OPTIMIZATION OF DESIGN PARAMETERS OF STEEL CHIMNEYS

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Abstract

In the highly competitive world of today, it is essential to design an efficient, versatile and cost effective system. To design such systems proper analytical, experimental and numerical tools are needed. Optimum design concepts and methods provide some of the needed tools. When these are properly implemented in to software, these give powerful numerical tools for designing best systems. Formulation of an optimum design problem involves transcribing a verbal description of problem in to a well-defined mathematical statement whose constituent elements are parameters, constraints and objective or merit function. Here, a stack design problem has been developed as a mathematical model. Design variables for the present problem are mean diameters d_i, shell thickness t_i, and height h_i of i_{th} lift. Design expressions and constraints have been formulated. The intent of the objective function is to minimize total mass and thus, cost of steel chimney to select design vectors [h], [d] and [t] while satisfying the nine constraints. For the present problem Random Search Methods have been used to design flowchart for the optimum solution because these are quite simple to program and are very reliable in finding a nearly optimal solution.

Key words: Drag coefficient, Terrain friction drag coefficient, Dynamic lift coefficient, Strouhal number, Frequency of vortex shedding, Natural frequency, Random Search Method.

NOTATION

A_k	area of cross-section, m^2	i	lift counter from top to bottom
C_d	drag coefficient	j	grid counter
C_f	terrain friction drag coefficient	I	area moment of inertia, mm^4
C_l	dynamic lift coefficient	M	resultant bending moment, Nm
C_1	Rs cost per unit area of steel sheet	M_E	equivalent end mass, Kg
C_2	Rs cost per unit volume of weld	M_i	mass of ith section, Kg
d_i	mean shell diameter of i_{th} lift of stack, m	n	exponent which depends on surface roughness, number of trial chimneys
D	external diameter of stack, m	P	uniformly distributed load, N/m
E	Modulus of elasticity	P_{cr}	critical buckling load, N
F_d	drag force, N	St	Strouhal number
F_g	gust load, N	t_i	shell thickness of i_{th} lift of stack, m
F_l	across wind force, N	U	design wind speed at height Z, m/sec
f_n	natural frequency of chimney, Hz	U_0	basic maximum wind speed at reference height Z_0
f_v	frequency of shedding pairs of vortices, Hz	$\overline{U}$	design wind speed averaged over entire stack height, m/sec
g	acceleration due to gravity, m/sec^2	W_k	total structural weight of stack at k_{th} section, kg
W_e	anticipated weight of ladder and platform, kg	z_i	distance measured from base to center of mass of section, m
h_i	height of i_{th} lift of stack, m		

Z_k section modulus of k_{th} section, m^3

ρ_a, ρ_s mass density of air, steel, kg/m^3

σ_a allowable yield stress of material, N/mm^2

Δ maximum permissible deflection, mm

∂, y deflection, mm

I. INTRODUCTION

Optimization techniques play an important role in structural design, the very purpose of which is to find the best ways so that a designer or a decision maker can derive maximum benefit from the available resources. A stack design problem has been represented as a mathematical model whose constituent elements are parameters, constraints and objective or merit function. Design parameters specify geometry, topology of stack and physical properties of its members. From design parameters, a set of derived parameters are obtained which are defined as behavior constraints e.g., stresses, deflections, natural frequencies and buckling loads etc. The objective or merit function has been formed to minimize total mass and thus, cost of steel chimney (4).

II. FORMULATION OF DESIGN PROBLEM

A. Design variables

For design purpose, self-supported steel chimney is treated as a cantilever beam of variable moment of inertia (1). Chimney is divided into a number of convenient zones as shown in Fig. 1. Design variables for problem are mean diameters d_i, shell thickness t_i, and height of i_{th} lift h_i. If chimney is divided into n elements, total number of design variables is therefore 3xn. W_1, W_2, W_n are structural weights of lifts, P_1, P_2, P_n are uniformly distributed loads on lifts of heights h_1, h_2, h_n and thickness t_1, t_2, t_n. Let chimney has an inside diameter D_i and physical height H_i, as determined by technical, operational and pollution considerations.

