The wind-induced vibrations of large cylindrical structures

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The Wind-Induced Vibrations of Large Cylindrical Structures

Vibrations dues au vent dans de grands ouvrages de forme cylindrique

Windschwingungen langer Zylinderbauwerke

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The difficulties caused by the wind-induced lateral vibrations have increased with modern high cylindrical structures and columns of large bridges. The nature of the excitation and the aerodynamic damping of lateral vibrations are discussed in this paper.

1. Introduction

In recent years, wind-induced lateral vibrations excited by the fluctuating lift forces have occurred with some large cylindrical structures in many countries. These dangerous vibrations are usually excited at low and medium wind velocities and have their predominant components in a plane perpendicular to that of the wind. The lateral vibrations have caused serious trouble in many cases, as described, for example, in papers [6,8,12,16,17, 20]. An illustration of a difficulty of this kind is the lateral vibration of the high cylindrical columns of a 330 m span arch bridge [9,12]. The vibration which was much stronger than in the case described by Kunert [6] produced in the columns additional dynamic stresses of up to roughly 780 kg/cm^2 that of course highly compromised their desirable bearing capacity. A similar problem recently arose with the cylindrical hangers of a large arch bridge in Canada. So it appears that the possibility of lateral vibration must be taken into account not only with masts and towers, but with all structures containing slender cylindrical members and thus, also with some steel arch bridges.

In general practice, the problem is not usually faced until the structure is finished and the cure is difficult. The prediction of the lateral vibration already in the design stage is therefore of major importance.

2. The Nature of Lateral Vibration Excitation

A considerable number of experiments have been carried out with the aim of elucidating the nature of lateral oscillations.

Understanding the problem has already had quite an interesting history. For many years, the lateral vibration was considered to be a response of the structure to fluctuating lift forces which accompany the regular eddy shedding creating the well-known pattern in the wake, usually called Karman street. This explanation leads to the solution of the response in terms of deterministic vibrations which results in very simple formulae even for rather complicated structures [8]. This approach seems justified, especially in the subcritical range; however, already the earlier measurements in the wake have shown that even in this range the vortex pattern is not perfectly periodic, with the only exception of extremely low Reynolds numbers (see Roshko [14]). Thus the lift is composed of periodic and random parts and the response should be solved in terms of random vibration. This approach shows the strong dependence of the intensity of vibration on the ratio of the random and periodic parts of the lift [9].

Later studies of cylinder behaviour in the supercritical range led to the conclusion that the lift is chaotic (see Fung [4]) and the statistical approach, based on Fung's power spectrum of lift, became very favourable for the whole supercritical range. Nevertheless, this calculation sometimes leads to considerably small amplitudes with large structures [9].

Finally, investigations in the region of very high Reynolds numbers proved a reappearance of harmonic component of the lift or narrow band lift in this domain, sometimes called the transcritical range. The papers by Roshko [15] and by Cincotta, Jones and Walker [2] represent very important contributions in this respect.

To provide further information about the fluctuating forces acting on the cylinder, pressure measurements on the surface of the body are useful [5]. Fig. 1 represents an example of such measurements carried out by the author and O. Fisher on a cylinder with a diameter of 31 cm at Reynolds number R = 265000 and Strouhal number S = 0.194. The upper trace is the motion of the cylinder, the lower traces show the surface pressures measured at two points situated 2.35 diameters apart in a plane perpendicular to the direction of the air flow. (The sensitivity of the two pressure pick-ups Disa Pu2a was different, as indicated). These measurements were made at a wind velocity, which was lower than that at the resonance (below the resonance). It can be seen that the pressures are approximately in phase with the motion. In the region of resonance, there was a distinct phase shift $\pi/2$ between the pressures and the vibration. Above the resonance, the periodicity was not so well pronounced as in the former cases. However, whenever the periodicity could be recognized, the phase shift between pressure and motion approached π. These observations of phase conditions

