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Factors affecting Response of Buildings to Wind and their Experimental Determination

Eléments ayant une influence sur la réponse d'édifices aux vents et leur détermination expérimentale

Faktoren, die die Reaktion von Gebäuden auf Windbelastungen beeinflussen und ihre experimentelle Bestimmung

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Wind action on buildings and structures has both static and dynamic effects. The static effects are primarily concerned with steady displacements obtained from steady forces and pressures resulting from time-averaged wind velocities. By custom, buildings have been designed to resist these effects. Dynamic effects, on the other hand are concerned with the tendency to set the structure oscillating. Increasing use of tall slender buildings with lightweight cladding and large column-free floor areas has forced engineers to pay much more attention to dynamic wind effects. Structural damping is a major factor which should be taken into account in this respect, since to decrease the resonant amplitudes of oscillation the dissipation of energy through structural damping must exceed the relevant energy inputs from the wind.

By applying the statistical theories used for communications technology the analysis of atmospheric turbulence is effected and its characteristics are represented by its energy spectra, its lateral correlation functions, and its probability distribution. Studies made to date, indicate that for heights up to that where the gradient winds prevail, variation in mean wind speed generally follows a power law profile, the exponent of which varies with ground roughness from about 0.15 for open unobstructed country to around 0.43 for heavily built-up urban centres, according to DAVENPORT [1] .

Investigations made by DAVENPORT [1] and SHIOTANI [2] show that the spectral density varies with the surface drag coefficient, which is a function of the ground roughness. Except for some slight falling-off of energy with height, spectra obtained at different locations are more or less similar in shape and this has led DAVENPORT to suggest a universal type of formula:

$$\frac{n\ S(n)}{K\ \bar{V}^2} = C\ \frac{x^2}{(1+x^2)^{4/3}}$$

where n is the frequency; $\bar{V}$ is the mean wind speed; K is the drag coefficient; x is directly proportional to $\frac{n}{\bar{V}}$ and C is a constant.

Spatial correlation studies by the same investigators yield a spatial correlation coefficient, (i.e. $\sqrt{\text{coherence}}$), approximated by the exponential function:

$$R \propto e^{-\frac{\Delta S}{L}}$$

where Δs is the spatial separation and L is the scale of turbulence proposed by TAYLOR [3] . But in this respect, SINGER,[4] investigating radio masts, found the spatial correlation coefficient of similar wind components measured at different heights to be a function of the height ratio. Moreover, he found that within his range of interest cross spectra were essentially zero.

Apart from considerations of stability against time-averaged wind forces, the designer of tall buildings must also concern himself with the direct consequences to his structures of the fluctuating dynamic character of the wind. These include, inter alia, collapse of the structure due to peak load or fatigue; minor damage to the fabric, lift shafts, or partitions arising either from excessive deflexion or high local loading; and discomfort to the occupants caused by high sway accelerations.

Preferably, design factors should be simple and easy to apply. In this respect DAVENPORT'S simplified dynamic approach, using a gust factor G which takes into account the dynamic characteristics of the structure, has much to commend it. He suggests on expression for the wind pressure, p , at a point on the structure given by:

$$p = G\,\bar{p} = \left(1 + g\,r\sqrt{B + \frac{SF}{Y}}\right)\bar{p}$$

where:-

h = structure height

n_o = fundamental natural frequency of structure

T = time interval used for finding averages;
$\bar{V}$ = design velocity;
g = peak factor depending on n_o, and T;
r = roughness factor depending on ground conditions and h;
B = excitation from background turbulence, depending on h
S = scale factor depending on height/width ratio of structure n_o & $\bar{V}$
F = wave number at resonance = $n_o/\bar{V}$
γ = critical damping ratio;
$\frac{SF}{\gamma}$ = excitation due to resonant turbulence.

Essentially, these formulae predict the static equivalent load corresponding to the maximum deflexion. In applying them to natural gust loading, investigators have made several assumptions, including the following:

(i) wind is a stationary random process
(ii) variation of wind velocity with height follows a power law
(iii) velocity distribution is Gaussian in character
(iv) pressure coefficients are independent of frequency.

