{\text{Inertia Force (Fluid)}}$
$\frac{\rho\bar{u}^2}{E}$	Cauchy Number	$\frac{\text{Inertia Force}}{\text{Elastic Force}}$
$\frac{\bar{u}^2}{\sqrt{Lg}}$	Froude Number	$\frac{\text{Inertia Force}}{\text{Gravity Force}}$
δ	Logarithmic Damping Decrement (alt. Critical Damping Ratio ζ	$\frac{\text{Energy Dissipated/Cycle}}{\text{Total energy of oscillation}}$

where $\sqrt{\overline{u'^2}} = \sigma_u$ etc. root mean square of the fluctuating component or standard deviation

$I_u = \sigma_u/\bar{u}_z$ turbulence intensity

$\zeta = \delta/2\pi$ critical damping ratio.

There are a number of other non-dimensional groups in common use, such as Force and Moment Coefficients, which are derivations of the groups above and will be defined when used.

To achieve dynamic similarity, one is required to maintain constant ratios between all the forces affecting the phenomena and the ratio of all similar variables, like length and density in the boundary layer and the structure must be constant. In practice it is rarely possible to satisfy all these requirements and so some physical understanding of the phenomena is required to assess the relative importance of the criteria to permit distortion to allow a practicable model to be made.

3.2 The Model of the Natural Wind

The natural wind has been modelled in the 4 x 3 metre section of the wind tunnel by the augmented development of a turbulent shear layer, or boundary layer. The wind tunnel layout to achieve this is shown in Figure 3. This development aims to model as accurately as possible the velocity profile, turbulence intensity, spectral distribution, and correlation length scales. In particular the large scale motions have been achieved by superimposing a fluctuating two dimensional separation bubble on the boundary layer developing over the roughness elements. The characteristics of the model of the natural wind used for the tests are given in Figure 4. These characteristics, which are standard for the suburban fetch model wind in the 4 x 3m section; were originally obtained by comparison with the full scale measurements in Melbourne by Brook[3] and Holmes[4].

3.3 The Aeroelastic Model of the Lift Testing Tower

The tower model was constructed with a central tubular steel spine which modelled the elastic properties of the tower in five steps and the aerodynamic shape and vertical mass distribution was added in twelve segments. The equivalent stiffness and mass distribution of the model in full scale units is given in Figure 1.

The response of the tower was not affected by gravitational acceleration and so the choice of time scale became one of suiting the materials available for the model and the wind tunnel speed. The scaling parameters used, and the rationale of their development is briefly as follows, where subscript "r" refers to the ratio of model over full scale, i.e. $\frac{\text{Length model}}{\text{Length full scale}} = L_r = {}^1/_{150}$

$$L_r = \frac{1}{150}, \; \bar{u}_r = \frac{1}{4}, \; \rho_r = \rho_{s_r} = 1, \; T_r = L_r/\bar{u}_r = \frac{1}{150}\,\frac{4}{1} = \frac{1}{37.5} = 0.02667,$$

$$\frac{\rho\bar{u}^2}{EI/L^4} = \text{Constant}, \therefore (EI)_r = \frac{1}{150^4}\cdot\frac{1}{4^2} = \frac{1}{81 \text{ x } 10^8}$$

$$\frac{p}{\rho\bar{u}^2} = \text{Constant}, \therefore \text{Force}_r = \bar{u}_r^2 L_2^2 = \frac{1}{4^2}\cdot\frac{1}{150^2} = \frac{1}{36 \text{ x } 10^4}, \text{Moment}_r = \bar{u}_r^2 L_r^3 = \frac{1}{4^2}\cdot\frac{1}{150^3} = \frac{1}{54 \text{ x } 10^6}$$

4. THE MODEL TESTS

The object of the model tests was to check that the requirements set out in Section 2. Aerodynamic Design of the Tower, could be achieved and to establish equivalent full scale wind load design data. Most of the testing was carried out on a 385ft high configuration and some values for the preferred aerodynamic configuration were obtained for a 350ft high configuration.