B. Design Expressions

For a cantilever chimney, steel structure experiences combined bending moment and shear forces (6, 12 & 13). Wind load over a differential area dA is shown in Fig 2.
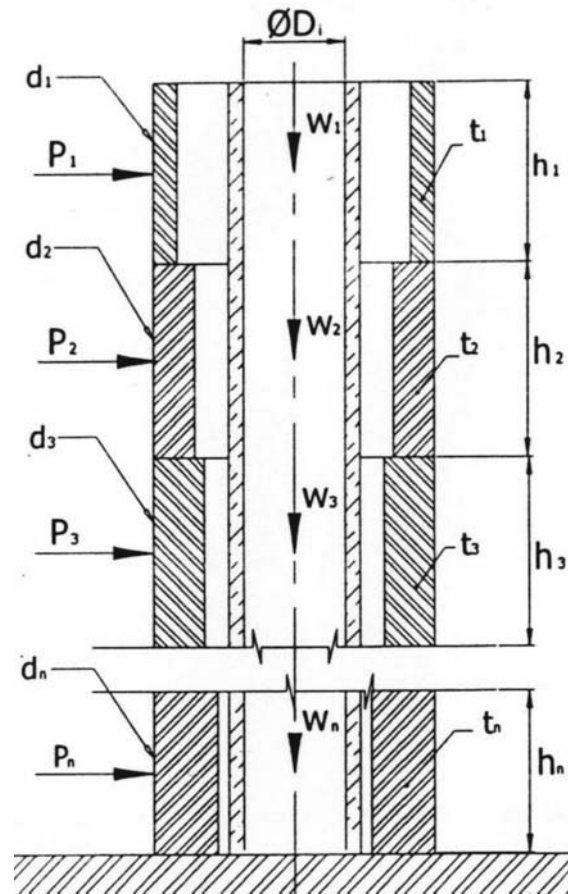

Fig. 1 Chimney Modeled as a Cantilever Beam

Along wind force is composed of static drag force and gust load. Along wind Force = Drag Force + Gust Load   ... [1]

Drag force acting at a distance z measured from base is given by:

$$F_d = \frac{1}{2}\frac{C_d \rho_a}{2n+1}\left(\frac{U_0}{Z_0^n}\right)^2 D\left(Z_2^{2n+1} - Z_1^{2n+1}\right)$$

... [2]

Gust load component acting at any section of stack is given by:

$$F_g = 2.18\, U_0^2\, C_d\, D \cdot \rho_a \sqrt{C_f}\, \frac{1}{Z_0^n}\frac{1}{n+1}\left(Z_2^{n+1} - Z_1^{n+1}\right)$$

... [3]

Lift force generated due to vortex shedding is given by:

$$F_1 = \frac{1}{2(2n+1)}C_1 \rho_a \left(\frac{U_0}{Z_0^n}\right)^2 D\left(Z_2^{2n+1} - Z_1^{2n+1}\right)$$

... [4]

Value of exponent n is defined in Central Pollution Control Board, Delhi, Probes/ 70/ 1997-98 (10). Values of coefficients C_d, C_f and C_l defined in Manohar (7). Resultant design force which acts at any cross section is vector sum of along wind forces and across wind force:

$$F = k_1 \sqrt{\left(F_d + F_g \right) + r F_1} \qquad \dots [5]$$

Where, r is dynamic magnifier at design wind speed and k_1 is overloading factor which takes into account uncertainties in loading. Resulting bending moment at any cross-section at distance z from base of chimney due to wind loads is given by:
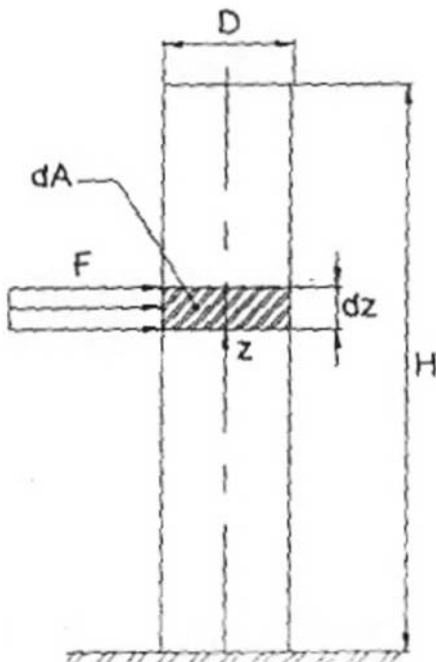

Fig. 2 Wind Load over a Differential Area

$$M = F \cdot \frac{H-z}{2} \qquad \dots [6]$$

C. Formulation of Objective Function

Cost function: The intent is to minimize total mass and thus, cost of chimney. Total cost of steel chimney depends on:

(a) Area and thickness of steel sheet

(b) Cost of manufacturing (i.e. cost of cutting and welding)

For a cantilever chimney made of n number of lifts of variable thickness, cost function is written as:

$$Cost = C_1 \cdot (d_1\, h_1\, t_1 + df_2 h_2\, t_2 + d_3\, h_3\, t_3 + \dots d_n h_n t_n)\, \pi\, p, + C_2\,(n-1) \qquad \dots (7)$$

D. Formulation of Constraints

Behavior constraint: To prevent material overstressing, resultant of bending and shear stresses and stresses resulting from self-weight of steel structure induced at k_{th} section is not to be greater than permissible yield stress of material.

$$\frac{W_1}{A_k} + \frac{M_k}{Z_k} \leq \sigma_a \qquad \dots [8]$$

Where, Z_k is given by:

$$Z_k = \frac{\pi\, d_k^3\, t_k}{4D} \qquad \dots [9]$$

Where, d_k and t_k are mean shell diameter and thickness at k_{th} section.

