A Microbarophone for Dust Devil Pressure Measurements¹

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ABSTRACT

The design and construction of a small, highly responsive pressure instrument with a sensitivity of approximately 0.1 mb is discussed. Two pressure sensors, or microbarophones, were used on a mobile tower to measure pressure variations near and within several dust devils. A pressure trace of a dust devil penetration is presented. The microbarophone is considered to have sufficient merit that it may be of use in other applications involving micro-pressure measurements.

1. Introduction

During a preliminary investigation of the pressure variations within large desert dust devils, the need for an inexpensive, fast-response, mobile pressure sensor became apparent. The fast response and mobility requirements are due to the characteristic dust devil size, translation speed, and life time.

Results of a dust devil census conducted over both flat desert terrain and populated areas showed that, of 2152 medium (10–50 ft dia.) and large (50–100 ft dia.) dust devils, 95 per cent had a visible life cycle of 4 minutes or less, and, in general, dust devil translation speeds were approximately 8–15 mph. Consequently, the radius of investigation is quite small, and therefore the instrumentation must be highly mobile in order to reach a dust devil before it dissipates. As a result of the mobility requirement of rapid transit over rough desert terrain, the pressure sensor should be small and immune to large amplitude, low frequency vibrations.

If one is successful in positioning the pressure instrument so that the dust devil will pass over it, the response of the instrument should be sufficient to record adequately a pressure pulsation with a period of approximately 2 sec. This means, of course, that the lag time of the instrument should be considerably less than 2 sec in order to minimize amplitude suppression and phase lag. Preliminary measurements indicated that the pressure within the dust devil could be approximately 3 mb below environmental pressure (Sinclair, 1964). This suggested a sensitivity of 0.1 mb, which was also commensurate with the design simplicity requirement.

The pressure sensor, or microbarophone, described herein met the above requirements and resulted in what are believed to be the first pressure profiles within a dust devil. In addition, the microbarophone is considered to have sufficient merit that it may be of use in other applications involving micro-pressure measurements.

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2. Instrumentation

The pressure instrument consists of a pressure antenna, microbarophone, amplifier, and recorder. Because of the high wind velocities in some dust devils, the design of the pressure antenna is a critical factor. Ideally, one desires an omni-directional pitot-type system in which not only static pressure but also the wind speed might be obtained. However, such a pressure sensing system requires airtight yet movable connections. The friction inherent in these connections must be small for fast response. It is evident that the construction of a low lag instrument of this type presents difficult and as yet unsolvable problems. Another approach is the fixed static pressure antenna² suggested by Prandtl and Tietjens (1934). It consists of a metal disk (0.125 inch thick, 4 inch dia.) supported by a narrow (0.250 inch dia.) metal tube. The disk has a 0.125 inch hole in the center which allows an air connection from the environment through the metal supporting tube to the detector. The pressure antenna is shown in the foreground of Fig. 1.

For flow parallel to the disk, this type of antenna permits pressure measurements of the desired accuracy. The suction effect due to flow past the 0.125 inch opening in the center of the disk is only about 0.01 mb for this type of antenna in a 45 mph wind.² In situations where there are large vertical wind components (dust devil case), static pressure errors occur due to dynamic pressure effects on the disk. Calibration of the antenna for 10-degree increments in angle of attack (θ) and for eight different wind velocities (V) was made in a small wind tunnel. The results for a wind speed of 24 mph (other wind speeds produced similar variations) are shown in Fig. 2. The plotted points represent averages of 2 separate runs. The average range for all points is approximately ± 0.04 mb. The dotted portions of the

² Investigations of Seismic and Sonic Disturbances, 1950, Final Report, Iowa State College, Physics Dept., ONR Project No. NR 350-017, 90 pp.

curve are simply the continuation of the slope at $\theta = 80$ deg. due to abnormal wind tunnel flow at these large angles of attack. Due to the symmetry of the pressure antenna the calibration needs only to be conducted from $\theta = 0$ deg to ± 90 deg.

