XI. Lunar and Planetary Instruments

SPACE SCIENCES DIVISION

A. A Folding Rotating Cup Anemometer,

J. B. Wellman

1. Introduction

A rotating cup anemometer has been designed, fabricated, and tested as a part of the science payload of the capsule system advanced development (CSAD) hard-landing Mars probe. The instrument is designed to survive the rigors of space flight and hard landing and to make meaningful measurements of Martian wind speed. The effort has been limited to developing the mechanical system but space has been reserved for an optical system for sensing rotation, utilizing a light-emitting diode and a phototransistor. Magnetic and capacitive pickups have also been considered.

From the early trade-off studies, the rotating cup anemometer emerged as the most likely candidate for the CSAD wind-speed measurement because of its broad range of sensitivity, linearity, ease of calibration, and simplicity of data processing. The goal has been to design a rotating cup anemometer that would be sensitive enough to satisfy the science goals and also satisfy the sterilization, impact, and geometry requirements of the CSAD lander. The resulting anemometer configuration is not only applicable to CSAD but may be worthy of consideration in other programs that impose severe volume restrictions or require survival under impact.

2. Design Criteria

The criteria that must be met by the anemometer design are of two types: performance (range and threshold sensitivity of the anemometer in a Mars atmosphere) and compatibility (size, weight, sterilizability, and survival under impact).

The performance criteria are determined to a large extent by the nature of the Mars winds. The surface wind speed is expected to vary from 0 to 200 ft/s with gusts as high as perhaps 450 ft/s. The surface pressure should be in the range of 5 to 20 mbars.

A threshold sensitivity requirement for the anemometer has been chosen to be between 5- and 10-ft/s wind speed. Above the threshold the instrument should be linear to 15% of the reading up to 200 ft/s and should survive gusts as high as 450 ft/s.

To be compatible with CSAD the instrument must survive sterilization and must be capable of surviving 2500 g of impact acceleration. The last constraint (and perhaps the most demanding) is that the anemometer fit within a cylindrical volume 1 in. in height and 1.5 in. in diameter.

3. Analytical Model

In order to determine the effects of anemometer geometry on its performance, an analytical model was investigated. The performance of a rotating cup anemometer is characterized by the ratio of the cup tangential velocity to the free-stream wind velocity. This performance factor can be calculated from experimental data by taking measurements of lift and drag forces on an anemometer cup as a function of angle of attack. The lift and drag forces are then resolved normal to the plane of the cup rim and a normal force coefficient is calculated (Ref. 1). The performance factor k is given by

$$k = \frac{\dfrac{C_1 - C_2}{C_1 + C_2} - \epsilon}{3 - \epsilon^2}$$

where C_1 and C_2 are the average normal force coefficients for the backward and forward directions of the cup and $(\pi/2) - \epsilon$ is the angle of attack at which the normal force coefficient passes through zero (Ref. 2). Since the lift and drag coefficients vary with Reynolds number, the performance factor will also, in general, vary with Reynolds number.

Calculations were made for a variety of cup shapes. The hemispherical cup and the conical cup exhibited performance factors several times greater than those of other geometries, such as vanes formed as sectors of a cylindrical shell. Furthermore, the conical cup exhibited a lesser dependence on Reynolds number than did the hemispherical cup. The conical cup with performance factor of 0.27 to 0.30 was considered the best cup geometry.

The threshold wind velocity is that for which the aerodynamic torque exerted on the cups is equal to the starting torque of the bearings. From the torque balance equation, it can be shown that the threshold velocity varies as the $-3/2$ power of the linear dimensions of the anemometer. In terms of the cup area A, the radius of the anemometer r, and the number of cups N, the threshold velocity V_s satisfies the proportionality

$$V_s \propto A^{-1/2}\, r^{-1/2}\, N^{-1/2}$$

The conclusion of the analytical study was that the anemometer should have three conical cups of 45-deg half-angle and that the dimensions of the anemometer should be as large as possible within the specific constraints prescribed.

4. Evolution of the Design

It was apparent from the analytical study that in order to satisfy the performance criteria the anemometer would need to be larger than the 1.5-in.-diam cylindrical volume in the lander; thus, a collapsible anemometer would be required.

