ACOUSTIC TRANSMISSION SYSTEM

68CP531-COM

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ABSTRACT

This paper describes equipment providing acoustical transmission over ordinary telephone lines and utilizing standard telephone handsets.

Included is a discussion of the more pertinent parameters which determine the final design of the equipment; among them are proper orientation of the granular carbon transmitter, maximum line bit rates, and tolerable total harmonic distortion. The frequency and transient response of all acoustical transducers employed in the equipment are presented. The results of local and cross-country tests are graphically summarized. Also included is a summary of the actual operational experience over a period of two years from large numbers of units in use over the entire country.

INTRODUCTION

In the data processing and communication fields there are many instances where information from a remote source must be transmitted to a central processing location. Sometimes special purpose communication links have been utilized. However, because of the expense in building and maintaining such links these systems can be exploited only by special users.

The advantages of utilizing public utility telephone facilities as the communication link between a remote source and a central processor are obvious. To this end the telephone companies offer a wide range of equipments which provides electrical line coupling to the telephone facility. However, these equipments are still too expensive for many potential users.

The most economical method of transmitting data over telephone line is by *acoustical* coupling through conventional telephone handsets. This paper describes acoustic-coupling transmitting equipment developed by the *Digitronics Corporation* and successfully applied in its *Data-Verter* data acquisition systems during the past three years. It features reliable digital data transmission at the rate of 600 bits per second using the *frequency-shift-keying* method of transmission.

MODULATOR

Both the modulator and transducer are of economical design and construction employing electronic and associated parts commonly used throughout the audio industry. The modulator circuit is given in Figure 1A with associated waveforms in Figure 1B.

The various stages comprising the modulator are straightforward. The simplicity of this design does not warrant a detailed explanation of its operation. However, some comments are made about some aspects of the design not immediately apparent. The multivibrator, comprising transistors Q_2 and Q_3, is started after the application of the d.c. supply voltages when the relay contact, K_1, transfers from normally open to a closed state. This takes place when an associated tape transport is activated to transmit data pre-recorded on a magnetic tape cartridge.

The *recovery time constant* of the oscillations is independent of the state of Q_1 and, therefore, the MARK or SPACE frequency being generated. It is obviously a function of the time constant involving C_2 and R_9 as well as C_1 and R_8. This results in the resulting MARK frequency wave train having twice the amplitude of that of the SPACE frequency as indicated in waveform, B, of Figure 1B. To compensate for this component of frequency distortion, the MARK frequency is applied to the input of the audio amplifier through greater voltage division than is the SPACE frequency. This is effected by R_{15} which is added to the junction of R_{12} and R_{13} through diode D_3, only during the time Q_1 is conducting at saturation, at which time the lower MARK frequency is being generated due to the large total resistance applied to the common base input of the multivibrator. When Q_1 is cut off the total resistance to the common base input of the multivibrator is made smaller, increasing the fundamental oscillation to that of the SPACE frequency.

A multivibrator rather than a sine wave oscillator is used to generate the fundamental frequencies required because it affords a simple means of providing an immediate, yet smooth, transition from one frequency to the other under direct control of the input baseband signal. However, the resulting high order of harmonics present in the oscillations must be removed to within practical limits prior application to the acoustic coupler transducer. Therefore, the simple transformer-coupled amplifer, comprising transistors Q_4 through Q_6, serves not only to drive the transducer, but also to filter out a significant portion of the undesirable harmonics.

There is, of course, a limit to which this can be done without seriously affecting the *transitional response* between the MARK and SPACE frequencies and, therefore, the desirable data bit rate on the line. Consequently, the high frequency roll-off characteristic has been limited to the point where the SPACE frequency is down approximately 3 db from the MARK frequency, as indicated by waveform E, of Figure 1B. This degree of roll-off eliminates most of the undesirable odd harmonics present in the multivibrator waveforms without seriously affecting the transient response of the amplifier. This deviation from a flat frequency response to the amplifier is properly compensated for by the frequency characteristics of the coupler and telephone transmitter.

