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Developments in Low-Speed Aeroelasticity in the Civil Engineering Field

Robert H. Scanlan*
Princeton University, Princeton, N.J.

The field of low-speed aeroelasticity in civil engineering has grown in application over the last four decades. Benefitting in broad terms from the guidance of earlier work done in aeronautics, the field has developed a distinct character of its own, centered principally on the problems of flows about bluff bodies. These problems can be conveniently classified into the categories of vortex-induced oscillation, galloping, flutter, and buffeting. Each has developed specialized theory based upon key experimental inputs. In particular, the field of suspension bridge aeroelasticity has received extensive experimental and analytical treatment since the days of the pivotal Tacoma Narrows incident. The present paper briefly outlines the state-of-the-art in civil engineering aeroelasticity, accompanying this with a number of appropriate references.

Introduction

By the time Eiffel Tower was built in 1889 in Paris, a generally sound sense had developed of the steady wind pressures to be considered in the design of important structures. In designing the tower, Eiffel is reported[1] to have assumed a steady wind pressure varying linearly from about 1.91 kN/m^2 (40 lb/ft^2) at the base to 3.83 kN/m^2 (80 lb/ft^2) at the top, 300 m above ground. For many years, right up to the Tacoma Narrows Bridge disaster in 1940, the only wind considerations used in civil design were static in nature. The Tacoma event initiated the era of aeroelastic considerations into civil engineering. In these, both the wind velocity and the structural motion may be considered highly time-dependent.

Civil engineering structures are, by aerodynamics standards, bluff bodies, and the flow over these unstreamlined objects becomes separated, the form of the wake becoming highly differentiated from that of the oncoming flow. The most distinguishing characteristic of the wake behind a bluff body is the shedding of vortices behind the body.

Often these are quite incoherent, and the wake is characterized simply as turbulent, its particular characteristics being a function of both incident flow turbulence and body-induced ("signature") turbulence. However, under certain circumstances—notably laminar or low-turbulence incident flow in definite Reynolds number ranges—the vortices shed into the wake roll up into a coherent, alternating pattern commonly known as a Karman-Bénard vortex trail. In a number of practical instances this phenomenon causes definite structural responses.

Generally, structural response itself induces additional aerodynamic *self-excited* forces. When it does so, an *aeroelastic* phenomenon is initiated. Four general classes of such phenomena have come to be known by the characteristic designations *vortex-induced oscillations, flutter, galloping,* and *buffeting*. These broad terms have taken on rather specific meanings as insights into each of the phenomena have deepened. Most of the aeroelastic phenomena occurring in civil engineering may be classified into these categories. All are in the low-speed flow regime since they are linked to the velocity of the natural wind, which rarely exceeds 112 m/s (250 mph) even in tornadoes.

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*Professor, Department of Civil Engineering.

Vortex-Induced Oscillations

In a wide range of Reynolds numbers of practical interest, rhythmic shedding of vortices from bluff bodies occurs, consonant with the relation $nB/U = \mathcal{S}$ where n is the frequency of shedding, B a cross-flow body dimension, U the wind velocity, and $\mathcal{S}$, ranging between 0.1 and 0.28, is the Strouhal number for the particular cross-sectional shape in question.†

When n satisfying the Strouhal relation approaches, for a given wind velocity U, a natural frequency n_b of the bluff body, the structure may be excited to resonance. This implies structural displacement, which in turn affects the boundaries of flow local to the body. Then it is observed that the body oscillation, once it has achieved a certain amplitude, takes over the control of the vortex shedding rhythm. This is the self-excited *lock-in phenomenon,* and it persists for a range of wind velocity beyond that required by the Strouhal relation for n to remain at the value n_b. Finally, at a wind velocity a few percent higher than the original lock-in value, the flow is distorted sufficiently that the lock-in ceases. The reason for this, in broad terms, is that there is, for flow over a moving body, a spectrum of fluid-induced forces acting on that body in which prominent spikes at both the Strouhal frequency n and the body natural frequency n_b are present. The greatest lock-in responses of both body and the fluid in its wake occur when n and n_b are very close to coincidence.

Many analytical models of this phenomenon—practically all empirical in nature—have been proposed. Most of these exceed in complexity those proposed by Strouhal,[2] Bénard,[3] and von Kármán.[4] Among the most successful has been that of Hartlen et al.[5] Simiu and Scanlan[6] discuss a number of these models; Blevins[7] also discusses this problem. An excellent and often-cited reference on experimental vortex shedding effects over a circular cylinder at high Reynolds numbers is Ref. 49.

