Weighted combinations of pressures, required in order to assess wind-induced moments for example, may be obtained by clustering together small numbers of pressure taps within common tributary areas on the exposed model surfaces. These in turn provide a discrete weighting to that tributary area by way of the averaging process within the manifold.

Ordinarily, pressures are measured relative to some reference pressure by connecting the reference pressure to a small cavity on one side of a pressure transducer membrane and the subject pressure to a cavity on the other side. One may, however, assess net wind-induced loads across structural elements by connecting single tap or manifolded pressures from different model surfaces to each side of the transducer membrane, thereby measuring the pressure differential. This approach then requires special consideration of the appropriate reference pressure that is no longer directly accounted for. It also requires small volumes on either side of the transducer membrane; not all commercially available transducers are suitable.

In all of these approaches, pressures at the surface of the model are transmitted to a pressure transducer located at some distance—either within the model or outside of the tunnel. Flexible plastic tubing with inner diameters of 1/16 in. or less is typically used. Except in the case where only mean loads are of interest, it is important that the frequency content of the fluctuating loads be correctly represented and that the average represents that of simultaneously occurring pressures. Therefore, it is crucial in these set-ups that the frequency response of the pneumatic transmission be properly considered. The fluctuating pressures at all frequencies of interest must be adequately transmitted to and measured by the transducer. Otherwise, some specific means of accounting for signal distortions must be implemented. Both the magnitude and phase of the frequency response should be considered. The magnitude consideration addresses the potential distortion in the signal level for various frequency components, while the phase consideration addresses potential distortion in the simultaneity of the pressures from different locations.

In all cases where the effective pressure acting over a tributary area is evaluated from a single pressure tap, it is necessary to consider carefully the extent of the tributary area and whether the measured localized pressure will adequately represent it. For example, appropriate tributary areas near sharp building corners should be smaller than those necessary in central areas of a building façade, because pressure gradients are typically greater near corners.

Porous-Polyethylene Cavities. More direct measurement of area pressures has been achieved using porous polyethylene materials in the model construction (e.g. Vickery et al. 1985). Porous polyethylene sheets approximately .005 to .020 in. in thickness are porous enough to effectively transmit fluctuating pressures in the dynamic range relevant for area loads, while still being solid enough to provide the aerodynamic geometry required for the model surface. In this approach, a small cavity is built into the model and covered by a thin sheet of polyethylene mounted flush with the exterior surface of the model and leaving a small pressure equalization volume behind it. The wind-induced pressures acting over the exterior surface are transmitted to the cavity and the averaged cavity pressure is measured using a single internal pressure tap. The technique is effective and offers a greater spatial resolution than using the multiple pressure tap approach. However, the model construction is considerably more involved.

On-Line Averaging. Averaging of measured pressures can also be done by combining the electronic transducer signals from individually measured local pressures. Analog averaging of the electronic signals from the transducers is possible. However, this is now rarely undertaken because digital sampling and averaging are more powerful, flexible, and cheaper.

Simple weighting to account for tributary areas, as well as negative weighting for net or differential loads, or the evaluation of moment loads are all handled similarly by software programming of the appropriate weighting values. The approach is discussed in Surry and Stathopolous (1978).

As with the pneumatic averaging approaches, careful consideration must be given to the appropriate distribution of local pressure taps and the frequency response of the systems carrying the pressures to the transducers. Unlike those approaches, the digitized signals may be manipulated to account for frequency response distortions or asynchronous sampling procedures.

Pressure Averaging for Modal Loads. The approach described previously of averaging pressures pneumatically has often been used because it reduces the number of pressure transducers required. This is advantageous because of both the size and cost of pressure transducers; however, the advent of compact solid-state pressure transducers is changing this picture. The ability to simultaneously measure large numbers of local pressures has prompted the development of techniques that use pressures measured over much larger areas of the structure or even the entire structure. The drop in the cost of computing and data storage has made it feasible to collect and process much larger data sets than previously. The following approach is one result of these advances.

Modal Loads from Integrated Pressures. The approach of integrating individually measured local pressures to assess modal loads is an expansion of the on-line averaging approach described in the previous section. It offers an alternative to the force balance approach of measuring modal loads in appropriate situations. The potential exists to apply this technique to a wide variety of structures, including long-span roofs, stadia, and even bridges. It can handle higher frequency modes, requires no mode shape corrections, and can be readily used to evaluate the generalized forces of modes with coupled degrees of freedom (3-dimensional mode shapes).