TELEPHONE CHARACTERISTICS

Of the large assortment of telephones which exist today in this country the two most common are the Bell System's type-300 and type-500. Of these, the type-500 is the most common.

Typical frequency characteristics of this telephone's granular carbon transmitter, type T_1, shown in Figure 3.

Note that the frequency characteristic of T_1 granular carbon transmitter peaks near 3000Hz and that the MARK frequency of 1300 Hz is approximately 6 db down from the SPACE frequency of 2100 Hz. This response of a telephone transmitter is actually preferred when compared with the attenuation characteristic of a typical, *unloaded*, line. That is, a line which does not contain lumped inductance at uniform intervals on the line for the purpose of equalizing the attenuation characteristic. Typical characteristics of both a *loaded* and *unloaded* line appear in Figure 4.

The type-500 telephone has a dynamic impedance of 600 ohms. It has a d.c. input resistance of approximately 110 ohms with a ±10% typical variation in this resistance depending on the orientation of the granular carbon transmitter. This change in the d.c. resistance of the transmitter is an indication that the carbon granules are free to "pack" differently within its confines. As orientation of the plane of the transmitter is varied from its most *efficient* vertical position to a completely horizontal position, increases in total harmonic distortion of as much as 20–25% have been observed with time. In addition, the *gain* of the transmitter decreases more rapidly and toward a lower asymptotic level when oriented in the horizontal position (see Figure 9). For these reasons the acoustic coupler is physically arranged in our equipment to maintain the plane of the granular carbon transmitter in a *vertical* position.

ACOUSTIC COUPLER

It is known from the theory of linear dynamic systems that the amplitude response, the phase characteristic, and the transient response are really equivalent ways of observing the inherent performance of an acoustical system. Poor transient response leads to fuzzy reproduction with poor definition. In designing our acoustic coupler, therefore, we sought:

a. response to the highest possible audio frequencies achievable.
b. a frequency response characteristic that is smooth and uniform, and free from sharp peaks and dips.
c. a sufficiently damped loudspeaker, especially near its natural base resonant frequency.
d. a speaker with the lowest possible bass resonant frequency.

Item (a) above is limited by the frequency characteristic of a telephone handset's granular carbon transmitter and the attenuation characteristic of a typical telephone line.

Items (b) and (d) are a function of the transducer employed with smaller speakers having higher bass resonant frequencies than larger speakers. Because space and economy were prime considerations, ordinary portable radio FM speakers were chosen. The type used in our system is a 250 milliwatt speaker with a voice coil resistance of 10 ohms and a base resonant frequency between 400 and 600 hertz. A typical frequency response is shown in Figure 6.

With the various characteristics of the telephone, telephone line, and coupler speaker in mind, the modulator and the physical aspects of the coupler were designed to accomplish items (b) and (c), above, for the complete system. The speaker enclosure shown in Figure 5, including the choice of surrounding acoustic materials, resulted from some theoretical considerations but mostly through empirical analysis.

Mechanical limitations necessitated the basic configuration of an *enclosed* speaker. Theoretically it is known that in such an enclosure the bass resonant frequency *increases* with *decreasing* volume of the enclosure. Since the bass resonant frequency is relatively high to begin with for the loudspeaker used (because of its small cone diameter of approximately 2.5 inches) a higher resonant frequency is undesirable. This is especially true since a MARK frequency of only 1300 hertz is used in transmission. The second harmonic of a bass resonant frequency larger than 600 Hz would appear, undesirably, within the spectrum of the transmission frequencies. Therefore, to reduce this shift in the bass resonant frequency and to effect adequate acoustical damping of the speaker, losses were introduced in the enclosure to flatten the portion of the frequency characteristic near the bass resonant frequency sufficiently.