As was expected, the pressure increased above its static value as either θ (or V) was increased (i.e., $\theta > 0$). As θ is increased negatively, the flow produces a low-pressure area on top of the disk, resulting in a rapid negative deviation of the pressure from its static value. This continues until $\theta = -30^\circ$, after which there is separation in the flow causing a pressure increase on the

disk top. In lieu of the more rapid variation in static pressure for $\theta < 0$ and the accompanying pressure effects due to separation, it is preferable to mount the antenna such that the most frequent variations of the wind from the horizontal result in a $\theta > 0$. This is especially important for high wind speeds. For accurate micro-pressure measurements in a moving medium, simultaneous measurements of θ are necessary either to correct the pressure data or to make certain that the wind error is insignificant. This was accomplished with sensitive bivanes and hot wire anemometers.

The microbarophone. The design of a sensor that meets all the requirements of simplicity, mobility, ruggedness, sensitivity and frequency response is usually not a straightforward task. The suggestion of the Mechano-Electronic Transducer (RCA 5734) coupled to an aneroid element was the first step to the final design. This transducer has previously been used by Curtis (1949), Curtis and Nickerson (1949), Pettersson and Clemenson (1950) and Talbot *et al.* (1951) in a number of physiological applications. It is believed that this is the first time it has been used to measure atmospheric pressure oscillations.

The transducer is a metal shell triode-type tube, 1.300 inch long and 0.328 inch diameter. A thin metal diaphragm seals the top of the tube and acts as a flexible pivot for the plate which extends 0.125 inch through the center of the diaphragm as a 0.031 inch diameter pin. This plate shaft is rigidly connected to the aneroid element by a thin-wall brass tube (0.064 inch dia.). Since the maximum safe deflection of the plate shaft is limited to ± 0.5 deg. of arc or an arc length of approximately $\pm 11 \times 10^{-4}$ inch for a 0.125 inch shaft length, the aneroid element must be selected such that maximum anticipated pressures (plus a safety factor) do not produce motions exceeding the elastic limits of the tube diaphragm. Preliminary dust devil pressure measurements indicated that a dynamic range of 10 mb should be sufficient even for the largest dust devil. Because of the immediate availability, an obsolete radiosonde aneroid element was used. For a 10-mb pressure change, this aneroid element moves approximately 4×10^{-4} inch, which is well within the maximum allowable plate shaft deflection. In addition to the desired static pressure changes, dynamic pressure effects of the wind may increase or decrease the aneroid movement depending on the orientation of the pressure antenna and the air motion. Since the vertical motion of the dust devil is characteristically upward, the pressure antenna was mounted with the static opening downward which means most of the wind variations from the horizontal produce a positive θ . In addition to the advantages of this orientation mentioned earlier, it also eliminates the possibility of dust clogging the air passage from the antenna to the detector. Preliminary observations near the ground and sailplane measurements of dust devil vertical velocity indicated that values rarely exceeded 2000 ft min^{-1} . Thus dynamic

FIG. 1. Shockproof container and amplifiers for two microbarophones. The pressure antenna is at the lower right.

FIG. 2. Dynamic pressure effects of the wind (V) on the antenna as a function of angle of attack (θ) for a wind speed of 24 mph. Note the flow separation at $\theta = -30$ deg.

FIG. 3. Schematic top-view of the microbarophone showing the arrangement of the aneroid and the transducer tube.

pressure variations will usually be less than 0.5 mb and probably most frequently near 0.1 mb. These pressure variations correspond to approximately a 10^{-5} inch movement in the aneroid element and hence are not significant with respect to the safe operation of the microbarophone (which has a maximum safe deflection of $\pm 11 \times 10^{-4}$ inch). Consequently, there was no design requirement for mechanical stops to limit the motion of the plate shaft.

