TECHNIQUES FOR MEASURING WIND LOADS ON FULL-SCALE BUILDINGS

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ABSTRACT

Wind pressure measurements are being made on a four-story building on the National Bureau of Standards campus at Gaithersburg, Maryland. Field data will be used to develop new design criteria and to improve wind tunnel modeling techniques. Simultaneous wind velocity measurements from six meteorological towers make it possible to relate pressure distributions and fluctuations on the building to the undisturbed wind field.

Techniques developed in the course of this study are fully described, including instrumentation, data acquisition, and data reduction and analysis. It is believed that the methods used for the measurement of pressures on roof areas and the establishment of a static reference pressure overcome major problems in making field measurements on full-scale buildings.

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INTRODUCTION

In recent years, considerable effort has been directed at improving criteria for the design of buildings to resist wind forces. This has been prompted by the increasing use of lightweight building elements and the trend toward tall slender buildings having low density and low structural damping. Economic circumstances demand a reassessment of the conventional use of static pressure coefficients which can result in gross overdesign of structural frames, particularly in urban locations.

Because of the complexity of wind effects on buildings, a theoretical solution in the near future is improbable and one is forced to depend largely on experimental observations. In principle, the information required for wind load design can be obtained from climatological records and from wind tunnel studies in which all of the relevant parameters have been properly scaled. However, it is seldom possible to obtain complete similitude and certain compromises become necessary. To successfully apply results obtained from wind tunnel studies, it is essential that the magnitudes of errors introduced by lack of similitude be known. As only a few full-scale tests have ever been conducted, there is very little reliable quantitative information with which to check wind tunnel tests.

In 1969, the National Bureau of Standards, in conjunction with the Environmental Data Service, undertook a study to document the loads experienced by full-scale buildings under strong wind conditions. The primary goals of the study are to provide data for establishing new building design criteria and to improve modeling techniques. The considerations given to selection of a test site, type of instrumentation, techniques of measurement and methods of data analysis are described in the following sections.

THE TEST SITE

The building research facility (Building 226) on the NBS campus at Gaithersburg, Maryland, was selected for the initial phase of the study. The building is 32 x 118 m (105 x 386 ft) in plan and 15 m (48 ft) high. It is located in an area that affords a relatively clear exposure to the prevailing northwesterly winds and its unique construction greatly simplified the installation of pressure transducers, cables, and pressure lines. The building is extremely smooth in the aerodynamic sense and has sharp roof-wall intersections which produce steady turbulent separations under strong wind conditions. Its length to height ratio is such that flow conditions over the central portions of the building are characteristically two-dimensional. The north face of the building is shown in Figure 1.

Although site selection was based primarily on the clear exposure to the north and west, winds from the southeast and south allow the shielding effect of other buildings to be studied. The location of Building 226 on the NBS campus is indicated in Figure 2. Local terrain can be classified as gently rolling.

INSTRUMENTATION

In selecting instrumentation with which to conduct the study, consideration was given to the following general requirements:

1. Minimum life of from 3 to 5 years
2. Troublefree, unattended operation
3. Maximum sensitivity and minimum drift
4. Suitable dynamic range
5. Acceptable cost.

While most of these requirements have been met in practice, one seldom finds the best of all characteristics in one transducer. Transducers used to measure the various parameters are described in the following sections.

Wind Velocity

To adequately evaluate the effects of wind on buildings and structures, a detailed description of the oncoming wind is required. Of particular importance are the mean wind velocity profile and properties of the atmospheric turbulence. The determination of mean velocity profiles is rather straightforward using a mast or tethered balloons to position anemometers at various levels. In order to describe the turbulent components of velocity, one must make use of statistical concepts. Accordingly, atmospheric turbulence can be described by

1. Intensity and spectrum of turbulence
2. Space and time correlations of velocity fluctuations
3. Probability distributions of the components of turbulence
4. Degree of stationarity

This requires that simultaneous records be collected for points having lateral as well as vertical separations and that the records include those frequency components which dominate the response of the building and its elements.

An array of meteorological towers with separations ranging from 15 to 107 m (50 to 350 ft) was installed in the area directly to the north of Building 226. The towers are close enough to the building to observe velocity-pressure correlations, yet far enough away to obtain reasonably undisturbed wind measurements. Although the towers are anchored at four points, they are of light construction and can be relocated with relatively little effort. The towers are 19 m (61 ft) high with the exception of the east tower which is 22 m (71 ft). The tower array, relative to the building, is shown in Figure 3.