Proper measurements of overall loads require a large number of simultaneously measured local pressures in order to fully capture the pressure field acting on the exterior surface of the entire structure. The advent of solid-state pressure scanning instrumentation has made this a viable task, but the required pressure tap coverage remains an issue of debate. Opinions on the number of pressure channels for a typical high-rise building model, for example, range from 200 to as high as 1000. The following considerations should be kept in mind when determining the required number of local pressure measurements:

- In evaluating overall mean loads, the spatial resolution required is greater, because the static pressure field over the exterior surface of the structure must be adequately resolved and may have areas of high-pressure gradients, particularly near corners and other flow separation points. On the other hand, mean loads do not require that the pressures be measured simultaneously, so that pressures from sequential tests may be combined.
- The dominant contribution of any modal load is the result of pressures fluctuating at the modal frequency. Fluctuating pressures are generally correlated over distances inversely related to the frequency. In other words, the higher the fluctuating frequency, the more localized the fluctuating pressures. There are notable exceptions to this, such as vortex shedding, where the fluctuations can become highly correlated over a narrow range of frequency. For most large building structures the correlation distances of the pressures fluctuating at the important modal frequencies (i.e., the first two or three modes) are of the same order of magnitude as the structure itself. This fact helps to reduce the spatial resolution of measurements required for assessing modal forces.
- Pressure fluctuations at frequencies lower than that of the fundamental mode of the structure contribute to the quasi-static or background loads. These loads can be important for some structures and simultaneous pressure measurement can provide a good indication of their distribution and magnitude. A pressure tap distribution, appropriate for mean loads, is required in this case.
- For many structures, vortices form at the windward edge and travel along the side of the structure in more or less discrete packets. Pressure taps must be placed sufficiently close if they are to capture the resulting dynamic loads. Spatial aliasing is another concern. This requirement may exceed that for mean pressures loads.
- Many buildings and structures have complicated architectural treatments that are difficult to adequately cover with pressure taps.

- Where higher modes are important, simultaneous pressure measurements have a distinct advantage.

Until further experience is accumulated, the requisite number of simultaneously measured pressures ought to be judged with particular care and on a case by case basis.

The modal loads acquired from this technique may be accumulated and analyzed in either the time or frequency domain. The methodology is discussed in Steckley et al. (1992) and Irwin and Kochanski (1995).

C5.2.2 Direct Load Measurements

High-Frequency Force Balance. The high-frequency base balance technique, first reported by Tschanz (1982), is based on an earlier approach used by Whitbread (1975). It is now a widely accepted technique for wind tunnel model studies. It offers a relatively economical and expeditious alternative to the more involved aeroelastic procedure. The technique involves the use of a very stiff high-frequency balance-model system that models only the exterior geometry of the structure. The wind tunnel study may be carried out at a stage in the design when only the exterior geometry of the structure has been fixed. When they become available, the remaining structural properties are combined analytically with the wind tunnel data to determine full-scale responses. The measured quantity in the aeroelastic procedure is the final response. In the base balance technique, on the other hand, it is the spectra of modal forces that are measured experimentally. The responses of the structure to these modal forces are then determined analytically. Changes in the structural properties can be readily accommodated by iteration of the analytical procedures. Parametric studies, in which the responses are predicted as functions of the structural parameters, are often feasible. Importantly, it is unnecessary to retest a new wind tunnel model unless significant changes in the exterior geometry are made.

The idea of measuring the modal force spectrum and then calculating the responses as they would occur for varying structural parameters had been considered prior to the development of the current base balance technique. Saunders and Melbourne (1975) attempted to record the modal spectrum by measuring it as seen through the mechanical admittance of an aeroelastic model. By knowing the model properties, reverse calculation yielded the modal spectrum which could then be combined with the desired structural properties. Major difficulties with this procedure are the errors introduced through the aeroelastic model properties, in particular the estimate of the damping. Measurements of modal force have also been made using pressure models, and this is discussed in the previous section.

Principles and Assumptions. The fundamental premise of the base balance technique is that the generalized or modal forces resulting from the wind can be estimated from the measured base moments experienced by a stationary model. The modal force is defined as the integral of the applied force weighted by the mode shape at the point of application.