The felt sound-absorbent material in the enclosure behind the speaker serves to damp or eliminate standing waves in the higher audio frequency range. It serves little in this regard in the lower frequencies due to the fact that all the material lies within a small fraction of a wavelength of the inner wall which is effecting a velocity node. Consequently, at the lower frequencies there is no motion of the air particles at the boundary of the acoustical material, nor is there motion of the material itself, to absorb acoustical power.

The felt sound-absorbent material employed in front of the speaker serves as a baffle to eliminate standing waves established between speaker and the hard plastic cover of the telephone handsets' transmitter. In addition, it serves as an acoustical low pass filter thus eliminating most of the remaining undesirable higher frequency harmonics contained in the amplifier output for the MARK and SPACE frequencies.

The resulting overall frequency response of the coupler including the telephone's transmitter is shown in Figure 7. Note that the slight pre-emphasis developed at the SPACE frequency is *intentional* to compensate for the high frequency attenuation characteristic of the line.

Most of the production quantity of speakers have characteristics closely approximating that shown in Figure 6. However, we have experienced roughly 10% of these speakers having an undesirable dip or peak in their characteristics between 1000 Hz and 2500 Hz. This is not surprising because the speaker is by no means a *quality* speaker and its specifications are rather loose. However, most of these less desirable speakers can and have been used by a slight mechanical adjustment of the coupler or the speaker to compensate for a de-emphasis or pre-emphasis which they produce in the overall response of the coupler. Low frequency (MARK) de-emphasis can be corrected by a slight adjustment of the speaker cavity geometry. De-emphasis near the higher SPACE frequency has usually been found to be the result of improper cone balance of the speaker. This is slightly more involved to correct. It can be corrected, however, by applying a slight pressure at various points in the rear of the cone while generating the critical frequency until the de-emphasis at that frequency is observed to disappear. Consequently, slight pressure is maintained at this point in the cone by inserting soft acoustical material between the rear frame supports of the speaker cone and this area of the cone. In practice, the number of speakers which require this corrective treatment have been found to be low enough so that it is more economical to discard them.

TYPICAL TRANSMITTING AND RECEIVING WAVEFORMS

A greater appreciation for the criteria essential to satisfactory acoustical coupling onto telephone lines, results from some familiarity with the method of demodulation provided by an AT&T subset (202A or 202C), located at the receiving end of the line.

To start with, the Dataset provides amplification of received FM signals at levels as low as, approximately, -40 dbm. Limiting is accomplished by a non-linear feedback method employed in the amplifier. Consequently, frequency distortion and total signal attenuation is tolerable above the -40 dbm limit.

Demodulation is accomplished in four stages. This is shown in Figure 8. First, the zero crossings of the input waveform are differentiated. Second a square-wave waveform of variable duty cycle (approximately 52% during MARK and 84% during SPACE) is generated by the triggering of a mono-stable delay circuit, of fixed delay, with each cross-over pulse. Third, the square-wave is passed through a demodulating low-pass filter, having a linear voltage vs. time waveform as illustrated. The demodulation delay, of approximately two milliseconds, has been omitted in this figure to avoid confusion regarding the actual point of transition. Fourth, the demodulated output is fed to a slicing amplifier, having a threshold corresponding to the "center" frequency of 1700 Hz, producing the final square-wave output signal.

Closer examination of Figure 8 indicates the danger of excessive harmonic distortion of the transmitted signal combined with a *non-linear* phase characteristic of the line. Such distortion produces asymmetry in the received signal which, in turn, results in instantaneous changes in duty cycle of the square-wave demodulator input waveform during time intervals when it should be consistently either 52% or 84%. If the distortion is serious enough, it will produce a dynamically irregular demodulator output waveform. Such an irregular waveform results in increased *jitter* in the transitions of the sliced output waveform and, at the same time, increases noise sensitivity of the system. One of the reasons for using a MARK frequency of 1300 Hz was to locate the more critical second harmonic (2600 Hz) further along the upper frequency roll-off characteristic of the coupler speaker. A SPACE frequency of 2100 Hz was chosen to maintain a center frequency of 1700 Hz.