In civil engineering the vortex shedding problem occurs mainly with reference to water flows around pilings, piers, and offshore tower legs, and wind flows about power line cables, flagpoles, chimneys, structural members, and bridge decks.

In spite of many attempts, the state of predictive theory for deflections in all these situations is relatively poor, not that such theory does not exist. The effort to predict the net aerodynamic forces on chimneys and the consequent oscillatory deflections may be exemplified by Ref. 8. Furthermore, most, if not all, of the existing theory requires a

†$\mathcal{S}$ may take on even higher values in supercritical regimes; values of $\mathcal{S}$ evolve, in fact, with Reynolds number.

strong experimental ingredient. Unfortunately for many wind-tunnel experiments on bodies with curved surfaces such as chimneys, the achievable Reynolds number does not coincide with that holding for full scale and the resulting Strouhal number for vortex shedding may be different from that for full scale.

For bluff bodies that do not have very rounded surfaces, it is generally believed that the Strouhal number for vortex shedding is not greatly affected by Reynolds number. The case of bridge decks is illustrated here. Scanlan and Wardlaw have discussed this case.[9,10] More recently, bridge decks have been treated analytically in Ref. 11, relative to vortex shedding. The analytical model proposed in that reference is nonlinear but not as complex as that of Ref. 5. It is therefore less versatile but gains in simplicity of application. As an example of the state-of-the-art, this will be discussed below.

Let h be the vertical displacement of a section model of a bluff structure of mass m, and assume it to be elastically supported, having a natural mechanical circular frequency of ω_n and a damping ratio-to-critical of ζ_n. The model under vortex excitation is then assumed to move in steady vertical (cross-wind) oscillation according to the equation

$$m[\ddot{h}+2\zeta_n\omega_n\dot{h}+\omega_n^2 h] = \tfrac{1}{2}\rho U^2(2B)H_0^*[1-\epsilon^2(h^2/B^2)]\dot{h}/U$$

where U is average cross-wind velocity, ρ air density, B a reference dimension of the body, and H_0^* and ϵ aerodynamic parameters to be identified.

These latter two unknowns require two identifying experiments with the bluff body. It is assumed, moreover, that the above equation governs oscillations at the phase of maximum amplitude during lock-in. This view coincides with the primary interest of the designer in predicting the limiting case in the prototype that the model represents.

Two convenient experiments at lock-in may be run with two different damping values, say ζ_{h1} and ζ_{h2}, accompanied by maximum amplitude excursions of h_{01} and h_{02}, respectively. It may then be shown[11] that the aerodynamic parameters H_0^* and ϵ have the values

$$H_0^* = \frac{R[\zeta_{h1}-(h_{01}^2/h_{02}^2)\zeta_{h2}]}{1-h_{01}^2/h_{02}^2}$$

and

$$\epsilon = (2B/h_{01})[1-R\zeta_{h1}/H_0^*]^{1/2}$$

with

$$R = 4\pi m\mathcal{S}/\rho AB$$

$\mathcal{S}$ being the Strouhal number for the bluff section in question and A the typical cross-wind dimension upon which it is based.

This model may be extended to three dimensions, as is described in Ref. 11. The approach outlined intentionally avoids the complexity of coupled oscillator models and focuses its usefulness in applications upon the case most interesting to the designer, namely, prediction of the vortex-induced "resonance" of greatest-amplitude response.

The topic of alleviation of vortex-induced response is treated in some detail in Ref. 6 and several other sources, a number of which are cited in the given reference. Undesirable vortex-induced oscillations are combatted in two basic ways: aerodynamically and mechanically. The first approach seeks to destroy the coherence of the shed vortex pattern through the use of spoilers, which may take the form of spiral strakes, shrouds, etc. The second approach opposes the vortex-induced motion by mechanical means, thus resisting lock-in. Much used in this context aside from ordinary stiffening, or increase of natural structural frequency, are forms of the tuned mass damper, notable ones of which are the so-called "Stockbridge" damper commonly used on electrical power line cables, and the dampers attached to exposed bridge structural members. Large tuned-mass dampers have been installed in the Citicorp Building in New York City, the John Hancock Building in Boston, and the Canadian National Tower in Toronto. Analogous dampers have also been used to damp the aerodynamically induced oscillations of heavy-water concentration towers in Canada.[9]

Flutter

Classical flutter of the lifting-surface type occurs when an aerodynamically forced coalescence of frequencies occurs between two degrees of freedom—flapping and pitching. Each may be positively damped in its own right, but flutter occurs through coupling of the two degrees of freedom, notably via the aerodynamic "stiffness" terms. This type of flutter occurs only relatively rarely with civil engineering structures.