The model was fitted with strain gauges at the base of the spine to measure th overturning moment about an axis through the base of the frame, which is approximately 8ft below ground level see Figure 1.

4.1 Excitation Modes and Probability

The excitation mode, both along - wind and crosswind were shown to be the fundamental cantilever bending mode. This can be seen in a record of the base bending moment given in Figure 5. This record shows the random build up and decay of oscillation amplitude which is typical of the response of tall structures to wind loading where the energy input per cycle is relatively small and the structure is behaving like a narrow band filter.

Probability distributions of the overturning moments about the base of the frame were measured for cross wind and along - wind motions of the 385ft and 350ft tower with 35% porosity shroud and are given in Figure 6. A normal (Gaussian) distribution is shown as a solid line and the number of upcrossings per hour for a narrow band normal distribution are given on the right hand axis. From Figure 5 it can be concluded that the average maximum amplitude per hour (full scale) will be about 3.5σ for the along-wind motions and 4.0σ or slightly above the cross wind motions at $\bar{u}_{top}$ = 80 ft/sec, where σ is the standard deviation or root mean square of the fluctuating component. This information is required when it comes to predicting extreme response probability distributions for a given lifetime and when deriving equivalent static design wind loads.

4.2 Wake Measurements

During the test series there were indications that a "lock-in" phenomena could be occuring on the 385ft configuration at low damping (ζ = 0.3%). The jargon "lock-in" is used here to describe the phenomenon whereby the periodic displacement (cross-wind) of the tower forces the vortex shedding to lock into the same frequency as the tower causing an increase in resonant response of the tower to the wake excitation and so on to a form of instability. The term is also used to imply any effect that the periodic displacement of the tower may have on the wake energy which is in turn transmitted back as a forcing mechanism on the tower. The effect is most likely to occur near the wind speed at which the natural vortex shedding frequency is the same as that of the structure, usually called the critical wind speed.

Using a hot wire anemometer several measurements of longitudinal wind speed spectra were made at the edge of the wake for wind speeds at and near the critical wind speed (71ft/sec) and are given in Figure 7. It can be seen that the wake spectra generally, and particularly the peak reduced frequency ($nD/\bar{u}$) were not significantly affected by the variation of wind speed or amplitude of the tower oscillation as obtained by varying the damping (ζ = 0.5% and 2.5%). From this it is concluded that for the amplitude range of these measurements (in excess of that likely to occur on the actual tower) there was no indication of the "lock in" phenomena. However the very large response measured early in the test series (Figure 8) for the low damping of $\zeta = 0.3\%$ indicates that the amplitudes at which "lock-in" could occur may not be very much greater. The other high response measured on one occasion with the wind at 45° for $\zeta = 0.5\%$ also indicates that amplitude effects could be starting to have an effect.

4.3 The Moment Measurements

A summary of the mean and root mean square of the fluctuating component of the overturning moments about the base of the frame for the most interesting configurations tested are given in Figure 8.

A number of configurations of shroud porosity were tested ranging from 50% porosity to zero porosity. There was little difference between the base overturning moments measured with 50%, 35% and 25% porosity shrouds. However there were small advanatages in favour of the 35% porosity shroud, both in performance and because it was in the middle of the porosity range, which led to it being regarded as the preferred configuration and the one for which most test results were obtained

The measurements have been plotted dimensionally in full scale values in preference to a non-dimensional presentation to facilitate comparison of the shroud performance on the one structural base at different wind speeds. Tower dimensions are given in Figure 1 and the first bending mode frequencies are noted on Figure 8. Discussion on these test results has been reduced to the conclusions given in the next section.

4.4 Displacements and Accelerations

For the original study an estimate of the top displacements and accelerations were made as a function of the wind speed probability at the site. As these results are only of specific interest they have not been reproduced here.