The transition between frequencies of the received signal must be *smooth* and *rapid* to produce a sharp transition across the slicing level in the demodulated output waveform and to minimize *bias* distortion at the sending end of the line. A sharp transition across the slicing level results in decreased noise sensitivity and minimizes jitter in the final output. In order not to exceed power levels on the telephone line recommended by the telephone companies we note that AT&T transmitting subsets are typically arranged to provide -6dbm at the sending end of the line. We have observed that some of the type-300 telephones have a gain roughly 3db above that of the type-500. We therefore set our transmitting power levels at -3dbm using a type-300 telephone recognizing that most of the telephones which will be encountered in the field will be that of the type-500. The adjustment of the -3dbm level is done within a 15 second period following deliberate *tapping* of the handset's transmitter since the output of a granular carbon transmitter decreases with time, thereafter, approximately as indicated by the curves of Figure 9 when left physically undisturbed. Photographs of typical waveforms, characteristic of our acoustic-transmitting and dataset-receiving system, are provided in Figure 10. The photographs were taken using a local telephone line without loading-coil correction networks. The subset used was an AT&T 202C, strapped for 900 bits per second. The telephone handset used was a type-500 with a T_1 granular-carbon transmitter.

Maximum values of total harmonic distortion for either carrier frequency through the acoustic coupler system are: Modulator output – 5%; Telephone output with vertical orientation – 10%; Telephone output with horizontal orientation – 35%.

The above percentages of total harmonic distortion supports the need for maintaining the telephone's transmitter in a vertical position. However, it should be noted here that non-linear phase distortion combined with the harmonic distortion of either carrier frequency is what is most significant in distorting the *symmetry* of the generated carrier frequency on the line. For example, if asymmetry of a given cycle of MARK frequency results in *zero-crossings* at the 202C demodulator which occur close enough in time to that normally produced by an undistorted cycle of SPACE frequency, the demodulator output would swing from the MARK level toward the SPACE level during this short interval of time constituting an unwanted transition in the output waveform. Therefore, relatively large amounts of harmonic distortion can be tolerated out of the coupler provided the coupler's phase characteristic is linear over most of the frequency spectrum of the modulated signals. To demonstrate this, the waveforms of Figure 10 were developed by means of *diode limiting* the final output of the modulator shown in Figure 1 and transfer-coupling it to the telephone line. The total harmonic distortion was 25% for MARK, 20% for SPACE. However, as indicated in the resulting waveforms of Figure 10, the phase characteristic was sufficiently linear from 300 Hz to 3000 Hz such that the symmetry of the generated signals were only slightly impaired. Consequently, the demodulation *eye pattern* of Figure 11 resulted at the transmission rate of 1200 bits per second. The eye pattern clearly indicates excellent symmetry and transitional response from MARK to SPACE and SPACE to MARK, despite the relatively large percentage of total harmonic distortion of the individual carrier frequencies.

ACTUAL FIELD PERFORMANCE

It has been emphasized that economy of design and manufacture were the prime consideration in the development of the acoustic coupler and the modulator circuits. The remaining portion of this paper deals with the actual performance of this equipment in the field.

The equipment underwent a period of field transmission tests at varying data rates up to 750 bits per second. These tests, concluded successfully over three years ago, were followed by system deliveries starting roughly three years ago. It is this extensive experience at actual customer sites throughout the country that is of most interest.

As of August of this year approximately one-thousand systems employing the subject acoustic coupler have been installed and are in use with customers located throughout the United States. Approximately ninety percent of these customers comprise retail outlets such as supermarkets, chain drug stores, mail-order companies, etc. The remaining ten percent constitute manufacturing facilities (in which payroll data are transmitted) and individual salesmen who transmit daily orders directly from their homes, motels, hotels, etc. In addition, approximately twelve systems have been installed and are functioning very well in Holland, although the acoustic coupler was not designed for use with European telephones and telephone lines.