The largest cone of 45-deg half-angle that could be fitted within the prescribed cylindrical volume would be 1.5 in. in diameter. Three of these cones could be included by nesting them within one another and locating them coaxially within the cylinder. The remaining space within and below the cups would be allocated to the hub and arm assembly. The maximum arm length could be achieved if the arms were nearly 1.5 in. long and hinged at one end to the hub so that they could rotate 180 deg to extend nearly to their full length outside the 1.5-in.-diam volume. This would require that the arms overlap in the folded configuration. In order to move the three arms with their attached cups to the open position with the arms 120 deg apart and the axes of the cups horizontal, a set of spring-loaded hinges would be necessary.

A system of three orthogonal hinge axes for each arm was considered first. The mechanical complexity of this type of arrangement was considered a significant drawback. A method of reducing the number of hinges from nine to six was envisioned. The inner hinge which attaches the arm to the hub would allow the arm to rotate outward 180 deg in the horizontal plane. The skewed axis that attaches the cup to the arm would allow the cup to rotate from its vertical folded position to the horizontal unfolded position with minimal interference among the cups. A preliminary model was built to test this type of hinge arrangement. The unfolding mechanism proved workable and a design incorporating shock resistance was accomplished.

The anemometer expands from its folded configuration (Fig. 1) of 1.5 in. in diameter to a deployed configuration (Fig. 2) of 5.5 in. in diameter. The weight of the anemometer alone is 0.95 oz.

Several aspects of the design can be visualized in Fig. 3. In the folded configuration the hub rests directly on the base, thereby relieving the load from the miniature ball bearings. The cups are supported by the cap, which transmits the load to the hub and also encloses the upper bearing to prevent contamination by particulate matter. The base is designed to fit congruently into the hub both to relieve the load during impact and to provide a baffle for the lower bearing. When the anemometer is permitted to deploy, the hub is raised a short distance from the base by a spring-loaded bushing. Rotation sensors can be incorporated into the base by machining the required cavity.

Fig. 1. Anemometer in folded configuration

5. Preliminary Testing

The unfolding process was tested by repeated operations and a time study was made using high-speed motion pictures. It was observed that the motion about the inner and outer hinge joints took place concurrently. The unfolding reached completion in less than 80 ms.

When the reliability of the unfolding mechanism had been demonstrated, the anemometer was mated to the collapsible boom. The assembly was collapsed into the boom retainer, and the combined package was subjected to a number of shock tests up to a maximum of 4000 *g*. In each case the anemometer survived with no damage.

In the next stage of evaluation the anemometer and boom were installed in the CSAD lander. The lander was