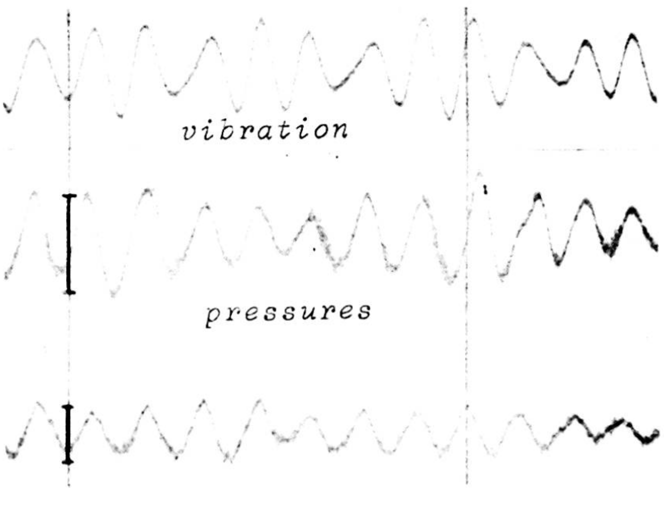

Fig. 1. Surface Pressures on a Circular Cylinder

between the fluctuating lift force and the response of the cylinder evidently agree with phase conditions of mechanical systems excited by an external force. Therefore, the outlined pressure measurements support the assumption that the lateral vibration may be considered as excited oscillations.

This conclusion is important because some authors tend to explain the lateral vibration of circular cylinders as oscillations induced by negative aerodynamic damping. This explanation does not seem justified for the following reasons:

1. The existence of fluctuating lift forces has been proven many times, even with steady cylinders performing no motion.

2. The mentioned phase shift $\pi/2$ at resonance (out of phase force) is typical for excited oscillations.

3. The negative aerodynamic damping, as usually understood, represents forces which are induced by the motion of a body, the cross-section of which is aerodynamically unstable. The square cross-section represents the well-known example of this kind. However, the instability clearly defined with the square cross-section cannot be defined in the same way with the circular cross-section. Furthermore, the self-excited vibration of bodies with unstable cross-section significantly differs from circular cylinder oscillations. The main feature of self-excited oscillations is the monotonous increase in steady amplitudes with wind velocity above a certain value. An example of wind-induced oscillations of this kind is given by Fig. 2. This figure represents the universal galloping response of square cylinders having different normal modes under the action of wind with constant and variable mean speed [11].