A type that occurs, or might occur, much more frequently with bluff structures is separated-flow flutter, in which a single degree of freedom (notably torsion) is excited aeroelastically. Such activity may be characterized as an aerodynamic input to system damping, such that the overall value of the latter turns from positive to negative with advancing value of the cross-wind velocity.

The flutter of suspension bridges has been the most studied phenomenon of its type in civil engineering. References 6 and 11-14 offer full bibliographies in this area. Rather than reproduce here the equations describing the phenomenon, a discussion of the main developments will be presented. For details, the reader is referred to the literature cited.

The Pivotal Tacoma Narrows Flutter Episode

Although bridges were destroyed by wind in what were almost certainly flutter modes long prior to the Tacoma Narrows case of 1940, it was nonetheless the latter episode that came to mark the beginning of the modern era of aeroelastic studies of suspended-span bridges. Occurring as it did at a time when a considerable body of general aerodynamic and flutter theory and experience had been developed relative to aircraft, and when the vortex trail was already well recognized as a distinct fluid phenomenon, the Tacoma episode initiated studies that soon struck closer to the mark of identifying underlying causes than had previously been possible.

However, it may now be recognized that the record of that time does not—even in its successful solution of the problem—make altogether clear the aerodynamic mechanisms at work at Tacoma Narrows. The problem was actually solved empirically by Farquharson et al.,[15] who built and tested elastically suspended, geometrically similar section models of the prototype and determined which forms were stable or unstable in the wind tunnel. The replacement bridge had an aerodynamically stable truss-section deck, while the original bridge deck, which was highly unstable, consisted of a squat H-section with solid 2.44 m (8 ft) girders on the outer edges and a 12.20 m (40 ft) wide solid roadway between. It should also be noted that the original bridge was torsionally "weak," while the replacement was torsionally stiff. Cross sections of the original and the replacement Tacoma Narrows Bridge decks are depicted in Figs. 1a and 1b, respectively.

The original H-section was unusually vulnerable to wind, exhibiting vortex-induced vertical motions from the inception of deck erection. However, these relatively benign motions were not, in the final analysis, the catastrophic ones that brought the bridge down. Much confusion has been engendered about this point. Instead, it was a separated-flow flutter in the fundamental antisymmetric torsion mode that, in the last few minutes of the bridge's short life, wracked it. The famous movie footage of the event clearly testifies to motion in this mode. This particular mode had not been witnessed at all in bridge observations prior to about 45 min before the final collapse (Ref. 15, Part I, Chap. 3).

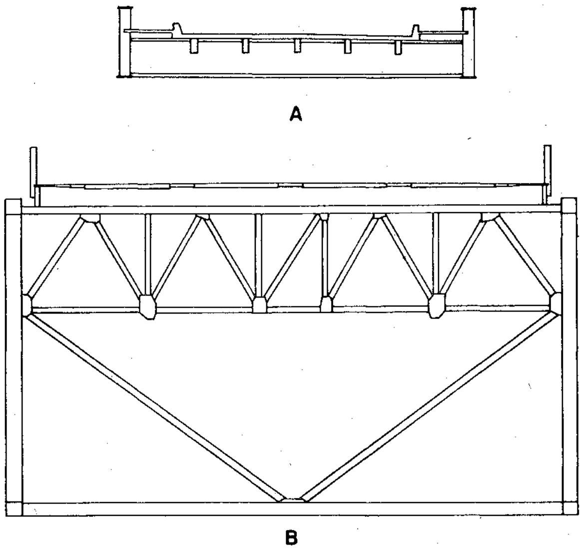

Fig. 1 Cross sections of a) original and b) replacement Tacoma Narrows Bridge decks.

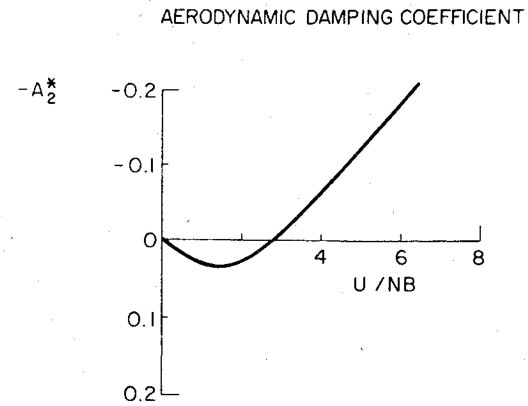

Fig. 2 Evolution of a parameter proportional to torsional damping ratio vs the dimensionless reduced velocity U/NB.