A fortuitously similar quantity to the modal force occurs in the more easily measured base overturning moment. In this case, the applied forces incur a weighting naturally through the moment arm influence line, which varies linearly with height. When the mode shape is proportional to the influence function, then the modal force and the base overturning moment are also proportional.

A similar approach can be taken for the twist modal force and modal torque. In this case, the loading is the torque per unit height, but the base torque influence line which is constant over the height of the structure, is less representative of twist mode shapes.

The base moments, including two overturning moments and the base torque, represent direct and exact measurements of the modal forces on a structure when the following conditions are met:

- The first three natural modes of the structure are decoupled and geometrically orthogonal in two sway directions and one twist direction.
- The fundamental sway mode shapes are linear functions of height and pivot at a point where the moments are measured.
- The fundamental twist mode shape is a height independent constant over the height of the structure.
- There are no significant motion-induced forces involved and so the nature of the forcing remains the same on a responding structure as it is on a stationary structure.
- The balance-model system is essentially rigid, with a high natural frequency, so that the measured moments are not significantly amplified by the mechanical admittance of the system in the frequency range of interest.

In practice these conditions are never fully met. However, in most situations adjustments can be made for all of these difficulties, with the exception of the possible effects of motion-induced forces.

The technique is also limited in that only the fundamental modes in each direction can be reasonably estimated. It must be assumed that contributions to the response from higher modes are negligible. Also, only limited information is obtained on how the mean and non-resonant time-varying loads are distributed over the structure. Such information, however, can be estimated or measured in a companion study of local pressures. A "second-generation" base balance approach, aimed at overcoming some of these limitations, is discussed in a later section.

Adjustments for Base Balance Mechanical Admittance. It is necessary that the base moments used to represent the modal forces be the moments as measured on a nearly rigid model. If the balance-model system responds dynamically to the wind loading, then the measured base moments will include the inertial loading effects of the system itself. If the motions are large, then the aerodynamic interaction of the model with the wind could also contaminate the measurements. Therefore an attempt is made to make the balance-model system as rigid as possible, while still being sensitive enough to provide reasonable signal strength. In this way the frequency range of interest falls at the low end of the mechanical admittance function of the model-balance system, where the dynamic amplifications are small. In some cases the natural frequency of the system cannot be raised sufficiently high and the base moment measurements are amplified. There is in principle no difficulty in adjusting the spectral density measurements to account for this, providing the mechanical admittance of the system is well identified and may be treated as linear and uncoupled. It is always assumed, however, that the frequency is still high enough that the model motion is insignificant.

Adjustments for Mode Shape. The assumption of a constant twist mode shape with height or that the modal amplitude of the fundamental torsional mode is independent of height is never true for real structures. A typical fundamental twist mode shape of most tall buildings lies somewhere near a linear function of height. In practical cases, the majority of the contribution to the torsional modal force comes from the upper half of the structure. The measurement of the base torque from the base balance may be made more representative of the generalized torque by artificially sheltering the lower portion of the model in such a way that the aerodynamic interference of the sheltering device is minimal. This is not easy to achieve and a more practical approach is to make adjustments to the measured base torque, as was suggested by Tschanz (1982). He argued that a realistic measure of the base torque relative to the generalized torque is given by the ratio of the measured base shear and base moment. Some experimental data for such comparisons are available. It is generally agreed that a value of about 0.70 represents an adequate empirical adjustment factor to apply to the measured base torque.

Although approximating the sway mode shapes by a linear function is sufficient in many cases, tall buildings and structures having mode shapes that significantly deviate from this approximation are not uncommon. The variation in mode shape can have a significant effect on the similarity of the modal force and the measured base moment spectral densities. Measurements aimed at quantifying these effects have been carried out by various researchers. The effect, which deviations from a linear mode shape function have on the final predicted response, differs depending on the type of response considered. The most notably affected response is the predicted acceleration. In the case of acceleration, the mode shape appears in the analytical portion of the response estimate, as well as the measured quantity. This accentuates the errors arising from the assumption of a linear mode shape. Typical corrections to predicted accelerations near the top of a structure because of non-linearly varying mode shapes may reach 20%. Further discussions of the effect of mode shape on building response estimates derived using the force balance technique are given in Vickery et al. (1985), Holmes (1987), and Boggs and Peterka (1989).