Wind instrumentation includes two U.S. Weather Bureau Model F420-C and two fastest mile anemometers mounted at the 10-meter level. The Model 420-C provides a continuous analog voltage proportional to wind speed while the fastest mile units employ a set of electrical contacts which close momentarily with the passage of each 1/60 mile of air. Both types have 3-cup rotors with relatively long distance constants and are used only for comparing observations at the site with Weather Bureau records. For measuring turbulent fluctuations, fast response anemometers are required, and the following criteria were considered in making a selection:

1. High frequency response
2. High sensitivity
3. Long-term stability
4. Long life expectancy
5. Reasonable cost.

Hot-wire and hot-film anemometers have excellent frequency response but require frequent calibration due to the accumulation of dust and other pollutants and require temperature compensation. Considerable developmental work is now in progress, and these devices may yet prove to be very satisfactory for outdoor applications. A better sensor for atmospheric measurements is the sonic anemometer; however, their cost makes it impractical to use them in any great quantity. Drag sphere anemometers are capable of measuring fluctuations of up to 10 or 15 Hz but exhibit a rather low sensitivity and tend to pick up tower vibrations. All mechanical anemometers such as the rotating cup or propeller have an inherently low frequency response. The rotating cup requires the use of a wind vane to determine direction and its accuracy is affected by vertical wind components. The main advantages of mechanical anemometers are their relatively low cost and long-term stability. The anemometers selected for this study are of the propeller type and have a fixed orientation. Three anemometers are therefore required to measure the u, v, and w components of turbulence at a point. The propellers of molded polystyrene have four blades and a diameter of 19 cm (7.5 in). A miniature DC generator produces an analog voltage output which is directly proportional to the wind speed. As presently configured, the anemometer output is 900 millivolts at the maximum rated speed of 40 m/s (90 mph) although sensitivities of twice this value are easily attainable.

Ideally the propeller responds only to that component of the wind which is normal to the plane of the propeller. However, the actual response follows the cosine law only approximately, and a first-order correction is required for certain ranges of relative wind direction. This correction can be made while data are being recorded or during subsequent analysis. A typical calibration curve is shown in Figure 4. All of the above criteria have been satisfied with the exception of high frequency response. Wind tunnel tests indicate the propeller anemometers have a distance constant of approximately 1 meter. Theoretically, the anemometers would indicate 90 percent of the true amplitude of a 2 Hz sinusoidal fluctuation when superimposed on a mean wind speed of 20 m/s (45 mph). However, predictions of response based on wind tunnel performance have been shown to depart significantly from actual response in the natural wind [1]. The frequency range increases directly with wind speed, and, although better frequency response would have been desirable, spectra can be defined well into the inertial subrange. Short-term observations can be made with a hot-film anemometer if higher frequencies are found to be of interest. A special wind tunnel facility to investigate the dynamic response characteristics of anemometers is now being designed in the Aerodynamics Section of the National Bureau of Standards.

The anemometers are mounted on pipe arms extending a minimum distance of 1.5 meters from the tower legs to reduce interference. They can be quickly moved to any level on the tower and from one tower to another. Currently, 21 fast-response anemometers are in operation. A three-component cluster is shown in Figure 5. The anemometers are kept in continuous operation and have proved to be extremely reliable. The generator bearings are purged with dry air piped from the compressed air supply in the building and are expected to perform satisfactorily for a minimum period of 3 years. The propellers will undoubtedly be damaged in severe hailstorms, but it is felt that the cost of replacement is offset by their other advantages.

Experience has shown that some form of lightning protection is required when transistorized equipment is connected to long runs of outdoor cable, even when the cables are properly shielded and grounded. Zener diodes and neon bulbs have proved to be a simple solution to the problem.

The anemometers are calibrated periodically in a wind tunnel, and tests have shown that both the cup and propeller anemometers have very good long-term stability. Related signal conditioning circuits are calibrated by driving the anemometers at known speeds with synchronous motors.

Pressure

The measurement of surface pressures on a full-scale building is an extremely difficult problem. Pressure intensities in strong winds can range from -4000 to +1400 N/m^2 (-0.6 to +0.2 psi) or more, ambient temperatures can range from -25 to +50°C, and thunderstorms are usually accompanied by wind-driven rain. As strong winds are of rare occurrence, it is highly desirable that the instrumentation be sufficiently sensitive to yield useful information during moderate winds. Requirements of wide dynamic range and high sensitivity are not generally compatible, and some compromise is required. Criteria for the selection of pressure transducers were essentially the same as those for anemometers with the additional requirement that installation in buildings be as simple as possible.

Pressure transducers are available with either exposed or enclosed diaphragms, each having certain advantages. An exposed diaphragm usually exhibits better frequency response and obviates the problem of rain-clogged pressure taps. However, these advantages are usually offset by the work required to install exposed-diaphragm transducers, particularly low-range transducers which have large diaphragms. Also, the natural frequency of most building elements is usually less than 10 Hz, a range which is easily attainable with enclosed-diaphragm transducers.

Several techniques are used to measure the diaphragm displacement and hence the pressure difference across it. These include potentiometers, strain gages, linear variable differential transformers, variable capacitance, and variable reluctance devices. Transducers utilizing potentiometers or strain gages have a relatively low cycle life, a characteristic which is undesirable for applications requiring continuous operation for long periods of time. The other techniques have been used extensively and are entirely satisfactory. To avoid problems with electrical noise where long cable runs are required, it is good practice to transmit analog signals in a modulated form.

The pressure transducers that were selected are of the differential type and consist of a flat magnetically permeable diaphragm clamped between two chambers containing electromagnetic coils. Diaphragm deflection results in an increase in gap on one side and a corresponding decrease in gap on the other side, changing the magnetic reluctance of the coils. Each transducer is equipped with a carrier demodulator, located at the data acquisition system, which converts the 3 kHz carrier into a DC voltage. A low-pass output filter limits the frequency response to 10 Hz. The operating range of the transducers is ±690 N/m^2 (±0.1 psid) and the corresponding electrical output is ±10 VDC. Their operating range can be increased by simply installing a stiffer diaphragm. Power and signals are transmitted by strain gage cable over distances of up to 90 m (300 ft).

