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Seismic Response of Infrasonic Microphones*

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Factors affecting the (unwanted) seismic response of infrasonic microphones are indicated. Past measurements of ground motion deduced from the radiated atmospheric sound measured with infrasonic microphones are reviewed, and such measurements are compared with seismometer measurements of ground motion. Seismic motions caused by the Japanese earthquake of May 1968 are used in this example. The seismic response of the infrasonic microphone used for this measurement was experimentally determined and the results are presented. A simple method of compensating for interfering seismic effects on microphones is described.

Key words: Compensation; ground motion; infrasonic microphones; seismic response.

1. Introduction

If seismic motions caused by a distant earthquake are strong enough, an earthquake-associated air-pressure wave may be observed. These air-pressure changes are observed coincident with vertical motions of the earth in the immediate vicinity of the microphone, and are caused by radiation of sound into the atmosphere by the ground motions. Observations on such acoustical radiation have been reported previously [Cook and Young, 1962; Donn and Posmentier, 1965]. The amplitudes of vertical ground motion deduced from the air pressure measurements have been compared with ground motions measured with seismometers operated in the vicinity of the infrasonic microphones [Cook, 1965; Donn and Posmentier, 1965; Golitsyn and Klyatskin, 1967]. In general quite good agreement has been obtained using the two methods.

In addition to the infrasound caused by local ground motions, air pressure waves have been observed originating from both the vicinity of the epicenter of an earthquake [Benioff and Gutenberg, 1939; Mikumo, 1968] and from intermediate regions along the seismic wave propagation path [Benioff et al., 1951; Donn and Posmentier, 1965; Press and Ewing, 1951]. The Alaskan earthquake of 1964 provided examples of both these classes of earthquake-associated atmospheric sound waves [Donn and Posmentier, 1965].

An example of an atmospheric pressure disturbance generated by the local passage of seismic waves from distant seismic activity is the record shown in figure 1. The acoustic data from microphones in the vicinity of Washington, D.C., appear in the upper portion of this figure. The microphone array at a typical station is designed for measuring four principal characteristics of infrasonic waves: (1) the amplitude and waveform of the incident sound pressure, (2) the azimuth of arrival of the wave, (3) the horizontal phase velocity, and (4) the dominant period of the wave. An infrasonic station normally has four or more microphones equipped with noise-reducing devices located at ground level, approximately in the same plane and spaced about 7 to 10 km apart. Figure 2 shows the microphone layout for the Washington, D.C., station.

Each line-microphone produces frequency-modulated voltages proportional to the sound pressure in the atmosphere. The tones are usually transmitted by telephone wires to a recording location. At this central recording location these tones are demodulated, amplified, filtered, and recorded in analog form both as ink-on-translucent-paper traces, and on magnetic tape. The system pass-band is designated N7 and is shown in figure 3.

The disturbance shown in figure 1 is related to an earthquake on May 16, 1968, with the epicenter under the sea floor 100 miles east of Hachinohe, Honshu, Japan (U.S. Coast and Geodetic Survey, Preliminary Determination of Epicenter: 0 = 00^h 48^m 55.4^s UT, 40.84° N, 143.22° E, h = 7 km, M_s = 7.9). This disturbance was much smaller at Washington, D.C., than the disturbance following the 1964 Alaskan earthquake. It was thought that the smaller ground motions would make intercomparison with seismic data more feasible. Note that this disturbance was distinguished from local pressure changes caused by turbulent motions of the wind, because of its presence at all of the microphones of a multipartite array.

The analog acoustic record shown in figure 1 is a superposition of the recordings from the various microphone sites. The waveform coherence between the various sites is quite good. Note that the time marks are almost coincident at the chart speed of ¾ in/min, indicating a high horizontal phase velocity. The disturbance was distinguished from acoustic waves propagating in the atmosphere parallel to the earth's surface, by its higher horizontal phase velocity. Rayleigh waves on the earth's surface have a horizontal phase velocity of about 3 km/s, compared with 330 m/s for acoustic waves in the atmosphere.