5. CONCLUSIONS

Conclusions from these test results are as follows:-

1. The tower without the porous shroud exhibited strong cross-wind oscillations about twice the amplitude of the along - wind oscillations. The mechanism appears to be wake dominated although the amplitude was sufficient to have included significant galloping excitation.

2. The addition of the porous shrouds did not reduce the mean drag by very much but generally the along-wind rms was reduced to a half and the cross-wind rms to a third of that for the configuration without a shroud.

3. All the porous shroud configurations showed "velocity effects" indicating significant dependence on the wake excitation. The 50% and 25% porosity shroud configurations showed reductions in rms response for cross-wind and 45° wind with increasing mean wind speed beyond 71 ft/sec at which the maximum wake energy occurs as per Figure 6. The 35% porosity shroud configuration did not show such a marked velocity effect except for the 45° wind direction. For damping $\zeta = 1.5\%$ for all three wind directions the rms response of the tower increased with wind speed.

4. At low damping, $\zeta < 0.5\%$ there was evidence of the vortex "lock-in" phenomenon. However for the damping in excess of $\zeta = 1.5\%$ there was no indication of the "lock-in" phenomenon, and wake spectra measurements confirmed that the wake was considered to be the likely limit of the motion of the full scale structure.

5. The excitation modes of both cross-wind and along wind motions were shown to be the fundamental cantilever bending mode. From probability estimates the average maximum amplitude per hour (full scale) was found to occur at 4.0σ and 3.5σ for the cross-wind and along-wind motions respectively.

ACKNOWLEDGEMENTS

Permission from Johns and Waygood Ltd. to publish this report is gratefully acknowledge as also is the co-operation of their staff throughout the investigation.

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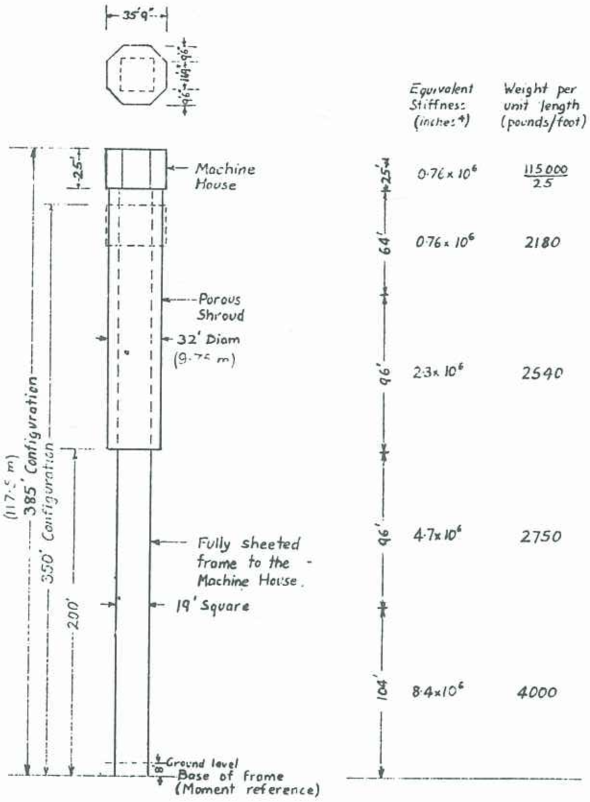

FIG 1 FULL SCALE CONFIGURATIONS MODELLED
Length Ratio 1/150, Velocity Ratio 1/4, Density Ratio 1,
Equivalent Stiffness Ratio $\left(\frac{1}{4}\right)^2\left(\frac{1}{150}\right)^4$

