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STRUCTURAL DAMPING OF STEEL CHIMNEYS

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Introduction

The influence of the non-dimensional mass-damping parameter k_s upon the dynamic response of structures to vortex excitation is well known. In fact it is now fairly well established that for structures such as chimneys the response to vortex-induced vibration depends inversely on the magnitude of k_s. With $k_s = 2m/\rho D^2$ it is suggested that a value of 25 is an appropriate minimum for chimney design. What is now required in the design of chimneys is more information on evaluating structural damping. To this end the present paper is concerned with the analysis of a chimney-damping layer-soil-foundation system. Previous ad hoc experiments (1) had suggested that the potential for significantly increasing the low-frequency damping level with an elastomeric damping layer was considerable and this concept is more fully examined here. A fuller description of the work may be found in (2).

Formulation of the Structural Response Problem

For the purpose of the present analysis it is convenient to consider the structural system shown in Figure 1 to be composed of three subsystems; namely the chimney, the damping layer at the base of the chimney and the foundation-soil structure. A constant parameter, linear model is developed for each of these subsystems which are then linked together in a receptance analysis. Steady-state responses to a harmonic force applied at the tip of the chimney are determined at various points in the coupled system. Continuum models are used for both the structure and the soil.

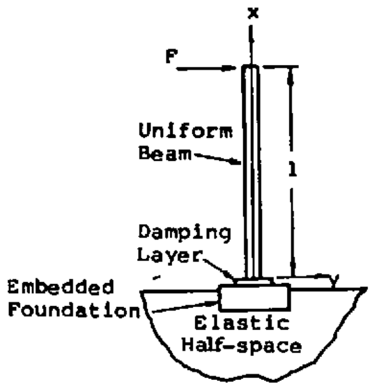

Figure 1 Physical Model

The principal physical assumptions made in the analysis are that: (1) the chimney behaves as a uniformly damped constant cross-section beam; (2) the effects of shear deformation, rotary inertia and gravity forces on the transverse vibration of the chimney can be neglected; (3) the damping layer is a massless, linear visco-elastic element;

(4) the foundation block is a rigid body whose only significant motions are horizontal translation and rocking in a vertical plane, and (5) frictional losses in the soil are small compared to radiation losses and can be neglected.

The receptance model of the system consists simply of three sub-systems each linked by two generalized co-ordinates which are the horizontal translations and the rotations at the points of connection. It is easily shown that the force vector at the base of the chimney is given by

$$\underline{F}_{bo} = -(\boldsymbol{\beta}_{oo} + \boldsymbol{\gamma} + \boldsymbol{\delta})^{-1} \boldsymbol{\beta}_{oi}\underline{F}_{bi} \qquad (1)$$

and that the tip response has the form

$$\underline{Y}_{bi} = \left[\boldsymbol{\beta}_{ii} - \boldsymbol{\beta}_{io}(\boldsymbol{\beta}_{oo} + \boldsymbol{\gamma} + \boldsymbol{\delta})^{-1} \boldsymbol{\beta}_{oi}\right] F_{bi} \qquad (2)$$

In these equations $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$, $\boldsymbol{\delta}$ are the appropriate receptances of the chimney, the damping layer and the soil-foundation system respectively; the subscripts i and o refer to tip and base co-ordinates on the chimney. The 1,1 element of the receptance matrix in equation (2) denoted α_{11}, relates tip deflections to the external force F. Once the force vector $\underline{F}_{bo}$ is known motions in other parts of the system are readily found. Knowledge of these forces and motions allows the fraction of the input power dissipated in each sub-system to be calculated from the algebraic sum of the power flows at its N connection co-ordinates with other sub-systems.

The elements of the matrix $\boldsymbol{\beta}$ are complex versions of the free-free beam receptances tabulated in (3). The equations of motion for a rigid foundation embedded in a side layer and resting on an elastic half-space have been developed by Beredugo and Novak (4) and these equations were used to determine the elements of the matrix $\boldsymbol{\delta}$.

The elements of the matrix $\boldsymbol{\gamma}$ are the flexibilities in translation and rotation of the damping layer-restraining mechanism. To be effective the damping layer must introduce a certain degree of flexibility between the chimney and its foundation. The necessary flexibility can only be achieved if the hold-down bolts are isolated from the chimney base plate by small pads of damping material. These isolating pads have a relatively small effect in comparison with the main damping layer on the total rotational and translational stiffnesses of the insert and hence the principal dynamic effects are those due to the main layer.