Pressure intensities over the four walls and roof of the building are measured by 47 transducers closely connected to wall pressure taps. The pressure taps consist of 3 mm (1/8 in) I.D. brass tubes installed flush with the exterior surface of the insulated aluminum spandrel and cladding panels. Tube length is 70 mm (2.75 in), and it is estimated that the pressure tap–transducer combination has a frequency response flat to 20 Hz. Roof pressures are measured with the transducers mounted in low-profile housings which allow the transducer arrangement to be changed easily and prevent the transducers from being flooded during periods of heavy rainfall. A major problem in obtaining pressure measurements on full-scale buildings is that of establishing a static reference pressure. For comparing test results with wind tunnel tests, the ambient pressure in the undisturbed wind field is a particularly convenient reference. The difference between inside and outside ambient pressure due to chimney action, air conditioning, and wind effect can be of the same order of magnitude as the surface pressures to be measured, even on buildings of low height. To overcome this problem, a static pressure probe is mounted on a wind vane on the most remote tower at a height of 10 meters. Pressure tubing, shielded from the sun to avoid solar heating, extends down the tower and across the ground to the north face of the building. All transducers in the building at a given level are then connected by a horizontal tube to this external reference tubing whose temperature is essentially the same as the tubing on the tower. It is believed that the maximum error in reference pressure due to oblique wind incidence on the pitot-static tube and due to temperature difference is approximately 5 N/m^2 (7×10^{-4} psi).

To relate wind speed and surface pressure requires an estimate of the air density. The static pressure line is connected at ground level to an absolute pressure transducer which is temperature compensated. This transducer is also a variable reluctance device with an output of 10 VDC at a full-scale pressure of 11 N/cm^2 (16 psia). Ambient air temperature is measured by means of an aspirated platinum resistance thermometer. The sensitivity after amplification is 18 mV per celsius degree.

DATA ACQUISITION SYSTEM

The large quantities of data inherent in full-scale investigations involving several different parameters required that careful consideration be given to selecting a data acquisition system. Several recording methods are available, each having certain advantages and disadvantages that generally make one method preferable for a given application. The more common methods include digital on magnetic tape, paper tape, or punched cards, and analog on magnetic tape, direct writing stripchart, or heat- or light-sensitive paper.

Analog data on a stripchart has the advantage of a continuous plot which can be scrutinized quickly. However, the time and cost of converting records to a form suitable for analog or digital analysis are usually prohibitive. Analog recording on magnetic tape has the advantages of wide frequency range and direct analysis by electronic means but can become very costly when a large number of data channels are required. Also, the operating range of most analog analyzers is above 2 Hz while frequencies much lower than this are of interest when dealing with full-scale structures.

Digital recording always involves a condensation of data, and a compromise must be made between the upper frequency limit and the length of record. This method has the advantages of multiplexing data channels and direct entry of data into a digital computer.

In selecting a data acquisition system, the following requirements were established:

1. Dynamic range and input impedance compatible with transducers
2. Capacity of at least 75 data channels
3. Automatic handling of data and simple entry of data into a digital computer
4. Reliability and storage capacity sufficient for unattended operation of up to 2 months
5. Satisfactory frequency response over the range of interest

6. Ability to start and stop the system automatically, depending on wind conditions
7. Reasonable cost.

The system that was finally selected is shown as a block diagram in Figure 6. It is completely under computer control and can accept up to 104 differential analog inputs in the range ±0.5 VDC to ±5 VDC, full scale. Although it is basically a digital system, any 13 channels may also be recorded on magnetic tape in analog form.

In normal operation, the analog signals enter a patch panel where channel assignments are made manually. The channels are then multiplexed and amplified, either sequentially or by random address, at five selectable scan rates ranging from 100 Hz to 20 kHz. The signals are converted to 12-bit binary numbers (11-bit + sign) in two's compliment format using a sample-and-hold amplifier and an A-D converter. The maximum sampling rate is 30 samples per second, and may be adjusted to any lower rate. The A-D converter is capable of a 100 kHz conversion rate where multiplexing is not required. Accuracy of the analog input section is usually within 0.05 percent of full scale ±1/2 lsb.

The data samples enter the computer core via an intercoupler and are then operated on by the processor. These operations include corrections for zero drift and changes in sensitivity, calculation of components, and conversion into engineering units.

The computer has a storage capacity of 8,192 12-bit words and is prewired to allow expansion to 12,288 words. Cycle time is 1.5 microseconds. In case of a power failure, the computer will preserve all memory information and is capable of automatically restarting after power is restored. Communication with the computer is by means of a teletype console and programs are entered by a high speed paper tape reader. Contents of the storage core may be printed out on the teletype or on paper tape using a high speed punch.

Normally, all data will be recorded on the 7-track magnetic tape unit at a packing density of 556 bpi. The recorder is a continuous read/write device and operates at 25 ips. For large quantities of data, a packing density of 800 bpi may be used. Data blocks begin with a record header containing information such as date, location, run number, transducer configuration, sampling rate, temperature, and barometric pressure. After being recorded, the data can be entered into a large computer for subsequent processing or can be read from the tape in limited amounts into the system computer. Two D-A converters allow any two channels to be monitored on an oscilloscope or plotted on a strip-chart recorder.