In order to assess correctly the effects of wind on a building it is necessary to know the spectrum of the wind; its spatial correlation, and the dynamic characterestics of the building. The dynamic characteristics include a knowledge of the natural frequency of the building and its damping. These are given by the following equations:

$$\frac{1}{\omega_r^2}[K]\{X^{(r)}\} = [M]\{X^{(r)}\}$$

$$\frac{1}{2\beta_r\omega_r}[C]\{X^{(r)}\} = [M]\{X^{(r)}\}$$

where the matrices $[K]$; $\{X^{(r)}\}$; $[M]$ and $[C]$ refer to the stiffness; the column mode shape; the mass and the damping, respectively. The results derived from application of these equations depends on the accuracy of determining the elements in $[K]$ and $[C]$. The elements in $[K]$ depend on the type of the structure and the properties of the materials used. Such factors as column and beam deformation; rotation of joints; floor and wall deformation; soil distortion and rigidity of foundations must be considered. Because of difficulties in obtaining experimentally the necessary information from full-scale buildings considerable reliance has had to be placed on mathematical models in order to evolve the methods of analysis now available.

Correlation of model tests with the behaviour of full-scale buildings has been attempted by several investigators using three different types of approach. One of these, known as the resonance method, involves excitation of the building by means of a vibrator; the second makes use of run-down tests by pulling the building laterally and letting it go; the third relies on wind as the means of excitation, and a somewhat similar method developed by TANAKA [5] , involves measurement of minute vibrations excited by irregular forces such as microtremors and others

NIELSEN [6] has shown that decay tests can lead to overestimation of structural damping by several hundred percent, and he has succeeded in obtaining vibration characteristics of a 9-storey steel-framed building by steady-state tests. From the natural frequencies, damping and mode shapes obtained for several modes in this test he found the stiffness matrix giving the "best fit" to the modal properties determined experimentally. But NIELSEN'S experiment showed that any increase in the force level applied produced a corresponding increase in percentage damping and a slight decrease in resonance frequency. He also found for his building an additional mode of vibration, further to the normal modes, generated by the floor slabs vibrating laterally in phase as deep horizontal beams.

Similar investigations have been carried out by ENGLEKIRK & MATTHIESEN [7] on an 8-storey reinforced concrete building combining rectangular frames with shear walls, and by CRAWFORD & WARD [8] , using random wind excitation on a steel-framed building with a central concrete core. In the latter instance the natural periods were computed both for frame action only and for frame and core combined. The experimental results lie somewhere between the two values calculated and the ratios of the first three modes of vibration are not in agreement with the observed ratios. The investigators considered that this discrepancy resulted either from the fact that the window sections were not considered in calculating the shear stiffness and/or possible beam flexure and non-interaction of the core and structure. No measurements were taken simultaneously on the central core and on the framed structure to confirm this hypothesis.