When actual customer use of the acoustic coupler began, we had no idea of the number of individual installations that would occur in which acoustic coupling would prove to be troublesome. We were therefore prepared to substitute an electrical line-coupling modem, such as a 202C subset or the more recent 202E dataset. To date we have never experienced this type of difficulty.

The average number of bits transmitted daily for each of the one-thousand systems presently in use has been approximated at 150,000. The transmission error rates experienced have been in the order of *one in* 10^6 due, primarily, to transient line conditions. We have received no reports from the field which would indicate to us that errors may have been caused by an incompatibility of acoustic coupling and telephone line frequency and phase characteristics.

The fact that we have limited the transmission rate to 600 bits per second and have taken certain precautions, such as optimizing the physical orientation of the telephones granular carbon transmitter, are undoubtedly some of the reasons for this successful experience with the coupler throughout the United States. However, it is also true that the general quality of the telephone line facilities have been significantly upgraded by the telephone companies especially in the past five years, as part of their increased activity in the field of data communications. Finally, it should be mentioned that the transmitting equipment, of which the acoustic coupler is part, is not *installed* by field service engineers. The equipment is shipped directly to a customer where typical office help uncrates the equipment and places it in operation using any of their business telephones. The high degree of success is considered due primarily to the quality and uniformity of the telephone systems in the United States and to the simplicity of the acoustic coupling equipment and its use well within conservative specifications.

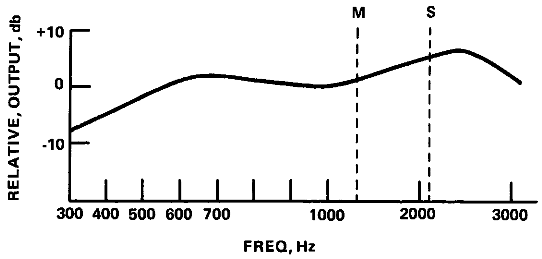

Fig. 7 Overall Response of Acoustic Coupler System

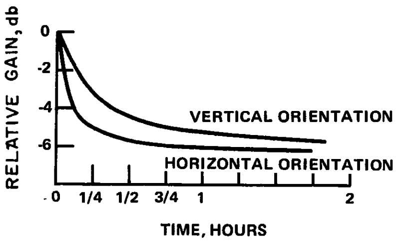

Fig. 9 Approximate Loss of Gain vs Time Characteristic for Type T_1 Granular Carbon Transmitter