The RCA transducer is clamped lightly, yet firm enough to prevent movement between two concave pieces of phenolic-type material (Fig. 3). Care must be exercised here in order that clamping pressure is not too large and it is evenly distributed on the metal shell of the transducer, otherwise tube damage may result. During normal operation the metal shell of the transducer becomes quite hot. In some initial tests a metal clamping arrangement was used, but it became apparent that the tube-to-clamp heat conduction was producing an undesirably long warm-up time. A clamp made of phenolic material resulted in a much shorter warm-up time. Overheating was not a problem as the exposed ends dissipated most of the heat by: (1) radiation and conduction to the air and (2) conduction via the tube pin to the aneroid connecting linkage. Also a small amount of heat was undoubtedly lost through the insulated clamp. This configuration was found to be the most satisfactory from the standpoint of drift and warm-up time. However, Talbot *et al.* (1951) describes two physiological instruments, a myograph and a ballistograph, in which the tube clamp acts as a heat sink to prevent excessive thermal drift and rapid aging. No effects of tube aging were noticed in two microbarophones which were operated intermittently over a period of 30 days for more than 100 hours.

The detector (aneroid) and transducer (RCA tube) are housed in a $2 \times 3\frac{1}{4} \times 3$ inch hermetically sealed aluminum box (Figs. 1 and 3). Two external pressure connections provide the pressure input from the antenna and the reference pressure. The reference pressure connection leads to a valve which is opened to the free air prior to the passage of the dust devil. Consequently,

the reference pressure in the box is essentially the undisturbed atmospheric pressure. The volume of the box (i.e., the reference pressure volume) was made as small as possible without sacrificing ease of assembly and maintenance. The small size was desirable since the transducer reached thermal equilibrium faster and hence warm-up time was reduced. Good stability was reached during actual field operations after a warm-up period of several minutes.

Two microbarophones were used to sense static pressure at two levels on the mobile tower. They are shown mounted in their shock-proof container in Fig. 1 (the unit on the left has its top removed). The two pressure reference valves are clearly shown at the top of the figure. The shock-proof container is made of composition board in order to insulate the units from external heat sources and is padded with foam rubber to minimize vibrations encountered in rapid transit over rough terrain.

The transducer is connected through a hermetically sealed junction in the side of the microbarophone (Fig. 3) to a standard Wheatstone bridge. The bridge is powered by a 450 v d.c. dry battery source which puts 180 v across the plate of the transducer. The 6 v d.c. transducer filament voltage is also supplied by dry battery. Changes in atmospheric air pressure (at the pressure antenna) result in movement of the aneroid element which in turn causes a displacement in the transducer plate shaft resulting in change in the plate current. This produces a change in the transducer resistance which unbalances the bridge causing a current to flow through a galvanometer.

Amplifier-recorder. The amplifier circuit diagram is shown in Fig. 4. Since the bridge circuit has a characteristic impedance of approximately 180,000 ohms, while the galvanometer has an impedance of 40 ohms, the bridge current was not sufficient to drive the galvanometer directly. Consequently, a d.c. direct coupled difference amplifier was used to match the bridge circuit with the galvanometer.

The d.c. coupled difference amplifier consists of two emitter follower amplifiers placed back to back. In order to minimize transistor temperature effects, the amplifiers (excluding the balance potentiometers, battery, and series resistances R_1 and R_2) were designed to fit into a 2.5 inch long and 1 inch diameter brass cylinder. In addition the two transistors were taped

FIG. 4. Schematic circuit diagram showing connection of bridge to galvanometer through the difference amplifier. The 50 K potentiometer is adjusted for a plate voltage of 180 v.

together to give them identical temperatures. The entire circuit may be easily removed, as the whole assembly is mounted on a 9-pin relay base. The original amplifier had far too large a gain for its purpose, so series resistors ($R_1 = R_2 = 250K$) were added in each lead from the bridge. These attenuated the signal from the bridge and increased the input impedance.