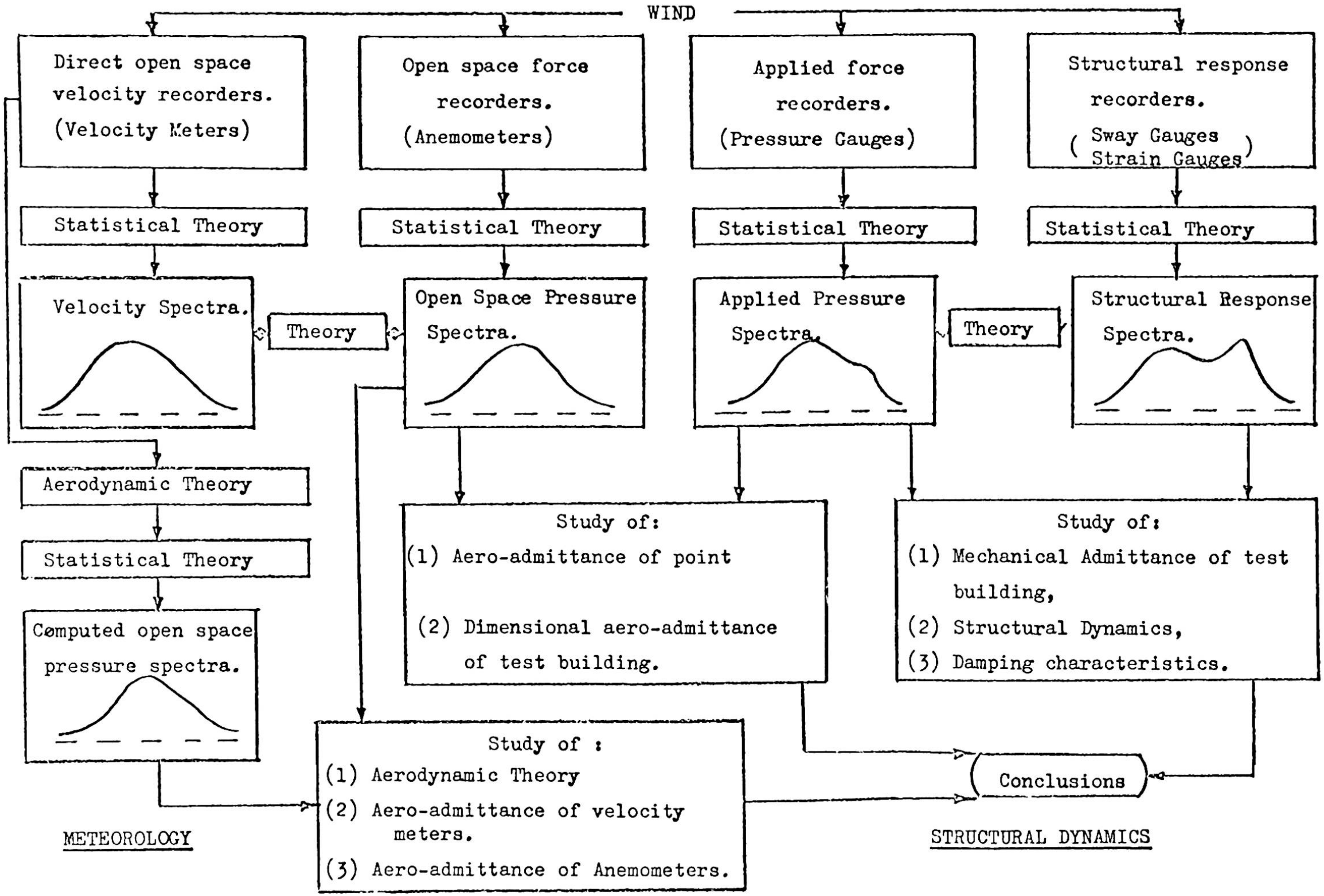


FIG. 1 - IDEALISED FLOW DIAGRAM FOR STUDY OF WIND EFFECTS ON STRUCTURES

The inadequacy of our present knowledge of these matters and the urgent need for comprehensive studies of natural winds and the response behaviour of full-scale structures under excitation from this cause are clearly demonstrated in the papers by BORGES [9] and by NEWMARK & HALL [10]. Such experiments are costly to execute and there is need for international collaboration in their planning to ensure that the results obtained from them are of real value, and cover both normal seasonal winds and those of typhoon magnitude.

An investigation, currently being undertaken at the University of Hong Kong is planned with this objective in mind. The nature of the investigation is diagrammatically set out in Fig. 1. but its scope must necessarily be limited initially, because of inadequacy of instruments for recording absolute wind velocities. In considering this figure it should be noted that a stationary statistical ergodic state is assumed and that the spectra referred to are vertically, horizontally and timewise correlated.

It is anticipated that considerable difficulties will be experienced in determination of the aerodynamic admittance of the experimental building. Difficulties are also anticipated in determining, with sufficient accuracy, the actual patterns of wind-flow over the experimental site due to the limited funds available for instrumentation and site levelling.

In brief, the Hong Kong research involves construction of an experimental building on a low-lying exposed land area on the south-east coast of Hong Kong Island. The building is of fully-welded steel-framed construction with reinforced-concrete floors and glass curtain-wall cladding, so arranged that any part of the cladding may be disconnected temporarily from the structural frame. The building measures 60 ft. x 30 ft. in plan and ten-storeys or 100 ft. tall. It is so designed that it can be divided vertically into four sections, as shown in Fig. 2., each capable of acting independently of the others. Under high velocity winds the separate sections will be coupled together with shear connectors at every floor-level

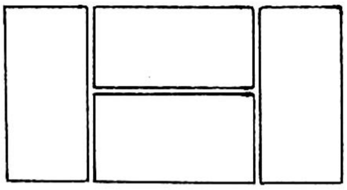


Fig. 2.