Treatment of Coupled Degrees of Freedom. Many structures, particularly buildings of more complex design, can exhibit coupling between the sway and twist motions and between the two sway directions. Modified base balance techniques may be used to estimate the modal forces in situations of coupled modal coordinates. Multi-degree-of-freedom aeroelastic models are another alternative.

Ideally, a relatively complete approach to the problem would be to measure, in any convenient coordinate system, the complete spectral density matrix of the actual modal forces, including the cross-spectra. The spectral density matrix can then be combined with the mechanical admittance matrix, as defined in a consistent coordinate system, to get the spectral density of the response. Because the mechanical admittance is most easily defined in the modal coordinates, it would be prudent to first transform the spectral density matrix of modal forces to the modal coordinate system.

The practical difficulty is the measurement of the modal forces. It must be remembered that the base moments only represent an approximation to the modal forces and only do so when measured in the modal coordinates. Coupled degrees of freedom represent a further complexity when making these representative measurements. Some progress can be made in cases in which it can be assumed that the base moments and torque represent proportional measurements of separate modal forces. This means that the twist response is largely contained in one mode and that the sway modes, although coupled, still lie in basically vertical planes. It then becomes valid to measure the base moments in a predefined coordinate system and then transform them to modal coordinates. Consideration should still be given to the poorer representation for the twist mode provided by the base torque.

Some linear combination of the measured base moments at each time instant may be used as an approximation to the generalized modal load. The weight factors for each moment must be carefully synthesized by a process that accounts for the component coupling as well as for the nonideal mode shapes. Once the generalized load is transformed to a generalized response by the mechanical admittance, it is frequently required that the response be decomposed into the various component directions. The total dynamic resonant response in each component direction can then be obtained by meansquare addition of the corresponding component from each contributing mode. See Tschanz (1982) and Irwin and Xie (1993) for details.

In frequency domain analyses for lightly damped systems with well separated frequencies, it is an accepted practice to neglect the off-diagonal terms of both the spectral density matrix of the modal force and the mechanical admittance matrix because they contribute little to the final response. Neglecting the cross-terms, however, only applies to the matrices AFTER transformation to the modal coordinates. In general, cross-spectra measured in standard or predefined coordinates can make significant contributions to the autospectra in the modal coordinate system. Note also that by the very nature of coupled systems, the frequencies may not be well separated. Only separation of a few percent in frequency is necessary to diminish the cross-modal response, but in situations in which this cannot be ensured, it is advisable to consider these effects. Where needed, a method to avoid this complication is to perform all calculations in the time domain. Time domain analysis has complications of its own and must be implemented carefully.

Force Transducers on Substructures. It is possible to mount components of a structure on force transducers and to get direct measurements of the wind-induced forces that are experienced. Examples are sections of bridge decks, segments of roofs, masts, and antennae, and so on. Such transducers must be sufficiently stiff to avoid local resonances of the transducer/substructure system.

C5.2.3 Miscellaneous

There are other techniques, which are less commonly used, but which have advantages for some applications. Two of these are briefly discussed in the following sections.

Multi-Level Force Balance. An extension of the high-frequency force balance technique that is usually implemented as a base balance is the multi-level force balance (Reinhold and Vickery, 1990). This has also been referred to as a second generation force balance. By measuring moments and shears at multiple levels, an improved estimate of the modal loads may be obtained, particularly in cases where the real mode shapes are not well represented by the idealized mode shapes inherent in the base balance approach. This is particularly true of torsion about the vertical axis of the structure and non-linearly varying sway modes.

The multiple force balance technique has the advantage that it does not require extensive pressure transducer equipment. However, it does require a specialized balance and more complicated models than its alternatives.

Forced Oscillation. The forced oscillation technique is used to determine information about the motion-induced or aeroelastic forces acting on a structure. These are the wind forces on a structure which are induced by the motion of the structure through the air (Scruton 1963). In absolute terms, these forces are often relatively small compared to the random wind forces and the inertial and elastic forces of the structure itself. However, because they are correlated with the structural motion, they can be thought of as wind-induced damping and stiffness forces, which effectively modify the structural damping and stiffness.

The technique of forced oscillation has become more common with the advent of solid-state pressure transducer equipment.

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