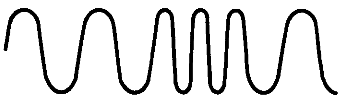

Fig. 10 Diode-Limited FSK Waveforms on Send End of Telephone Line

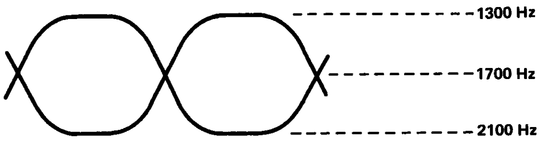

Fig. 11 Demodulation Eye Pattern Resulting from Waveforms of Fig. 10

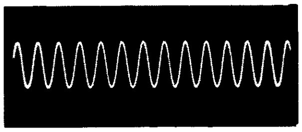

PHOTO 1 – Continuous MARK on input of line.
H = 1 ms/cm
V = 1 v/cm

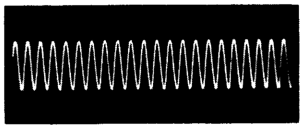

PHOTO 2 – Continuous SPACE on send end of line.
H = 1 ms/cm
V = 1 v/cm

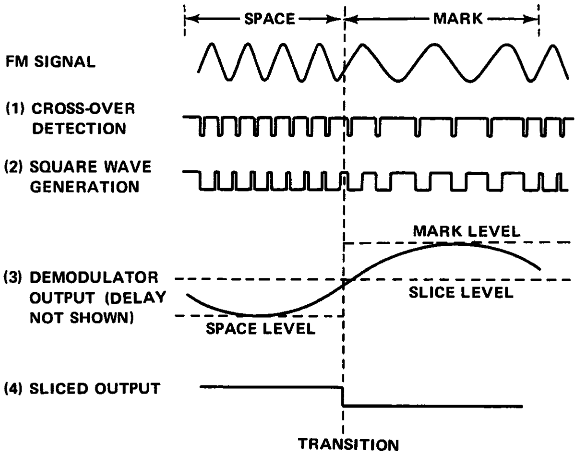

Fig. 8 Principle Stages of Subset Demodulation

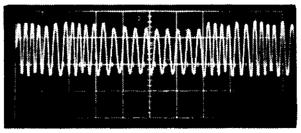

PHOTO 3 – Data Transmission, on send end of line.
H = 2 ms/cm
V = 1 v/cm

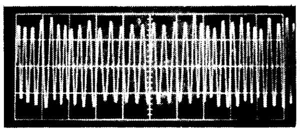

PHOTO 4 – Same as above on receive end of line.
H = 2 ms/cm
V = 0.1 v/cm

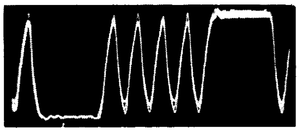

PHOTO 5 – Subset Demod Output, (Term. 14-15 on TB-2)
H ≅ 3.5 ms/cm
V = 1 v/cm

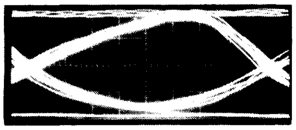

PHOTO 6 – Demodulation Eye Pattern.

MARK LEVEL

CENTER FREQ. LEVEL (1700 Hz)

SPACE LEVEL

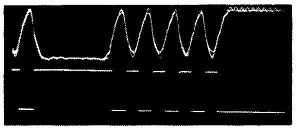

PHOTO 7 – Subset Demodulated Output (Term. 14-15 on TB-2) and Final Output (Pin 3 on J-5).

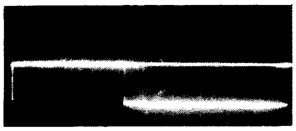

PHOTO 8 – Final Output display arranged for observation of jitter and bias distortion.