The analog front end can be calibrated periodically and automatically by generating DC voltages with the programmable voltage reference. FET switches substitute the reference voltage for the transducer outputs.

Although the computer has an internal clock, master time in days, hours, minutes, and seconds is supplied to both the analog recorder and the computer by a time code generator/reader. One channel of the analog tape is reserved for this time signal, which is is IRIG B code. Whenever the system goes into the record mode, the start and stop times are printed out by the teletype along with a notation indicating which recorder was placed in operation. An automatic tape search unit facilitates the retrieval of analog data which can be re-entered in the patch panel and converted to digital form.

Although the system described above is not yet fully operational, its flexibility is practically unlimited. The ability to continuously monitor any channel and go into the record mode, either analog or digital or both, when levels are sufficiently high eliminates an obvious problem with manual operation. The criteria for recording data can be changed, based on past events, so that repetitious recordings are avoided.

DATA REDUCTION AND ANALYSIS

In this study the amount of data is obviously large and, hence, the processing of data should be well planned. The data are recorded in digital form on magnetic tape and subsequently processed by a UNIVAC 1108 high speed computer. The quantities of interest include the mean and standard deviation, extreme values, auto- and cross-correlations, power and cross-power spectral densities, and aerodynamic admittance functions. Certain precautions must be taken to insure reliable results, such as duplicating data, checking reading errors in data, etc. A schematic diagram is shown in Figure 7 which describes the procedure for analyzing single sample records. The procedure for analyzing a collection of sample records is shown in Figure 8. Programs were written towards the goal of preserving accuracy and saving computer time. They were improved as experience was gained.

Tests for Basic Characteristics of Wind and Pressure Data

In order to analyze the pertinent statistical properties of a single sample record, certain critical assumptions should be verified before proceeding with a detailed analysis. Since the wind and pressure data are random, it is desirable to know whether or not they are stationary and/or normal. If a sample record is stationary, certain analytical procedures can be greatly simplified.

Because the multi-channel data are recorded under the same wind conditions, only one wind record and a representative pressure record need be tested for stationarity. However, certain precautions must be taken with pressure data. Some pressure transducers may be located where strong flow separation or vortex shedding occurs, imposing a dominant periodicity on the randomness of the signal. For discrimination between periodic and random signals, the following scheme by Simon and Walter [2] is used. Since computing moments of a signal on a high speed computer is relatively fast, the first few moments of the pressure data are calculated and compared with those of known distributions, such as Gaussian, uniform, and quasi-sinusoidal functions. In this way the random signals can be classified.

The normalized distribution moment coefficients are

$$C_k = \frac{1}{\sigma}\left[\frac{\frac{1}{N}\sum_{i=1}^{N}(y_i-\bar{y})^k}{\frac{(2)^{k/2}}{\sqrt{\pi}}\,\Gamma\left(\frac{k+1}{2}\right)}\right], \quad k < 1 \text{ and even} \tag{1}$$

where

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i \tag{2}$$

and

$$\sigma = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i-\bar{y})^2\right]^{1/2} \tag{3}$$

y_i is the amplitude of the signal, k is the kth moment, and N is the number of data points. This expression for C_k has the property that the coefficient of a Gaussian function is unity for even moments. An example is given in Figure 9 which compares the moment coefficient distribution of a wind record with other known functions. This particular wind record is clearly random and nearly Gaussian. On the other hand, a pressure record with strong periodic components will be identified by this technique.

The stationarity is tested according to the scheme given by Bendat and Piersol [3]. The method is to divide a single record into N equal time intervals and to compute a mean value and mean square value for each interval. The computed results are aligned in time sequence. If the variations of trend are less than would be expected due to statistical sampling variations, the data can be treated as stationary.

The test for non-normality is that recommended by Geary and Pearson [4], namely, calculating the skewness and kurtosis of the sampled data. With known characteristics, the data can be classified as having a skewed, platykurtic, or leptokurtic distribution.

Auto- and Cross-Correlations, Power and Cross-Spectra

Procedures for computing auto- and cross-correlations, and power and cross-spectra are described by Harris [5]. However, the Fast Fourier Transform method saves about two orders of computing time on a high speed computer for calculating spectra, and the inverse of the Fast Fourier Transform gives the correlation function. In this study the FFT scheme by Gentleman and Sande [6] is used.

SUMMARY

The main objectives of the research program described in this paper are the development of improved design criteria for wind loads and the improvement of wind tunnel modeling techniques. A description of the test site and the criteria used in selecting instrumentation have been presented. Detailed measurements of wind structure and the method used to establish a reference pressure should facilitate future wind tunnel studies to check modeling techniques. The use of a computer-controlled data acquisition system should result in the efficient collection of reliable field data under strong wind conditions.

ACKNOWLEDGEMENTS

Many people have contributed to the success of this program. The technical assistance of Mr. H.C.S. Thom of the Environmental Data Service, ESSA, deserves particular recognition. The Aerospace Environment Division of NASA provided instrumentation during the initial stages of the program and their interest and assistance is gratefully acknowledged.