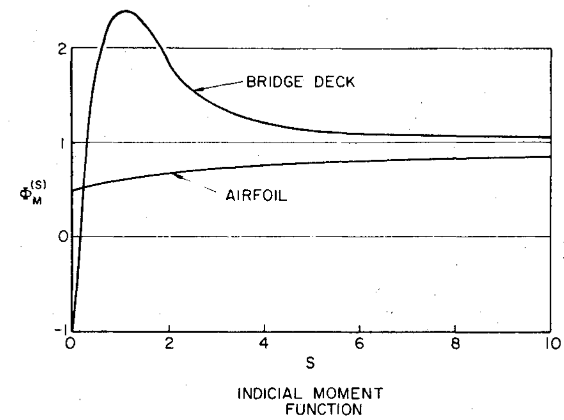

Fig. 3 Comparison of indicial lift (moment) functions for a bluff bridge deck section and a streamlined airfoil.

Unfortunately for the record, some of the writings of von Kármán leave a trail of confusion on this point. Perhaps the most glaring inaccuracy is his apparent insistence in his popular autobiography[16] that "the culprit...was the Karman Vortex Street." In fact, it can clearly be shown that the rhythm of the failure (torsion) mode has nothing to do with the natural rhythm of shed vortices following the Karman vortex street pattern. However, since a body with changing angle of attack does in fact shed *motion-induced* wake vortices, there was indeed a "non-Karman" trail of vortices shed, in flutter fashion, in the wake of the deck.

Others have added to the confusion. A recent mathematics text,[17] for example, seeking an application for a developed theory of parametric resonance, attempts to explain the Tacoma Narrows failure through this phenomenon. The result, however, is more confirmatory of the benign vertical oscillations of the bridge than of the low-frequency fundamental destructive mode.

If the single-degree-of-freedom flutter tendency is attributed to a change in the effective torsional damping due to aerodynamic causes, with increase of cross-wind velocity, this damping goes through an evolution, first starting out positive, then gradually reversing and becoming increasingly negative. This evolution of the torsional damping is the single most common characteristic of all bridge decks that exhibit instability under wind. It is not exclusively confined to H-sections but is found also with a wide variety of open-truss decks, a typical example being the Golden Gate Bridge. Such decks rarely exhibit any coherent vortex-shedding tendency, since their geometry "shreds" and disorganizes the flow. These observations tend further to dissociate the distinct phenomenon of bridge flutter in general from that of vortex shedding. A typical plot for many bridges is suggested in Fig. 2, wherein the evolution of a parameter proportional to torsional damping ratio is given vs the dimensionless reduced velocity U/NB.

Bridge Flutter vs Classical Flutter

Most bridge flutter, then, is not associated with the Karman vortex street, nor is it the same as classical two-degree-of-freedom flutter. Bleich[18] soon after the Tacoma Narrows incident, made an analytical study of bridge flutter using Theodorsen airfoil flutter theory. It has since been made manifest that such an effort is doomed to failure because of the huge physical dissimilarity between a bluff bridge deck section and a streamlined airfoil.

Scanlan and co-workers[19,20,22] have reiterated this point. A classical disproof of the applicability of airfoil flutter theory to bluff bridge decks has been through the comparison of indicial lift (moment) functions for the two cases (see Fig. 3). In the airfoil case, the well-known Wagner[21] function describes the monotonic increase in unsteady lift following a step change in angle of attack. In the typical bridge case the corresponding indicial function[20,22] is initially highly peaked and followed by a decay to steady conditions from above, rather than from below. Foersching[23] has stated that Theodorsen flat-plate aerodynamics in bluff-body contexts is "physically completely irrelevant." This is emphasized also by Selberg and Hjorth-Hansen.[24]

Because of the complexity of bluff-body flows, theory surrounding them, as in the case of bridge deck stability studies, has required a strong measure of experimentally based input rather than depending on a pure development from basic physical principles alone.

Typical Wind Studies for Long-Span Bridges

The most useful device in long-span bridge studies for wind stability has been, as stated above, the elastically sprung, scaled deck section model. Occasionally it has been useful to supplement this with a full-span aeroelastic model.[25] These latter are much more rare and costly. Therefore a trend has developed toward trying to get the maximum use from section models—mainly by treating them as analog sources of flutter derivative data and coupling the resulting information with analytical treatments for the full bridge. References 6, 13, 19, and 26 are descriptive of this trend.

