ACROSS WIND RESPONSE OF TALL CHIMNEYS

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
CIVIL ENGINEERING
(With Specialization in Structural Engineering)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled "ACROSS WIND RESPONSE OF TALL CHIMNEYS" in partial fulfilment of the requirements for the award of the Degree of MASTER OF ENGINEERING in Civil Engineering with specialization in STRUCTURAL ENGINEERING, submitted in the DEPARTMENT OF CIVIL ENGINEERING, UNIVERSITY OF ROORKEE, is an authentic record of my own work carried out during a period of 8 months from october 88 to May 89, under the supervision of Dr. P.K. Pande and Dr. Krishen Kumar, Professor, Civil Engineering Department, University of Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

Dated: 20 May 1989

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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CONTENTS

ABSTRACT

In the present age of rapid industrilisation, chimneys are very useful for effective and safe disposal of industrial waste gases into the atmosphere. Their heights are increasing day by day reaching to 300 m. to meet the anti pollution requirements. Due to increased height the effect of wind predominates in the design of chimney. The wind force may be considered in the direction of wind or along wind and prependicular to the direction of wind or across wind seperately. Along wind excitation is due to gustiness of wind while across is mainly due to periodic shedding of vorticies under winds.

In the persent study, there is an attempt to analyse and compare the along wind response obtained by approach given by Davenport, and in case of across wind by approaches given by Rumman and Vickery. Two types of chimneys, one having constant taper throughout the height and second having constant diameter in upper half portion and constant taper in lower half portion are analysed. The heights of chimneys are taken as 100 m.,150 m, 200 m and 250 m, and for different top diameter to base diameter ratios, varying from 0.35 to 0.65, the responses have been computed.

First type of chimney has also been analysed for small as well as large taper formulations given by Vickery and the results are compared to identify the distinguishing taper value. The chimneys are assumed to be located in open terrain, which is more commenly encountered. The responses have been computed for fixed base condition. The maximem wind velocity at reference height of 10 m. is considered as 50 m/sec.

By comparing the across wind response of the constant taper type chimney by both formulation of small and large taper, as suggested by Vickery, it is concluded that large taper formulation will be applicable when the top diameter to base diameter ratio is less than 0.5 and small taper formulation will be valid when above ratio lies between 0.5 and 1.0 as suggesting by Vickery and Basu. While comparing the across wind response obtained by approaches given by Rumman and Vickery, it is seen that Vickery's results are relatively on conservative side mainly because in the modified formulation Vickery has applied a peak factor of 4.0 Generally the along wind response will be more than the across wind response except when the eddy shedding frequency coincides with one of the structure natural frequency of vibration leading to resonant condition. The across wind non resonance response has much smaller values. According to Rumman, the across wind resonance will occur at about 2/3 height of chimney (for the tapered chimneys) in the first mode and at the top of chimney in the second mode of vibration. Second mode resonance occurs at a very high wind velocity that is rare but the response in second mode is much more significant compare to the first mode response.

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LIST OF SYMBOLS

$A(z)$	Projected area lumped at height z
B	Background turbulence factor
B'_s	Spactral Band width
C_T	Terrain coefficient
C_L	R.M.S. Lift coefficient
C_l	Lift coefficient
D_b	Diameter at base
D_t	Diameter at top
f_i	Frequency of ith mode of vibration
g	Peak factor
H	Height of the chimney
L	Correlation length
$m(z)$	Mass per unit height
Re	Reynolds number
S	Strouhal number
$S(n)$	Spactral energy at frequency f
$S_{v10}(f)$	Velocity spectrum at a reference height of 10 m
t_t	Thickness at top of chimney
t_b	Thickness at base of chimney
$\bar{V}(z)$	Mean wind-speed at height z
z	Height along the chimney from ground
α	Power law exponent
δ	Total logarithmic decrement
β_s	Structural damping as a fraction of critical
ρ	Mass density of air
q_i	Modal multiplier for ith mode

CHAPTER 1.

INTRODUCTION

1.1. GENERAL: Chimneys, normally a final component of any fuel burning plant are used to discharge the effluent efficiently for optimal functioning of the industry or thermal power plant. The construction of tall reinforced concrete chimney has been on the increase in the last few decades, due primarily to the increasing demand of air pollution control. Chimneys in the range of 300 meters or so are not uncommon. Due to increase in the height and reducing the shell thickness for economic point of view, the chimneys become tall and slender. The wind in particular, constitutes one of the major forms of structural loading and even moderate wind are capable of imposing critical forces on the structures.

Wind induced response of chimney, can be investigated as along wind or in the direction of wind and across wind or perpendicular to the direction of wind. The along wind response comprises of static and dynamic response. The across wind response will be due to vortex induced excitation because of eddy shedding from the down stream face. It would be critical when the shedding frequency coincides with the natural frequency of the structure. Besides, the phenomenon of ovalling occurs when the thickness of shell is less.

The response of the chimney is affected a lot due to interference of the upstream chimney, though such cases are rare. In those cases the responce may become double or even triple. In case of multiflue chimneys, when the cross section of the chimney is not circular, galloping instability may also occur.

1.2. OBJECTIVE AND SCOPE: The objective of the dissertation is to examine the across wind response of the chimney by existing methods. The phenomenon of across wind has been less successfully tackled essentially because unlike the along wind response where a single mechanism i.e. buffecting is the dominent source of excitation, many causes contribute to the same. B.J. Vickery (40) and Wadi. S. Rumman (31) has given different approaches for obtaining the across wind response, in this disertation the response obtained by above two approaches has been compared by considering two types of chimneys of four different heights and different top diameter to bottom diameter ratio. The along wind response for all the chimneys has also been evaluated by the approach given by B.J. Vickery (39).

The responses have been obtained for the reference wind velocity(at 10 m. height from the ground level) not exceeding by 50 m/sec. The terrain is assumed as flat open type. Because generally the chimney is located outside the town or large cities. The responses have been computed for fixed base condition considering the chimney as a cantilever. The damping of the chimney plays an important role in the wind vibrations and consists of an aerodynamic component besides the usual structural damping. The damping for W.S Rumman's approach is taken as 2 percent, but for B.J. Vickery's approach it is taken as 1 percent, because Rumman has already taken its effect in his approach. In Rumman's approach for calculating the across wind response, first and second modes of vibrations of the chimney are considered. The Vickery's approach is general and can be used for any mode of vibration of the structure. Badruddin (2) has given modified values of lift coefficient, strouhal number and correlation length. The along wind response has been evaluated by considering wind as comprising of a mean and a fluctuating component. Davenport's approach (7) has been used for computing the along wind response.

CHAPTER 2

REVIEW OF LITERATURE

2.1. GENERAL:- The development of more slender structures like tall chimneys, some of them are as shown in Fig.2.1., and the increasing frequency of failure of such structures, has produced more concern regarding the effects of wind forces on structures. The vortex induced excitation due to high velocity winds are important dynamic problems which are still to be throughly investigated.

This chapter describes the work so for reported by various investigators regarding wind characterstics, forces and their effects on chimneys, codel provisions, etc.

2.2. WIND CHARACTERISTICS:- In order to estimate static and dynamic response of a chimney, it is necessary to have adequate information of the characteristics and effects of common wind storms in different meteorological situations. The measured wind data is generally analysed by statistical means, to obtain,

(i) Mean wind speeds for various time periods (typically averaged over period of about an hour).

(ii) Instantaneous maximum wind speeds associated with given mean wind profiles.

(iii) Velocity variance (especially of the longitudinal wind component).

Wind speed data collected over a number of years are represented in terms of wind rose diagrams. By the help of wind rose it is possible to statistically forecast the likely maximum wind speed at a site for a given return period. Generally in case of chimneys return period is taken as fifty years (16).

The probable maximum wind speed at any height Z is calculated by (23).

$$\frac{Vz}{Vo} = \left(\frac{Z}{Zo}\right)^{\alpha} \qquad \ldots\ldots\ldots(2.1)$$

where Vz and Vo are velocities of wind at height Z and reference height (Zo) respectively. coefficient α is known as power law exponent and depends on surface roughness.

IS:4998 Draft code (17) has specified different value for power law exponent for different types of terrain as shown in Table 2.1.

According to A.C.I. code (1) values of the power law exponent for different terrain types are given below in Table 2.2.

TABLE 2.1

Terrain Category	Terrain Description	power law exponent
1	Open with a few or no obstructions .	0.11
2.	Open with well scattered obstructions.	0.14
3.	Numerous closed spaced obstructions. $H \leq 10$ m	0.25
4.	Numerous large or high closely spaced obstructions.	0.36
Seac Coast	-	0.14

TABLE 2.2

Types of Surface, Grouped according to their aerodynamic roughness

Category	Description	α	C_T
1.	Exposed sites in windy areas,i.e. exposed coast lines, Undulating moorland Desert.	1/7.5 =0.13	0.005
2.	Exposed sites in less wind areas open inland country with heads and buildings less exposed costs.	1/5.5 =0.18	0.015
3.	Well wooded inland country, built up areas.	1/3.5 =0.28	0.050

According to IS:875 (Part III) Draft code (19) the maximum basic wind speed at the reference height of 10 meter from ground level varies from 33 m/sec to 55 m/sec dividing the map of India into six zones. Design wind speed can be obtained by multiplying basic wind speed by probability fector, defining risk (K1), terrain, height and structure size roughness factor(K2 and local topography factor (K3).

2.3. STRUCTURAL RESPONSE:- Structures are excited in along wind direction due to gustiness of wind while across wind oscillation is caused by the formation and alternate shedding of vortices on downstream face. The analysis of structural response due to wind action is carried out by considering each of these seperately.

2.3.1. ALONG-WIND RESPONSE:- Excitation of structures in the along wind direction occurs due to buffecting by gusts.

Davenport (7) has developed a method for perdicting the statistical properties of the response of cantilever like structures to wind turbulence considering the structure to behave like an elastic system with its response depending on the frequency of excitation. Davenport provided an expression which estimates the peak factor

$$g = \sqrt{(2 \ln f_o \bar{t})} + 0.57/\sqrt{2 \ln f_o \bar{t}} \quad \ldots\ldots (2.2)$$

in which the effective frequency f, for a structure is the number of times the displacement trace crosses the mean-value line in unit time and $\bar{t}$ is the sample time, usually 3600 sec.

Vickery (39) has proposed approach for obtaining along wind response by modifying the approach given by Davenport (7). Vickery carried out theoritical estimates of the loads acting on elastic structures and compared the response of these structures in tarbulent flow with model and full scale observations.

2.3.2. ACROSS WIND RESPONSE:- Although the mechanism of vortex shedding and the character of the lift forces causing vibrations to occur in the cross wind direction have been the subject of a great number of studies, the available information does not permit an accurate prediction of these oscillatory forces.

The phenomenon of vortex shedding, which occurs most easily in comparatively smooth air streams, has been the subject of a considerable research programme at National Physical Laboratory under Scruton (37). On the basis of experimental observations it is found that bending oscillations in case of slender structures are excited more significantly in a plane normal to the direction of wind. Because of symmetry of their construction, oscillations usually occur in non-coupled modes and mostly in bending rather then in torsional modes.

Roshko (29) carried out experiments on a large circular cylinder in a pressurised wind tunnel at Reynold's number ranging from 10^6 to 10^7. The study revealed that a definite vortex shedding occured with the Strouhal number equal to 0.27, for Re>3.5 x 10^6.

Sachs (35) had studied results of both wind tunnel tests and oscillations on full sized masts to ascertain the value of the lift coefficient under resonant conditions. Wind tunnel tests of circular sections gave values of lift coefficient between 0.20 to 0.33 with an average of 0.27. The full size structure studied gives the value of lift coefficient between 0.12 to 0.19 for critical Reynold's number lying between 10^6 to 10^7.

Vickery (40) suggested the values of the lift coefficient C_L, Strouhal number S and correlation length L (expressed in diameters) under all type of conditions as 0.20, 0.22 and 1.0 respectively. Though Vickery suggested above values for the corresponding coefficients, he himself felt the necessicity of establishing some basis on which these could be adopted. Cincotta (5) and Schmidt (34) observed the values of C_L, S and L as 0.15, 0.25 to 0.29 and 0.6 respectively in Reynolds number range 3 x 10^6 to 2 x 10^7.

On the basis of experimental observations Vickery (40) described that the lift forces are narrow band random in character with a frequency $f = \frac{S\bar{V}}{D}$. As the diameter is variable, local resonanse takes place at different heights with different wind speeds. As the wind speed increases, the resonance first appeared at the tip and then shifts downward.

Rumman (32) suggested that the resonance will occur in a resonant zone when the shedding frequency coincides with the natural frequency of the structure. The size of resonant zone should not exceed three times the critical diameter or 175 feet. He also suggested that resonance in the first mode of vibration generally occurs at 2/3rd height of the chimney and resonance in the second mode has two peaks. The first peak corresponds due to resonance at the top of the chimney and second peak corresponds due to resonance at about mid - height of the chimney.

2.4. CODE PROVISIONS:- IS:Code (17) specifies a minimum thickness of concrete shell as 15 cm for internal diameter of 6 meters or less. When the internal diameter exceeds 6 meters, the mimimum thickness in cm is $15 + \frac{D_i - 600}{120}$

where D_i = Inside diameter of concrete shell in cms.

IS code has grouped the chimneys into two catagories. Category 1 includes those chimneys for which critical wind velocity is never reached. Category 2 of the code gives the limiting value of H/D ratio corresponding to maximum mean minute speed expected in a particular locality for which no oscillation would occur. Category 2 includes those chimneys for which critical velocity is within the range of velocities expected at the site and it is their higher mass that ensures dynamic stability. Code recommends that oscillations would not occur when mass damping parameter exceeds 20.

The German Code DIN 1056 recommend that investigation on vortex shedding can, however, be relevant for chimneys of circular cross section if G/V is less than 2.0Kn/m^3, where G is the sum of all self weights above the top of the foundation and V is the volume enclosed by the outer surface of the chimney. ACI:307-79 is silent on the dynamic aspects but has been incorporated in the new draft code.

IS. draft code specifies that vortex locking phenomenon occurs when Strouhal number is equal to 0.20. The phenomenon of ovalling can be avoided by providing shell thickness more than 1/75 of the diameter of the chimney at the top. The phenomenon of interference on the downstream chimney due to buffecting of upstream chimney will be maximum when chimneys are spaced 5 times the diameter of chimney at the base and this phenomenon occurs when spacing is less than twenty times the diameter of chimney.

CHAPTR 3

ANALYTICAL METHODS

3.1. PRELIMINARY REMARKS:- Effect of wind on any structure can be broken up into two parts - one which produces response in the direction of wind or along wind response and the other which produces response in the direction perpendicular to wind or across wind response. Along wind response may further be devided into two parts - one which produces a static response and the other causing a dynamic one. In the design of structures to resist wind loads the possibility of a significent dynamic response is therefore a factor which can not be ignored. Dynamic response can reach dangerous levels if the frequency of dynamic excitation is close to the natural frequency of structure since a small exciting force would then cause a large amplitude build up.

In the following sections, these two principle forms of wind loads have been described, along with the analytical procedures which have been used to evaluate the magnitude of the response of chimney.