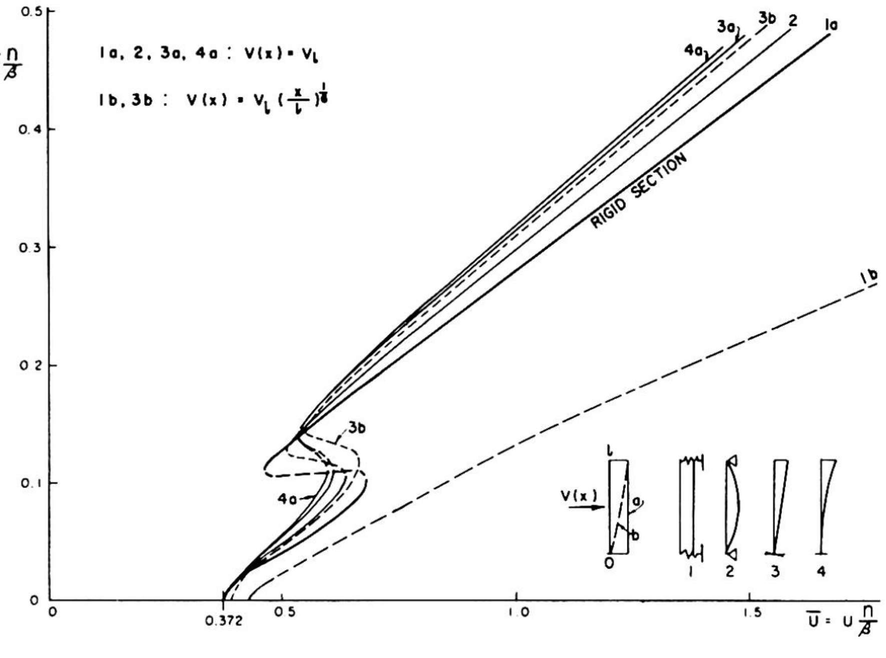

Fig. 2. Universal Galloping Response of Square Cylinders Having Different Normal Modes

$\bar{a} = \frac{a}{h}$ - reduced amplitude of displacement

h - length of side of the prism

$U = \frac{V}{\omega h}$ - reduced air velocity

V - air velocity

ω - natural circular frequency

$n = \frac{\rho h^2}{4\mu}$ - mass parameter

μ - mass per unit of length

ρ - air density

β - reduced damping coefficient (log. decrement/2π)

This representation holds generally for all bodies with different mass, damping and normal modes but with square cross-section [11]. In other cases of negative aerodynamic damping, the character of the response as a function of wind velocity is similar; however, this character is principally different from that of circular cylinder vibration. Laberal response of circular cylinders always implies either a more or less well pronounced resonance peak alike as curve *a* in Fig. 3, or a continuous progressive increase in amplitudes, as diagrammatically shown by curve *b* in the same figure. According to the previous, the latter case is typical for the supercritical range with the purely random lift.

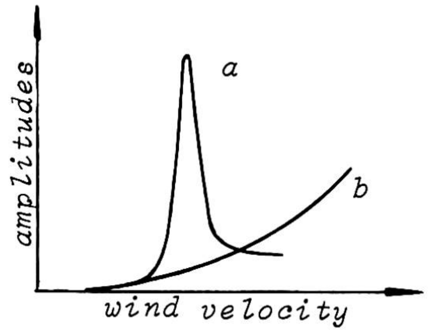

Fig. 3. General Character of Lateral Vibration

For all these reasons, the assumption that the lateral vibrations of circular cylinders can be calculated as excited (forced) oscillations seems to be well founded. The problem, of course, is to know the lift forces as functions of all main factors which govern the phenomenon. For a reliable prediction, the lift forces should be defined by their power spectra and cross-spectra as functions of Reynolds number, intensity and scale of the turbulence and dimensionless amplitude of vibration.

Despite the large amount of experimental work which has been carried out, a full description of lift forces is not available. The research of ground wind effects in relation to launch vehicles has recently provided some very interesting information concerning the range of very high Reynolds numbers inaccessible in standard wind tunnels. Especially the work of Cincotta, Jones and Walker [2] must be referred to here because the range of very high Reynolds numbers is particularly important for large structures. As for the nature of lift forces, these authors came to the following conclusions concerning different ranges of Reynolds numbers:

In Reynolds Number Range:	The Nature of Lift is:
1.4 to 3.5 million	Wide band random
3.5 to 6 million	Narrow band random
6 to 18.2 million	Random plus periodic

The Strouhal number determined from the autocorrelation functions increases with the increase in Reynolds number from 0.15 to 0.3, but the value 0.3 remains constant throughout the random plus periodic range.

So far, the previous measurements by Fung [4] and Roshko [14] agree with these results.

However, the measurements by Schmidt [18] in the range of Reynolds numbers up to 5 million led to another result. His power spectrum for lift force at R = 5 million has no well-pronounced peak. Contradictions of this kind occurred with other measurements too. It seems likely that these contradictions have their reason in differences in surface roughness of the body and the intensity and scale of the turbulence of the flow.

2.1 The effect of turbulence

The extent to which the behaviour of bluff bodies in wind can depend on turbulence is demonstrated by Fig. 4. The sharp peak caused by vortices in smooth flow completely disappeared due to turbulence and the character of response is quite different in both cases.