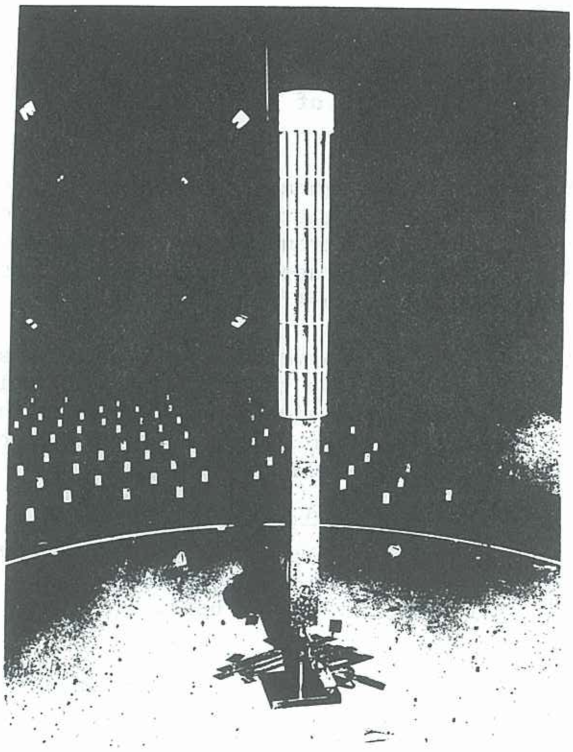

FIG. 2 1/150 SCALE MODEL OF LIFT TESTING TOWER CONFIGURATION 385 ft HIGH, 50% POROSITY SHROUD.