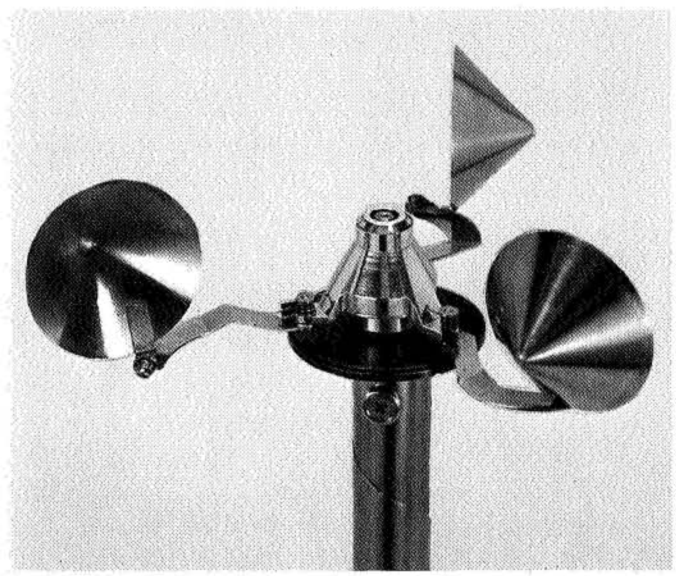

Fig. 2. Anemometer in deployed configuration

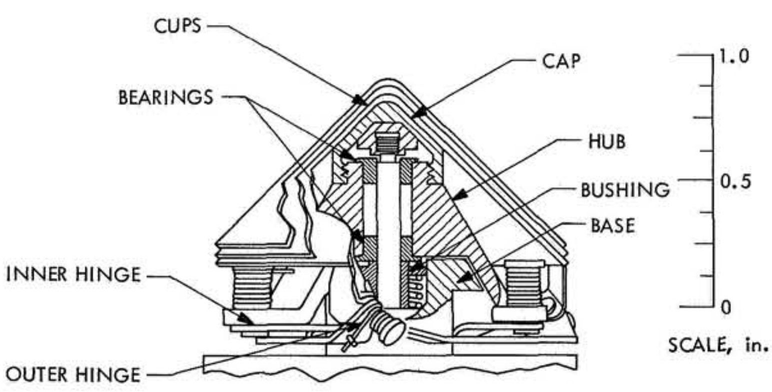

Fig. 3. Cut-away view of anemometer in folded configuration

then sterilized at 125°C for approximately 16 h. Two drop tests of the CSAD lander were made from 250 ft into the dry lake bed at Goldstone, Calif. The capsule velocity at impact was 120 ft/s. In both cases the boom extended on command and the anemometer deployed and began rotating in the wind (Fig. 4).

The compatibility of the anemometer with the CSAD lander was demonstrated by these tests. However, it was observed that the anemometer interfered somewhat with the radio transmission from the lander; the full import of this observation is not yet known. Some changes in the materials used in the cups may be necessary to overcome this problem.

Fig. 4. Anemometer and CSAD capsule after drop test

A brief experiment in a Mars atmosphere flow system was conducted to determine the threshold sensitivity of the anemometer. A value of 10 ft/s at a pressure corresponding to 7 mbars of Mars atmosphere was observed. Although the threshold measurements are incomplete, it appears that the present design is capable of satisfying the threshold criterion. More extensive threshold and linearity measurements will be made.

References

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2. Corcoran, J. W., and Esau, D. L., *Comparison of a Theoretical Model for Anemometer Cups with Experimental Data.* Beckman and Whitley, Inc., Mountain View, Calif., Oct. 1964.

B. Selection of Wind Measurement Instruments for a Martian Lander, *J. M. Conley*

1. Introduction

Selection of instrument types for the measurement of wind velocity at the surface of Mars has received considerable study during the past several years (Refs. 1–3). Unfortunately, very little experimental work has been done toward determining the parameters necessary for arriving at rational selections of instrument types. This preliminary parametric study of all known instruments will be followed by experimental measurements under Mars surface conditions in order to more thoroughly investigate those instruments that appear to be promising.

Any complete trade-off study must, of course, be mission-dependent; i.e., the instrument selection process is a function of the mission characteristics, such as launch and interplanetary environments, landing shock, lander size, and orientation capability. During the progress of this work, the probable configuration of the first Mars lander has varied from the large *Voyager* soft lander to small, short-life hard landers and, for this reason, these studies have been broadened. The primary emphasis has been on determining the present state of development of the various instrument types and identifying those parameters for which more information is required.

A small wind tunnel has been completed to make the required measurements under Mars surface conditions and will be described in a subsequent SPS article.

2. Wind Instrument Constraints and Characteristics

Theoretical studies (Ref. 4) and observations of the Martian yellow clouds indicate that the expected near-surface wind speeds are in the range of 0 to 60 m/s and that maximum continuous wind speeds up to 140 m/s can be expected. For the JPL series of VM-1 to VM-10 model atmospheres, it is assumed that the dynamic pressure is approximately constant for the various densities (actually $\rho^{1.48}V^2$ = constant). The presently accepted Mars surface atmospheric density falls in the range of 1×10^{-5} to 3.5×10^{-5} g/cm^3. An atmospheric temperature range of approximately 145 to 320°K must be accommodated. Other constraints and instrument properties that must be considered are discussed in general terms.

a. Quantity measured. The functional relation between the instrument output and the atmospheric variables affecting it is described under this heading. It varies from a linear proportionality to wind speed for tracer-type instruments to a complex function of gas thermal conductivity, viscosity, pressure, temperature, and wind speed for the thermal transport (hot wire)-type instruments.

b. Component measured. The geometry of some sensors makes them sensitive to particular wind components. For example, the rotating cup and hot wire anemometers measure the component perpendicular to the instrument axis, and no amount of manipulation of the signal will allow the vector wind to be completely specified from the basic instruments. However, since mission constraints on size, weight, and data transmission may be severe for early Mars landers, thorough investigation of the simpler devices is desirable.