The chimneys have been idealized as multi-degree lumped mass systems by assuming discrete masses and projected areas to be concentrated at various modes along the height. Only horizontal motions have been considered and these are assumed to be independent of vertical as well as rotational displacements, which are neglected because of their relatively small magnitudes.

3.2. <u>NATURAL FREQUENCIES AND MODE SHAPES:</u>- The dynamic characterstics of the chimney are best identified by the natural frequencies and the mode shapes of the chimney. For obtaining across wind response first two modes have only been considered in each case since the higher modes cannot be excited within the range of velocities encountered in India.

The equation of motion for free vibration of a multi degree lumped system is written as

$$[m]\{\ddot{x}\} + [K]\{x\} = 0 \quad \ldots\ldots\ldots\ldots \quad (3.1)$$

where $[m]$ = A diagonal matrix containing masses of the system

$\{x\}$ and $\{x\}$ = Column matrices of acceleration and displacement respectively

$[K]$ = Square stiffness matrix and is symmetric for linear structural problems.

The eigen values problem for evaluating the mode shapes and the corresponding natural frequency of vibration has been solved numrically by using a computer programme based on Holzer's boundary condition method using transfer functions. The method envolves a trial and error procedure wherein the natural frequency of vibration is assumed first and the boundary condition determinant is written. The trial frequency is increased in small increments till the determinant obtained from the boundary conditions changes sign. A search is then made within this increment till the required accuracy of convergence of natural frequency is achieved. The value of determinant of boundary condition is almost zero, at the prescribed accuracy of convergence ($\times 10^{-5}$) implying that the boundary conditions are satisfied (4). The higher modes of vibrations of structure are obtained in a similar manner and the programme has the capability of directly converging to any desired mode of vibration independent of the earlier eigen vectors. The orthogonality conditions are thus not required in this method.

3.3. DAMPING:- Damping comprises mainly of two components - structural and aerodynamic, and can be represented by the logarithmic decrement δ defined as the logarithm of the ratio of two successive peak amplitudes in an unforced decreasing oscillations. In fact aerodynamic damping is frequently ignored.

Aerodynamic logarithmic decrement δ_a at a given wind speed can be obtained by using the following expression (24)

$$\delta_a = \frac{\sum_{0}^{H} \rho_a \; C_D(z) \; A(z) \; \bar{V}(z) \; \phi^2(z)}{K \; f_i \; \sum_{0}^{H} m(z) . \phi^2(z)} \quad \ldots . \quad (3.2)$$

where the value of K is taken as 2 for along wind and 4 for across wind excitation.

The value of the structural logarithmic decrement δ_s depends upon the response of the structure. For the case where the variation of stress induced in a small element of volume dv is very small, an approximate expression for δ_s is as follows (24).

$$\delta_s = E\,J\,\frac{\Sigma \sigma^n \; dv}{\Sigma \sigma^2 \; dv} \quad \ldots\ldots\ldots\ldots (3.3)$$

where E is the elastic modulus, J and n are material constants and σ is the stress induced in volume dv.

The assumption of small variation in induced stress in a volume dv is justified in the present case because the chimne has been divided into small segments. The value of E, J and n used in the analysis by Badruddin are as follows.(22)

For concrete $E = 2.35 \times 10^6$ N/cm^2

$J = 29.427 \times 10^{-9}$

$n = 2.60$

The variation of δ_s and δ_a with wind speed for various chimneys taken into consideration by Badruddin (2) is shown in Figure 3.1. As can be seen, the value of δ_s for concrete chimney increases with increase in wind speed upto a certain value whereafter it becomes constant. The aerodynamic damping for all type of chimneys shows a contineous variation with wind speed. The value of δ_a for concrete chimneys increases with increase in wind speed for along wind vibrations. For across wind vibrations, the value of δ_a first increases and then starts decreasing as the wind velocity increases. In case of across wind vibration second mode dominates the forces in the lower portion of the chimney.

Figure 3.1 shows the variation of total damping $\delta (= \delta_s + \delta_a)$, i.e, sum of aerodynamic and structural damping, with wind speed. The damping of the chimney is always larger for along wind excitation compared to the across wind excitation.

3.4. <u>ALONG WIND RESPONSE:</u>- The wind velocity, which is an erratically fluatuating quantity with no regular periodicity can be considered to be comprised of the sum of mean and a fluctuating component. The fluctuating component can further be considered as made up of single frequency components with frequencies spread over a wide range. The description of the fluctuating components is quite often facilitatedby the concept of an energy spectrum which represents the energy associated with each frequency component over the entire range of interest. The general behaviour of chimney in the direction of wind (or along wind) comprises two particular types of loading - static and a stochastic loading of the stationary random type (dynamic). The first is relevant to the mean wind loading and the second to the superimposed gust loading.

3.4.1. <u>STATIC RESPONSE:</u>- The wind velocity at a height Z above the ground can be expressed as

$$V(z,t) = \bar{V}(z) + v(z,t) \quad \ldots\ldots\ldots\ldots\ldots \quad (3.4)$$

where $\bar{V}(z)$ is mean component

$v(z,t)$ is the time varying component centered on mean

The value of instantaneous drag force (static) at height z can be calculated as.

$$\bar{P}(z) = \frac{1}{2}\rho C_D(z).A(z).\ \bar{V}^2(z) \quad \ldots\ldots\ldots (3.5)$$

where $C_D(z)$ = coefficient of Drag at height z

$A(z)$ = Projected area per unit length at height z

Drag coefficient at any height z depends upon the Reynold's number, for a circular cylinder. The value of drag coefficient for Reynold's number greater than 3×10^5 is taken as 0.8, and for Reynold's number less than or equal to 3×10^5 as 1.2 (8).

3.4.2. DYNAMIC RESPONSE:- The problem of gust (dynamic) response can be simplified if coupling effects between different modes of structure are omitted. The response of the chimney in each mode can then be separately analysed and then the results superimposed.

According to Davenport (7) the spectra of the fluctuating velocity component along the height of chimney may be assumed to be constant and thus it is taken as equal to spectrum of horizontal gustiness at frequency f at a reference height of 10 meters $S_{v10}(f)$ and is expressed as (7)

$$S_{v10}(f) = \frac{4C_T}{f}\ \bar{V}_{10}^2\ \frac{x^2}{(1+x^2)^{4/3}} \quad \ldots\ldots (3.6)$$

where $$x = \frac{1200\ f}{\bar{V}_{10}} \qquad \text{. . . . . (3.7)}$$

C_T = Terrain coefficient, depending upon the type of terrain, as shown in Table 2.2

$\bar{V}_{10}$ = Mean wind velocity at reference height in m/s.

The root mean square value of the dynamic response at height z in the direction of wind in the ith mode is given by multipling the response obtained by generalised mode shape of the structure by the r.m.s. modal coefficient, defined as(7)

$$\sqrt{\bar{a}^2} = \frac{1}{N_i}\left[\frac{\sum_0^H \rho.C_D(z).A(z).\bar{V}(z)\ \phi_i(z)}{m_{ei}\ w_i^2}\right] \times$$

$$\left[3C_T B.\bar{V}_{10}^2 + \frac{\pi^2\ \bar{V}_{10}\ S_{v10}(f_i)}{7H\ \delta_i}\right]^{1/2} \qquad \text{. . . . . (3.8)}$$

where $$m_{ei} = \frac{1}{N_i}\int_0^H m(z)\ \phi_i^2\ (z)\ dz$$

$w_i = 2\ \pi\ f_i$

$N_i = \int_0^H \phi^2{}_i\ (z)\ dz.$

$S_{v10}(f_i)$ = Spectrum of horizontal gustiness at frequency f_i at reference height of 10 m

δ_i = Logarithmic decrement for ith mode

B = Background turbulence factor, depends upon type of terrain (Fig.4.1)

The probable maximum deflection in the ith mode may be obtained by multiplying the r.m.s. value of response by a factor g_i known as peak factor, which is defined by Davenport (7) as.

$$g_i = \sqrt{2 \, Log_e \, (f_i \, \bar{t})} + \frac{0.57}{\sqrt{2 \, Log_e \, (f_i . \bar{t})}} \quad . . . (3.9)$$

where $\bar{t}$ is the average period, generally taken as 3600 secs, of the largest response suffered by a structure in its life time.

Thus along wind response according to Davenport (7) can be obtained by multiplying the response obtained by generalised mode shape to the peak facter, and r.m.s. modal coefficient ($\sqrt{\bar{a}^2}$) fpr each mode seperately and then superimposing them.

3.5. ACROSS WIND RESPONSE :- Across wind response or the response of the structure perpendicular to the direction of wind has been determined by two approaches given by W.S. Rumman (32) and B' J. Vickery (40). These two approaches are summerised below.

3.5.1. RUMMAN'S APPROACH :- The across wind response will be due to vortex shedding in the down stream face of the chimney. It has maximum value when resonance will take place, that is when the shedding frequency of vortices coincides with the natural frequency of the structure. The forcing function on the chimney representing the lateral forces due to vortex shedding is modelled as.

$$F(z,t) = \frac{1}{2}\rho C_l \bar{V}^2(z).\ D(z).\ \sin\left[2\pi\ f_s(z + \Psi\ (z))\right] \quad .. \ (3.10)$$

where C_l is lift coefficient, $\Psi(z)$ is a random angle uniformly distributed between 0 and 2π whose use will produce lateral sinusoidal forces at different levels that will be randomly out of phase, and $f_s(z)$ is the shedding frequency (cycles/sec) at any level z, determined from the Strouhal number relationship, as follows.

$$f_s(z) = \frac{\bar{V}(z)}{D(z)}\ \bar{S}. \quad \ldots\ldots\ldots\ldots \ (3.11)$$

Rumman analysed many chimneys using above procedure, taking seven runs for various values of Ψ (z) in each case. Figure 3.2 shows the average response as well as the average plus one standard deviation of seven analyses for first and second mode responses. It is to be noted that the peak of the first mode would take place when the wind profile is such that this shedding frequency (f_s) at about 2/3rd of the height from the base coincides with the first mode frequency of the chimney. The first peak of second mode response would take place when the wind profile is such that the shedding frequency near the top coincides with the second mode frequency of the chimney, whereas the second peak would occur when the wind profile creates a shedding frequency at about mid height that coincides with the second mode frequency of the chimney.

For estimating the forces due to first mode response the Strouhal number may be taken as 0.20. The modal multiplier q_1 for the average plus one standard deviation response can be obtain as follows.

$$q_1 = \frac{\rho_a}{16\,\pi^2\,S^2}\;\frac{C_1}{\beta^{2/3}} \times 2.20 \times \frac{D_c^3\;\phi_c\,(z_2 - z_1)}{\int_0^H m(z)\;\phi_1^2(z)\,dz} \qquad \ldots\ldots (3.12)$$

where ρ_a = mass density of air

C_1 = Lift coefficient

S = Strouhal number (usually taken as 0.20)

β = Fraction of critical damping (usually taken as 0.02)

$(z_2=z_1)$ = Resonant Zone.

Resonant zone $(z_2 - z_1)$ as shown in figure 3.3. can be obtained as follows.

$$(z_2-z_1) = \frac{0.15\,D_c}{\text{Taper}} \qquad \ldots\ldots\ldots\ldots\ldots (3.13)$$

where Taper is change of diameter per unit height

This value of resonant zone should not to exceed $3D_c$ or 175ft(53.3m). The maximum value of the modal multiplier q_1 would occur when the value of $D_c^4\,\phi_c$ is maximum. In case z_2 exceeds H, locate D_c so that z_2 is equal to H. The mean wind speed at critical height from the base is obtained as follows.

$$\bar{V}_c = \frac{1}{T_1} \cdot \frac{D_c}{S} \qquad \ldots\ldots\ldots\ldots\ldots (3.14)$$

and the reference mean wind speed at reference height of 10m from ground would be

$$\bar{V}_{ref} = \left(\frac{Z_{ref}}{Z_c}\right)^{\alpha} \bar{V}_c \quad \ldots\ldots\ldots\ldots (3.15)$$

The modal multiplier for second mode response q_2, can be approximated by the following expression (31).

$$q_2 = 3.08 . \frac{\rho a}{16\pi^2 S^2} : \frac{C_1}{\beta^{2/3}} . \frac{D_c^3 \, \phi_c \, (z_2 - z_1)}{\int_0^H m(z) . \phi_2^2(z) . dz} \quad \ldots . (3.16)$$

First peak of the second mode across wind response would probably occur at z_2=H, thus in this case

$$(z_2 - z_1) = \frac{0.15 \; D_o}{0.925 \times \text{Taper}} \quad \ldots\ldots\ldots (3.17)$$

where D_o is diameter at the top of the chimney. This resomant zone value should not exceed $3D_c$ or 175 ft(53.3 m)

The critical diameter for second mode will be at on elevation of $H-0.5(z_2-z_1)$ and can be obtained arithmatically as

$$D_c = D_o + \frac{3D_c}{2} \times \text{Taper} \quad \ldots\ldots\ldots\ldots (3.18)$$

The critical wind speed of the second mode can also be obtained by using the equation

$$\bar{V}_c = \frac{1}{T_2} . \frac{D_c}{S} \quad \ldots\ldots\ldots\ldots (3.19)$$

The value of time period for first mode of vibration T_1 can be obtained approximately by the equation as follows

$$T_1 = 0.0025 \times \frac{H^2}{D_o} \sqrt{\frac{\rho}{E}} \left(\frac{t_o}{t_H}\right)^{0.22} \left(\frac{D_o}{D_H}\right)^{1.1} \quad \ldots\ldots (3.20)$$

where t_o and t_H is thickness of shell at the top and base of chimney respectively. D_o and D_H is the other diameter of the chimney at the top and base respectively.

Similarily the time period for second mode of vibration can also be obtained approximately as

$$T_2 = 4.1 \times 10^{-4} \times \frac{H^2}{D_o} \sqrt{\frac{\rho}{E}} \left(\frac{t_o}{t_H}\right)^{0.009} \left(\frac{D_o}{D_H}\right)^{0.78} \quad \ldots (3.21)$$

The lift coefficient, C_1, to be used for the across wind response has been found to vary with the aspect ratio. The formulas given below can be uses for the lift coefficient.

$$C_1 = 0.67 \qquad \text{for} \frac{H}{D'} > 20 \quad \ldots\ldots\ldots (3.22\ a)$$

$$C_1 = 0.67 - 0.005 \left(20 - \frac{H}{D'}\right)^{1.45} \quad \text{for} \ \frac{H}{D'} \leq 20 \quad \ldots (3.22b)$$

where D' = Average outside diameter over the top third of the chimney.

The second peak in second mode response generally does not occur in practice upto the wind velocity 55 m/sec., which is the permissible maximum wind speed at reference height (10m) from the ground level according to IS: 875 part (III) Draft code (19).

The first mode response can be obtained by multipling the response obtained given by the generalised mode shape by modal multiplier q_1. Generalised mode shape is the mode shape of vibration assuming top deflection as unity. Similarly second mode response can also be obtained by multipling the modal multiplier q_2 by the generalised mode shape.