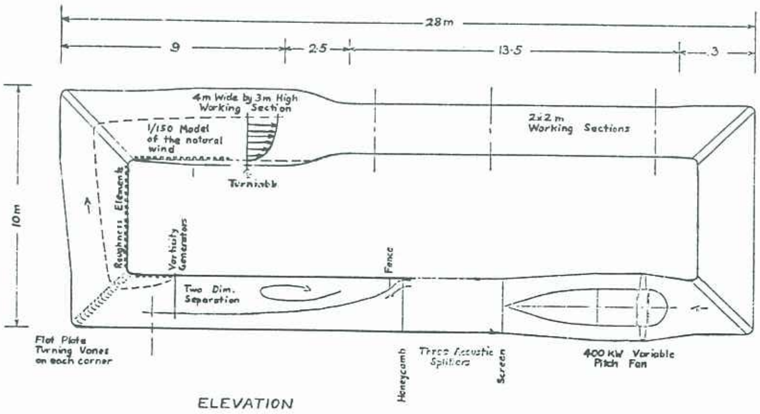

FIG. 3 WIND TUNNEL USED FOR GENERATION OF A 1/150 MODEL OF THE NATURAL WIND IN A 4x3 m CROSS SECTION

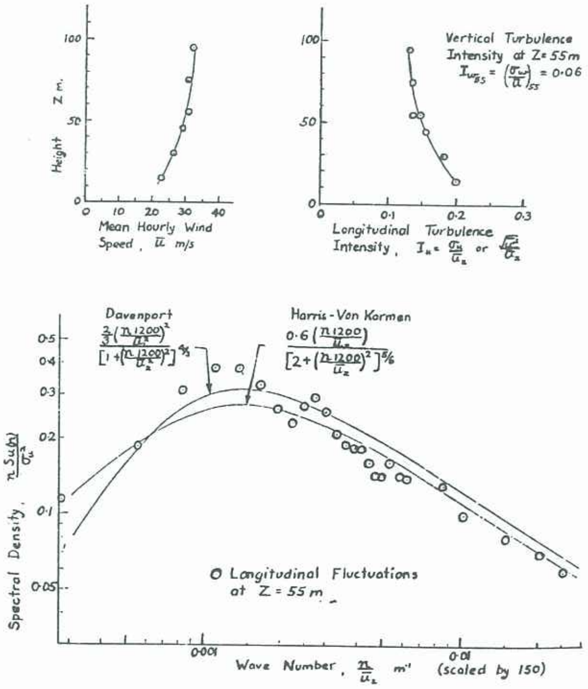

FIG. 4 CHARACTERISTICS OF 1/150 SCALE MODEL OF WIND FLOW OVER SUBURBAN FETCH

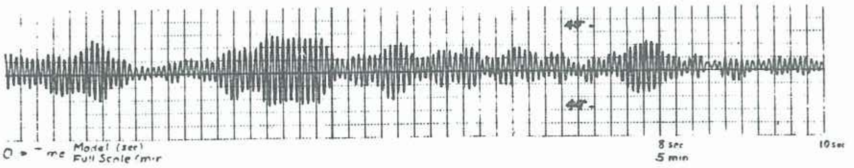

FIG. 5 TRACE OF CROSSWIND OVERTURNING MOMENT ABOUT THE BASE
350 ft TOWER, 35% POROSITY SHROUD. $\bar{u}_{350} = 80$ ft/sec, $\zeta = 1.5\%$, $n = 0.4$ Hz

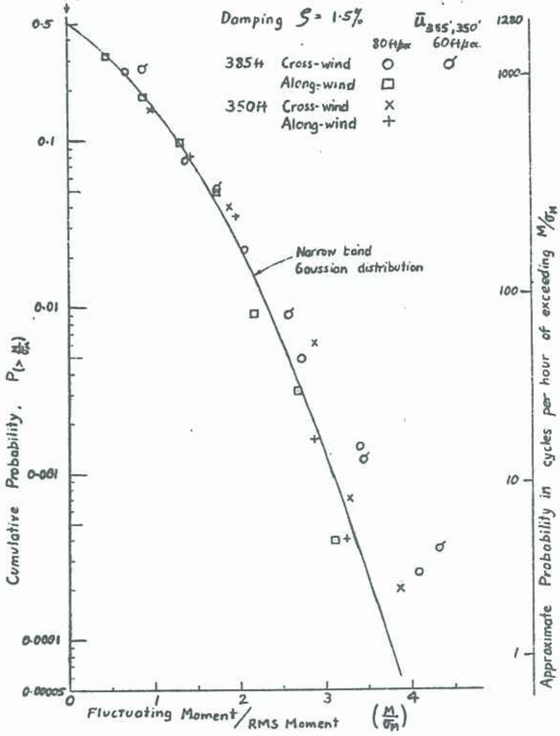

FIG. 6 PROBABILITY DISTRIBUTION OF OVERTURNING MOMENTS ABOUT THE BASE OF THE FRAME

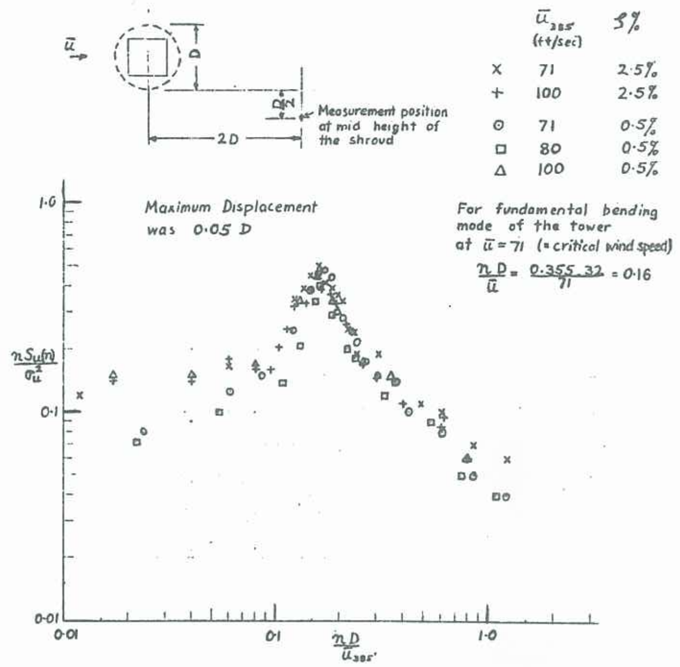

FIG. 7 SPECTRA OF LONGITUDINAL WIND SPEED AT THE EDGE OF THE WAKE SHED FROM THE 35% POROSITY SHROUD, 385 ft TOWER.