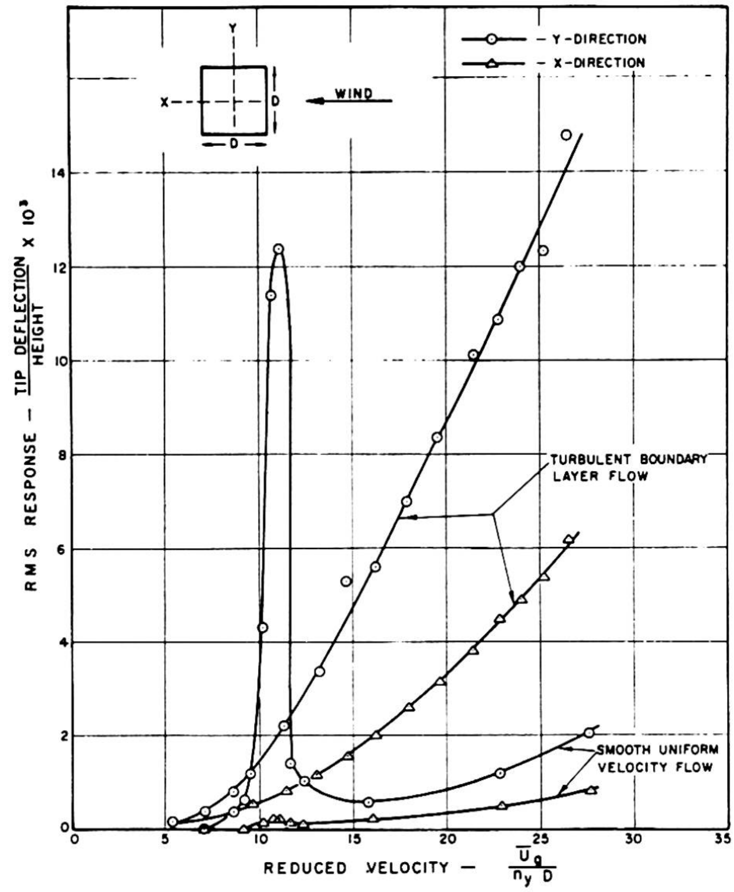

Fig. 4. Response of a Square Cantilevered Prism in Turbulent and Smooth Flow. (Measured in the Boundary Layer Wind Tunnel Laboratory of The University of Western Ontario by P. Rosati)

The turbulence and the surface roughness thus highly affect the nature of aerodynamic forces acting on the cylinder. These factors therefore also affect the value of the critical Reynolds number which divides the subcritical range from the supercritical one. Some information of this kind is provided by Simon [19]. Uncertainty in the estimation of the critical Reynolds number is sometimes very unpleasant.

For example, the columns of the large arch bridge mentioned in the introduction performed the strongest vibration at R = 551000. It was not quite clear in which regime the columns vibrated at this R. This made the decision of how to suppress the vibration difficult. Vibrations were decreased by filling the columns with granulated gravel. The efficiency of such a method depends on the regime of the flow round the body as discussed in paper [12]. This explains why this approach to the cure of vibration may fail in some cases, as was experienced with a Canadian bridge, whereas the same cure may be successful in other very similar cases [6,9,12].

This example indicates that the elucidation of the effect of atmospheric turbulence on the lift nature is really desirable.

2.2 Dependence of lift on the motion

The influence of the motion on the lift forces is a further important factor. To study it experimentally two approaches can be used: the motion is controlled by an exciter, or by changing the structural damping. The former way has been used more often.