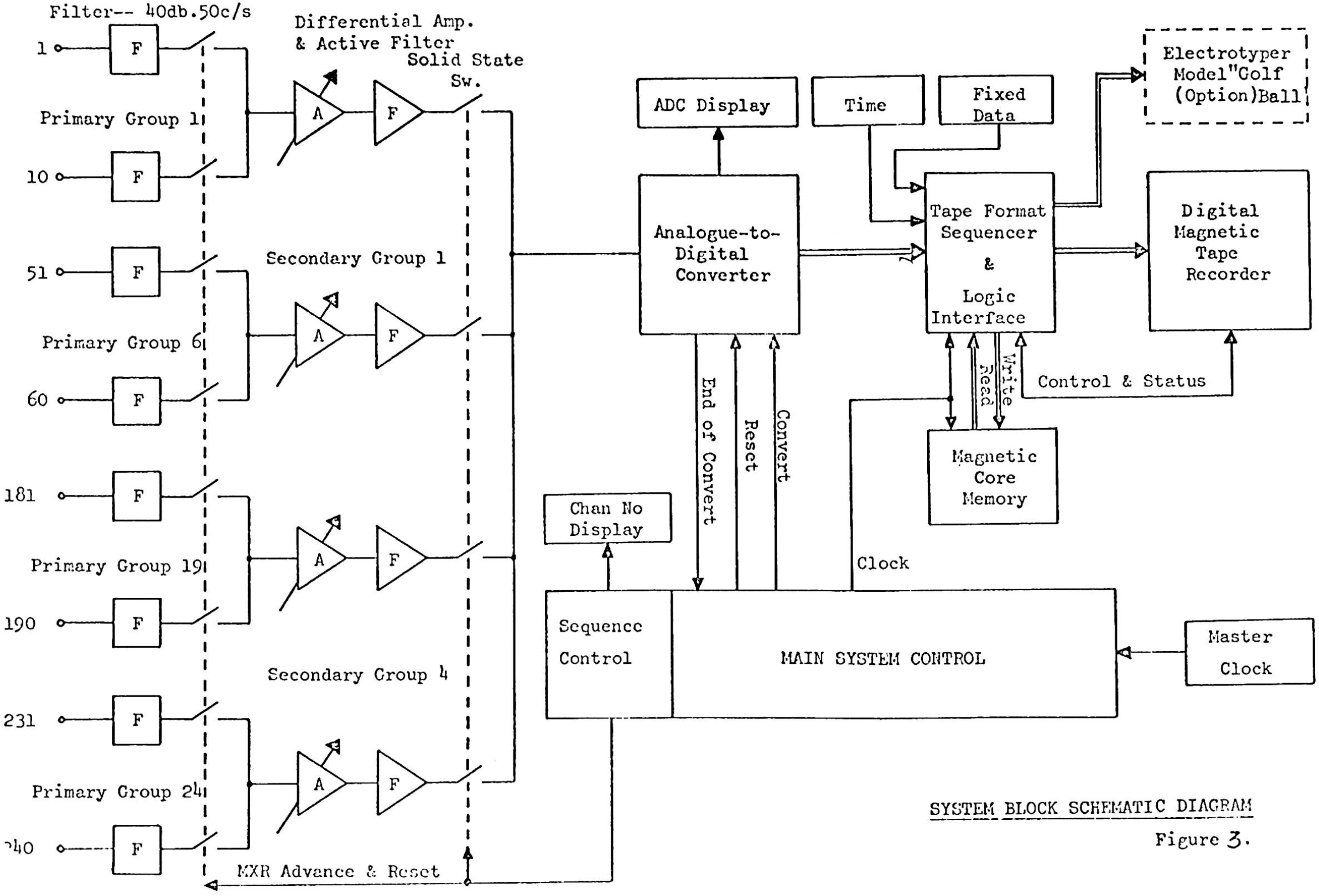
so that the whole building can act as a single monolithic unit. Uncoupled, the sections will be tested for sway under seasonal winds of moderate velocity. Dynamometers, installed across the vertical joints at various floor levels will record the drag effects of wind between the uncoupled sections.