3.5.2. VICKERY'S APPROACH :- The forces due to vortex shedding are considered in two uncorrelated parts, those which exist on a stationary cylinder and those which are induced by motion of the cylinder. The forces on a stationary body are modelled, primarily, as a narrow-band random force with a spectrum centered on the shedding frequency and with a band-width depending on the intensity of turbulance but those forces due to lateral velocity fluctuations are also modelled. The motion dependent forces are modelled as amplitude dependant damping forces which are negative in the vicinity of critical velocity and are dependent on turbulance and decrease in the absolute magnitude with the r.m.s. motion of the cylinder. The modal yields on expression for the tip motion of a chimney of the form.

$$a = \frac{C}{\left\{ k_s - k_a \left(1 - {}^{a}/_{a_L}\right)^2 \right\}^{1/2}} \qquad \ldots\ldots\ldots(3.23)$$

where C = A constant dependent upon the aerodynamic and structural parameters.

$K_s = m.\ \beta_s / \rho.\ D^2$, the structural mass-damping parameter

$K_a = m.\ \beta_a / \rho.\ D^2$, the aerodynamic mass damping parameter

a_L = A limiting r.m.s. tip displacement.

The equation has approximate solutions.

$$a = C/\{K_s - K_a\}^{1/2} \qquad \text{for } K_s >> K_a \ldots\ldots (3.24,a)$$

$$a = a_L\{1 - K_s/K_a\}^{1/2} \qquad \text{for } K_s << K_a \ldots\ldots (3.24,b)$$

The first solution corresponds to a forced random vibration regime with reduced structural damping while the second corresponds to a 'lock - in' regime where the amplitude is determined by the non-linear aerodynamic damping. Linking these two regimes is a 'transition' regime near $K_s = K_a$ in which the amplitude increases very rapidly with decrease in K_s and the response changes in character from a typical randam response with peak values of the order of three or four times the r.m.s. value to on almost sinusoidal response with peak values only slightly in excess of $\sqrt{2}$ times the r.m.s. value. (41)

The variation of peak factor g with the ratio of structural damping to aerodynamic damping for varying scales and intensities of turbulence is shown in Figure 3.4 (42). In the analysis, the response has been regarded as random forcing with linear positive damping at a value below that provided structurally, so in this regin the response is narrow band Gaussian and thus the value of peak facter g is taken as 4.0.

According to Vickery (42) the formulation of small taper and large taper can be simplified considering the dynamic forces as equivalent static loads varying linearly from zero at base to maximum at top as follows.

$$w\ (z) = \frac{1}{2}\, C\ \ V_m^2\ \bar{D}\ (z/H) \qquad \ldots \ldots \ldots\ (3.25)$$

When top dia to base diameter ratio, is near, 1.0 that is, small or no taper case

$$V_m\ =\ 1.1\ \ f\bar{D}\ /\ S \qquad \ldots \ldots \ldots \ldots\ (3.26)$$

$$C\ =\ 3.4\ g\ C_L\ (L/\lambda\ )^{1}\ 2\ \ x\ (1/\sqrt{\beta}). \ldots \ldots (3.27)$$

When diameter at top to diameter at base ratio θ is small, that is, large taper case

$$C\ =\ \frac{3.64\ g\ C_L}{\sqrt{\beta}}\ \left(\frac{L}{\lambda}\right)^{1/2}\ \frac{1}{(1-\ \theta)^{5/2}(1+5\ \theta)^{3/2}} \ldots (3.28)$$

$$V_m\ =\ 4\ f\ \bar{D}\ /\ [S(1\ +\ 5\ \theta)] \qquad \ldots \ldots \ldots \ldots (3.29)$$

$$\lambda =\ \ H/\bar{D} \qquad \ldots \ldots \ldots\ (3.30)$$

the values obtained by the two formulations will be equal at the limiting taper, that is,

$$\frac{w\ (z)\ \text{for}\ \theta \cong 1}{w\ (z)\ \text{for}\ \theta << 1} = 0.071\ (1 - \theta)^{5/2}\ (1+5\theta)^{7/2} = 1.0$$

or $\theta = 0.5$

Therefore, theoritically it may be concluded that the small taper case will be valid when top diameter to base diameter ratio, θ is between 0.5 and 1.0 while the large taper case will be valid when the value of θ is less than 0.5.

A) Chimneys of constant or Near Constant diameter (small or no taper)

For free standing chimneys, excited in the first or second modes the bulk of excitation is due to forces over the top one - third. Typically the response computed assuming forces over the top third only amounts to more than 90 percent of that computed assuming excitation over the complete height (42). It is therefore reasonable to neglect the variation of the wind speed with height and assume a constant speed equal to the average over the top one third. The modal coefficient will then become.

$$q = \frac{\dfrac{g\ C_L}{8\ \pi^2\ S^2} \cdot \dfrac{\rho \cdot \bar{D}^3}{m_e} \cdot \left[\dfrac{\sqrt{\pi}\ L}{2(\lambda+2)}\right]^{1/2} \phi\ (B,K)}{\left\{\dfrac{1}{H} \int_0^H \phi^2(z)\ dz\right\}^{1/2} \cdot \left\{\beta_s - K_a \cdot \rho\ \bar{D}^2 / m_e\right\}^{1/2}} \quad \ldots (3.31)$$

λ = Aspect ratio $H/\bar{D}$

$\bar{D}$ = Average diameter at top third

C_L = R.M.S. lift coefficient

S = Strouhal number

$\phi(z)$ = Mode shape

$m_e = \int m(z)\,\phi^2(z)\,dz \,/\, \int \phi^2(z)\,dz$

L = correlation length in diameters

β_s = Structural damping as a fraction of critical

K_a = Aerodynamic damping coefficient

g = A peak factor $\simeq 4.0$

$$\phi(B_s, K) = \frac{1}{\sqrt{B_s}} K^{3/2} \exp.\left\{ -\frac{1}{2} \left([1 - K^{-1}] / B_s \right)^2 \right\} . \quad (3.32)$$

B_s = A spectral Band width

$K = V/\bar{V}_c = 1.1$, that is the peak response occurs at a wind speed which is about 10 percent greater than the critical speed defined by the Strouhal number.

$\phi(B_s,K) = 1/\sqrt{B_s}$ for $K = 1$ and

$\simeq 1/\sqrt{B_s}$ for $K = 1.1$

The spactral band width B_s, depends upon the turbulence intensity of wind. Its value varies between 0.08 and 0.32 for smooth and turbulent flow respectively. The values of B_s for different turbulent intensity is given in Table 3.1

TABLE 3.1

Turbulence Intensity	Spactral Band width
0.04	0.08
0.06	0.11
0.10	0.16
0.12	0.18
0.20	0.32

(B) Chimney with taper :-

For tapered chimney the modal coefficient can be obtained as

$$q = \frac{g\ C_L\ \rho.\ D_c^4 \quad \phi_c \quad (-\pi\ L/\ 2.\ t)^{1/2}}{8\ \pi^2\ S^2\ m_e \int_0^H \phi^2(z)\ dz.\ (\beta_s - K_a.\rho.\ \bar{D}^2\ /m_e)^{1/2}} \quad . \quad (3.33)$$

where D_c = Critical Diameter

ϕ_c = Deflection (generalised) at critical height

$$t = \left\{ -\frac{d\ D(z)}{dz} + \alpha . \frac{D(z)}{z} \right\}_{z = z_c} \quad \ldots\ldots (3.34)$$

α = Power law exponent

For analysis of across wind excitation an important consideration is the assessment of the values of lift coefficient

C_L, Strouhal number, S, and correlation length L, under different Reynold's number. Various values of these coefficients have been suggested by different investigators on the basis of experimental observations. Some of the relevant values reported so far have been listed in Table 3.2

TABLE 3.2

Investigators	Values of			Range of Reynolds Number, Re
	C_L	S	L	
Vickery (40)	0.20	0.22	1.0	All the regions
Scruton (37)	0.27	0.20	-	$\leq 10^5$
Fung (13)	0.14	-	-	$> 3x10^5$
Sachs. (35)	0.2-0.33	-	-	$10^6 - 10^7$
Cincotta (5)	0.15	0.25-0.29	0.6	$3x10^6 - 2x10^7$
Schmidt (34)	0.15	0.25-0.29	0.6	$3x10^6 - 2x10^7$
Roshko (29)	-	0.27	-	$\simeq 8x10^6$
Rumman(32)	0.67	0.20	-	$H/D' \geq 20$

According to Table 3.2, it is easily seen that the values of these coefficients for circular cylinders vary with the Reynold's number. Thus in the present study, the values of coefficients C_L, S and L suggested by Vickery (40) have been adopted for the Re less than $3.5x10^6$. However, these coefficients are modified for heigher Reynold's number, on the basis of information available. For Reynold's number Re $\geq 3.5x10^6$, the r.m.s. lift coefficient has been taken as 0.15. For the Strouhal number on expression is derived on the basis of values reported by Cincotta and Schmidt and Roshko.as.

$$S = 0.25 + 0.04\ (Re-3.5x10^6)\ /\ 1.65x10^7 \quad . \ . \ . \ . \ . \ 3.35$$

The values of S given by above equation beyond $R_e = 2x10^7$ is an extropolation of the results at lower Reynold's numbers, with the assumption that it varies linearly with Re (in Range $R_e \geq 3.5x10^6$)

CHAPTER 4

ANALYSIS OF CHIMNEYS

4.1. DESCRIPTION OF CHIMNEYS ANALYSED: For comparision of acros wind response between two approaches suggested by Rumman (31) and Vickery (41) and also for the computation of along wind response by approch suggested by Devonport (7) two types of chimney have been studied. First having constant taper from top to base and second type which has constant diameter in the top half portion and constant taper in the lower half portion of the chimney. For both types of chimneys four different heights have been considered, i.e., 100 meter, 150 meter, 200 meter and 250 meters. And for each height sevendifferent chimneys having different values of top diameter to base diameter ratio have been analysed. For the first type of chimney top diameter to base diameter ratio, D_t/D_b, have been taken as 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65 And for the second type of chimneys this ratio has been taken 0.513, 0.55, 0.588, 0.625, 0.633, 0.7 and 0.738. The other dimensions of chimneys such as base diameter, top thickness and base thickness are taken on the basis of data available for few existing chimneys.

For first type or constant taper type chimney a fixed H/D_b ratio for a particular height of chimney has been adopted Usually the H/D_b ratio varies between 10 and 12 in existing chimneys. So a value of 10.0 has been adapted for 100 m. high chimneys, 10.5 for 150 m high chimneys, 11.0 for 200 m high chimneys and 11.5 for 250 m high chimneys. The top thickness of chimneys is adopted such that the top diameter to the top thickness ratio lies between 22 and 47. This ratio should not be more than so to avoid ovalling. And the base thickness ratio should not be less than the value obtained by the H/t_b ratio as given in Table 4.1 (28).

TABLE 4.1

D top/D base	D_{base} / t_{base}
0.9 to 1.0	28
0.8 to 1.0	30
0.7 to 0.8	32
0.6 to 0.7	34
0.5 to 0.6	38

The base thickness have been varied as the average diameter of the chimney changes. Because as the average diameter increases correspondingly the base moment will increase and thus for uniform stresses at the base, the base thickness has also been increased proportional to the increase in average diameter of the chimney.

For second type of chimneys, the outer diameter of the chimney in the upper half has been kept as constant. But the thickness of shell has been varied proportional to the top diameter. The outer diameter at base has been kept same as in the case of constant taper type chimney. The outer diameter at top can be obtained by taking average of top diameter and mean diameter of the constant taper type chimney. Shell thickness at top is also taken proportional to the top diameter, keeping ratio of top diameter to top thickness between 22 and 47 as in the first type of chimney. Shell thickness at mid - height is proportional to the top diameter of chimney. Shell thickness at base is proportional to sum of top diameter and the average diameter of the chimney so that the stress at base may be nearly constant as considered in the first type of chimney.

Thus dimensions of chimneys assumed considering the above criteria for both types of chimneys are shown in Tables 4.2 to 4.9.

TABLE 4.2 - 100 m HIGH FIRST TYPE CHIMNEY

D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
Top diameter D_t (m)	3.5	4.0	4.5	5.0	5.5	6.0	6.5
Base diameter D_b (meter)	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Top thickness t_t (meter)	0.16	0.16	0.18	0.18	0.18	0.20	0.20
Base thickness t_b (meter)	0.35	0.36	0.38	0.39	0.40	0.41	0.43

TABLE 4.3 - 150 m HIGH FIRST TYPE CHIMNEY

D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
Top diameter D_t (meter)	5.00	5.72	6.43	7.15	7.87	8.58	9.30
Base diameter D_b (meter)	14.30	14.30	14.30	14.30	14.30	14.30	14.30
Top thickness t_t (meter)	0.18	0.18	0.20	0.20	0.20	0.22	0.22
Base thickness t_b (meter)	0.45	0.47	0.48	0.50	0.51	0.53	0.55

TABLE 4.4 - 200 m HIGH FIRST TYPE CHIMNEY

D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
Top diameter D_t (meter)	6.37	7.28	8.19	9.10	10.01	10.92	11.83
Base diameter D_b (meter)	18.20	18.20	18.20	18.20	18.20	18.20	18.20
Top thickness t_t (meter)	0.22	0.22	0.24	0.24	0.24	0.26	0.26
Base thickness t_b (meter)	0.60	0.62	0.64	0.67	0.69	0.71	0.73

TABLE 4.5 - 250 m HIGH FIRST TYPE CHIMNEY

D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
Top diameter D_t (meter)	7.61	8.70	9.79	10.88	11.96	13.05	14.14
Base diameter D_b (meter)	21.75	21.75	21.75	21.75	21.75	21.75	21.75
Top thickness t_t (meter)	0.26	0.26	0.28	0.28	0.28	0.30	0.30
Base thickness t_b (meter)	0.72	0.75	0.77	0.80	0.83	0.85	0.88

TABLE 4.6 - 100 m HIGH IInd TYPE CHIMNEY

D_{top}/D_{base}	0.513	0.550	0.588	0.625	0.663	0.700	0.738
Top diameter D_t (meter)	5.13	5.50	5.88	6.25	6.63	7.00	7.38
Base diameter D_b (meter)	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Top thickness t_t (meter)	0.16	0.16	0.18	0.19	0.20	0.22	0.23
Mid height thickness (m)	0.18	0.19	0.21	0.22	0.23	0.25	0.26
Base thickness t_b (meter	0.35	0.36	0.38	0.39	0.40	0.41	0.43

TABLE 4.7 - 150 m HIGH SECOND TYPE CHIMNEY

D_{top}/D_{base}	0.513	0.550	0.588	0.62	0.663	0.700	0.738
Top diameter D_t (meter)	7.33	7.87	8.41	8.94	9.48	10.01	10.55
Base diameter D_b (meter)	14.30	14.30	14.30	14.30	14.30	14.30	14.30
Top thickness t_t (meter)	0.18	0.19	0.20	0.21	0.23	0.24	0.26
Mid height thickness (m)	0.20	0.21	0.23	0.24	0.26	0.27	0.29
Base thickness t_b (meter)	0.45	0.47	0.48	0.50	0.51	0.53	0.55

TABLE 4.8 - 200 m HIGH SECOND TYPE CHIMNEY

D_{top}/D_{base}	0.513	0.550	0.588	0.625	0.663	0.700	0.738
Top diameter D_t (meter)	9.34	10.01	10.70	11.38	12.07	12.74	13.43
Base diameter D_b (meter)	18.20	18.20	18.20	18.20	18.20	18.20	18.20
Top thickness t_t (meter)	0.22	0.24	0.24	0.26	0.28	0.30	0.32
Mid height thickness (m)	0.24	0.26	0.27	0.29	0.31	0.33	0.35
Base thickness t_b (meter)	0.60	0.62	0.64	0.67	0.69	0.71	0.73

TABLE 4.9 - 250 m HIGH SECOND TYPE CHIMNEY

D_{top}/D_{base}	0.513	0.550	0.588	0.625	0.663	0.700	0.738
Top diameter D_t (meter)	11.16	11.96	12.79	13.59	14.42	15.23	16.05
Base diameter D_b (meter)	21.75	21.75	21.75	21.75	21.75	21.75	21.75
Top thickness t_t (meter)	0.24	0.26	0.28	0.30	0.32	0.34	0.36
Mid height thickness (m)	0.28	0.30	0.32	0.34	0.36	0.38	0.40
Base thickness t_b (meter)	0.72	0.75	0.77	0.80	0.83	0.85	0.88

These assumed dimensions of the chimneys are also compared with the dimensions of existing chimneys. By composion with these chimneys we have seen that the dimensions assumed are within pratical limits.