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Figure 1 North wall of Building 226, National Bureau of Standards

Figure 2 Location of Building 226 on the NBS campus

Fig 3
Tower Array

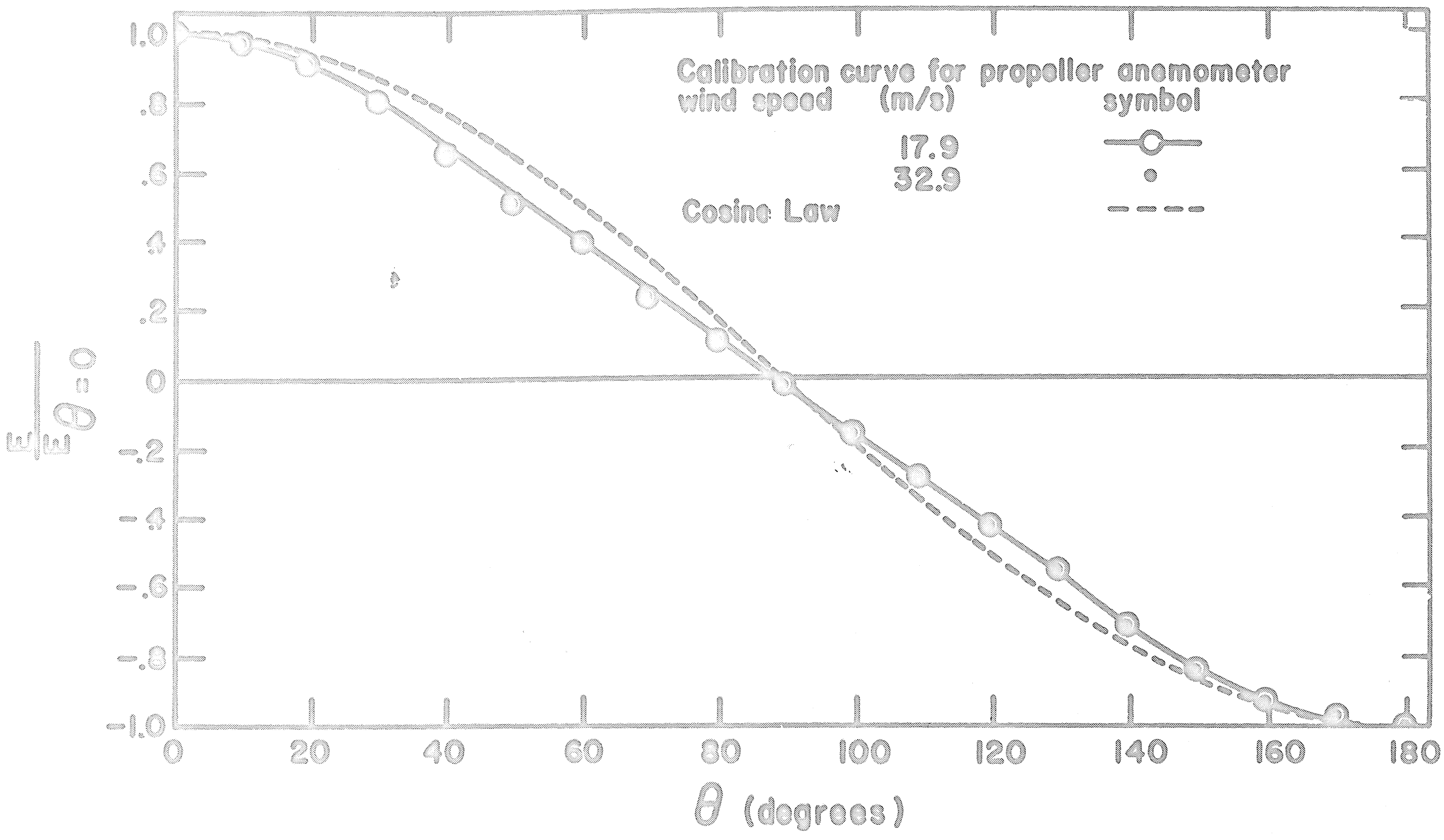

Figure 4 Propeller anemometer calibration curve

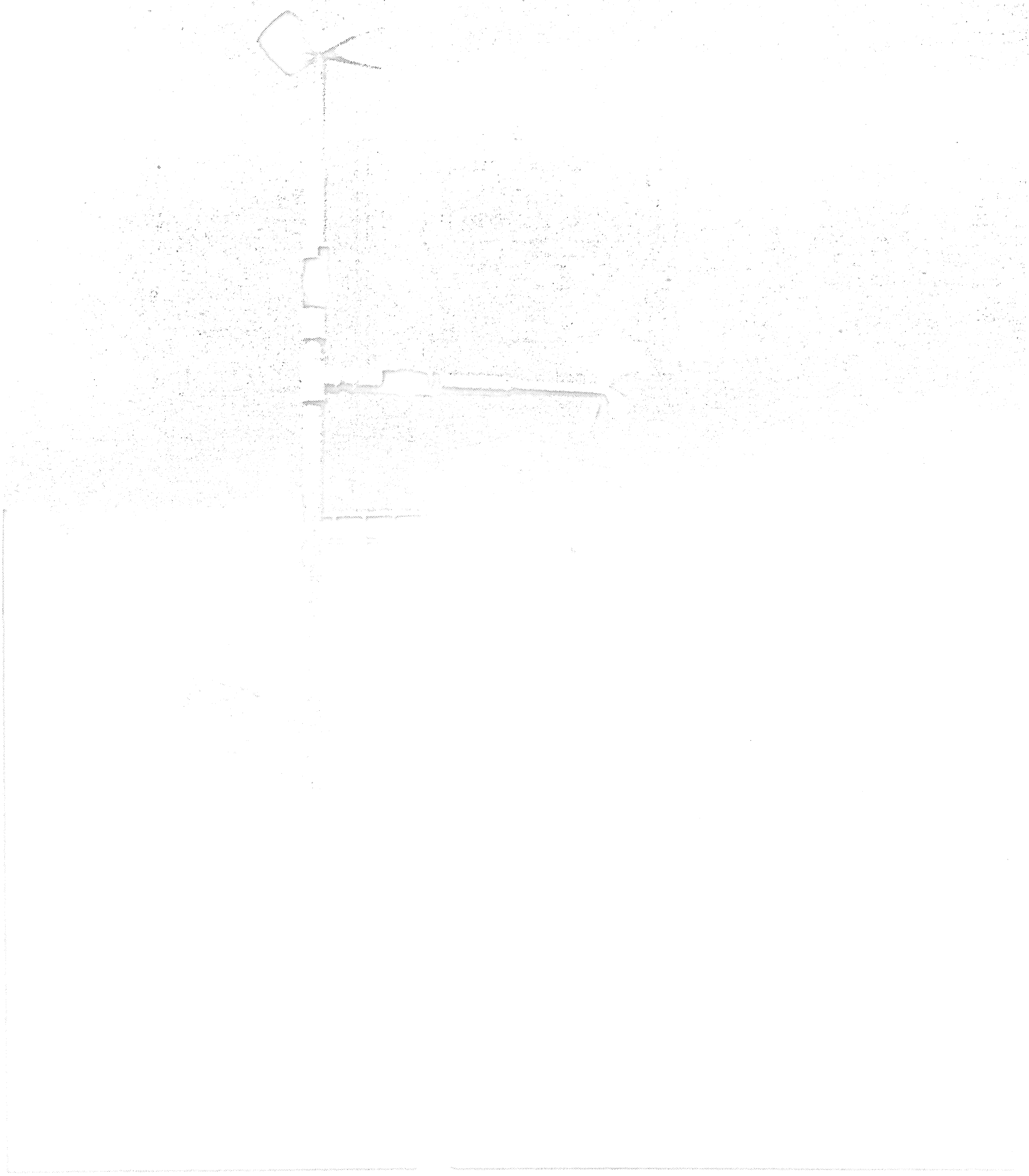

Figure 5 Anemometer cluster for measuring three wind components