The disturbance started at 0135 UT and was lost in noise at about 0214 UT. The observed periods ranged from 17 s to 40 s. The maximum amplitude occurred at

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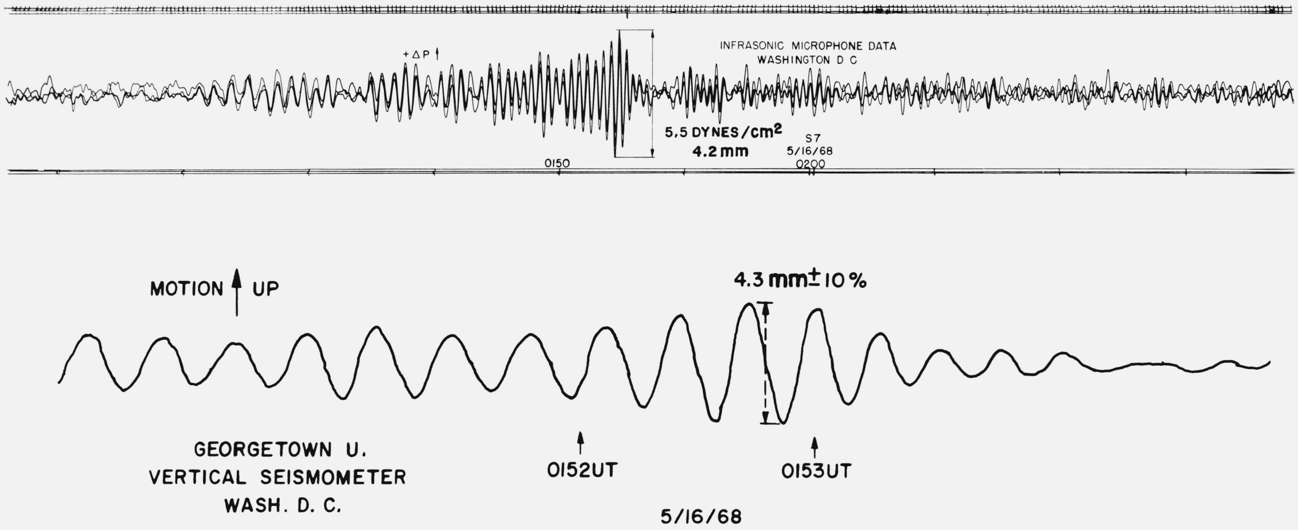

FIGURE 1. *Seismic disturbance of May 16, 1968.*

0153 UT and was 5.5 μbars at a period of 19 s. The ground displacement computed from these pressure data was 4.2 mm. The ground motion determined from seismometers located in Washington, D.C., was 4.3 mm. The Georgetown University Seismometer Laboratory made the recordings of ground motion shown in figure 1 available. The short-period worldwide standard seismograph was used in making the recording. The seismic data were corrected for system amplitude response before being compared with the infrasonic microphone records. Both measurements may be considered accurate to within ± 10 percent.

R. K. Cook [1965] has shown that the air pressures for such a disturbance are due to an integrated effect of the sound radiated by Rayleigh waves over a large area, as opposed to a seismometer which measures motion at a point; hence, it seems reasonable to consider infrasonic microphone data in order to obtain a more representative picture of ground motion over an area of the earth's surface. Infrasonic data will be useful for measurement of very large amplitude ground motions because the sound pressure levels will probably be larger than the pressure variations due to local winds. It is possible that for very large ground motions the dynamic range of sensitive seismometers will be exceeded, and then acoustical measurements can provide the desired measurements of the motions. But the microphones must perforce be