c. Accuracy. The accuracy of an anemometer is usually specified in terms of percent of full scale, but since relatively crude measurements should be acceptable in the present application and since the wind-speed range of the models is so great, it is desirable to consider the accuracy as a percent of reading. Thus, a logarithmic response has merit. Stability of the instrument zero and sensitivity and lack of hysteresis are the determining factors for this parameter since fixed nonlinearities can be readily compensated.

d. Range. All of the instruments considered are potentially capable of operation over the full range of postulated Mars wind speeds, but design trade-offs inflict some severe penalties on several of the instruments in return for a large dynamic range.

e. Distance constant or frequency response. The frequency response requirement has not been specified for any proposed mission but is given for each instrument. Unless some on-board harmonic analysis is done, it is not likely to be of importance. Available response varies from the kHz region for thin hot wires to 0.02 Hz for a rotating (cup or propeller) anemometer at low wind speeds. In some cases, the distance constant is a more appropriate parameter. This is the length of a column of moving air required to produce a 63% response, or alternately, the product of the time constant and the wind speed.

f. Atmospheric temperature effect. Many of the anemometer types suffer from a strong sensitivity to variations in atmospheric temperature. Additionally, the sensor itself will be exposed to the Martian atmospheric temperature and deployed electronics will need to operate at 145°K or be heated.

g. Blown dust effect. The erosion and contamination effects of Martian dust storms may severely affect some instruments. Examples are possible breaking of a thin hot wire and contamination of the bearings of a rotating device.

h. Sterilization. Both chemical and thermal sterilization may be required for instruments landed on Mars. Chemical sterilization may be necessary only in case of a high-spore population prior to the heat cycle and would consist of immersion in an atmosphere of 12% ethylene oxide and 88% Freon 12. The terminal heat sterilization would be attained by heating to approximately 125°C for 24 h.

i. Shock and vibration. Landing shocks for a hard lander are expected to be in the 1200- to 2500-g range with a duration of 1 to 3 ms. Type-approval shock levels may be as great as 5000 g. Mars atmospheric entry accelerations will be of the order of 250 g with pulse half-width of several seconds. The launch vibration environment is not so readily specified since the vehicle is unknown, but sinusoidal accelerations of 15 g rms in the 100- to 2000-Hz range are typical.

j. Deployment considerations. The mission constraints will probably require that the anemometer be stowed within or near the lander during entry and landing. Thus, the anemometer and mast must be stowed until some time after landing and then deployed. A somewhat arbitrary deployed height of 1 m has been selected. (Greater heights are certainly desirable and under many circumstances easily obtainable.)

The difficulty of obtaining a stiff deployable mast under the severe weight restrictions of a small lander makes it highly desirable that the cross section presented to the wind by the anemometer be small. A bending load of 0.03 $lb/in.^2$ of mast and instrument surface is produced by a 140-m/s wind. For a mast 1 in. in diameter by 6 ft in height, this may be an appreciable force, adequate to cause oscillation of the mast, malfunction of some instruments, or erroneous data. A small, lightweight sensor is thus highly desirable. Also, some proposed masts have very little capability for routing wires to the sensor. Thus, a minimum number of the smallest possible lead wires is desirable. Radiation from other deployed sensors may necessitate shielded wires or a very low-impedance sensor.

An early lander will probably not be leveled; therefore, the anemometer should be designed to operate when the lander is resting at a large angle with respect to the horizontal. The *Voyager* constraints specified a 35-deg angle, which would produce an error of 18% for a cosine law response to wind velocity. This could in some cases be corrected if the lander orientation were known.

k. RF interference. RF reflectors should be kept as far as possible from the telemetry antennas. This may require that the anemometer be kept lower than is desirable if the antenna is deployed on the same or another mast. A large, high-gain antenna (or solar cell panel) may produce severe interference with the wind flow in this case. Ideally, the anemometer sensor and mast would be fabricated of RF transparent material and thus could be deployed far enough above the antenna to be out of the region of influence (perhaps 10 antenna diameters).

A more subtle consideration is the presence of rapidly moving metal parts (e.g., rotating anemometers) on the lander. Under some conditions, the radio signal reflected from such parts may be of great enough amplitude to produce severe multipath effects, and the doppler frequency may be great enough to cause a narrow-band phase-locked receiver to lose lock. It is therefore desirable (or perhaps necessary) that any "rapidly" moving parts be fabricated of RF transparent material.

l. Thermal vacuum. Cold welding during the interplanetary cruise must be considered for any instrument employing moving parts. However, this problem must also be solved for a deployable mast and many other instruments. If necessary, a low-pressure atmosphere could be provided in the instrument compartment. The Mars atmosphere obviates this problem during operation.