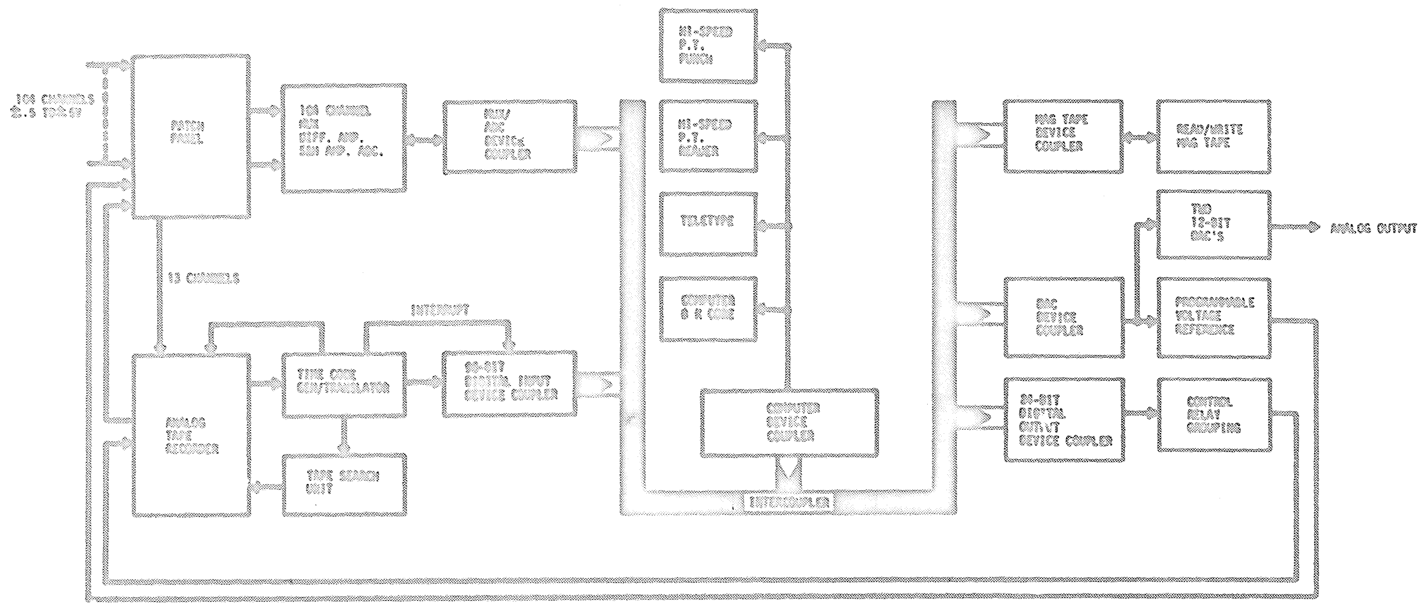

Figure 6 Data acquisition system

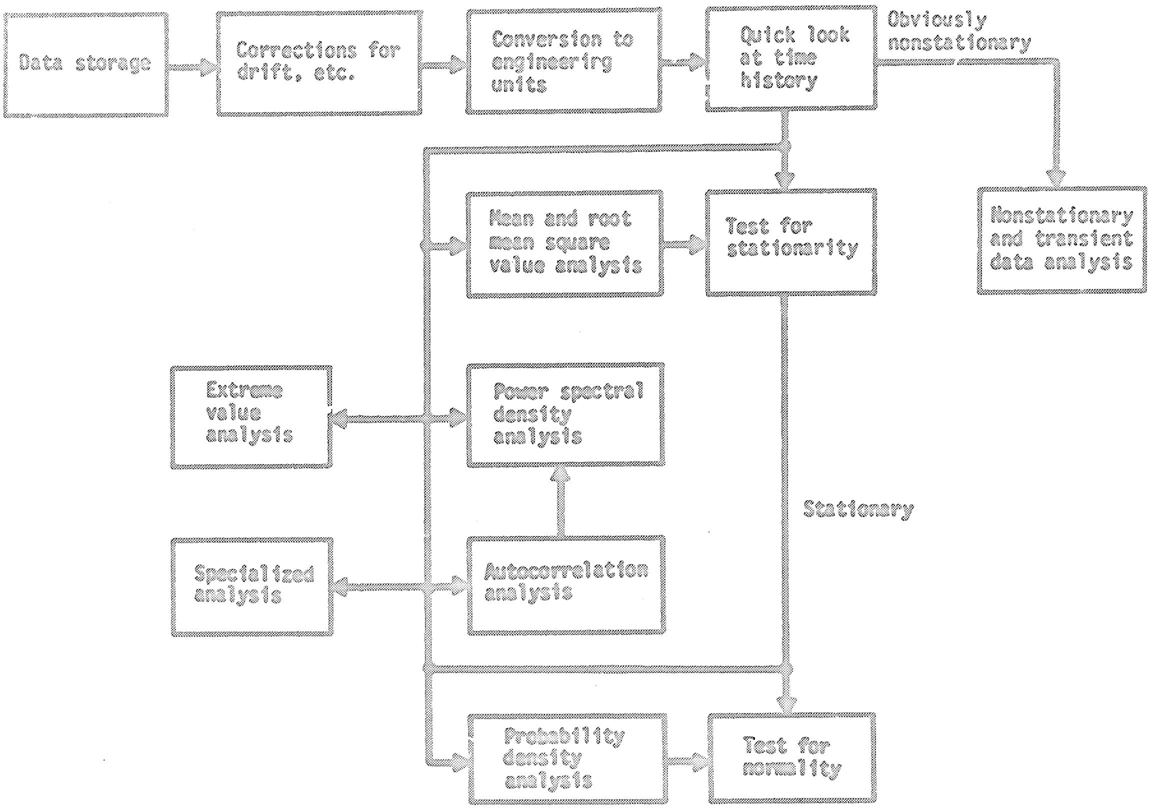

Figure 7 Procedure for analyzing single sample records

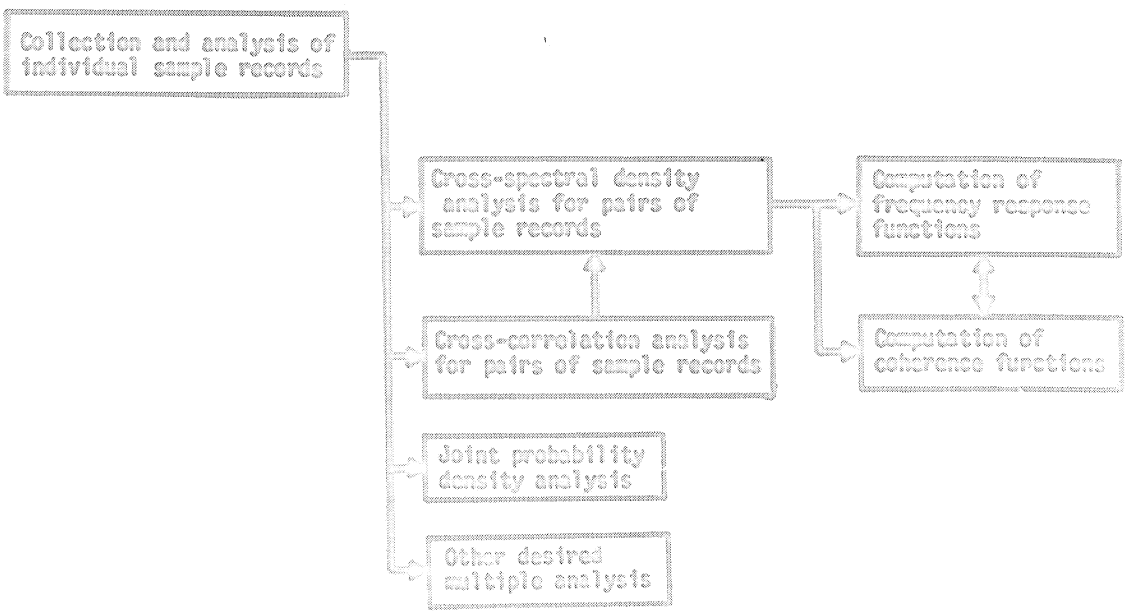

Figure 8 Procedure for analyzing a collection of sample records

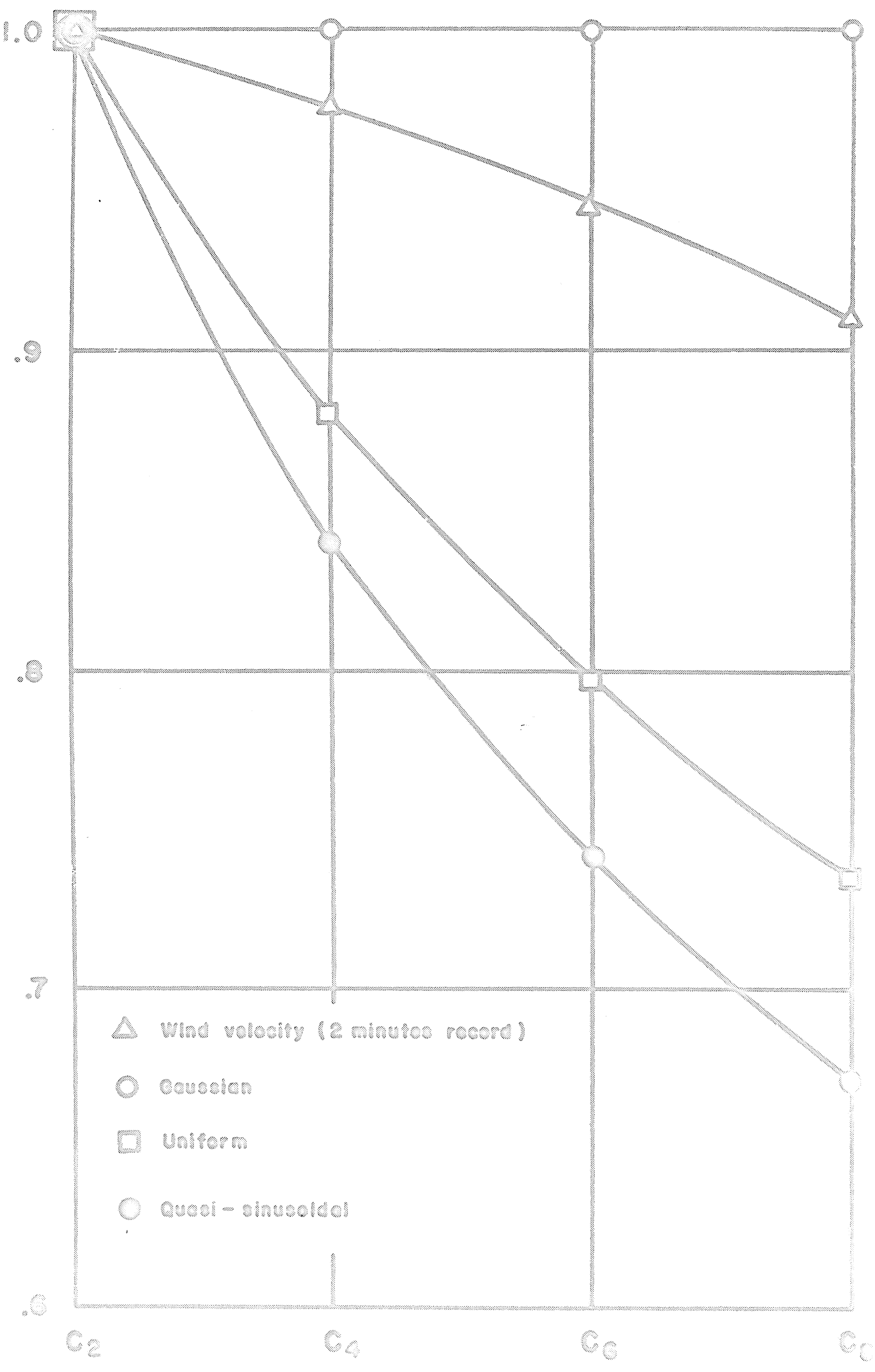

Figure 9 Distribution moment coefficients of a wind speed record

found blocked with debris not filtered out by the MUA fan.

7. Broken belts on exhaust and supply fans.
8. Hoods with equipment protruding from underneath them.
9. Hoods with missing or damaged filters.

These installations indicate that any kitchen ventilation system is useless if not properly applied and maintained.

Every hood must be balanced to perform properly. The hood must also be maintained to keep its balance. The filter and duct system must be regularly cleaned, and the fans must be periodically checked and serviced. Peak performance and efficiency can only be achieved by proper adjustment and maintenance of the ventilation hood.

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