Total structural weight at k_{th} section is:

$$W_1 = \frac{1}{4} \cdot g \cdot p_s \cdot \pi \cdot \sum_{i=1}^{k} d_i\, t_i\, h_i \qquad \dots [10]$$

Area of section A_k is given by:

$$A_k = \pi \cdot d_k \cdot t_k \qquad \dots [11]$$

For finding moment M_k, values $z_2 = H$ and $z_1 = z_k$ are substituted in expressions [2], [3] and [4] and resulting values of F_d, F_g and F_l are used in expressions (5) and (6).

Deflection constraint: Deflection under extreme loading conditions must be at most Δ. Therefore, calculated deflection ∂ must be less than or equal to Δ. Maximum deflection of a cantilever beam subjected to a uniformly distributed load P as shown in Fig. 3 is given by:

$$y_{\max} = \frac{1}{8} \cdot \frac{P \cdot H^3}{EI} \qquad \dots [12]$$

Expression (12) is used to find top deflection of a self-supported steel chimney by substituting $P = F/H$.

To avoid excessive arithmetic, value of EI is taken as that of base section. It is recommended that

maximum allowable deflection for a steel chimney is to be less than or equal to H/200 (3 & 5).

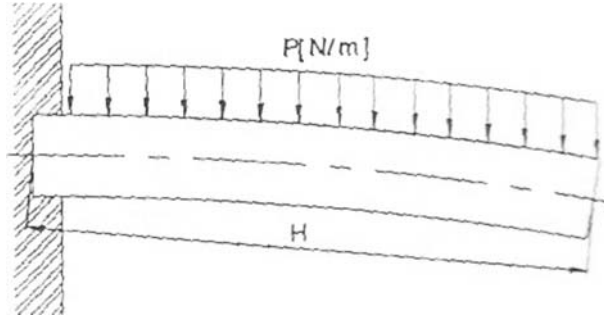$$\frac{1}{8} \cdot \frac{F \cdot H^2}{EI} \leq \frac{H}{200} \qquad \ldots [13]$$

Fig. 3. Deflections due to Wind Loads

Buckling constraint: Stress induced in chimney shell is to be less than buckling stress. Assuming a fixed end condition, critical buckling load is calculated by:

$$P_{cr} = \frac{\pi^3 E R_k^3 t_k}{4 h_k} \qquad \ldots [14]$$

Where, R_k is radius of stack shell at k_{th} section, $R_k = d_k/2$ and downward self load W_k (for a self-supporting chimney) is to be less than or equal to P_{cr}.

$$W_k \leq P_{cr} \qquad \ldots [15]$$

Constraint on frequency of vortex shedding: Frequency of vortex shedding at design wind speed is given by:

$$f_v = \frac{\overline{U} \cdot St}{D} \qquad \ldots [16]$$

Natural frequency of a cantilever chimney constructed of lifts of different thicknesses is:

$$f_n = \frac{1}{2\pi} \cdot \sqrt{\frac{3 \cdot E \cdot I}{M_E \cdot H^3}} \qquad \ldots [17]$$

Where, M_E is equivalent end mass that would make chimney vibrate at same frequency as does a mass carried at top and is obtained by:

$$M_E = \sum_{i=1}^{n} \left(\frac{Z_i}{H}\right)^2 M_i \qquad \ldots [18]$$

Resonance is avoided by making natural frequency of chimney as large as possible. This is expressed mathematically as:

$$f_n \geq f_v \qquad \ldots [19]$$

Diameter constraint: Inner diameter of chimney should not be less than d_j, as determined by requirements of exit velocity and volume of flue gas to be handled, so

$$d_k - t_j \geq d_i \qquad \ldots [20]$$

Constraints on height of lifts: Maximum height of a lift is often limited to 12.1 meters to account fabrication and installation difficulties, so

$$h_i \leq 12.1 \qquad \ldots [21]$$

Explicit bounds on thickness of steel sheet: To avoid practical difficulties while manufacturing, restrictions on minimum and maximum thickness of structural steel sheet are:

$$t_{min} \leq t_j \leq t_{max} \qquad \ldots [22]$$

$$h_{min} \leq h_i \qquad \ldots [23]$$

Minimum cost and mass design problem is to select design vectors (h), (d) and (t) to minimize cost function expression (7), while satisfying the m\nine constraints of Ex. (8) through Ex. (23)