In addition to the mission constraints and instrument characteristics described, other factors that must be considered are radioactive thermal generator environment, space radiation, deployment shock, launch pressure profile, total weight, deployed sensor weight, volume, power, and cost.

3. Anemometer Types

All of the known anemometers have been classified according to the physical principle of operation (Table 1). In some cases a further division is convenient and has been made according to whether the measurement is made locally (immediate vicinity of the lander) or remotely (tracking a balloon, etc.). Since the limited missions that are likely for the immediate future will probably preclude the use of the remote technique, it will not be considered at this time. Only the significant characteristics are discussed for each instrument type; none of the other constraints is expected to be critical.

a. Thermal transport. These instruments, typified by the hot wire anemometer, operate on the principle of forced convective cooling of a heated element by the wind. They possess several distinct advantages, particularly high sensitivity, rapid response, and the easy deployment associated with their small size. Unfortunately, the stability of the sensitivity and zero are quite poor due to contamination problems and the output is sensitive to gas composition, pressure, and temperature.

A wide variety of instrument forms has been reported, varying from the Kata thermometer (a heated, large-bulb, alcohol thermometer) to fragile platinum wires 20 μin.

Table 1. Anemometer types and typical examples

Anemometer type	Typical instrument examples
Thermal transport	Hot wire, hot film, heated thermistor
Dynamic pressure	
Pitot	Servoed pitot, multiport pitot devices
Drag device	Drag bodies with strain gages or other pickups
Rotating	Rotating cup, propeller, wind vane
Sonic	
Remote	Rocket grenade experiment
Local	Pulse or continuous wave transmission over fixed baseline
Tracer	
Remote	Radar- or laser-tracked chaff, aerosols, shock wave
Local	Ion or thermal gradient tracer
Vortex frequency	Vortex shedding cylinder, hot wire detector

in diameter by 0.005 in. in length. The most suitable type for the present application would seem to be a quartz-coated cylindrical hot film. The sheathed or quartz-coated wires and films are much less susceptible to contamination than the thin hot wires, although at the expense of sensitivity and frequency response. The problem of sensitivity to gas composition, pressure, and temperature is more difficult. It may be possible to reduce the data after these parameters are known but the experiment would then be compromised by dependence on other instruments. Another possibility is that the instrument be calibrated on-site by means of pressure measurements or that the zero be determined by means of a mechanical device, which would intermittently shield the sensor from the wind. Temperature compensation is also possible. None of these techniques can be fully evaluated until the actual magnitude of the zero and sensitivity variations of a specific instrument under mission conditions are determined for the extremes of Martian model atmospheres.

Quantity measured. The relationship between flow velocity and heat transfer rate is given by King's law:

$$H = k\theta + (2\pi k\, c_v\, \rho d_s V_s)^{1/2}\, \theta$$

where

θ = difference between wire and fluid temperature

k = thermal conductivity of fluid

c_v = specific heat at constant volume

ρ = density

d_s = sensor diameter

V_s = fluid velocity normal to sensor

Since the heat transfer rate is proportional to the power, we have, for operation in the constant resistance mode and suppressed zero,

$$E_0 \propto V_s^{1/4}$$

where E_0 is the instrument output voltage.

Component measured. The magnitude of the wind component normal to the axis is measured. The wind azimuth determination has a fourfold degeneracy when two orthogonal horizontal sensors are used.

Accuracy. The accuracy of this type instrument is presently unknown under mission conditions. One percent or better can be achieved after calibration under laboratory conditions.

Range. Operational range is approximately 3 to greater than 140 m/s.

Frequency response. Frequency response is very high (greater than 10 kHz).

Atmospheric temperature effect. Effect of atmospheric temperature is severe, but can be compensated to some degree.

Blown dust effect. Limited measurements reported in Ref. 3 indicate that a shielded sensor is not abraded under simulated Martian conditions.

Shock and vibration. The sensors are normally considered to be delicate since they are small, but should readily support their own weight under acceleration. Resonant frequencies are probably higher than any shock or vibration components likely to be transmitted to the sensors.