In the range of random plus periodic lift at very high Reynolds numbers (6-18.2 million), Cincotta and associates [2] found a very strong increase in the lift with the amplitude at the coincidence of the frequency of excitation with the frequency determined by the pertinent Strouhal number. (This resonance case is of major importance). Assume that with small vibration amplitude v (with structures usually $v/D < 0.1$, even in very serious cases) this increase can be expressed by a linear law

$$\frac{C_L}{C_{L_s}} = 1 + k\frac{v}{D}$$

Here C_L is the lift coefficient at vibration with the amplitude v, C_{L_s} the lift coefficient of a stationary cylinder, k a constant and D the diameter. Then a coefficient $k = 47.0$ can be derived from data contained in paper [2], which means a considerable increase in lift with the amplitude.

In subcritical range, a much lower increase was found by Bishop and Hassan [1]. From their data a coefficient of $k = 2.25$ can be calculated for R = 6000 and small dimensionless amplitudes.

Finally, in supercritical range, characterized by random lift, Fung [4] did not find any remarkable increase in lift with the amplitude of motion. (See also [10]).

All these authors applied external excitation of the vibration. There is also a possibility of controlling the amplitude of the vibration without any interference with the mechanism of the excitation by changing only the intensity of damping. Plotting the resonance amplitudes against structural damping can provide some information about the character of excitation; however, even this involves complications. If the dependence of resonance amplitudes on the inverse value of the structural damping is linear (Fig. 5 curve a) the excitation may be supposed harmonic and independent of the amplitude. If this dependence has character, as curve b in Fig. 5, the reason for this may be the random nature of the fluctuating lift or the presence of positive aerodynamic damping. The latter factor is discussed in the next paragraph.

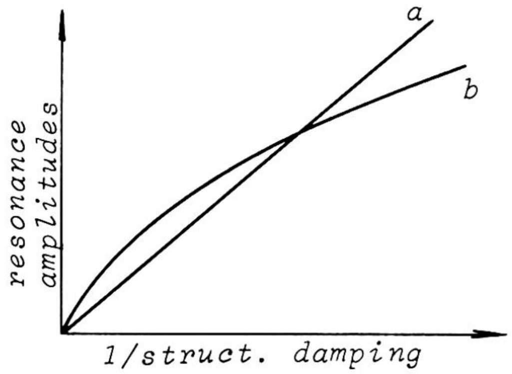

Fig. 5. Dependence of Resonance Amplitudes on Inverse Value of Structural Damping

2.3 Positive aerodynamic damping

Severe lateral vibrations usually occur with structures having extremely low structural (system) damping. In such cases the resistance of the air flow to the motion of the structure can result in a positive aerodynamic damping which is comparable with the structural damping. The intensity of the aerodynamic damping can be estimated as follows.

Assume a cylinder under two dimensional flow conditions moving with the velocity $\dot{v}$ perpendicularly to the direction of the wind blowing with the velocity V (Fig. 6), which is the situation with lateral vibration. Then the resultant relative wind with the velocity V_{rel} acts on the body under the angle of incidence α.

Neglecting the mass effect, the drag force on a unit of length has a component in the direction of the motion

$$F_y = \frac{1}{2}\rho C_D D V_{rel}^2 \sin\alpha \tag{1}$$

Here ρ is the air density and C_D the drag coefficient; with small angles α $\sin\alpha \doteq \tan\alpha = \dot{v}/V$ and $V_{rel} \doteq V$.

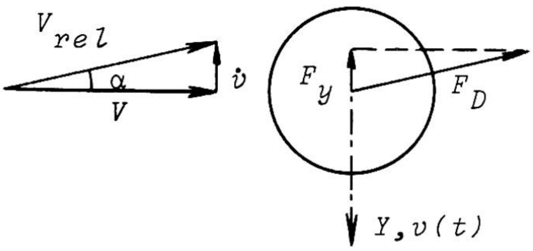

Fig. 6. Vibrating Cylinder in the Flow

The mean wind speed increases with the height of the structure which may be taken into account by putting

$$V(x) = Vw(x) \tag{2}$$

Now V means the wind speed at a reference point x_r and $w(x)$ a function describing the mean wind increase, so that $w(x_r) = 1$. Then the air resistance which acts on a differencial unit of length of a structure at position x is

$$f(\dot{v})dx = \frac{1}{2}\rho C_D D V w(x)\dot{v}dx \tag{3}$$

Under the assumption that this holds even during vibration (quasi-steady approach) this resistance of the wind to the lateral vibration evidently has a nature of viscous damping.