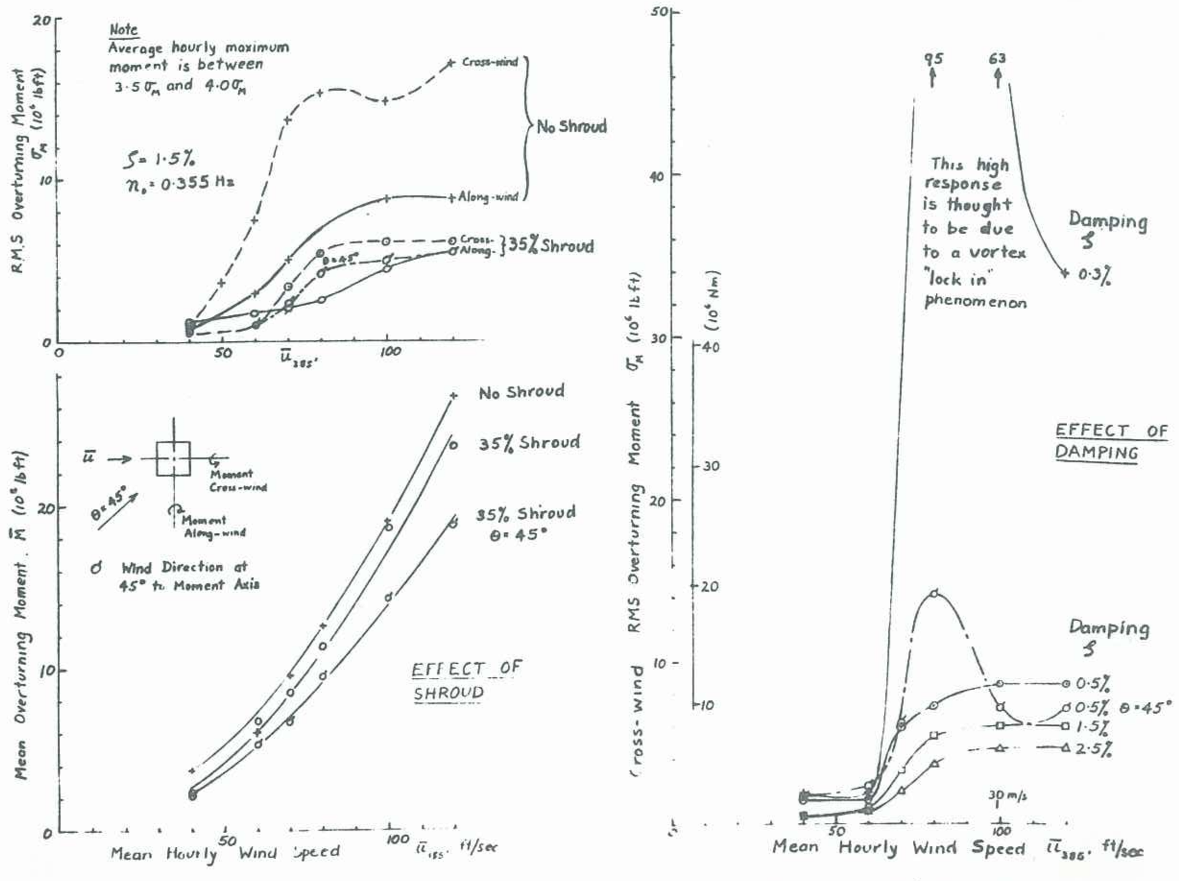

FIG 8 MEAN AND RMS OVERTURNING MOMENTS ABOUT THE BASE OF THE 385' TOWER FRAME