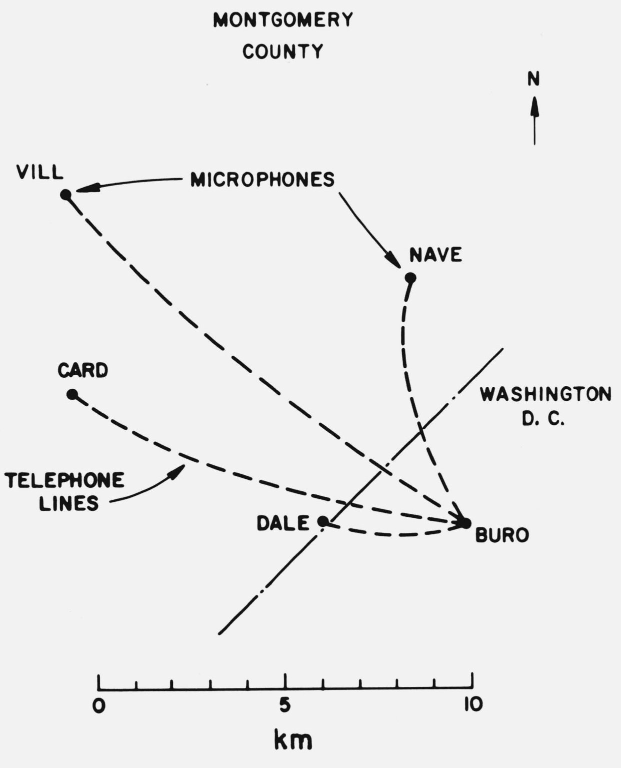

FIGURE 2. *Microphone site layout.*

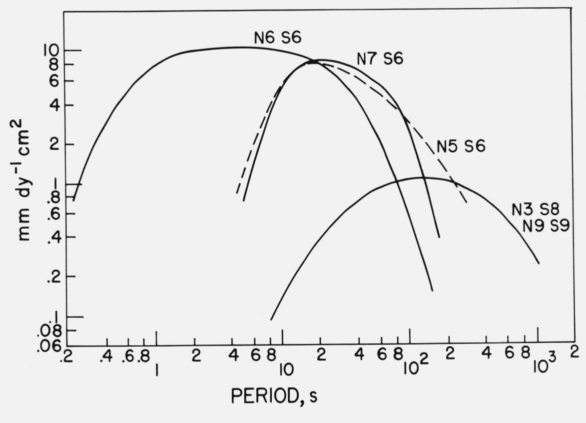

FIGURE 3. *Microphone system response.*

located on the surface of the earth, and they are therefore subjected to the latter's seismic motions. It is therefore necessary to determine the effects of the microphone's seismic motions on its electrical output. The effects might be small or negligible, but they must be known quantitatively.

2. Seismic Response Considerations

In attempting to test and evaluate the seismic response of infrasonic microphones several factors must be considered. Rayleigh waves occurring at the location of the pressure transducer generate peak pressure changes in the atmosphere calculated according to the relation

$$\Delta P = \rho c \omega X$$

where

$\omega = 2\pi f$
$f =$ frequency of the wave
$X =$ double amplitude of ground motion
$\Delta P =$ peak-to-peak pressure change in the atmosphere
$\rho =$ density of air
$c =$ velocity of sound in air.

This pressure change would be measured by the microphone together with any other instrumental seismic response effects that might be present. A frequently used form of infrasonic microphone is one that uses the motion of a diaphragm to detect pressure changes. This is the type of detector that will be considered here.

In addition to the pressure $\Delta P = \rho c \omega X$, such a transducer will respond to accelerations independently of any pressure changes occurring in the atmosphere. A transducer such as that shown in figure 4 will show seismic response due to both the diaphragm inertia and the inertia of air columns in the unit. Also, when the transducer is moved vertically through the atmosphere, a pressure change will be introduced whose magnitude will be equal to $\rho g X$. Pressure changes due to air motion past the microphone's openings to the atmosphere could also occur. The various factors contributing in theory to the seismic response are summarized as follows:

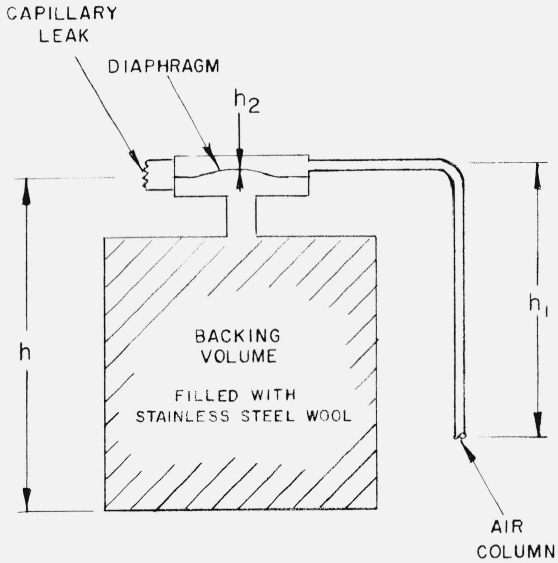

FIGURE 4. *Schematic view of microphone.*

Total Pressure Change ΔP_{Total}	=	Hydrostatic Equation* $\rho g X$	+	Bernoulli Pressures* $1/2\,\rho V^2 + \ldots$
Open Tube Air Column Effects* $\ldots\ \rho\omega^2 h_1 X$ +	Diaphragm Inertia $\omega^2 \rho_{brass} h_2 X$		Local Radiation + $\rho\omega c X$	Closed Tube Air Column Effects $\ldots + 1/2\,\rho\omega^2 h X$

where:

$g =$ local gravitational acceleration
$X =$ displacement double amplitude
$h_1 =$ vertical height of microphone's external air column
$h_2 =$ thickness of diaphragm
$h =$ length of microphone's internal air column
$V =$ maximum velocity of motion
$\omega = 2\pi f$
$\rho =$ density of air
$\rho_{brass} =$ density of the diaphragm
$c =$ velocity of sound in air.