Ahead and on one side of the building, approximately 200 ft. away from the nearest face two lines of free-standing latticed-steel masts, approximately 175 ft. tall, are being erected. Quick-response gust anemometers, designed by the Electrical Research Association of Great Britain, are attached to the masts in pairs at fixed height intervals. Collectively these anemometers, 60 in number, are being used to determine the wind spectra and the spatial correlation.

The pressure distribution over the faces of the building is being measured by 72 pressure gauges developed by the Building Research Station at Watford. The sway response of the building is to be recorded by Physitech Inc. electro-optical tracking instruments, which track the paths of targets attached to various points of the building.

The Benson-Lehner data logger installed accepts up to 240 channels of low-level analogue inputs in the range ± 10 mV to ± 500 mV full-scale deflexion, time multiplexes the data, makes an analogue-to-digital conversion, and records the binary or binary coded decimal equivalent on one-half inch wide, 9-track, magnetic tape. Operation of the system is illustrated in Fig. 3.

The analogue signals are sampled sequentially at the rate of 10 samples/second/channel by a reed relay multiplexer followed by a solid state submultiplexer which also performs the function of amplifying the low-level signals to ±10 volts f.s.d. for maximum A-D converter resolution. No arithmetic is performed within the system, therefore all data indicated or recorded will be a function of the analogue signal level and amplifier gain. Identification data is included in the information recorded on the magnetic tape to provide the means of knowing which groups of channels have been selected for the scan sequence. This identification data also serves to identify the gain setting of the amplifier, as an individual amplifier gain is permanently associated with a particular channel group.



SYSTEM BLOCK SCHEMATIC DIAGRAM

Figure 3.

Analogue data is converted into a 9-bit binary two's complement digital format by the conventional method of successive approximation, each bit conversion occupying a time of 1.5 microseconds. The system accepts a continuous stream of data during the entire data acquisition and recording process, i.e. the scanning of the input channels is a continuous operation. Whilst interlock gaps are being generated on the magnetic tape, in accordance with IBM System/360 format requirements, digital data is stored in a buffer core store. The store is an AMPEX RF-2 of size 4096 words x 12 bits and, in operation, is made to resemble two independent stores of 2048 x 12. As one half of the store is being filled with digital data, the other half is unloaded at a transfer rate of 28,800 characters per second, via the tape format sequencer, to the digital magnetic tape unit.

The whole project is now nearing completion and recording is expected to commence in September of this year.

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SUMMARY

The response of a building to winds is governed by the meteorological data, the interaction of the wind and the building and the dynamic characteristics of the building. The available data is reviewed.

The author describes a project which will allow correlation of results from an experimental, 10-storey building with model results and existing code requirements. Wind velocities, pressure distributions over the building and the deflexion responses of the building will be measured.

RÉSUMÉ

La résistance au vent d'un bâtiment dépend des données météorologiques, de l'interaction du vent et de la construction, ainsi que de ses caractéristiques dynamiques. Les données connues sont revues ici. En plus, l'auteur décrit un projet qui permet de comparer les exigences des normes existantes avec les résultats d'un bâtiment d'essai de dix étages ainsi qu'avec les valeurs mesurées sur modèles réduits.

ZUSAMMENFASSUNG

Der Windwiderstand eines Gebäudes richtet sich nach den meteorologischen Gegebenheiten, nach der Wechselwirkung von Wind und Gebäude und nach den dynamischen Charakteristiken der Bauten. Diese Gegebenheiten werden berücksichtigt. Der Verfasser beschreibt ein Projekt, welches die Beziehung von Resultaten eines zehnstöckigen Gebäudes mit Modelergebnissen und bestehenden Norm-Anforderungen erlaubt. Gemessen werden die Windgeschwindigkeiten, Druckverteilungen über das Gebäude sowie die Ausbiegungen.