E. Standard Definition of problem

After normalizing constraints, using defined data, optimum formulation for design of industrial steel chimney is obtained.

$$\text{Find } X = \begin{vmatrix} d_1 \\ dsub \\ d_3 \\ \dots \\ t_1 \\ t_2 \\ t_3 \\ \dots \\ h_1 \\ h_2 \\ h_3 \end{vmatrix} \qquad \dots [24]$$

$$f(x) = C_1 \cdot (d_1 h_1 t_1 + d_2 h_2 t_2 + d_3 h_3 t_3 + \dots d_n h_n t_n) \, \pi \, p_s + C_2 \, (n-1)$$
$$\dots [25]$$

Subject to behavior constraint:

$$\frac{W_k}{A_k} + \frac{M_k}{Z_k} - \sigma_a \leq 0 \qquad \dots [26]$$

Deflection constraint:

$$F \cdot H - 0.04 \cdot E \cdot I \leq 0 \qquad \dots [27]$$

Buckling constraint:

$$-\frac{1}{4} \cdot g \cdot p_x \cdot \pi \cdot \cdot \sum_{i=1}^{k} d_i t_i h_i + \frac{\pi^3 \cdot E \cdot R_k^3 \cdot t_k}{4 h_k} \leq 0 \qquad \dots [28]$$

Vortex shedding frequency:

$$-\frac{1}{2\pi} \sqrt{\frac{3 \cot E \cdot I}{\sum\limits_{i=1}^{n} \left(\frac{Z_i}{H}\right)^3 M_i H^3}} + \frac{\overline{U} \cdot St}{D} \leq 0 \qquad \dots [29]$$

Inner diameter constraint:

$$- d_k + t_k + d_i \leq 0 \qquad \dots [30]$$

Height of lifts constraint:

$$h_i - 12.1 \leq 0 \qquad \dots [31]$$

Thickness constraint:

$$t_{min} \leq t_i \leq t_{max} \qquad \dots [32]$$

III. OPTIMUM SOLUTION TECHNIQUES

There are many techniques to solve problem defined in expressions (24) to (32). One of these methods for present problem is Random Search Method (2, 8, 14 & 15). Random search methods are very simple to program and are quite reliable in finding a nearly optimal solution. Flowchart developed based on this method is shown in Figures 4,5 and 6. Steps involved are as below:

(i)   Generation of a trial design vector using one random number for each design variable.

(ii)   Verification of constraints at trial design vector. Eqality constraints are considered satisfied whenever their magnitudes lie within a specified tolerance. If any constraint is violated, continue generating a new trial vector that satisfies all constraints.