The exciting aerodynamic forces are small during the lateral vibration. Therefore steady lateral vibration cannot differ too much from the normal mode of free vibration $v_n(x)$ and may be expressed as

$$v(x,t) = av_n(x)\cos\omega_n t \tag{4}$$

where a is the amplitude at the reference point x_r, and ω_n the circular frequency of the n-th mode. The mode $v_n(x)$ is chosen in such a scale that $v_n(x_r) = 1$.

The work done during a period T of steady vibration by aerodynamic damping forces (3) on the whole structure is

$$W = \int_o^l \int_o^T f(\dot{v})dx dv(t) \tag{5}$$

After substitution from (3) and (4)

$$W = \int_o^l \int_o^T \frac{1}{2}\rho C_D D V w(x) a^2 \omega_n^2 v_n^2(x) \sin^2\omega_n t dx dt \tag{6}$$

and after integration with respect to t

$$W = \frac{1}{2}\pi\rho C_D D V a^2 \omega_n \int_o^l w(x) v_n^2(x) dx \tag{7}$$

The maximum potential energy calculated as maximum kinetic energy for the deflection (4) is

$$L = \int_o^l \frac{1}{2}\mu(x)\dot{v}^2 dx = \frac{1}{2}a^2\omega_n^2 \int_o^l \mu(x) v_n^2(x) dx \tag{8}$$

where $\mu(x)$ is the mass of the structure per unit of length.

Logarithmic decrement of damping can be defined as $\delta = \frac{W}{2L}$. This yields for log. decrement of aerodynamic damping with lateral vibration in variable mean wind

$$\delta_a = \frac{\pi\rho C_D D V \int_o^l w(x) v_n^2(x) dx}{2\omega_n \int_o^l \mu(x) v_n^2(x) dx} \tag{9}$$

Here the Strouhal number may be introduced.

$$S = \frac{\omega_n D}{2\pi V} \tag{10}$$

With constant mass $\mu(x) = \mu$ and constant mean wind speed $w(x) = 1$ the log. decrement of aerodynamic damping is simply

$$\delta_a = \frac{\pi \rho C_D D}{2\omega_n \mu} V = \frac{\rho}{4} \frac{C_D}{S} \frac{D^2}{\mu} \tag{11}$$

In variable mean wind but with constant mass, the log. decrement of aerodynamic damping

$$\delta'_a = \delta_a c \tag{12}$$

where the constant

$$c = \frac{\int_0^l w(x) v_n^2(x)\,dx}{\int_0^l v_n^2(x)\,dx} \tag{13}$$

expresses the decrease in aerodynamic damping due to variable mean wind velocity. This is calculated for some simple normal modes in Table 1.

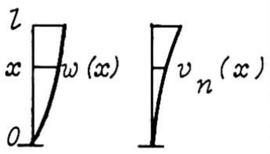	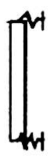					
Mode $v_n(x)=$	1		x/l		x^2/l^2	
Wind incr. $w(x)=$	$(x/l)^{\frac{1}{6}}$	$(x/l)^{\frac{1}{3}}$	$(x/l)^{\frac{1}{6}}$	$(x/l)^{\frac{1}{3}}$	$(x/l)^{\frac{1}{6}}$	$(x/l)^{\frac{1}{3}}$
Constants c	$\frac{6}{7}$	$\frac{3}{4}$	$\frac{18}{19}$	$\frac{9}{10}$	$\frac{30}{31}$	$\frac{15}{16}$

Table 1. Decrease in Aerodynamic Damping c Due To Variable Mean Wind Velocity

The wind increase $w(x)$ is taken here, as recommended by Davenport [3]. The exponent 1/6 corresponds to conditions in open country, 1/3 to centres of large cities. The top $x=l$ is considered the reference point. In other cases, the reduction c can be calculated from (13) or estimated according to Table 1, because its value is not too sensitive to the exact form of the normal mode and very little to changes in the wind profile with cantilevered structures.