4.2. NUMRICAL DATA :- The values of various material constants used in the analysis are given in Table 4.10.Grade of concrete of the chimneys is assumed as M25. The modulus of elasticity of concrete has been adopted as the short-term modulus as specified in IS:456 - 1978, which is close to the value given in CICIND Modal Code (20) as 3.0x 10^7Kn/m^2.

TABLE 4.10 - MATERIAL CONSTANTS.

Modulus of Elasticity of concrete	$E_c = 2.85 \times 10^7$ kn/m^2
Poisson's ratio of concrete	$\nu_c = 0.20$
Modulus of rigidity of concrete	$G_c = 1.1875 \times 10^7$ kn/m^2
Modulus of elasticity of steel	$E_s = 2.1 \times 10^8$ kn/m^2
Specific weight of concrete	$\gamma_c = 25$ kn/m^2
Mass density of air	$\rho = 1.208$ kg/m^3
Kinematic viscosity of air	$\nu_a = 1.5 \times 10^{-5}$ m^2/s

The value of fraction of damping to the critical is taken as 0.02 for both types of chimneys and in both the approaches of analysis. For this damping the logarithmic decrcment is taken as 0.1256. The band width of spectrum B_s is taken as 0.30 for both types of chimneys.

4.3. **TERRAIN TYPE :-** Wind is air in motion relative to the surface of the earth. The natural wind pattern is extremely complex due to the turbulence associated with any wind movement during the storms. Wind fluctuates randomly during a storm and therefore is not amenable to simple mathmatical formulation of time varying wind force for use in dynamic analysis. The turbulent wind shown variations of velocities both vertically and laterally. For the purpose structural analysis, the estimation of wind pressures on exposed surfaces is commonly done by considering the wind pattern with regard to its direction, velocity and its variation with respect to time and space.

The mean profile of wind velocity described by an empirical power law given by

$$\bar{V}(z) = \bar{V}(zo) \times (\frac{z}{z_o})^{\alpha} \ldots\ldots\ldots\ldots (4.1)$$

where $\bar{V}(z)$ and $\bar{V}$ (zo) are the mean wind velocities at height z and z_o. respectively, α is power law exponent depending upon the roughness of terrain as shown in Tables 2.1 and 2.2.

The spectrum of horizontal gustiness of wind $S_{v10}(f)$ at frequency f at the reference height of 10 meter and the spactral energy S(f)can be written as (7)

$$\int_0^{\infty} S(f) \cdot S_{v10}(f)\, df = (3\ C_T\ \bar{V}_{10}^2)\ B \ldots\ldots\ldots\ldots (4.2)$$

where C_T and B are tarrain coefficient and background factor respectively. The values of terrain coeiffieient for different terrain conditions are given in Table 2.2.(35). Back ground factor, B is a function of width and height of the structure, as shown in Figure 4.1 (35)

For the analysis of across and along wind response of chimneys, terrain type 1 (or open terrain) only has been considered. The following parameters have been adopted analysis:

Power law exponant, α = 1/7 = 0.143

Back ground turbulance factor, B = 0.65

Terrain coefficient, C_T = 0.005

Maximum permissible wind speed at the reference height = 50 m/sec.

4.4. <u>ALONG WIND RESPONSE:</u>- The along wind response of both types of chimneys is obtained by the method suggested by Davenport (7) which is already discussed earlier in section 3.4.

The along wind response, e.t., deflection at top of chimney, shear force at the base and bending moment at the base, considering the static and dynamic response, is given in Table 4.11 and 4.12.

The variation of deflection at top for first type of chimneys for all four heights and the various values of the ratio of top to base diameter is as shown in Figure 4.2 and for second type of chimney it is shown in Figure 4.3.

By the results obtained for along wind response it may be concluded that maximum bending moment at the base generally occurs at top to base diameter ratio of 0.60 for first type of chimney and the variation of bending moment with this ratio is within ± 23 percent. For second type of chimney maximum bending moment at the base occurs at top to base diameter ratio of 0.65 approximately and the variation of bending moment with this ratio is within ± 26 percent.

The value of deflection at the top of chimney to the height ratio increases with height. Maximum value of this for 250 m high first type of chimney is 1:185 and for second type of chimney is 1:80.

TABLE 4.11 - ALONG WIND RESPONSE OF FIRST TYPE CHIMNEYS

HEIGHT (meter)	D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
100	Deflection at top (m)	0.238	0.237	0.232	0.231	0.150	0.146	0.142
	Shear force at base (kn) $\times 10^{-3}$	2.80	2.97	3.15	3.33	2.31	2.39	2.54
	Bending momentaat base (kn-m)$\times 10^{-3}$	150.3	161.5	172.6	183.8	129.6	137.0	144.5
150	Deflection at top (m)	0.528	0.522	0.506	0.501	0.329	0.48	0.310
	Shear force at base (kn) $\times 10^{-3}$	6.76	7.15	7.63	8.02	5.61	8.79	6.15
	Bending moment at base (kn-m)$\times 10^{-3}$	545.2	583.8	622.2	660.8	469.6	747.8	524.3
200	Deflection at top (m)	0.887	0.880	0.858	0.837	0.821	0.801	0.520
	Shear force at base (kn) $\times 10^{-3}$	13.06	13.81	14.56	15.31	16.06	16.92	11.71
	Bending moment at base (kn-m)$\times 10^{-3}$	1387.2	1493.8	1600.3	1696.8	1793.3	1909.9	1334.3
250	Deflection at top (m)	1351	1.327	1.303	1.270	1.247	1.224	0.795
	Shear force at base (kn) $\times 10^{-3}$	20.64	21.89	23.14	24.70	25.24	26.80	18.73
	Bending moment at base (kn-m)$\times 10^{-3}$	2808.5	3000.1	3191.7	3383.3	3574.0	3765.6	2704.8

TABLE 4.12 - ALONG WIND RESPONSE OF SECOND TYPE CHIMNEYS

Height (meter)	D_{top}/D_{base}	0.513	0.550	0.588	0.625	0.663	0.700	0.738
100	Deflection at top (m)	0.467	0.282	0.247	0.344	0.211	0.193	0.185
	Shear force at base (kn) $\times10^{-3}$	2.60	1.86	1.99	3.16	2.22	2.34	2.41
	Bending moment at base (kn-m)$\times10^{-3}$	152.9	109.0	116.6	185.4	131.5	138.9	146.4
150	Deflection at top (m)	1.099	0.980	0.590	0.803	0.448	0.453	0.416
	Shear force at base (kn) $\times10^{-3}$	6.34	6.74	4.83	7.55	5.40	5.64	5.87
	Bending moment at base (kn-m)$\times10^{-3}$	553.7	592.5	424.2	669.7	478.9	501.2	523.3
200	Deflection at top (m)	1.961	1.706	1.554	0.933	1.283	0.789	0.725
	Shear force at base (kn) $\times10^{-3}$	12.14	12.92	13.71	9.70	15.28	10.70	11.26
	Bending moment at base (kn-m)$\times10^{-3}$	1414.11	1510.0	1607.4	1139.4	1811.5	1281.6	1343.2
250	Deflection at top (m)	3.01	2.67	2.360	2.166	1.986	1.219	1.131
	Shear force at base (kn) $\times10^{-3}$	19.18	20.47	21.78	22.97	24.79	17.1	17.90
	Bending moment at base (kn-m)$\times10^{-3}$	2802.4	2992.6	3186.2	3376.4	3570.0	2540.9	2702.6

4.5. ACROSS WIND RESPONSE:- For both types of chimneys have been analysed by both the approaches suggested by Rumman (30) and Vickery (41). The across wind response has also been analysed by the two formulations of Vickery (41) large taper and small taper for the chimneys having constant taper. The responses by large taper formulation are given in Table 4.13. and by small taper formulation in Table 4.14. The across wind response of this type of chimney has also been obtained by Rumman's approach (30) and is given in Table 4.15.

Across wind response of second type of chimney has been evaluated by considering small taper formulation only because the taper at top on-third height of the chimneys is zero. The responses are given in Table 4.16. Across wind response of second type of chimney has also been evaluated using Rumman's approach and is given in Table 4.17.

The variation of deflection at top for the chimney of of type-I for all cases analysed is shown in Figure 4.4. and and for type II chimney in Figure 4.5.

The variation of bending moment along the height for 200 m high type-I chimney having top diameter to base diameter ratio as 0.5 is shown in Figure 4.6 and the variation of deflection for both modes for this chimney by Rumman's approach is shown in Figure 4.7.

TABLE 4.13- ACROSS WIND RESPONSE (LARGE TAPER) FIRST TYPE CHIMNEYS VICKERY'S METHOD

Height (meter)	D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
100	Deflection at top (m)	0.12	0.13	0.14	0.16	0.19	0.220	0.270
	Shear force at base (kn) $\times 10^{-3}$	4.50	5.50	6.40	7.90	10.00	12.00	17.00
	Bending moment at base (kn-m)$\times 10^{-3}$	68.0	84.0	99.0	120.0	160.0	190.0	260.0
150	Deflection at top (m)	0.200	0.220	0.230	0.240	0.320	0.360	0.450
	Shear force at base (kn) $\times 10^{-3}$	8.00	9.90	11.00	14.00	18.00	22.00	30.00
	Bending moment at base (kn-m)$\times 10^{-3}$	190.0	230.0	270.0	340.0	430.0	540.0	730.0
200	Deflection at top (m)	0.240	0.270	0.290	0.310	0.400	0.460	0.570
	Shear force at base (kn) 10^{-3}	11.00	14.00	16.00	22.00	26.00	32.00	43.00
	Bending moment at base (kn-m)$\times 10^{-3}$	350.0	430.0	510.0	2400*	830.0	1000.0	1400.0
250	Deflection at top (m)	0.470*	0.32*	0.340	0.360*	0.510*	0.540	0.660
	Shear force at base (kn) $\times 10^{-3}$	180.0*	150.0*	19.00	260.0*	380.0*	39.0	52.0
	Bending moment at base (kn-m)$\times 10^{-3}$	2700.0*	2100.0*	780.0	3500.0*	4900*	1600	2100

(*) indicates that second mode governs)

TABLE 4.14 - ACROSS WIND RESPONSE (SMALL TAPER) FIRST TYPE CHIMNEYS VICKERY'S METHOD

Height (meter)	D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
100	Deflection at top (m)	0.091*	0.110*	0.110	0.130	0.150	0.160	0.180
	Shear force at base (kn) x10^{-3}	13.0*	21.0*	4.9	6.2	7.7	8.9	11.0
	Bending moment at base (kn-m)x10^{-3}	83*	130*	76	96	120	140	170
150	Deflection at top (m)	0.150*	0.18*	0.18	0.21	0.25	0.26	0.30
	Shear force at base (kn) x10^{-3}	23.0*	37.0*	8.8	11.0	14.0	16.0	20.0
	Bending moment at base (kn-m)x10^{-3}	230*	340*	210	270	330	390	490
200	Deflection at top (m)	0.18*	0.23*	0.23	0.26	0.30	0.33	0.38
	Shear force at base (kn) x10^{-3}	31*	51*	12	16	20	23	29
	Bending moment at base (kn-m)x10^{-3}	420*	640*	400	510	640	750	930
250	Deflection at top (m)	0.21*	0.26*	0.26	0.31	0.35	0.39	0.44
	Shear force at base (kn) x10^{-3}	37*	61*	15	19	24	28	35
	Bending moment at base (kn-m)10^{-3}	640*	970*	600	770	970	1200	1400

(*) indicates that second mode governs)

TABLE 4.15 - ACROSS WIND RESPONCE FIRST TYPE CHIMNEY RUMMAN'S METHOD

Height (meter)	D_{top}/D_{base}	0.35	0.40	0.45	0.50	0.55	0.60	0.65
100	Deflection at top (m)	0.037	0.043	0.047	0.056	0.062	0.064	0.073
	Shear force at base (kn) $\times 10^{-3}$	1.56^x	2.66^x	0.49	0.63	0.75	0.85	1.05
	Bending moment at base (kn-m)$\times 10^{-3}$	44.5^x	74.1^x	33.8	43.8	52.1	59.2	73.1
150	Deflection at top (m)	0.064	0.074	0.082	0.094	0.104	0.109	0.124
	Shear force at base (kn) $\times 10^{-3}$	3.00^x	5.24^x	7.98^x	1.19	1.41	1.62	2.00
	Bending moment at base (kn-m)$\times 10^{-3}$	128.8^x	218.5^x	325.2^x	122.2	145.6	167.9	207.2
200	Deflection at top (m)	0.081	0.095	0.107	0.119^x	0.130	0.139	0.158
	Shear force at base (kn) $\times 10^{-3}$	4.48^x	7.77^x	12.16^x	17.4^x	2.06	2.38	2.92
	Bending moment at base (kn-m)$\times 10^{-3}$	255.0^x	432.1^x	660.1^x	922.4^x	280	325.6	399.0
250	Deflection at top (m)	0.098	0.133	0.124	0.142^x	0.169^x	0.164	0.187
	Shear force at base (kn) $\times 10^{-3}$	5.67^x	9.91^x	14.93^x	21.56^x	29.54^x	2.95	3.64
	Bending moment at base (kn-m)$\times 10^{-3}$	404.2^x	688.4^x	1013^x	1427^x	1913^x	503.6	621.5

(x) indicates that second mode governs)

t TABLE 4.16 - ACROSS WIND RESPONCE SECOND TYPE CHIMNEY VICKERY'S METHOD

Height (meter	D_{top}/D_{base}	0.513	0.550	0.588	0.625	0.663	0.700	0.738
100	Deflection at to (m)	0.13	0.15	0.15	0.17	0.18	0.19	0.20
	Shear force at base (kn) $\times 10^{-3}$	2.2	3.0	3.8	4.9	6.1	7.3	9.0
	Bending moment at base (kn-m)$\times 10^{-3}$	38	52	66	83	100	120	150
150	Deflection at to (m)	0.23	0.25	0.27	0.30	0.31	0.34	0.35
	Shear force at base (kn) $\times 10^{-3}$	3.8	5.1	6.8	8.7	11.0	13.0	16.0
	Bending moment at base (kn-m)$\times 10^{-3}$	100	140	180	230	280	350	410
200	Deflection at to (m)	0.29	0.31	0.36	0.38	0.40	0.43	0.45
	Shear force at base (kn) $\times 10^{-3}$	5.2	6.8	9.4	12.0	15.0	18.0	22.0
	Bending moment at base (kn-m)$\times 10^{-3}$	190	250	340	430	530	640	780
250	Deflection at to (m)	0.36	0.39	0.42	0.45	0.48	0.52	0.55
	Shear force at base (kn) $\times 10^{-3}$	6.5	8.7	11	14	18	22	27
	Bending moment at base (kn.m)$\times 10^{-3}$	300	400	520	650	820	1000	1200