(iii)   If all constraints are satisfied, retain current trial vector as best design if it gives a reduced objective function value compared to previous best available design. Otherwise discard current
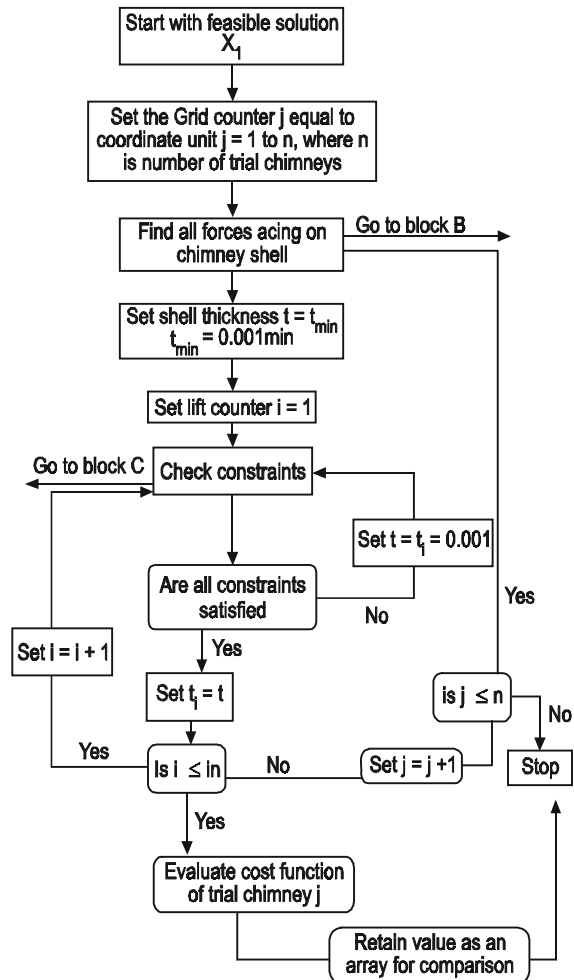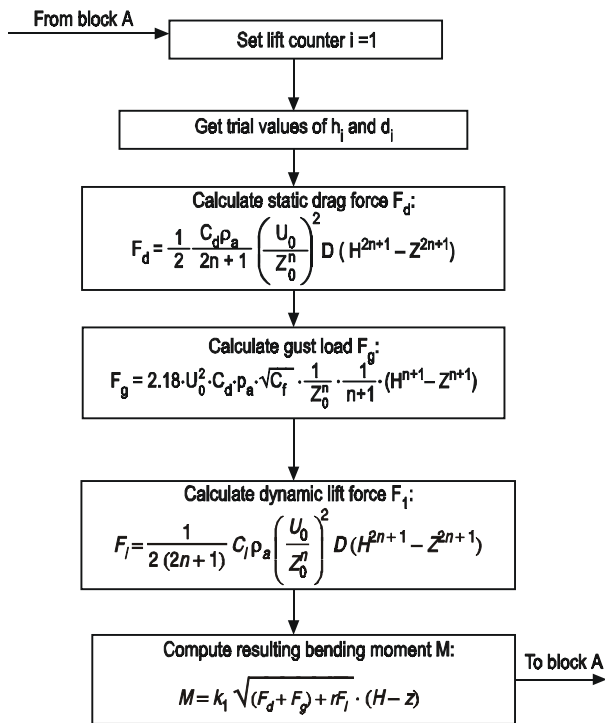

Fig. 4. Flow Chart of the Main Program

Fig. 5. Block B of Fig. 4

feasible trial vector and proceed to step 1 to generate a new trial design vector.

(iv)   Best design available at the end of generating a specified maximum number of trial design vectors is taken as solution of the constrained optimization problem.

IV. CONCLUSIONS

For designing a structural system, conventional and optimum design processes are used at different stages of design. In conventional design, it would be sometimes difficult to decide whether to increase or decrease the size of a particular structural element to satisfy the constraints. Furthermore, conventional design can lead to uneconomical design and involve a lot of calendar time. These shortcomings have been omitted by applying optimization technique. For this, design variables, expressions and constraints have been formulated. The objective or merit function has been formed to minimize total mass and thus, cost of steel chimney expression [7] to select design vectors [h], [d] and [t], while satisfying the nine constraints of expressions [8] through [23] with the help of random search methods.
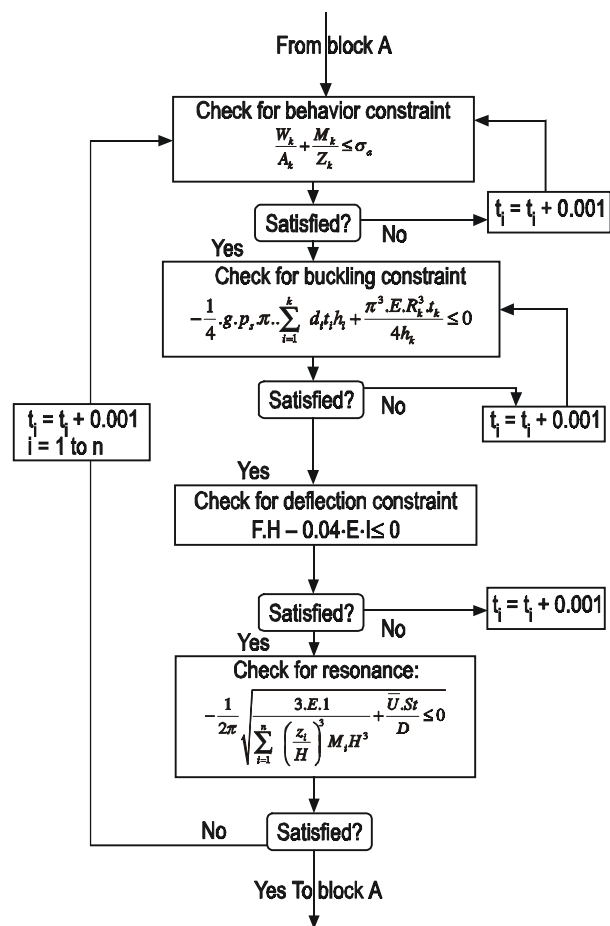

Fig. 6. Block C of Fig. 4

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