The existence of the positive aerodynamic damping has been recognized and experimentally proven. From the point of view of structures, Scruton [16] and Davenport (e.g. [3]) pay a great deal of attention to this damping. Davenport experimentally studied it in detail and presented its general discussion [3]. However, the aerodynamic damping has found little application with lateral vibration of cylindrical structures, where it should be considered at least in two directions: when estimating the effect of changes in damping, and when evaluating the experiments.

The practical importance of the first application is evident from the numerical value of the aerodynamic damping.

The expression (11) provides constant damping for resonance vibration in regions in which C_D and S may be considered constant. In subcritical range with $S = 0.2$, $C_D = 1.2$ and $\rho \doteq 1/8\ kg\ m^{-4}s^2$

$$\delta_a = \frac{3}{16}\frac{D^2}{\mu} \tag{14}$$

In transcritical range for $S = 0.3$, $C_D = 0.54$ (see [2])

$$\delta_a = \frac{0.9}{16}\frac{D^2}{\mu} \tag{15}$$

In supercritical range the damping must be calculated with respect to the wind velocity.

The columns of the mentioned arch bridge have $D = 1\ m$, $\mu = 29.9\ kg\ m^{-2}s^2$ and the aerodynamic damping (14) is $\delta_a \doteq 0.0063$. The log. decrement of structural damping was of the same order, namely $\delta_s \doteq 0.0078$. Thus the total damping $\delta_a + \delta_s$ should be introduced into calculations. On the other hand, the increase in δ_a by application of strakes (spoilers) due to the increase in C_D (see [10]) contributes to the total damping and thus to the effectiveness of such advices.

As for the evaluation of vibration experiments, this task is complicated by the simultaneous presence of three factors: the aerodynamic damping, the randomness of lift (even when dominant frequency is well pronounced), and the dependence of excitation on the amplitude of motion. Neglecting the aerodynamic damping can therefore affect the result concerning the two latter factors.

3. Structural Damping

The structural damping represents a further factor, the estimation of which is always uncertain. It is very small with modern structures, often $\delta_s < 0.01$, which is the main reason for the frequent occurance of strong lateral vibration, especially with all welded structures. Finding suitable devices to provide a considerable increase in structural damping would, therefore, be the most important contribution to the practical part of the problem. (Reed and Duncan's [13] hanging chains represent an example of this kind.) Some effective coating or other means without any additional construction would be desirable.

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SUMMARY

Despite the increasing understanding of the lateral vibration of cylindrical structures, the preciseness of a quantitative calculation necessary for a reliable prediction is limited. For prediction of dynamic behaviour of large structures in wind, experimental investigation on models in wind tunnels is therefore most recommendable.

RÉSUMÉ

Malgré les connaissances croissantes sur les vibrations latérales des structures cylindriques, la précision requise pour une prévision valable n'est guère obtenue par un calcul quantitatif. C'est pourquoi on ne peut assez recommander des essais expérimentaux sur modèles réduits dans le tunnel aérodynamique quand il s'agit de prévoir le comportement dynamique d'une grande structure soumise au vent.

ZUSAMMENFASSUNG

Trotz des wachsenden Verständnisses seitlicher Schwingungen zylindrischer Bauwerke ist die Genauigkeit für eine quantitative Rechnung, notwendig zu einer wirklichen Voraussage, beschränkt. Deshalb ist für die Voraussage über das dynamische Verhalten langer, windausgesetzter Bauwerke die experimentelle Untersuchung im Windkanal am Modell das wohl empfehlenswerteste.

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