TABLE 4.17 - ACROSS WIND RESPONCE SECOND TYPE CHIMNEY RUMMAN'S METHOD

Height (meter)	D_{top}/D_{base}	0.513	0.550	0.588	0.625	0.663	0.700	0.738
100[α]	Deflection at top (m)	0.036	0.042[x]	0.044	0.052	0.059	0.064	0.071
	Shear force at base (km) $\times 10^{-3}$	0.32	0.45	0.61	0.80	1.04	1.31	1.69
	Bending moment at base (kn-m)$\times 10^{-3}$	21.2	29.0	37.2	47.5	60.2	72.9	91.4
150[α]	Deflection at top (m)	0.094	0.108	0.119[x]	0.135	0.148	0.167	0.180
	Shear force at base (km) $\times 10^{-3}$	2.97	4.12	5.38	7.42	9.47	12.25	15.29
	Bending moment at base (kn-m)$\times 10^{-3}$	196.7	264.9	345.9	447.2	551.7	694.4	840.5
200	Deflection at top (m)	0.163	.178	0.206	0.219	0.237	.244	0.257
	Shear force at base (km) $\times 10^{-3}$	13.3	17.8	24.6[x]	1.69	2.11	2.57	3.10
	Bending moment at base (kn-m)$\times 10^{-3}$	882.2	1149.7	1541[x]	252.9	313.5	379.9	457.4
250	Deflection at top (m)	0.244	0.264	0.284	0.303	0.324	0.344	0.365
	Shear force at base (km) $\times 10^{-3}$	2.18	2.88	3.75	4.74	5.95	7.26	8.83
	Bending moment at base (kn-m)$\times 10^{-3}$	329.3	434.2	560.8	706.7	883.1	1074	1301

(α) indicates that second mode goverens fot all taper in case of shear and moments

(x) indicates that second mode governs for cases before this

CHAPTER 5

DISCUSSION OF RESULTS

5.1 COMPARISION OF ACROSS WIND RESPONSE ANALYSED BY LARGE AND SMALL TAPER FORMULATIONS SUGGESTED BY VICKERY:-

Comparision between across wind response analysed by using large taper formulation and small taper (including no taper) formulation suggested by Vickery for all four heights for first type of chimney is given in Table 5.1.

At the first instance the approximate criterion given by Vickery to distinguish between the small and large taper formulations has been checked. Thus the creterion of minimum percentage difference between the first mode shear forces at the base of chimney obtained by the two formulations have been adopted. These demarkating cases have been marked by astric (*) in the Table 5.1.

It is observed from Table 5.1 that the distinction between the small and large taper analysis occurs in all the cases at D_t/D_b ratio (θ) of 0.50. Hence the approximate result given by Vickery and Basu (42) is seen to hold for all the cases investigated.

Further, this criterion has been applied to base bending moments also since the design of chimney directly depends on the bending moments. In this case also demarkating cases have been marked by astric (*) in the Table 5.1

TABLE 5.1 COMPARISION BETWEEN SMALL AND LARGE TAPER RESPONSE IN THE FIRST MODE

Height of Chimney (m)	Top dia. to base dia ratio	Base Shear Small taper (kn)x10^{-3}	Base Shear large taper (kn)x10^{-3}	Base B.M. small taper (kn-m)x10^{-3}	Base B.M. large taper (Kn-m)x10^{-3}
100	0.35	3.1	4.5	47	68
	0.40	4.0	5.5	62	84
	0.45	4.9	6.4	76	99
	0.50	6.2^x	7.9^x	96^x	120^x
	0.55	7.7	10.0	120	160
	0.60	8.9	12.0	140	190
	0.65	11.0	17.0	170	260
150	0.35	5.5	8.0	130	190
	0.40	7.3	9.9	170	230
	0.45	8.8	11	210	270
	0.50	11^x	14^x	270^x	340^x
	0.55	14	18	330	430
	0.60	16	22	390	540
	0.65	20	30	490	730
200	0.35	7.7	11	240	350
	0. 40	10	14	320	430
	0.45	12	16	400	510
	0.50	16^x	22^x	510^x	650^x
	0.55	20	26	640	830
	0.60	23	32	750	1000
	0.65	29	43	930	1400
250	0.35	9.1	13	370	530
	0.40	12	16	490	650
	0.45	15	19	600	780
	0.50	19^x	24^x	770^x	990^x
	0.55	24	31	970	1300
	0.60	28	39	1200	1600
	0.65	35	52	1400	2100

(x) indicates demarkation for applicability between small and large taper formulations.

However, the results obtained is same as for the shear force criterion, as is evident from Table 5.1.

5.2. COMPARISION BETWEEN ACROSS WIND RESPONSE BY TWO APPROACHES:-

Comparision between across wind response of the chimneys analysed by using two different approaches suggested by Rumman and Vickery for both first and second type chimneys is shown in Tables 5.2 and 5.3 respectively.

MOMENT RESPONSE:- In some of the cases the second mode is also excited by the wind velocities within the design limit of wind velocity of 50 m/s, at reference height of 10 m. This is not true for both the methods since in most of the instances (all except large tapered 250 m high chimneys) of first type chimney (tapered throughout) and all cases of second type of chimney (constant diameter in upper half portion) where the second mode was excited in the Rumman's method, it could not be excited in the Vickery's method.

The first mode response values of Vickery are persistently larger except for the 250 m high second type of chimney.

Rumman's method gives larger values in second type of chimneys compared to first type chimney except for the 100 m high chimney. However, the Vickery's method gives smaller values in second type of chimneys compared to first type except if the second mode is excited.

TABLE 5.2 COMPARISION OF ACROSS WIND RESPONSES BETWEEN RUMMAN'S AND VICKERY'S APPROACH FIRST TYPE CHIMNEYS

Height of Chimney (meter)	Top dia to base dia ratio	Top Deflection Rumman's (meter)	Top Deflection Vickery's (meter)	Base Bending moment Rumman's (kn-m)x10^{-3}	Base Bending moment Vickery's (kn-m)x10^{-3}
100	0.35	0.037	0.12	44.46^{x}	68
	0.40	0.043	0.13	74.05^{x}	84
	0.45	0.047	0.14	33.82	99
	0.50	0.056	0.16	43.79	120
	0.55	0.062	0.15	52.06	120
	0.60	0.064	0.16	59.19	140
	0.65	0.073	0.18	73.10	170
150	0.35	0.064	0.20	128.8^{x}	190
	0.40	0.074	0.22	218.5^{x}	230
	0.45	0.082	0.23	325.2^{x}	270
	0.50	0.094	0.24	122.2	340
	0.55	0.104	0.25	145.6	330
	0.60	0.109	0.26	167.9	390
	0.65	0.124	0.30	207.2	490
200	0.35	0.081	0.24	255.9^{x}	350
	0.40	0.095	0.27	432.1^{x}	430
	0.45	0.107	0.29	660.1^{x}	510
	0.05	0.119^{x}	0.31	922.4^{x}	650
	0.55	0.130	0.30	280	640
	0.60	0.139	0.33	32.56	750
	0.65	0.158	0.38	399.9	930
250	0.35	0.098	0.47	404.2^{x}	2700^{x}
	0.40	0.113	0.32	688.4^{x}	2100^{x}
	0.45	0.124	0.34	1013^{x}	780
	0.50	0.142^{x}	0.36	1427.7^{x}	3500^{x}
	0.55	0.170^{x}	0.35	1912.8^{x}	970
	0.60	0.165	0.39	503.6	1200
	0.65	0.188	0.44	621.5	1400

(x) indicates second mode values, since it governs these responses.

TABLE 5.3 COMPARISION OF ACROSS WIND RESPONSES BETWEEN RUMMAN'S AND VICKERY'S APPROACH SECOND TYPE CHIMNEYS

Height of Chimney (meter)	Top dia to base dia ratio	Top Deflection Rumman's (meter)	Top Deflection Vickery's (meter)	Base Bending moment Rumman's (kn-m)x10^{-3}	Base Bending moment Vickery's (kn-m)x10^{-3}
100^{α}	0.513	0.036	0.13	21.18	38
	0.550	0.042	0.15	29	52
	0.588	0.045	0.15	37.15	66
	0.625	0.052	0.17	47.47	83
	0.663	0.059	0.18	60.21	100
	0.700	0.064	0.19	72.90	120
	0.738	0.071	0.20	91.40	150
150^{α}	0.513	0.094	0.23	196.7	100
	0.550	0.108	0.25	264.9	140
	0.588	0.119	0.27	345.9	180
	0.625	0.135	0.30	447.2	230
	0.663	0.148	0.31	551.7	280
	0.700	0.167	0.34	694.4	350
	0.738	0.180	0.35	840.5	410
200	0.513	0.163	0.29	882.2^{x}	190
	0.550	0.178	0.31	1149.7^{x}	250
	0.588	0.206	0.36	1541^{x}	340
	0.625	0.219	0.38	252.9	430
	0.663	0.232	0.40	313.5	530
	0.700	0.244	0.43	379.9	640
	0.738	0.257	0.45	457.4	780
250	0.513	0.244	0.36	329.3	300
	0.550	0.264	0.39	434.2	400
	0.588	0.284	0.42	560.8	520
	0.625	0.303	0.45	706.7	650
	0.663	0.324	0.48	883.1	820
	0.700	0.344	0.52	1074	1000
	0.728	0.365	0.55	1301	1200

(α) indicates that second mode governs in the case of all tapers for base bending moment in Rumman's approach.

(x) indicates that second mode governs .

DEFLECTION RESPONSE:- Maximum deflection at the top of chimney to height ratio for first type of chimneys is 1:500 in Vickery method and 1:1200 in Rumman's method. For second type of chimney this ratio in the two methods is 1:400 and 1:660 respectively.

The difference in the responses obtained by these two approaches are due to following reasons.

1. In Rumman's method for obtaining modal multiplier two third power of the total damping in denominator is used but in Vickery's method square root of the total damping in denominator is used. This will give rise to larger response (nearly twice for same damping) in the Rumman's method.

2. In all cases, in the Vickery's method a peak factor of 4.0 has been used (for Gaussian random type vibrations) against probably smaller values of the modal peak factors used by Rumman, since his formulation is based on random generation of the phase angle of the exciting forces so that the peak factor is implicit in the reasons.

3. The resonant height in the Vickery's method is fixed as the top one-third in case of chimneys with small taper while the resonant zone is generally 18 to 20 percent of the chimney height in Rumman's method and for the case of 250 m high second type chimney, this value is 17 percent. This factor would yield Rumman's values about 60 percent of those given by Vickery.

4. The taper of the chimney is under square root in Vickery's method in the denominator while it is to the power 1.0 in Rumman's

method. Also in the formar it is defined as $(t + \alpha . z/H)$ where t is the taper (dD/dz) as defined by Rumman. This would cause larger response in Rumman's method.

5. The constants, which include the dynamic lift coefficient C_L, however, are 0.035 and 0.186 in the two methods, giving response ratio due to this constant as 0.19, that is only 19 percent response in Rumman's method compared to Vickery.

5.3 COMPARISION OF ALONG AND ACROSS WIND RESPONSE:- The along wind response for all type of chimneys are evaluated by Davanport approach (7) and the across wind response for all types of chimneys are evaluated by Vickery's approach. The comparision between both results are shown in Table 5.4 for first type of chimneys, and in Table 5.5 for second type of chimneys.

Moment Response:- The along wind response is invariably higher than the across wind response except for the 100 m high chimneys of both types having the smallest taper considered.

The along wind response can be as large as four times the across wind response for first type chimneys and reaches a factor of 10 for second type chimneys. The difference however decreases as the taper decreases.

Deflection Response :- The behaviour of deflections at the top of chimney is similar to the base moments described above.

TABLE 5.4 COMPARISION BETWEEN ALONG AND ACROSS WIND RESPONSES BY DAVENPORT'S AND VICKERY'S APPROACHES FIRST TYPE CHIMNEYS.

Height of Chimney (meter)	Top dia to base dia ratio	Top Deflection Aong wind (meter)	Top Deflection Across wind (meter)	Base bending moment Along wind (kn-m)x10^{-3}	Base bending moment Across wind (kn-m)x10^{-3}
100	0.35	0.238	0.12	150.4	68
	0.40	0.237	0.13	161.5	84
	0.45	0.232	0.14	172.6	99
	0.50	0.231	0.16	183.8	120
	0.55	0.15	0.15	129.6	120
	0.60	0.146	0.16	137	140
	0.65	0.142	0.18	144.5	170
150	0.35	0.528	0.20	545.2	190
	0.40	0.522	0.22	583.8	230
	0.45	0.506	0.23	622.2	270
	0.50	0.501	0.24	660.8	340
	0.55	0.329	0.25	469.6	330
	0.60	0.48	0.26	747.8	390
	0.65	0.31	0.30	524.3	490
200	0.35	0.887	0.24	1387.2	350
	0.40	0.88	0.27	1493.7	430
	0.45	0.858	0.29	1600.3	510
	0.50	0.837	0.31	1696.8	650
	0.55	0.821	0.30	1793.3	640
	0.60	0.801	0.33	1909.9	750
	0.65	0.52	0.38	1334.3	930
250	0.35	1.351	0.47	2808.5	2700[x]
	0.40	1.327	0.32	3000.1	2100[x]
	0.45	1.303	0.34	3191.7	780
	0.50	1.27	0.36	3383.3	3500[x]
	0.55	1.247	0.35	3574	970
	0.60	1.224	0.39	3765.6	1200
	0.65	0.79.5	0.44	2704.8	1400

(x) indicates second mode values , since it governs these responses.

TABLE 5.5 COMPARISION BETWEEN ALONG AND ACROSS WIND RESPONSES BY DAVENPORT'S AND VICKERY'S APPROACHES SECOND TYPE CHIMNEYS.

