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AMPLITUDE DETERMINATION OF AN ULTRASONIC TRANSDUCER BY MEANS OF AN ACCELEROMETER ASSEMBLY

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ABSTRACT

An accurate method for measuring the amplitude of vibration at the tip of an ultrasonic transducer assembly used for cavitation experiments has been developed. The method consists of monitoring the voltage output from a suitable accelerometer which is mounted at the top of the vertical transducer assembly where it is readily accessible and not subject to the severe experimental environment that may exist in the vicinity of the test specimen which is attached to the lower end. A calibration of absolute amplitude at the horn tip versus the voltage output from the accelerometer makes it possible to determine the desired amplitude under any test conditions. The accelerometer is capable of operation at frequencies up to approximately 20 Kc./sec. and can measure amplitudes in the range 0-3 mils with an accuracy of ± 0.1 mils.

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CHAPTER I

INTRODUCTION

The University of Michigan Laboratory for Fluid Flow and Heat Transport Phenomena has conducted ultrasonic-induced cavitation studies in a variety of fluids over a wide temperature range for the past several years.[1,2,3,4,5,6] The high-temperature ultrasonic cavitation vibratory facility utilized in these studies has been described elsewhere.[1,7] However, the major features of the facility will be reviewed here. Figure 1 is a schematic block diagram of the high-temperature ultrasonic vibratory facility showing the audio oscillator, power amplifier, transducer-horn assembly, test specimen, oscilloscope, frequency counter, high-temperature furnace and cavitation vessel, and accelerometer. The signal supplied by the variable frequency audio oscillator is amplified and applied to the piezoelectric crystals. The resultant periodic motion of the crystals effectively constitutes a standing wave generator with the amplitude of the standing wave being increased as it traverses the exponential horn assembly. The use of exponential horns as velocity transformers in this fashion was first suggested by Mason.[8] The movement of the horn tip, to which a test specimen has been attached, results in a rapid variation in local pressure, causing the periodic formation and collapse of an intense cavitation cloud. The final result is an accelerated erosion of the test specimens subjected to the collapsing bubble cloud.

It has been shown by several investigators[9,10,11] that the amount of damage sustained by the test specimen is heavily dependent on the amplitude of the horn tip to which the specimen is attached. In fact, there exists a minimum