When full-span aeroelastic models of bridges have been constructed, they have been tested under simulated scaled conditions of wind in the Earth's boundary layer. References

6 and 27-29 describe such simulation. It is not particularly easy to accomplish, especially as Reynolds and Rossby numbers are violated during standard testing with air at atmospheric pressure. However, assuming achievement of the proper scaling parameters, the full-span bridge aeroelastic model, though costly, serves as a complete analog of the gamut of conditions to which a given design may be subjected. With a full complement of such testing, no further analytical studies of response are required.

On the other hand, the study of section models first lends certain insight into appropriate geometric form and then yields mainly a set of sectional flutter characteristics that must be incorporated into further analytical studies. Reference 11 gives representative examples of such studies.

The very important initial contribution from section model studies is the determination of the appropriate geometric configuration of the deck section. Thus a number of single-roadway decks (as opposed to double-deck sections) have emerged streamlined in contour. A notable first in this regard was the Severn Bridge, followed by the Lillebaelt, Bosporus, and Humber designs. In the United States, several streamlined deck sections have appeared, notably the Pasco-Kennewick and Luling designs. Scanlan and Wardlaw[10] have reviewed a number of deck designs with comments on each. Ito and Shiraishi[30] have illustrated a number of typical approaches to deck section design used in Japan with aerodynamic stability as the main objective.

Galloping

Broadly speaking, the term "galloping" has come to be associated with large-amplitude, relatively low-frequency oscillatory instabilities induced by wind. The phenomenon probably first known by the galloping designation occurred in ice-coated power lines and was treated by Den Hartog,[31] whose criterion against incipient instability still stands:

$$\frac{dC_L}{d\alpha} + C_D < 0$$

where C_L is the (average) steady lift coefficient of the bluff section, C_D is its drag coefficient, and α is the angle of attack of the wind.

The phenomenon is analyzable in terms of such steady or *average* aerodynamic coefficients only because of the extreme detuning between the natural frequency of typical structural motion (low) and that of vortex shedding (relatively high), permitting the actual local pressure fluctuations to be ignored in the galloping context.

The nonlinear large-amplitude character of galloping has been assessed analytically by Parkinson[32] and Novak.[33] While such studies are important in understanding the full nature of the phenomenon, the Den Hartog criterion has been of most immediate use to the designer, since he is interested mainly in avoiding the phenomenon at its start.

A type of galloping called "wake galloping" can occur when an elastically sprung object lies in the wake, or sheared flow, of another object. Such instability has been observed with bundled power lines.[34]

Practical solutions to vertical cross-wind galloping have not been easy to come by in practice, since the configurations (icing) causing it have been transient and because large amplitude self-excited oscillations are hard to damp. Since the near-circular sections of power lines do not permit galloping, one effective solution has been to avoid ice formation by permitting a power line to heat up to the ice-melting temperature. Wake galloping, on the other hand, is best avoided by arranging, if possible, that the wake of one object be rendered as incoherent as possible when impinging on a downstream object. In power lines this can be accomplished to some extent through the use of uneven spacers that tie bundles of conductors together.

It is of interest to contrast galloping, vortex-induced oscillation, and flutter. While each occurs at or near a natural frequency of the structure in question, the frequency of galloping is usually so low that the motion is effectively detuned from other motions; and because of the low translational velocity involved, steady-state (as contrasted to motional) aerodynamic derivatives are usually adequate for the analytical description of the phenomenon. As a matter of fact, the "steady-state" derivatives so used are actually time averaged during the course of detailed flow events that may well include vortex shedding at a fairly high rate. The important structural deflections under both galloping and vortex shedding are mainly translational, across-flow (or occasionally along-flow); in flutter, the single most important motional component is rotational. Under vortex shedding, the structural deflections are self-limiting in amplitude, basically through fluid-dynamic effects; whereas under galloping and flutter, they are not, and can instead proceed to destructive proportions.

Buffeting

In boundary-layer flows of the Earth's atmosphere, passage of air over terrain, trees, buildings, etc., sets up turbulence. This incident turbulence causes intermittent air pressures upon surfaces encountered. Further, the objects of particular study, typically buildings and bridges, that the wind strikes, themselves trip off additional signature turbulence that further causes iregular pressures over the body, particularly over the aft surfaces. Thus the primary wind problems of civil engineering structures are due first to steady wind pressures and second, to the fluctuating pressures due to incident and signature turbulence.