In experimentally testing seismic response on a vibration shaker, the effect of translating the transducer vertically through the atmosphere will have to be taken into account. Effects of local sound radiation by the shaker will be negligible. Note that the relation listed for air column effects is valid for an open-ended tube at low frequencies. The closed tube relation is half of this value. Microphone response to vertical displacements was tested at the National Bureau of Standards at Gaithersburg, Maryland, where Mr. James R. Houghton made available a shaker capable of producing approximately sinusoidal, vertical motions. The tests were performed at an ambient temperature of 22° C, a relative humidity of 20 percent, and an ambient pressure of 757 mm of Hg. The frequency of vertical motion was adjustable over the range 1 Hz to 0.01 Hz. The double amplitude was set to 4 in.

The microbarograph system consisted of a pressure transducer [Cordero et al., 1957] equipped with a 7.5 s high-pass acoustical filter. The system pass-band including Discriminator N4 and Filter Amplifier N10 had 3 dB points at 1 and 20 s. Figure 4 shows a schematic view of the system microphone mechanical configuration. The

* There are no contributions due to the hydrostatic equation or Bernoulli pressures during seismic wave transit. These two effects are important during an experimental evaluation of the microphone with a vibration shaker. The relation shown for open tube air column effects is valid only during vibration shaker type experiments at low frequencies.

microbarographic system was calibrated with a pistonphone, and a portable fixed-frequency pressure calibrator was operated before and after the seismic response tests. The pistonphone was a stainless steel wool-filled 50-gal volume equipped with a brass bellows variable-volume element to produce dynamic pressure changes. Theoretical considerations made it desirable to vary the key parameters while subjecting the infrasonic microphone to vertical displacements on a shaker at a number of frequencies. Since the experiment was performed in the presence of local atmospheric pressure variations, a time of low atmospheric pressure noise was chosen. Further, it was necessary to choose vibration amplitudes large enough for the expected pressure variations to be larger than the local noise level.

3. Experimental Results

The system response on a vibration shaker table was found, within experimental error, to be independent of the orientation of the microphone inlet to the atmosphere. Hence, it is inferred that inlet air blast and Bernoulli effects did not contribute to the electrical output of the microphone.

At longer periods than 5 s per cycle, the observed change in pressure closely approached the value to be expected from the hydrostatic term in the pressure equation. There is no direct frequency dependence involved in this term. Figure 5 shows the pressure measured as a function of frequency.

If the value for ΔP determined from the hydrostatic equation is subtracted from the observed pressure changes and the resulting data plotted as a function of frequency squared, the result is approximately a straight line in agreement with the predicted f^2 dependence. See figure 6 for a log-log plot of ΔP versus frequency squared.

The vertical external tubing length was varied in 5-in increments and the output of the system measured with the frequency of vibration kept constant at 1 Hz. The variation of pressure as a function of length of tubing below this valve is linear and changes as expected

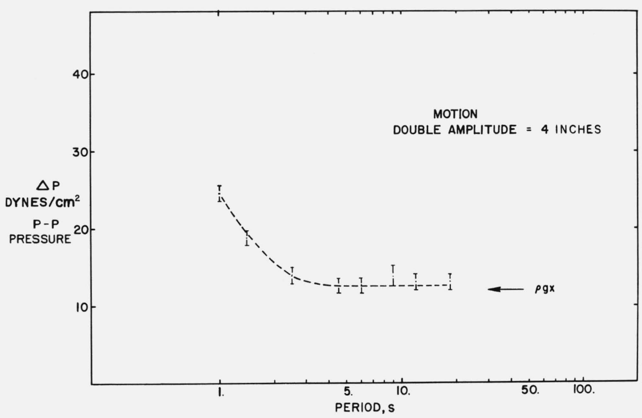

FIGURE 5. *Experimental response of microphone as a function of frequency of vertical motion.*