Deployment considerations. The sensor itself can be deployed very readily. Deployed calibration devices could add great complexity.

b. Dynamic pressure. The instruments of this class can be conveniently divided into those which utilize a pressure gage to determine the dynamic head produced by the wind at ports (pitot devices) and those which measure the drag force on an object placed in the wind stream (drag devices). All operate on the principle of determining the dynamic pressure associated with the wind motion and given by $\frac{1}{2}\rho V^2$, where V is the wind speed. They have the common disadvantages of low sensitivity at low speeds and a dependence on atmospheric density. The dynamic pressure due to a 3-m/s wind at an atmospheric density of 2×10^{-5} g/cm^3 is 9×10^{-4} mbars, and that for a wind of 140 m/s in a 3.5×10^{-5}-g/cm^3 atmosphere is 3.5 mbars. Thus, a dynamic range of 3800 is required. Small pressure gages reputed to meet these specifications have been built. The drag-type instruments require either precise leveling, very stiff masts, or heavy counterbalances. (One type actually measures the drag force on the mast itself.) If the dynamic pressure method is used, the deployment considerations strongly favor the pitot device.

Several pitot devices have been proposed. A pitot-static tube servoed to point into the wind, multiport devices that utilize the ratio of heads at ports symmetrically located around a vertical cylinder, and a horizontal tube mounted on a radial arm and rotated rapidly around a vertical axis are typical. The rotating tube reduces the required dynamic range but at the expense of considerable mechanical complexity. The multiport schemes would almost certainly require leveling to approximately 5 deg. The following considerations are applicable to any of the pitot-type devices.

Quantity measured. The pitot-static tube yields $\frac{1}{2}\rho V^2$, whereas a simple pitot gives $p + \frac{1}{2}\rho V^2$, where p is the ambient atmospheric pressure. This holds within 5% for yaw angles less than 15 deg and Reynolds numbers greater than 30. Gas compressibility effects must be considered for Mach numbers greater than ~ 0.4.

Component measured. The magnitude and direction of the horizontal component are obtained.

Potential accuracy. Five percent or better accuracy is estimated with leveling, unknown without.

Range. Operational range is 3 to 140 m/s.

Frequency response. Frequency response requirement is approximately 10 Hz for a sensitive gage. Long-pressure tubes will slow the response.

Deployment considerations. Severe difficulties with some masts exist due to pressure tubes or large deployed gages.

c. Rotating. This category includes not only the rotating cup- and propeller-type instruments but also the wind vane, which yields direction only. They are the most popular earth anemometers because of their relatively low cost, high accuracy, and simplicity. They are also relatively insensitive to atmospheric density. All operate on the principle of aerodynamic lift and, therefore, require that the Reynolds number be adequate (~ 100) to establish good circulation. This is satisfied by a 1-in. chord at 3 m/s in the least-dense Mars atmosphere. The operation threshold is then established when the torque produced by the lifting surface exceeds the bearing starting torque. Theory and experiment indicate that thresholds in the range of 1 to 3 m/s can be achieved under Mars conditions of gravity (3/8 earth g) and atmospheric density. The devices are nonlinear at low wind speeds due to the increasing bearing loads and to Reynolds number effects. Development of bearings suitable for space flight would require considerable effort.

Quantity measured. For wind speeds above threshold the response is directly proportional to wind speed except for the low-speed nonlinearity mentioned above. Wind-tunnel calibrations of specific instruments under mission conditions are needed to establish the magnitude of these effects.

Component measured. The rotating cup measures the magnitude, not the angle, of the component normal to its axis. The propeller measures the component parallel to its axis; some propeller designs yield a nearly cosine response. Three of these would give the vector wind. The vane may be used either to point a propeller into the wind or to measure only wind azimuth or elevation.

Accuracy. A 1% magnitude accuracy or 5-deg direction accuracy should be achievable under Mars conditions. Without leveling this would be reduced to about 20%. Wind-tunnel tests under mission conditions are needed.

Range. Operation from 3 to 60 m/s should be readily achieved. The instruments will survive to 140 m/s but their operation at high speeds requires further investigation.

Distance constant. This parameter will fall in the range of 50 to 300 m. Wind-tunnel measurements are needed.

Atmospheric temperature effect. The rotation sensor must either operate at a temperature of 145°K or be heated. Sensitivity of the anemometer calibration to gas temperature is small.