Numerical Results

The results presented in this section show how the system damping level is affected by, first of all, radiation damping in the soil and then by the addition of a resilient damping layer at the base of the chimney. In the calculations chimneys with heights of 20m, 50m and 100m have been considered. The dimensions of the chimneys and their foundations are suitable for design wind speeds up to 45m/s in accord with the relevant British Standards and Codes of Practice. The foundations were assumed to be fully embedded and a single set of soil parameters appropriate to a medium strength soil with a corresponding shear wave velocity of c = 200m/s has been used. The chimney damping level has been assumed to have a value of $\delta_c = .01\pi$ independent of frequency, this value being suitable for unlined steel shells. The value of $2m/\rho D^2$ was approximately 300 for each chimney. It is recognised that tall chimneys usually have slightly tapered cross-sections made from material that becomes progressively thinner towards the top. Also many tall chimneys are of multi-flue design, and obviously the dynamic response of such chimneys will differ somewhat from those studied here. One would not however expect such differences to alter the essential conclusions reached in the study.

In Figure 2 the normalized tip receptance is shown as a function of the frequency parameter λl for the 20m chimney, the results for the taller chimneys being essentially the same. The four peaks on the curve correspond to the lowest four beam modes of the chimney; the cantilever frequencies are denoted by the arrows marked f_1^c, etc. If the soil-foundation structure were completely rigid the resonance peaks would all have nearly the same amplitude, it being approximately 400 for the value of damping assumed.

As may be seen from the figure the fundamental mode peak has about this amplitude while the higher modes have peaks which are somewhat reduced in amplitude. This increase in the apparent damping level of the chimney is due to radiation damping in the soil. The receptances of the soil-foundation subsystem were found to be very heavily damped both in translation and rotation due in large measure to the presence of the side layer. Its undamped natural frequencies are indicated by arrows labelled f_1^f and f_2^f on Figure 2. In the frequency range around f_1^f and f_2^f the high damping forces have a beneficial effect on the chimney response. However, it does not appear practicable to take advantage

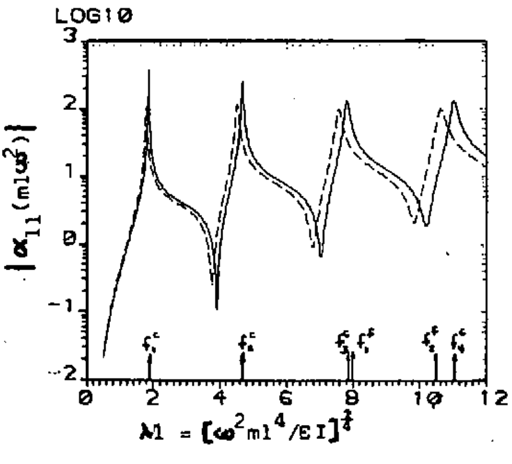

Figure 2 Normalised Tip Receptance of 20m chimney Without (——) and with (---) the Added Damping Layer. The Damping Layer has a Stiffness Ratio of $\mu_r = 23$ and a Loss Factor of $\eta = .18$.

of this effect in the frequency range encompassing the fundamental modes of steel chimneys.

The response with a suitable damping layer is shown by the dotted curves in Figure 2. Computations of the power dissipated in each subsystem show that nearly all of the low-frequency vibratory energy is dissipated in the damping layer in contrast to the situation without the layer where most of the energyis dissipated in the chimney. In order for the damping layer to work it must be sufficiently flexible, rotational flexibility being more important than translational flexibility. Clearly there is a lower limit on the degree of support flexibility that can be tolerated without impairing structural stability. It would appear that the useful range of rotational stiffnesses is approximately $10 < \mu_r < 50$ depending on the damping layer loss factor where μ_r is the rotational stiffness of the damping layer divided by EI/l of the chimney. Curves showing the increase in first mode damping as a function of μ_r are easily computed and these indicate that for the chimneys considered it would be practical to introduce enough additional damping to satisfy the $k_s \gg 25$ criterion.

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