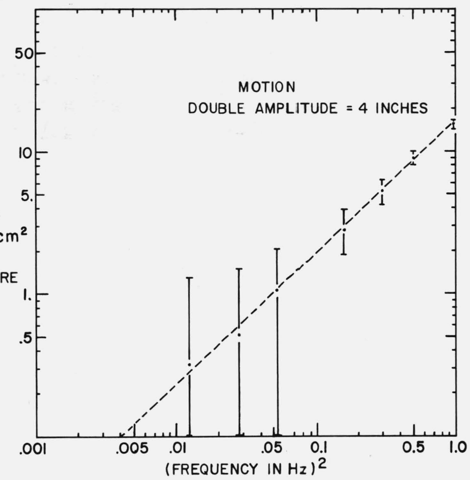

FIGURE 6. *Response of microphone as a function of frequency squared.*

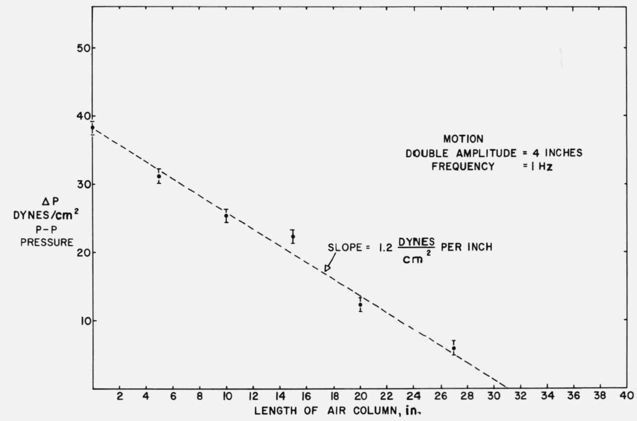

FIGURE 7. *Effect of air column length.*

($\Delta P \approx 1.2\ h_1$ at 1 Hz, where h_1 is in inches; fig. 7). This is approximately the slope of the line in figure 7.

Table 1 presents the contributions of the various seismic response mechanisms to the total pressure change observed. The outputs have been computed at frequencies of 1 Hz and 0.1 Hz and for displacement amplitudes of 0.001 in, 0.01 in, 0.1 in, and 1 in. Typical values are included in this table to show the relative importance of the various effective elements. The hydrostatic relation is also included for comparison purposes, although normally it would not be a factor in determining Rayleigh wave seismic response. The diaphragm compliance and effect of any backing volume sensitivity will reduce the system response, but these effects are not included in this worst-case consideration.

Because local background seismic noise amplitudes can be over 20 μm, the displacement amplitude of 0.001 in is a reasonable reference to use. Table 1 shows that the "loudspeaker action" effect from seismic waves will domi-

TABLE 1. *Seismic response contributions*

Generation mechanism		Displacement X, inches			
		$X=0.001$	$X=0.01$	$X=0.1$	$X=1$
1 Hz	$\rho g X$	0.003 μbar	0.03 μbar	0.3 μbar	3 μbar
	$\omega c \rho_{air} X$	.638 μbar	6.38 μbar	63.8 μbar	638 μbar
	$\omega^2 \rho_{brass} h_2 X$	.002 μbar	.02 μbar	.2 μbar	2 μbar
	$\omega^2 \rho_{air} h_1 X$	.003 μbar	.03 μbar	.3 μbar	3 μbar
0.1 Hz	$\rho g X$	0.003 μbar	0.03 μbar	0.3 μbar	3 μbar
	$\omega c \rho_{air} X$	.0638 μbar	.638 μbar	6.38 μbar	63.8 μbar
	$\omega^2 \rho_{brass} h_2 X$	$.2 \times 10^{-4}$ μbar	2×10^{-4} μbar	.002 μbar	.02 μbar
	$\omega^2 \rho_{air} h_1 X$	$.3 \times 10^{-4}$ μbar	3×10^{-4} μbar	.003 μbar	.03 μbar

$h_1 = 10$ in
$h_2 = 0.001$ in
$\rho_{brass} = 8.7$ g/cm^3
$g = 980.1$ cm/s^2

nate. The effects due to transducer seismic response are typically less than 1 percent of the "loudspeaker effect" at the pertinent frequencies. Thus, for this infrasonic microphone configuration, it is quite reasonable to deduce ground motions from observed pressure changes without correcting for instrument seismic response. Also, with the proper length of air column termination, one can null out the seismic response of the microphone at infrasonic frequencies. In the NOAA infrasonic microphone, the return hose from the microphone to the noise-reducing array accomplishes this. The open tube relation used here for computing this form of seismic compensation is valid only for shaker-type experiments with negligible local radiation. A seismically compensated microbarograph has been described [Ewing and Press, 1953] for use at periods longer than 20 s. A different method of seismic compensation is used.

Consideration of air column effects would suggest that caution should be exercised, for example, in installing an infrasonic microphone in a deep well and routing a tube to the surface. Since the air column seismic response is directly proportional to the length of the air column, a person might, in fact, be constructing a system sensitive to vibration. For 0.001-in tube displacements at 1 Hz, the seismically induced pressure amplitudes for an air column 10 ft long would be 0.03 μbar. This is over three times the internal noise level of the microphone now used by NOAA. Noise due to local vibrations would be increased.

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