Height of Chimney (meter)	Top dia to base dia ratio	Top Deflection Aong wind (meter)	Top Deflection Across wind (meter)	Base bending moment Along wind (kn-m)x10^{-3}	Basebending moment Acrosswind (kn-m)x10^{-3}
100	0.513	0.467	0.13	153	38
	0.550	0.282	0.15	109	52
	0.588	0.247	0.15	116.6	66
	0.625	0.342	0.17	185.4	83
	0.663	0.211	0.18	131.5	100
	0.700	0.193	0.19	138.9	120
	0.738	0.185	0.20	146.4	150
150	0.513	1.099	0.23	553.8	100
	0.550	0.98	0.25	592.5	140
	0.588	0.59	0.27	424.2	180
	0.625	0.803	0.30	669.7	230
	0.663	0.488	0.31	478.9	280
	0.70	0.453	0.34	501.2	350
	0.738	0.416	0.35	523.3	410
200	0.513	1.961	0.29	1414.1	190
	0.550	0.706	0.31	1510	250
	0.588	1.554	0.36	1607.4	340
	0.625	0.933	0.38	1139.4	430
	0.663	1.283	0.40	1811.4	530
	0.700	0.789	0.43	1281.6	640
	0.738	0.725	0.45	1343.2	780
250	0.513	3.01	0.36	2802.4	300
	0.550	2.67	0.39	2992.6	400
	0.588	2.36	0.42	3186.2	520
	0.625	2.166	0.45	3376.4	650
	0.700	1.219	0.52	2540.9	1000
	0.663	1.986	0.48	3570	820
	0.738	1.131	0.55	2702.6	1200

CHAPTER 6

6.1. CONCLUSIONS :- Responses have been obtained for two type of chimneys having four different heights 100 m, 150 m, 200m. and 250 m. and for different top diameter to base diameter ratio. Across wind response has been analysed by the methods suggested by Rumman and Vickery (considering both small and large taper formulations).

Based on the results and discussion presented in the previous chapters the following conclusions about the dynamic response of chimneys can be drawn.

1. Along wind response is seen to be more than the across wind response, except for the 100 m high chimney having the smallest taper.

2. Maximum along wind response occurs for the top diameter to base diameter ratio D_t/D_b between 0.6 and 0.66.

3. The along wind deflection can be as small as 1/700 of height for the 100 m high chimney having contineous taper and can be as large as 1/80 of height for the 250 m high chimney having constant diameter in top half region. The maximum across wind deflection at top to height of chimney ratio are 1/500 and 1/400 respectively obtained by Vickery's method.

4. Across-wind bending momentresponse at the base may be governed by the second mode of vibration, which depends upon the method of analysis also. Since the critical velocity is

different in the different methods and may not be attained in one while coming with the design wind speed in the other.

5. The distinction between the expressions given by Vickery for across - wind response for small and large taper with respect to base bending moment as well as base shear using the 'exact' expressions is found to lie at top to base diameter ratio of 0.50.

6. Vickery's method gives larger across - wind response compared to Rumman (Comparing respective modes) except for the 250 m tall chimney.

7. Chimneys with constant diameter in the top half portion shows larger base bending moments compared to the chimneys of contineous taper by the Rumman's method while reverse is true in Vickery's method.

6.2. SCOPE FOR FUTURE WORK:- In the present dissertation, the theoritical results have been evaluated by using the formulations given by various investigators. ~~Though~~ These results should also be ~~obtained~~ verified by ~~studying for~~ observations on prototype in field and on models in the wind tunnel and should be compared with the theoritical results. The role of damping and lift coefficient should also be studied on the across wind response of the chimney.

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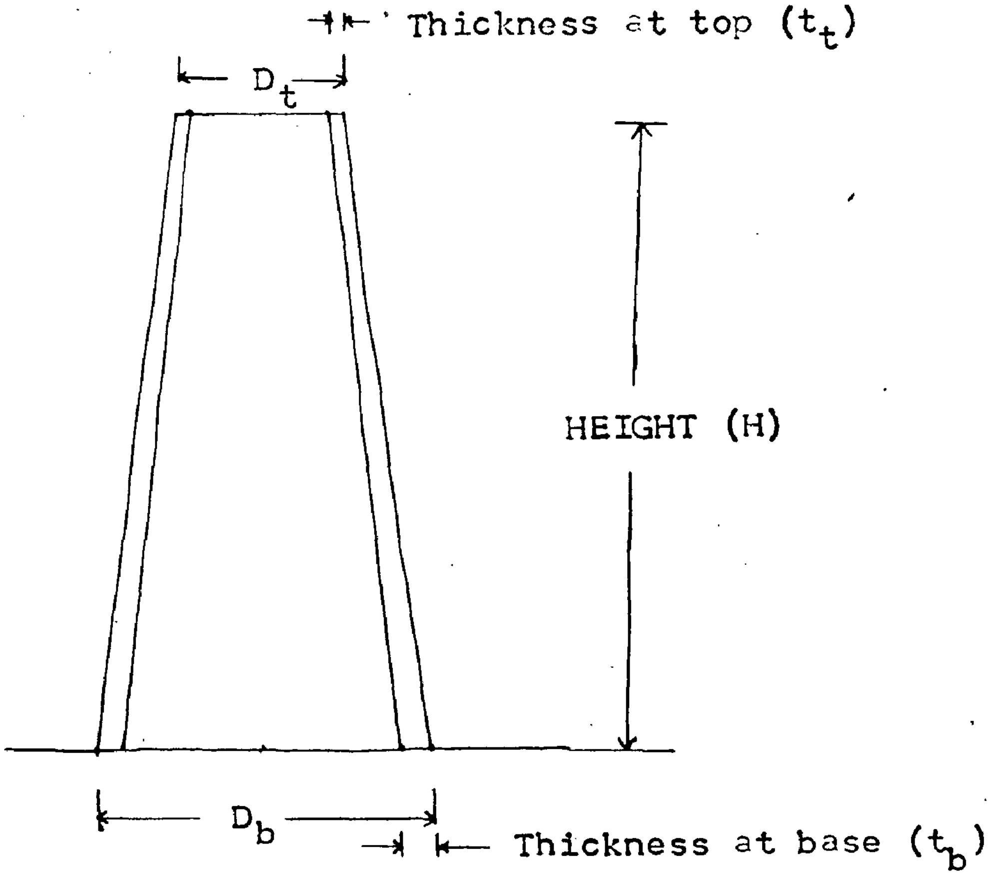
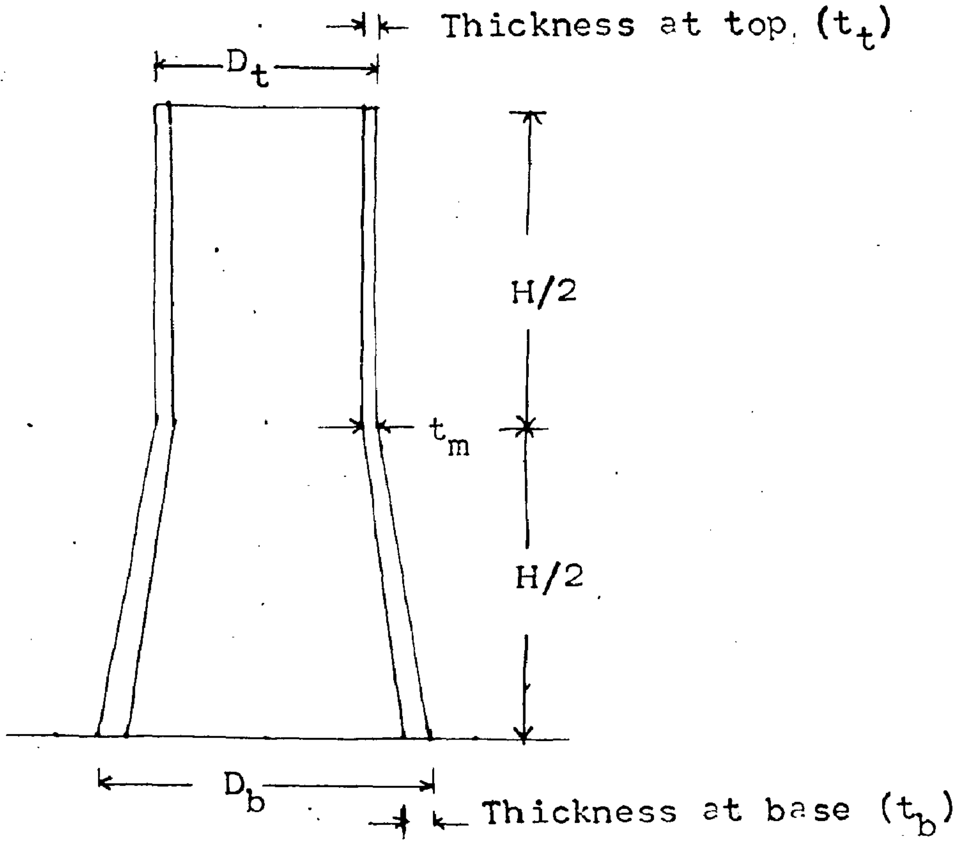


FIRST TYPE CHIMNEY



SECOND TYPE CHIMNEY

FIG. 2.1 VARIOUS TYPES OF CHIMNEY

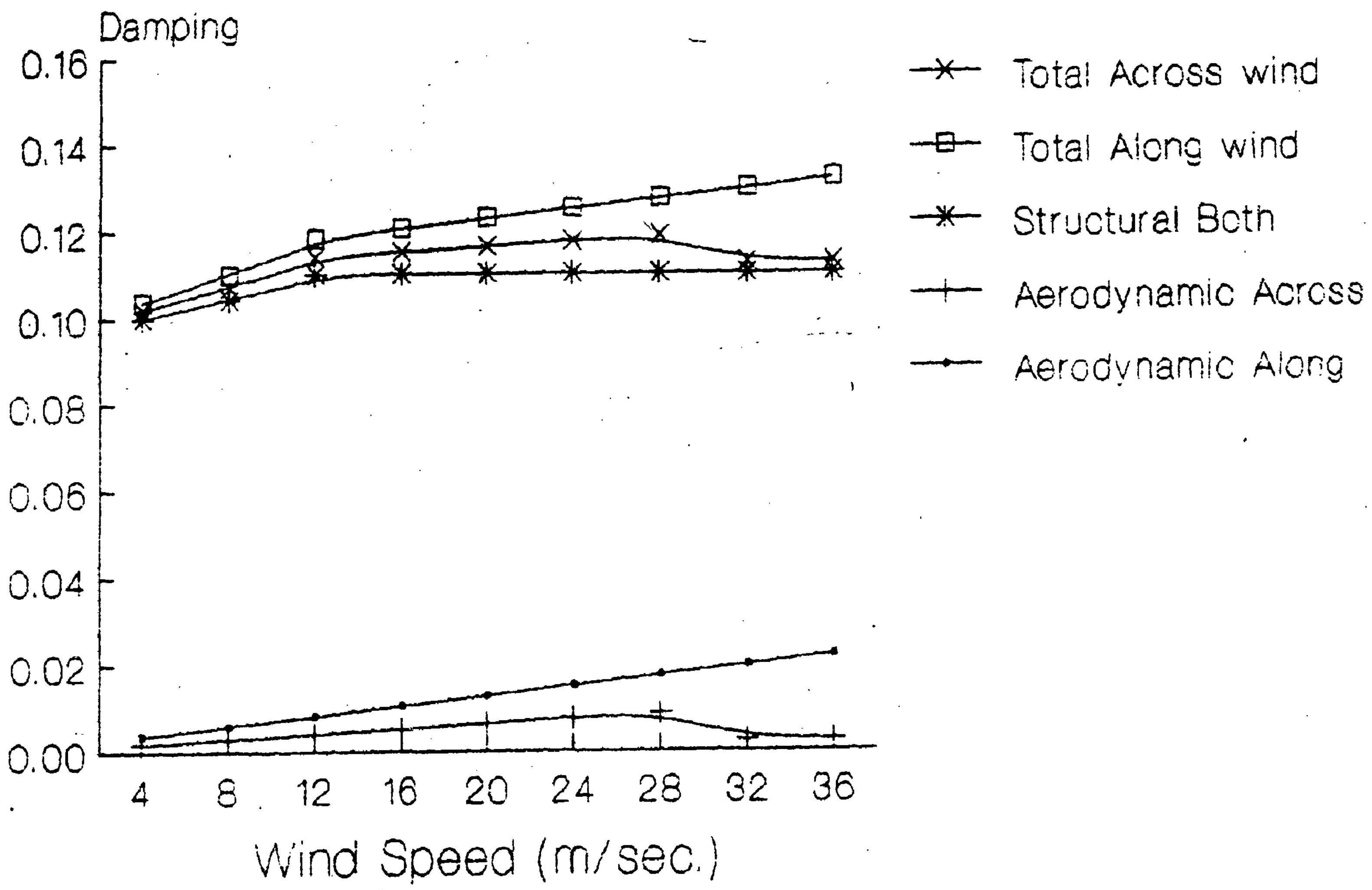


Fig 3.1 Variation of damping With wind speed

Fig. 3.2 ACROSS WIND RESPONSE BY RUMMAN'S APPROACH

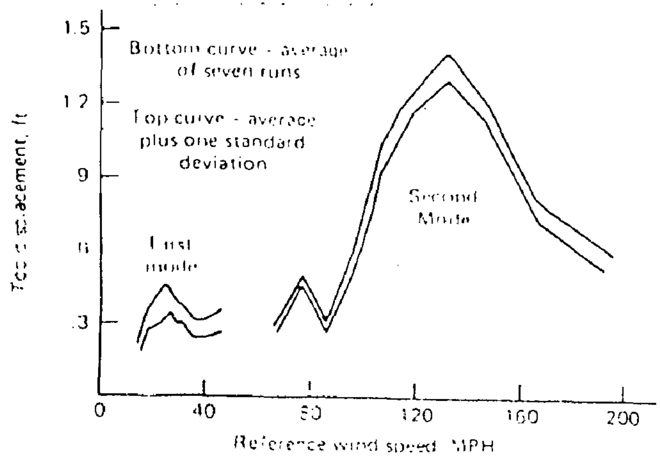


Fig. 3.3 SYMBOLS FOR ACROSS WIND ANALYSIS BY RUMMAN'S APPROACH

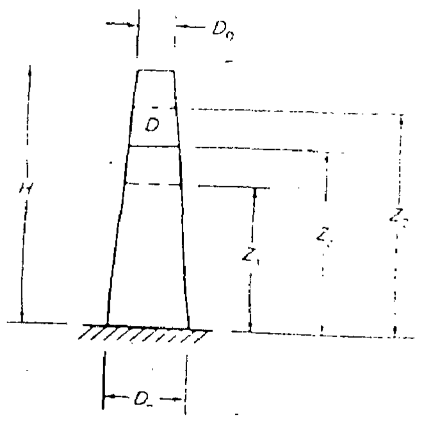
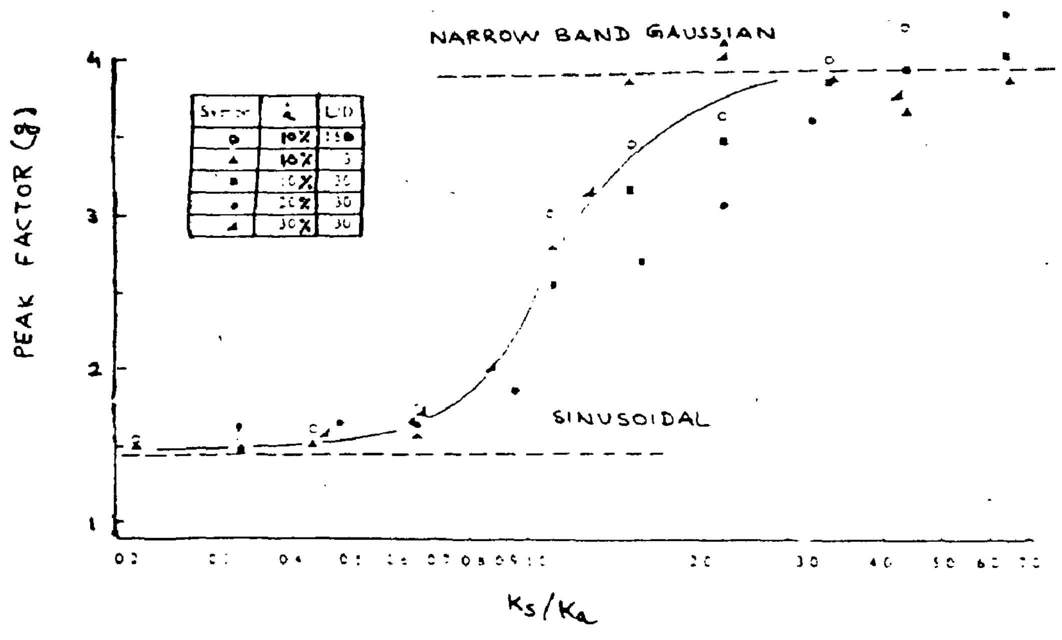