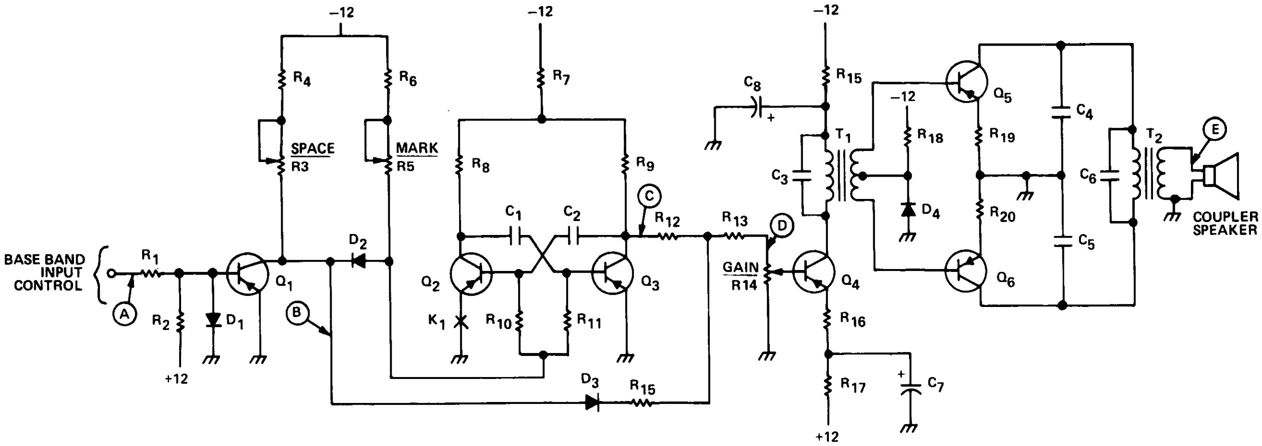

Fig. 1A Modulator Circuit

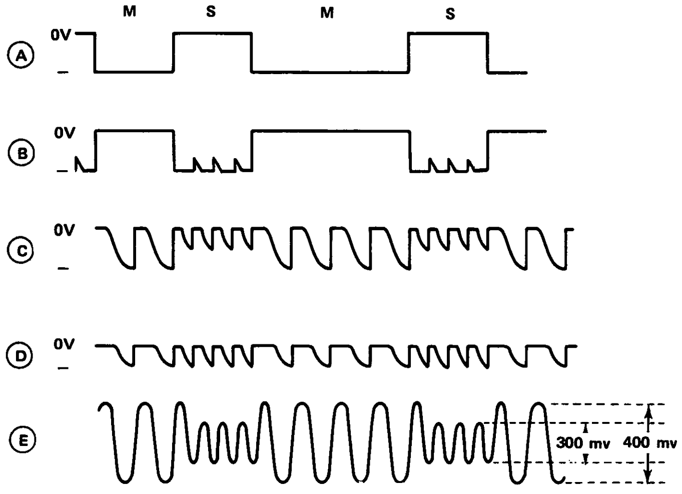

Fig. 1B Modulator Waveforms

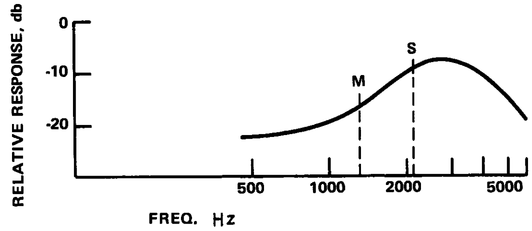

Fig. 3A Granular Carbon Transmitter Response

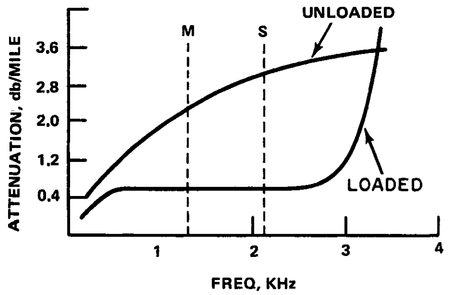

Fig. 4 Telephone Line Attenuation Characteristics

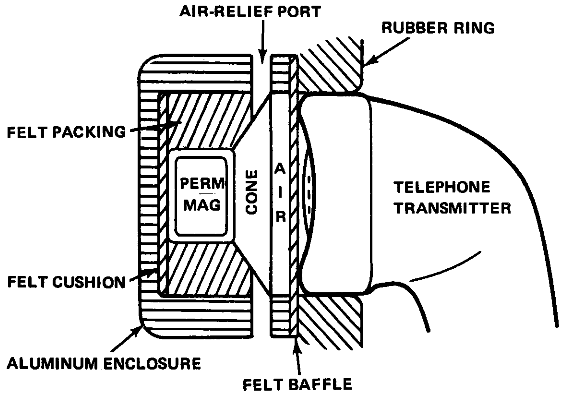

Fig. 5

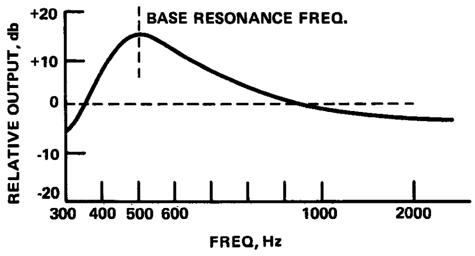

Fig. 6 Typical Frequency Characteristic of Coupler Speaker