Blown dust effect. The bearings must be shielded and a baffle or labyrinth seal should be provided.

Sterilization. The bearing lubricant must not be adversely affected.

Shock and vibration. Small instrument bearings can survive the 5000-g shock when very lightly loaded. A light load will also be required during vibration to prevent chatter.

Deployment considerations. The rotating cup anemometer can be folded into a compact form and readily deployed as described by Wellman (see *Section A*). Deployment of a two- or three-axis propeller or a vane would require considerably more space.

RF interference. Two possible methods of solving this problem are apparent. The cups and arms or vanes can be fabricated of a dielectric material, or the instrument can be electrostatically shielded by a large disk at the base. The second method may influence the wind-flow pattern excessively.

d. Sonic. Sonic anemometers are based on the fact that sound waves are propagated at a fixed speed with respect to the medium. Thus, the apparent speed with respect to a stationary observer is modulated by the wind. All of the instruments in this category utilize this effect to determine wind speed. The speed of sound c in a gas is given by

$$c = \left(\frac{\gamma RT}{M}\right)^{1/2}$$

where

γ = specific heat ratio
R = universal gas constant
T = absolute temperature
M = mean molecular weight

Thus, the instrument is quite sensitive to both gas composition and temperature.

The most promising sonic anemometer presently available is a pulse-type device which, using six transducers at opposite ends of three baselines, measures the three orthogonal components of wind speed. The instrument is sensitive to the speed of sound and this may be a major barrier to its use; it would also be large and difficult to deploy. However, it does possess one very important feature. If nearly calm conditions should prevail during any measurement period (approximately 30 ms), and an independent measurement of the air temperature is available, then a very precise measure of the speed of sound, and thus γ/M, will be obtained. An additional measurement of the received signal amplitude would yield the acoustic impedance ρc, and thus M and γ. In this manner not only the wind speed but also the important thermodynamic properties of the atmosphere would be determined.

Quantity measured. The difference in propagation time in opposite directions is measured. This time difference Δt is given by

$$\Delta t = \frac{2L}{c^2}\,\frac{V_b}{1 - V_b^2/c^2}$$

where L is the baseline length and V_b is the speed of the wind component parallel to the baseline.

Component measured. One pair of transducers yields the component parallel to the line joining them; three orthogonal sets give the vector wind.

Accuracy. A very sophisticated earth atmosphere instrument is capable of $\pm 3\%$ with temperature compensation and known atmospheric composition. A detailed study as well as experimental measurements would be required to estimate the instrument performance under Mars conditions. The nonlinearity should be of no consequence.

Range. Theoretically, the device can not operate beyond the speed of sound. In actual practice turbulence around the sensing heads will probably set a much lower limit, perhaps about 60 m/s. This effect will be accentuated by the large sensors required because of the low acoustic impedance of the Mars atmosphere.

Distance constant. This is several times the baseline length, which should be about ⅓ m.

Atmospheric temperature effect. Besides the effect on the speed of sound, the transducers must either operate at 145°K or be heated. This would require a minimum of several watts per head and any insulation would aggravate the turbulence problem.

Blown dust effect. Impact of dust on the transducers would necessitate either higher signal levels or a coded pulse, such as a chirp.

Shock and vibration. Articulated arms may be used to deploy the sensors and multiple caging mechanisms may be required for restraint. Transducer crystal breakage may be a problem.

Deployment considerations. The minimum baseline length would be about ⅓ m. Deployment of a two- or three-axis instrument from a folded configuration may be difficult. Also, the sensors would need to be some distance from sound reflectors to prevent multipath effects. Wind-drag loads on the boom would be high.

RF interference. The matrix of arms used to support the transducers may seriously perturb antenna patterns.

Volume. Stowed volume would be high.

e. Tracer. The tracer category includes all anemometers that record the motion of an individual element of fluid. This may be accomplished by injecting and tracking smoke puffs, ion clouds, temperature gradients, balloons, radar chaff, and shock waves. This is the only physical principle for which the true fluid velocity would seem to be measured directly. The output of the sensor may be in terms of sequential positions of the tracked elements (theodolite-tracked balloon), the traverse time for a fixed baseline (ion tracer anemometer), or a velocity (doppler radar or laser beam tracking aerosols). Thus, although the velocity seems to be measured directly, the effects of transducers, diffusion of the tracer element, turbulence, and other factors must be considered.