Fig. 3.4 VARIATION OF PEAK FACTOR WITH K_s/K_a



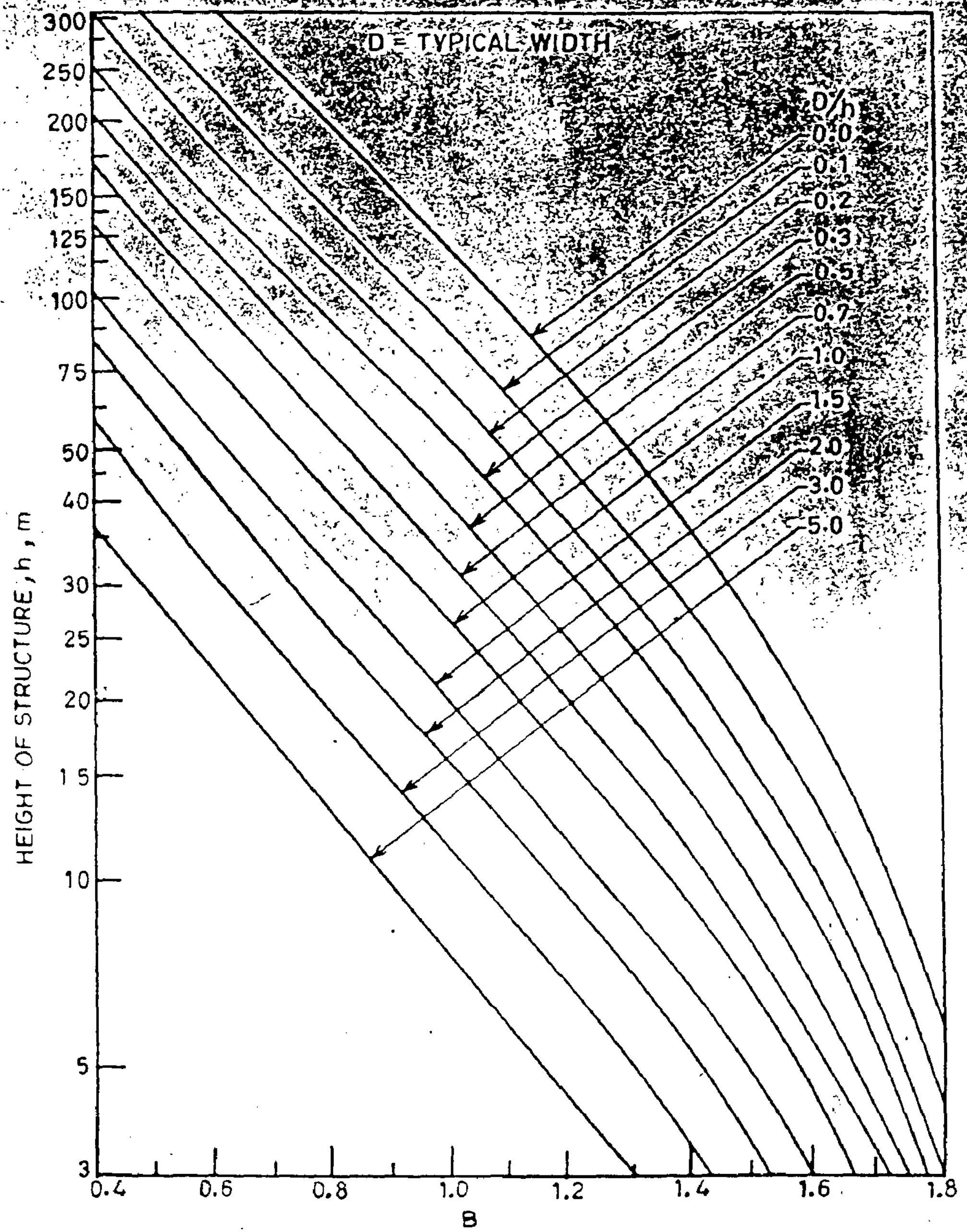


Fig 4.1 Background turbulence factor

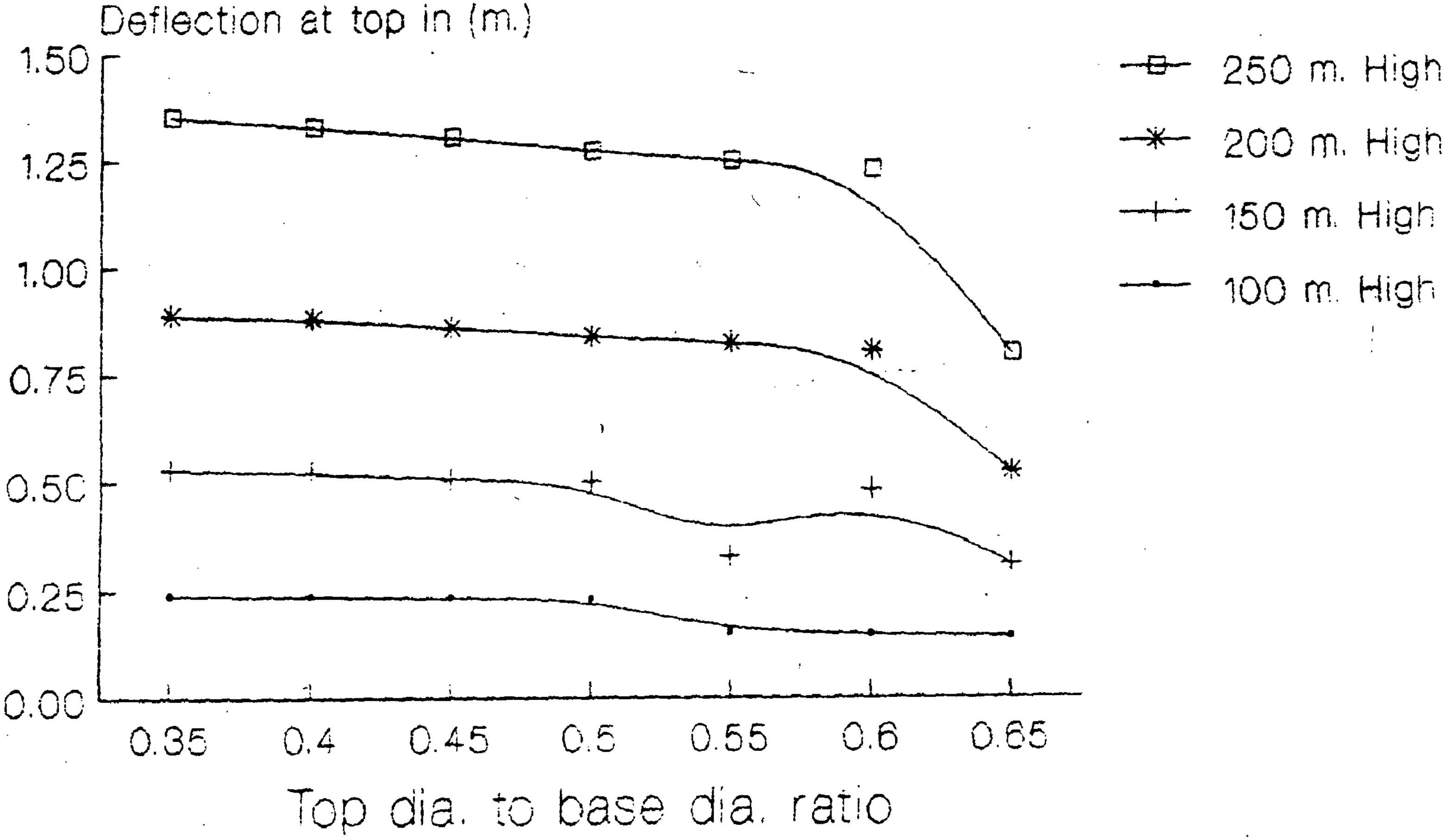


Fig. 4.2 Variation of deflection at top
First type of chimney (Along Wind)
Vickery's Approach

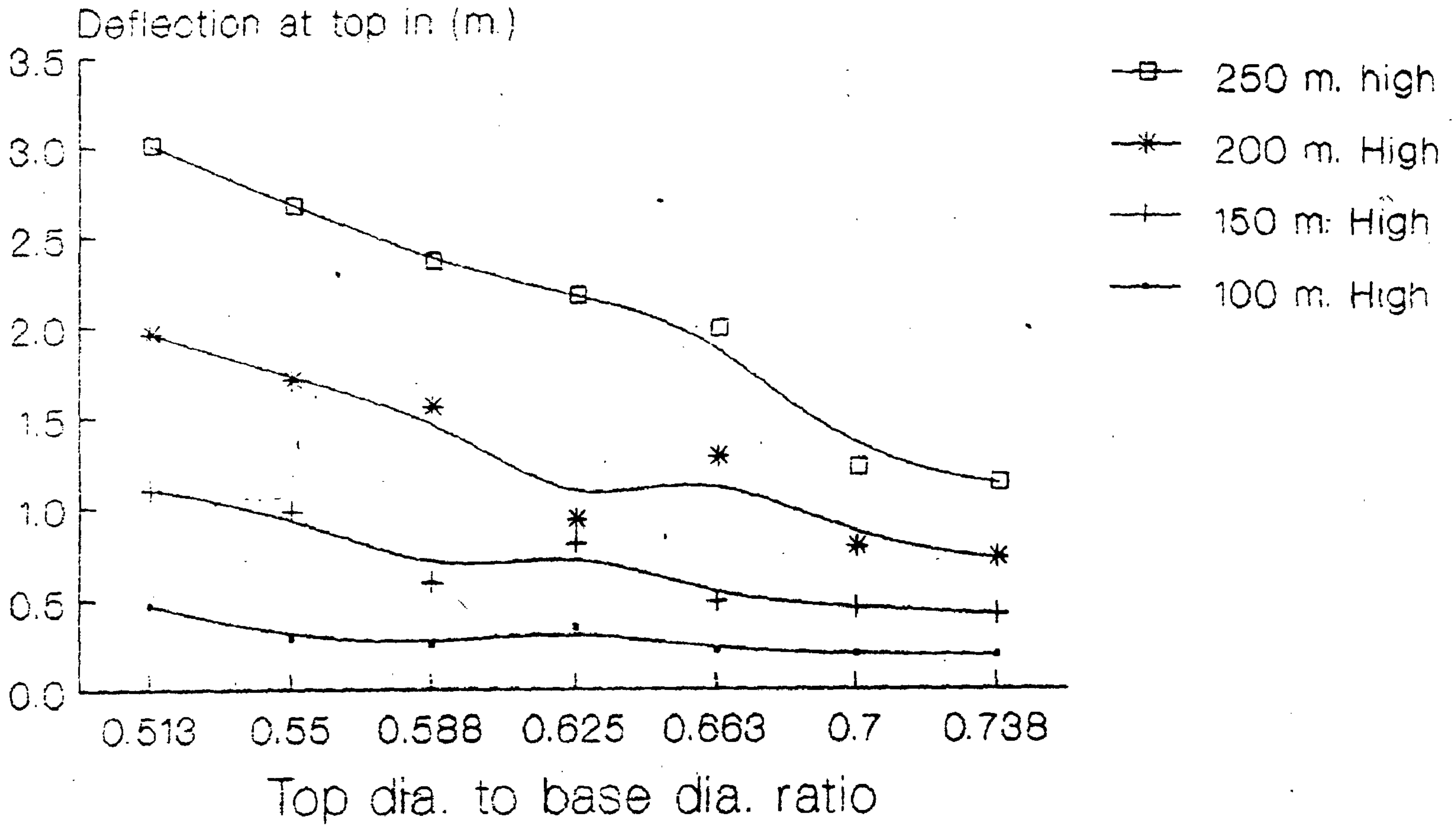


Fig.4.3 Variation of deflection at top
Sceond type of chimney (Along Wind)
Vickery's Approach

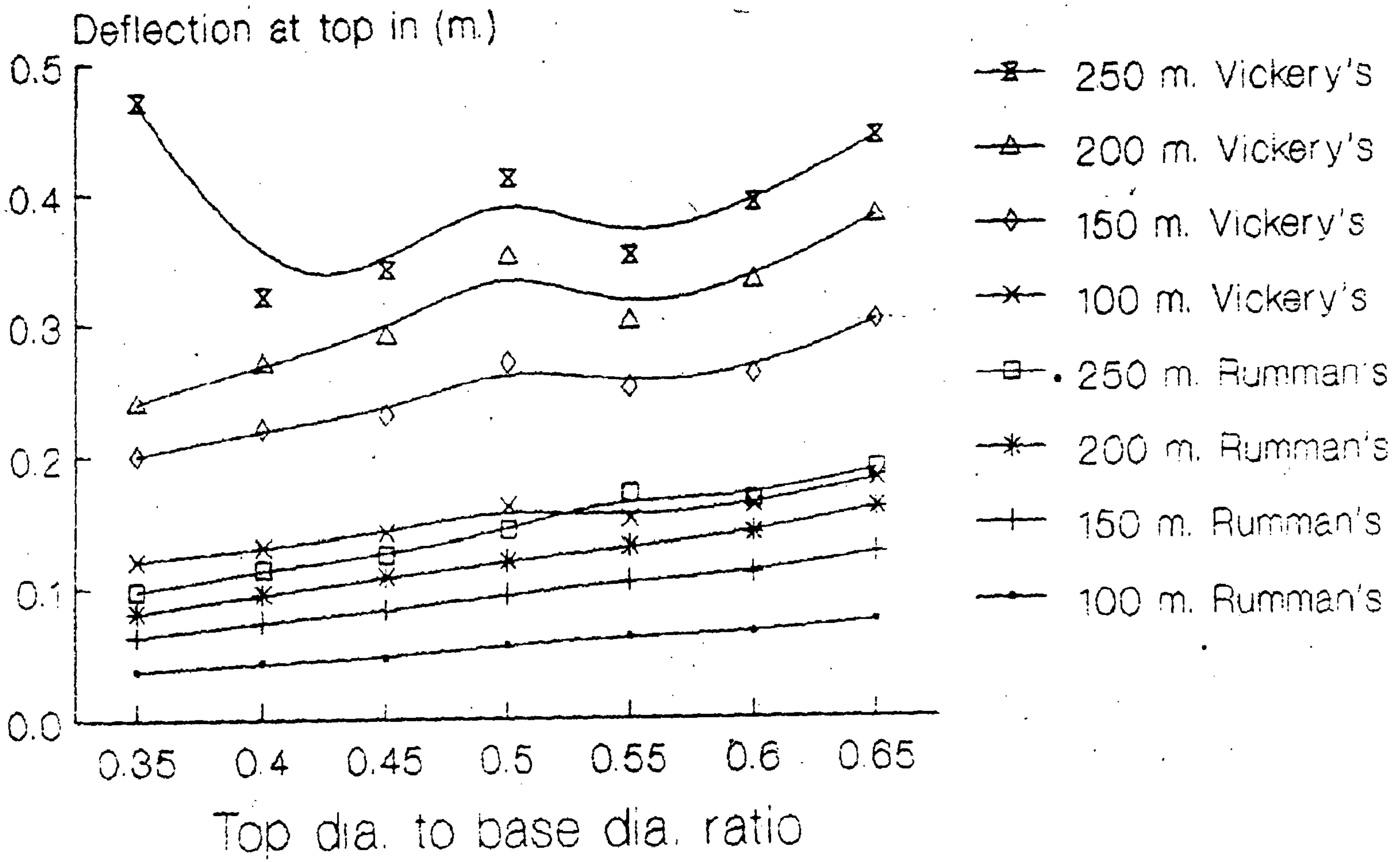


Fig. 4.4 Variation of deflection at top
First type of chimney (Across Wind)
Rumman's & Vickery's Approach