For the most part, structures are so stiff that buffeting by turbulence, while causing some structural motion, does not induce self-excited aerodynamic forces ascribable to that motion. It may be argued that along-stream motion induced in buildings, even when appreciable, is almost invariably such as to add small aerodynamic damping to the system. On the other hand, cross-wind motion of buildings may exhibit a certain amount of negative damping contributed by the flow. Most buildings exhibit random sway under wind, the across-wind motion being comparable to the along-wind. Reference 6 deals in some detail with the nonaeroelastic response of buildings to frontal buffeting, and some results of general wind-tunnel tests on aeroelastic models of buildings are cited therein. In wind-tunnel tests of multistorey buildings, which deflect as shear beams, the first mode being practically a straight line, the aeroelastic building models often consist of rigid forms articulated and sprung only at the base. It is suspected, however, that those buildings subject to twist may occasionally undergo more important aeroelastic excitation. Few cases of this have been authenticated to date.

Bridges, however, when long enough in span to permit appreciable deflection, have exhibited self-excitation during buffeting. Again, an example is the Golden Gate Bridge.

The bridge buffeting problem was first formulated by Davenport,[35] following many of the aircraft buffeting precepts laid down by Liepmann.[36] Some time later, Simiu,[37] Scanlan and Gade,[38] and Scanlan[26] laid down an analytic theory of bridge buffeting that included the evolution of bridge section flutter derivatives in the process. Irwin[39] and Holmes[40] have contributed notably to analytical studies of bridge buffeting, with observation of the aeroelastic nature of the whole phenomenon. Japanese contributions along these lines are typified by Refs. 41 and 42.

The analytics of the buffeting problem are accompanied by a number of difficulties, notably the possible inadequacy of the linear superposition ideas most commonly used. A particular problem is whether or not mean-flow flutter derivatives remain valid under incident turbulence. While one study of this has been made by Scanlan and Lin,[43] this question has not been conclusively answered. One avenue of attack on this problem has been opened by Ref. 44, wherein a flap system providing large-scale turbulence to a bridge deck section model can be used to verify the model's aerodynamic admittance and flutter derivatives under incident turbulent flow of proper scale.

It is well worth noting, however, that instances of near-laminar flow have unexpectedly been observed over buildings by Durgin[45] and bridges by Teunissen[46] at fair elevations. These phenomena suggest that one cannot *count* on turbulence in the Earth's boundary layer on all occasions.

In some instances, the presence of turbulence can alleviate aeroelastic problems, notably the manner in which flutter of suspension bridges occurs. Under turbulence, onset of flutter is substantially delayed, whereas in purely laminar flow it initiates quite abruptly. It is therefore quite striking that, in nature, where turbulence is usually present, it should not be relied on in all design situations.

Some possible reasons why turbulence delays the onset of bridge flutter have been discussed by Scanlan.[26] Most probably, its presence excites the participation of many structural modes which, given a certain amount of aeroelastic coupling among them, act like energy dispersers, or tuned mass dampers, with respect to one another. Another source of intermodal coupling, namely, certain nonlinear structural characteristics, has recently been called to the author's attention by Abdel-Ghaffar.[47]

An important area, not adequately dealt with in the present paper, but concerned with phenomena of a strictly analogous nature, is the ground wind effects on prelaunch space vehicles. Reference 48 describes the treatment in this field.

Conclusions

A brief overview of a representative range of aeroelastic problems occurring in civil engineering has been given. These fall conveniently into the categories of vortex shedding, galloping, flutter, and buffeting. All of these phenomena, in their various aspects, are concerned with flows around bluff bodies. In this circumstance, though analytical models are necessary and useful in the attendant studies, basic experimental contributions are indispensable, since the flow characteristics observed are rarely calculable from first principles.

The study of aeroelasticity in the civil engineering context has, however, benefitted greatly from the literature and examples set forth by aeronautics; yet this literature has had to be taken more as a general guide to methodology than as a fullblown, directly transferable set of precepts. The chief intervening physical factors have been the strongly different flows about the typical bluff body seen in civil engineering as against those surrounding the highly streamlined bodies common in aeronautics.

In the last two decades, a number of conferences and symposia have been held that included papers on the wind and other fluid-interactive effects upon civil engineering structures. References 50-63 are proceedings of such conferences, listed for the interested reader.

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