Several disconnect switches were placed in the circuit to protect the galvanometer from off-scale inputs from the amplifier and/or bridge. Switch S_1 is closed only after the amplifier has been balanced with the galvanometer. Before the bridge is connected into the circuit by switch S_2 , it is balanced after a short warm-up period by use of a 20 volt d.c. meter across the bridge output. When this coarse adjustment has been made, the bridge is connected into the circuit and further adjustments of drift are made with the bridge balance control.

The recorder consists of a Century (24 channel galvanometer) Dynamic Visual Monitor (DVM) and a 16 mm Bolex movie camera. The DVM (Model 20c) measures only $6 \times 7 \times 8$ inches and is shock resistant up to 12 g, which makes it ideal for mobile applications. The data presentation is on a 2.5×4 inch translucent screen which is photographed continuously at 32 frames per second. The galvanometer optical system is so designed that a twelve-inch optical arm is achieved which produces a d.c. sensitivity of 0.0315 ma. per inch deflection on the display grid. The galvanometers are electromagnetically damped to 64 per cent of critical while retaining a flat frequency response, within ± 5 per cent, from zero frequency to 60 per cent of its natural frequency (70 cps).

3. Drift factors

The drift of the microbarophone is a result of the separate drift characteristics of the transducer, the aneroid element, and the d.c. amplifier. The transducer drift is primarily due to the tube environment and plate voltage. Since a high amplification factor was desired, a plate voltage between 150–200 v was considered. In the arrangement described here, where the mount acts as an insulator in order to decrease initial drift, it was found that drift was minimized if a plate voltage of 180 v was used. Drift was increased markedly if the tube was in any type of air flow. This was minimized in the microbarophone by the detector housing. Convection currents were probably present, but their effect, while unknown, is considered relatively minor.

Since the transducer dissipates a considerable amount of heat, the air as well as the aneroid element (metal diaphragm and enclosed air) within the microbarophone housing increase in temperature. Thus, due to the heating, the microbarophone cavity air and the aneroid element produce opposing apparent pressure changes.

The well-known d.c. amplifier drift was recognized

from the start. None of the standard techniques of stabilization was employed, since the combined drift due to all the elements in the system was insignificant during the sampling period. This simplified the system electronically and reduced the cost for a reliable mobile unit. After sufficient warm-up, total drift was approximately 10–20 per cent of full scale (10 mb) per 1.5 hours. The sampling period lasted approximately 20 sec as the dust devil approached and passed over the mobile tower. Thus, the drift error is approximately two orders of magnitude less than the recording error (approximately 0.1 mb) during the sampling period. For other applications where longer term stability is required, the amplifier section may be eliminated if the transducer output operates through a suitable load, or the amplifier may be stabilized by one of the standard drift-compensation methods.

4. Response characteristics

The pressure system (microbarophone, amplifier, recorder) response to a step function change of 5 mb is shown in Fig. 5. The system is highly underdamped, having a damping ratio of approximately 0.13. The response time (time to reach and remain within 5% of the final value) is about 0.09 sec with a delay time of 0.002 sec and a rise time (time from 10 to 90% of the input step function) of 0.006 sec. The data reading error band (accuracy to which the recorded data can be read) of ± 0.1 mb is reached in approximately 0.16 sec. Because of the low degree of damping, large response ratios (ratio of the maximum overshoot of the element to the amplitude of the sinusoidal forcing function) will occur for forcing frequencies in the region of 15 cps to 45 cps. The natural frequency of the system is approximately 34 cps. To suppress these errors due to the dynamic response of the system, the recorded data were smoothed over an appropriate time interval. These values are with reference to a stationary atmosphere or one in which the air is moving parallel to the pressure plate. Near and within dust devils, the vertical component of the air may reach values of 2000 ft min^{-1} even quite close to the ground. Consequently, the pres-

FIG. 5. Response following a step change of pressure.