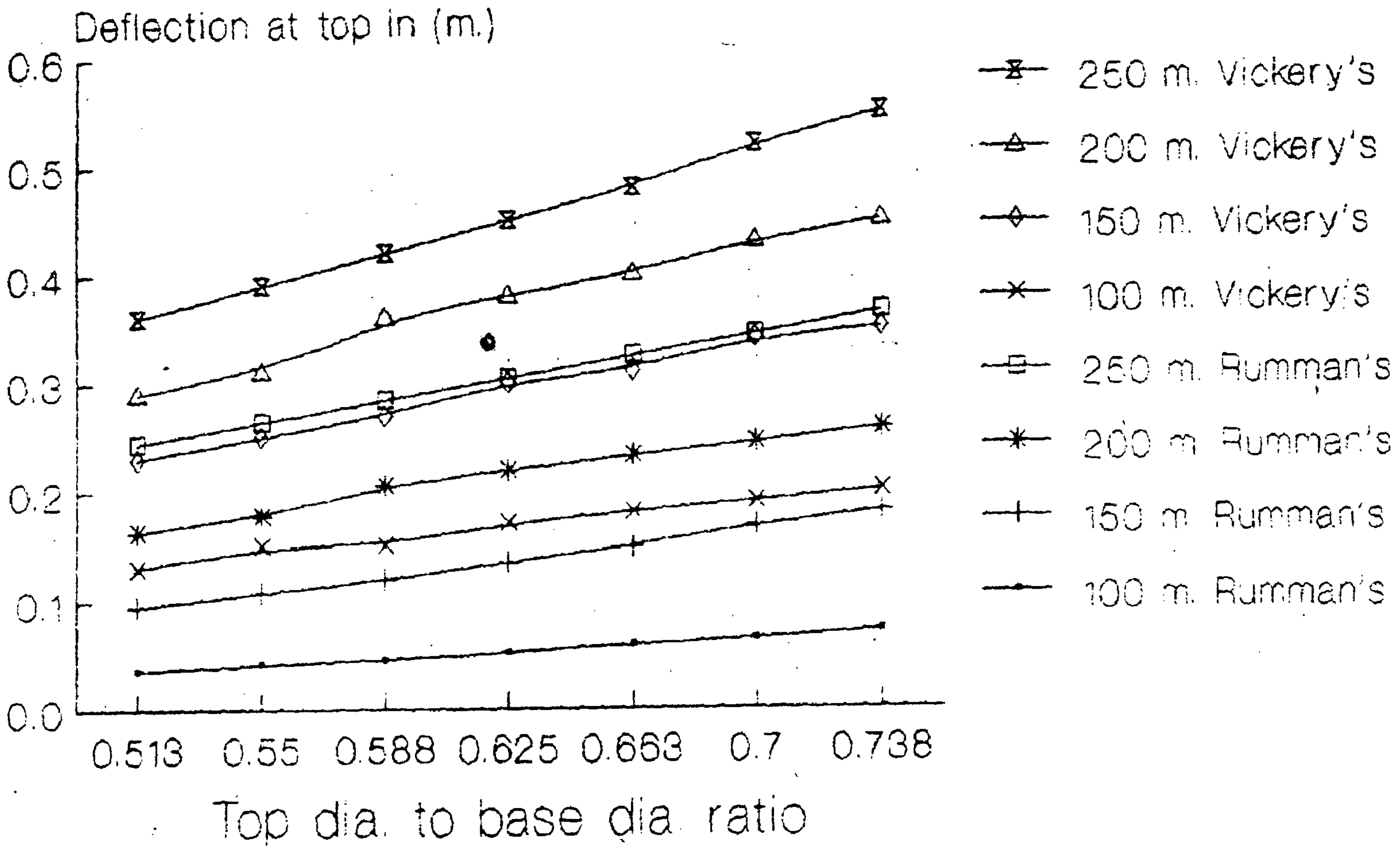


Fig.4.5 Varition of deflection at top
Second type of chimney (Across Wind)
Rumman's & Vickery's Approach

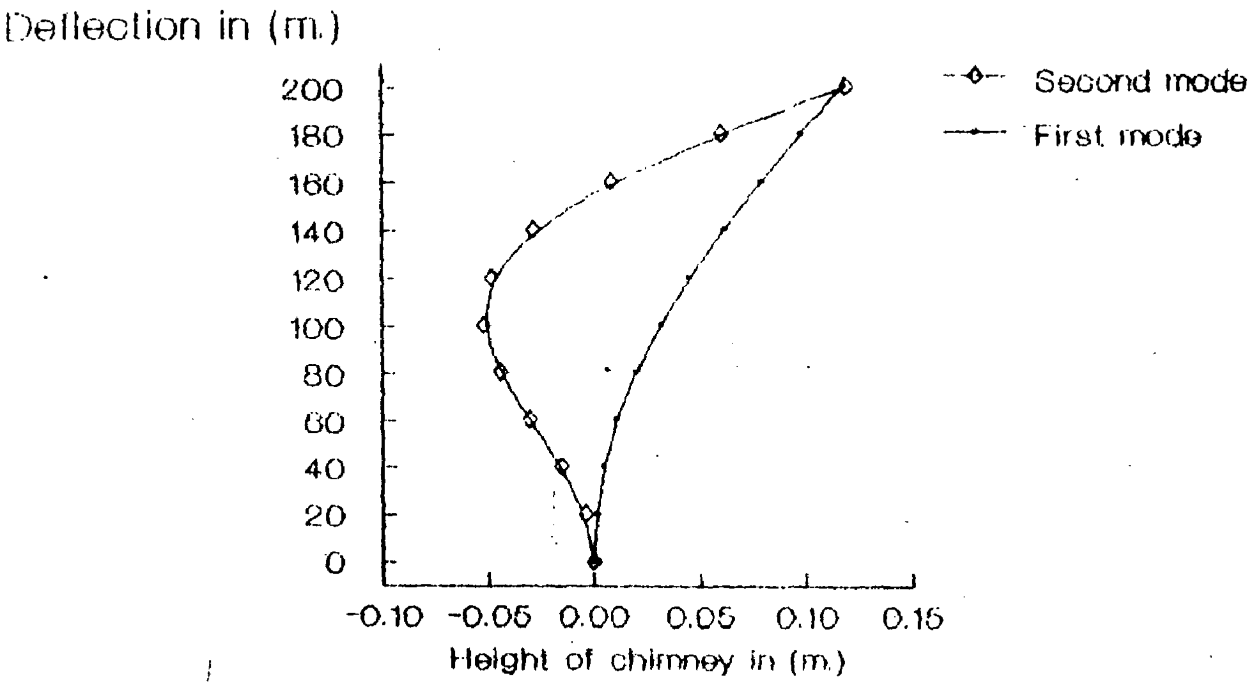


Fig4.6 Variation of deflection
For 200 m. high first type chimney

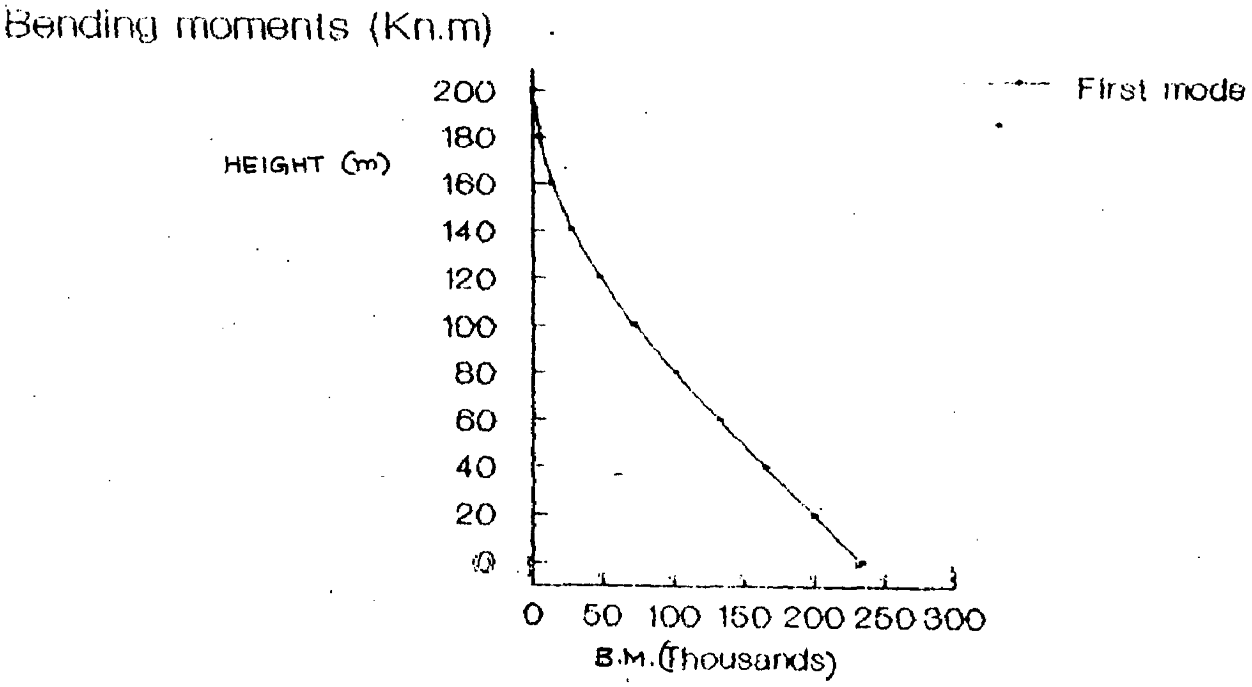


Fig 4.7 Variation of bending moment
For 200 m. high first type chimney

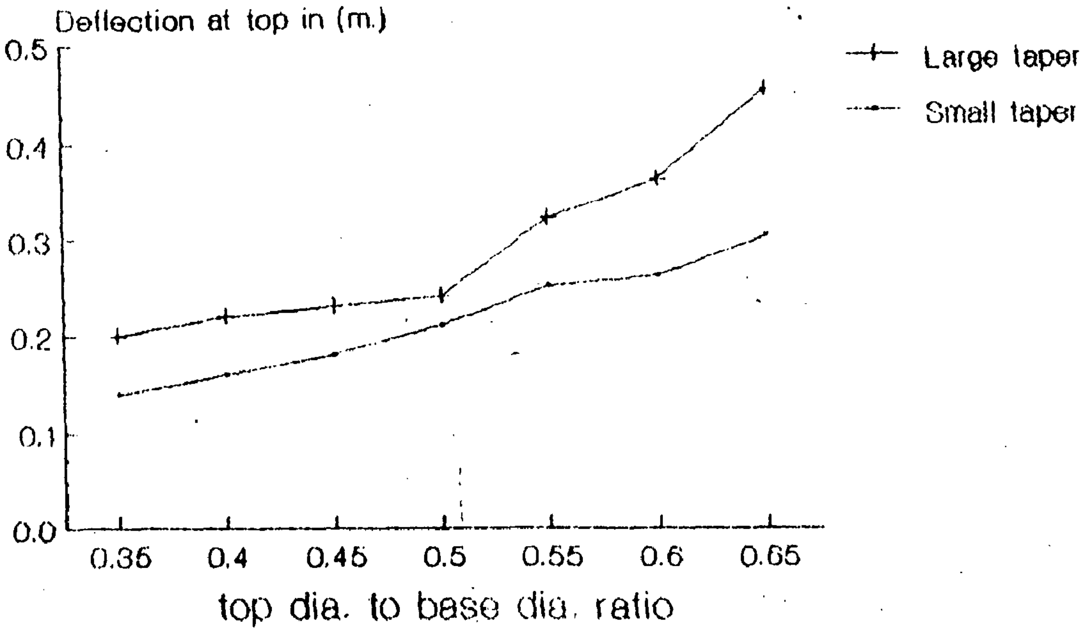


Fig.5.1 Small & large taper comparision
First type of chimney (Across Wind)
Vickery's Approach (150 m. High)

APPENDIX

The computer programme for obtaining the across wind response using the Rumman's procedure has been made for computation. The important steps involved in the process are briefly described as follows:

1. The dimensions of the structural element of chimneys, material and fluid (air) properties and terrain roughness condition, power law exponant, damping coefficient etc. are provided as input data.
2. Lumped mass at the specified nodes and the moment of inertia and cross sectional area of the elements at that node are computed.
3. Obtain the natural frequency of vibration for first and second mode and corresponding mode shape are computed by Hol zer's boundary condition method using transfer functions upto a desired accuracy.
4. By the help of generalised mode shape obtain the deflection shear force and bending moment at all nodes.
5. Calculate $D^4\phi$ at each node and obtain its maximum value. corresponding diameter will be critical diameter and corresponding height from ground will be resonant height.
6. Obtain mean wind speed at resonant height by equating the frequency of first mode of Vibration of structure to the shedding frequency of the verticies.

7. Obtain the mean wind speed at reference height of 10 m using power law by resonance velocity.

8. Obtain critical resonant zone $(z_2 - z_1)$ by the formula given by Rumman and it should not exceed by three times the critical diameter or 175 feet.

9. Obtain the value of $\int m\phi_1^2 \, dz$ by using Simpson's rule for obtaining the integration.

10. On the basis of H/D' ratio obtain the lift coefficient.

11. Obtain modal multiplier for first mode by using the formula given by Rumman.

12. Compute the modified first mode response by multiplying the earlier calculated response by modal multiplier for first mode.

13. For second mode computation, obtain the critical diameter for second mode assuming that the resonance will occur at the top of the chimney and equating $z_2 = H$.

14. Calculate the critical resonant zone for second mode by the formula and it should not exceed by three times the critical diameter or 175 feet.

15. Compute the value of $\int m \phi_2^2 \, dz$ by using Simpson's rule for obtaining the integration.

16. Evaluate the modal multiplier for second mode by using the formula suggested by Rumman.

17. Compute modified second mode response by multiplying the generalised response obtained by generalised mode shape by modal multiplier for second mode.

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