The local tracer instruments consist of a source of ions or heat located at the center of a circular detector which may consist of either a series of integral detectors, a loop of wire, or a spherical screen. The source is pulsed and the transit time of the ions or thermal gradients is determined. One severe disadvantage of this device is that wind components normal to the plane of the detector may cause the ions to miss the detector. The spherical screen detector obviates this problem but complicates data interpretation.

Quantity measured. The transit time of the tracer is measured and is related to the wind speed by $V = \ell/t$, where ℓ is the distance from source to detector and t is the transit time. The source can be retriggered by the detector, in which case the pulse frequency is proportional to wind speed.

Component measured. The magnitude of the component in the source-detector plane is measured. Direction can also be determined by means of schemes such as discrete detectors at azimuth angle intervals of 360/m deg, where m is any integer.

Accuracy. Accuracy is determined by the finite size of the ion cloud, which is influenced by diffusion and turbulence. Accuracies of 5% have been quoted. Wind tunnel tests are required.

Range. Range is dependent on the size of the instrument. Five to 50 m/s has been quoted and a greater range should be feasible.

Distance constant. The distance constant is equal to the detector diameter, of the order of ⅓ m or less.

Deployment considerations. The detector diameter must be determined before specific data can be given. However, even a spherical detector should be readily foldable.

RF interference. No moving parts are involved but a large detector may perturb antenna patterns.

f. Vortex frequency. When a cylinder is immersed in a moving fluid, it sheds vortices alternately from the two sides. Close behind the cylinder these vortices are well defined between Reynolds numbers of about 40 to 2000. They persist to some degree up to Reynolds numbers of 10^5 or greater, but are not as well defined. The frequency of shedding n is approximately proportional to the wind speed and is given by $n = S(V/d)$, where S is the Strouhal number and d is the diameter of the cylinder. The Strouhal number is approximately constant and equal to 0.21. More precise expressions, involving the Reynolds number, have been developed empirically. The technique of measuring the vortex frequency by placing a hot wire anemometer in the wake of a cylinder has been widely used in wind-tunnel work. Maintaining the detector downstream of the cylinder would, however, be difficult. It might be possible to construct the cylinder of piezoelectric material and detect the pressure changes associated with the vortex shedding. The same method might be used with a cylindrical hot film anemometer.

Quantity measured. A frequency proportional to the wind speed is determined. There is a dependence on kinematic viscosity at low speeds.

Component measured. The magnitude, but not the direction, of the component normal to the cylinder axis is measured.

Accuracy. Low-speed accuracy will be dependent on a knowledge of the kinematic viscosity of the atmosphere. At high speeds, accuracies of the order of 2% are obtained.

Range. The dynamic range for a given cylinder diameter is 50:1 for a relatively clean signal. The use of a phase-locked tracking filter may extend this range to 1000:1 if lock can be acquired and maintained.

Frequency response. The lowest vortex frequency would be of the order of 5 Hz for a 1-in. cylinder and a 1-m/s wind speed.

Atmospheric temperature effect. This effect would be small and readily corrected.

Blown dust effect. An acoustic transducer would suffer from dust storms but a quartz-sheathed hot film should be resistant.

Deployment considerations. A very small and rugged sensor should be possible.

4. Discussion

Preliminary studies indicate that the only relatively compact and simple instrument that yields both magnitude and direction is the tracer type. It would be highly desirable to fabricate such an instrument and test it under simulated mission conditions. The thermal transport and dynamic pressure instruments do not presently seem to be promising but they will be used as laboratory references in testing the others and may thus be further evaluated. The folding rotating cup anemometer (*Section A*) performed well in the capsule system advanced development program and its performance characteristics at low atmospheric density will be measured. It would also be desirable to determine whether or not the vortex shedding frequency of a single or multiple cylinder can be extracted from the noise with a narrow-band phase-locked tracking filter. All of these experiments can be performed in the JPL Mars wind tunnel.

Further evaluation of the sonic anemometer will require considerably different facilities. However, if one of the simpler anemometers proves adequate, the combination of one of these and a sonic densitometer would perform the function with greater economy of space, weight, and electronics complexity.

The Mars wind tunnel has been used for preliminary tests of the rotating cup anemometer and a threshold of approximately 3 m/s has been measured. Further work awaits evaluation of the low-speed flow profile of the tunnel.

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