FIG. 6. The relation of the torque (applied to the tube plate shaft) to the observed displacement for 13 independent measurements. The standard deviation of these measurements is indicated by the short vertical lines. The curve represents the best fit by eye to the data.

sure antenna can experience significant dynamic pressure effects which lead to "apparent" static pressure changes. In these cases, the data are corrected using the bivane hot-wire anemometer system. This system reaches 90 per cent of the final value after a step function change in approximately 0.11 sec and stays within this error band after 0.5 sec. Hence, when w is large and fluctuating, the actual response of the pressure sensing system is more nearly that of the bivane hot-wire anemometer system.

5. Errors

The plate shaft of the transducer has a minimum free cantilever response of 12,000 cps. Due to the aneroid element, amplifier, and recorder, the natural frequency of the pressure instrument is approximately 34 cps. Consequently, distortion of the recorded signal due to phase and/or amplitude lag is not significant in light of the sampling time of several seconds or more. However, some distortion may occur over short periods when the vertical motion is large and fluctuating. In these cases the natural frequency of the system is more nearly that of the bivane-anemometer system and

FIG. 7. Deviation of the static pressure from the environmental pressure at a point 6 ft above the ground during the passage of a dust devil directly over the pressure antenna.

therefore a certain degree of smoothing the recorded trace is desirable.

Another possible source of error is inherent in the transducer itself. There is a significant decrease in the torque required to move the tube pin from its natural zero point as displacement increases (see Fig. 6). This non-linear effect may be eliminated by mechanically displacing the tube pin such that essentially the linear portion of the curve is used. Alternatively, one could take the non-linear region into account through calibration, or operate within a sufficiently small region that the torque-displacement relationship can be considered linear.

To minimize some of these errors, periodic calibrations of the pressure instrument were carried out. In addition, after each dust devil penetration, the entire system was immediately recalibrated with a water manometer.

6. Results

During the summer of 1962 several dust devil penetrations were made with two microbarophones. The pressure antennas were mounted at the 6-ft and 30-ft levels of a 30-ft mobile tower. Temperature and wind velocity were measured simultaneously with pressure. A pressure trace for the 6-ft level is shown in Fig. 7. The abscissa refers to the time it took for the dust devil to approach the stationary tower and pass over it. The ordinate is a measure of the static pressure deviation (in mb) from the initial environmental pressure prior to dust devil penetration.

Corrections have been applied for significant dynamic pressure effects due to large vertical gusts acting on the pressure antenna. In addition, the data were smoothed by using a 1.0 sec running mean in order to smooth some of the higher frequency oscillations more characteristic of the instrumentation than of the dust devil. As was expected, the pressure decreased toward the dust devil center with the center of the dust devil

passing over the tower sometime between the 8th and 10th second. The increase in pressure near the dust devil center (between 8th and 9th sec) requires further analysis. It appears to be connected with the simultaneously measured downdraft in the dust devil core.

The pressure trace shows a maximum pressure drop of over 3.5 mb. This occurs over a horizontal distance of approximately 30 feet and hence may represent the largest horizontal pressure gradient ever measured in the atmosphere. Substantially larger gradients will undoubtedly come from tornado measurements.

7. Conclusions

Through the design of a new micro-pressure instrument, the pressure variations near and within a dust devil have been measured successfully for the first time. Ives (1947) has made some prior pressure measurements with an aneroid barometer which gave pressure changes between the dust devil core and its environment of 17 to 85 mb. These values are considered too large even for the largest dust devil, and one therefore is led to suspect that large overshoot and vibrational errors occurred during the measurements.

For future dust devil measurements, the following improvements to the microbarophone should be considered:

- 1) Employ magnetic or oil damping to the aneroid to reduce the excessive overshoot;

- 2) Match the time constants of the microbarophone and the bivane-anemometer systems more closely;
- 3) Replace the Dynamic Visual Monitor with a multi-channel recording galvanometer. (This will reduce the extremely time-consuming job of reading data from film records.)

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