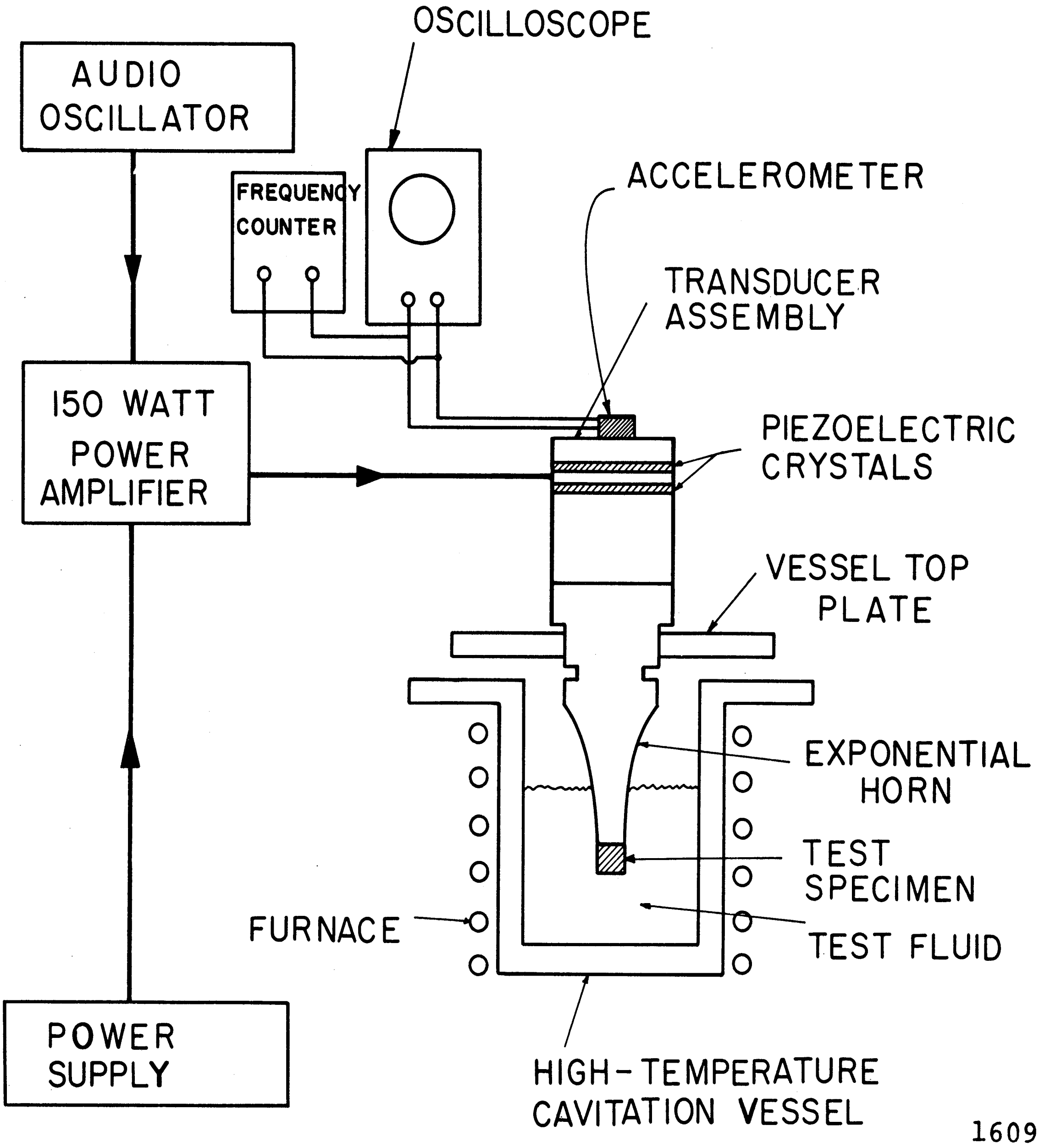

Figure 1. Block Diagram of the High-Temperature Ultrasonic Vibratory Facility

threshold amplitude for a given facility[10] below which no damage is suffered by the test specimen. Hence, it is clear that it will be necessary to determine the amplitude of the specimen with reasonable accuracy and to maintain this amplitude within acceptable limits for the duration of a test. In addition, it is important that any given amplitude be reproducible for future investigations so that comparisons may be drawn between various specimen material-fluid-temperature combinations. The problem of amplitude measurement is made difficult since the amplitudes characteristic of the magnetostrictive and piezoelectric devices used for ultrasonic cavitation studies are in the range of 1 to 5 mils, while the frequency of operation is generally 15 to 20 Kc./sec. Other investigators[9,10] have utilized a voice coil arrangement, which surrounded the exponential section of the transducer, to determine the amplitude of the device. During operation, a voltage is induced in the voice coil which is proportional to the amplitude at the horn tip. The output from the voice coil may be displayed on an oscilloscope or fed to a vacuum tube voltmeter and/or frequency counter for analysis. This arrangement requires that an absolute determination of the amplitude of the horn tip be made by direct observation in air utilizing a suitable high-power microscope. Such a calibration would result in a plot of absolute amplitude of the horn tip versus the voltage output from the voice coil, and would enable one to determine the amplitude easily in any fluid as long as the characteristics of the exponential horn-voice coil system were not changed by the conditions of the surrounding environment. This calibration is particularly necessary since it would be difficult or impossible to directly observe the motion of the horn tip during a test in water, and especially during an investigation in an opaque fluid, e.g., liquid metals at elevated temperatures, where the vessel would also be opaque. Hence, it is necessary to be able to easily measure some secondary quantity that is directly related to the absolute amplitude in a reproducible and reliable manner.

In the case of our experiments, some of which were conducted in liquid metals at temperatures in excess of 1500°F, it was not possible to utilize a voice coil arrangement, as described previously, because of the severe surrounding environment. Such a voice coil assembly depends on the exponential variation in cross-sectional area of the horn device for its operation. However, the horn assembly is in close proximity to a corrosive test fluid at a very high temperature, and any calibration obtained in air at room temperature could not be expected to be valid at the elevated temperature, assuming, of course, that the voice coil would be operable under such conditions. As a result it was necessary to determine the amplitude in our investigations by some other method.

Since the horn tip approximately describes simple harmonic motion, the vertical displacement measured from some suitable datum plane taken as the origin is given by:

$$y = A \sin \omega t \tag{1}$$

where:

y = displacement at time, t

A = maximum amplitude

$\omega = 2\pi$ x frequency of vibration

t = time

Hence, the acceleration, a, can be determined by differentiating expression (1) twice:

$$a = -A\omega^2 \sin \omega t = -y\omega^2 \tag{2}$$

$$\text{When } y = y_{max.} = A,\ a = a_{max.} = -A\omega^2 \tag{3}$$

Thus, it is seen that the acceleration at the horn tip is proportional to the amplitude at the horn tip, and suggests the use of a suitable commercially available accelerometer whose voltage output would be proportional to measured acceleration and, hence, amplitude, at a given frequency. Such an accelerometer could be mounted at some point along the transducer horn assembly where the temperature variation is very slight during the investigations. Hence, its operation would be unaffected by the severe environment existing at the horn tip. Nevertheless, for a fixed accelerometer position, it would be possible to determine a suitable calibration of absolute amplitude (as determined by direct visual microscopic observation in air) versus voltage output from the accelerometer. Such a calibration would be valid for operation of the transducer-horn assembly at elevated temperatures since the accelerometer responds to changes in acceleration only.

CHAPTER II

ACCELEROMETER DESCRIPTION

The requirements of a suitable accelerometer for this application include an ability to operate at a frequency of 20 Kc./sec., which is the normal frequency of operation of our ultrasonic cavitation facility. In addition the sensitivity of the accelerometer must be sufficiently large so that the output can be easily measured with an oscilloscope and/or vacuum tube voltmeter. The weight of the accelerometer should be a minimum so as to only slightly disturb the ultrasonic unit. The accelerometer chosen for this application was the GLENNITE accelerometer Model #CA260502, supplied by Gulton Industries, Inc., of Metuchen, New Jersey. This accelerometer has a sensitivity of 1.32 mv./g* over a wide frequency range, a resonant frequency of 138 Kc./sec., a nominal frequency range extending from 3 cps to 20 Kc./sec., a nominal acceleration range from 0 to 2000 g,* a transverse response of only 1.7%, and a weight of 1.3 grams. It is easily mounted to the transducer-horn assembly at a suitable location by means of a threaded stud. A consideration of equation (3) above shows that for a frequency of 20 Kc./sec., and an amplitude of only 0.1 mils, the maximum acceleration would be approximately 2000 g.* Hence, the output from the accelerometer would be approximately 2.5 volts, which is easily measured. It should be noted that an acceleration of approximately 2000 g constitutes the upper limit of applicability of <u>any</u> accelerometer, due to mechanical limitations.

It was decided to mount the accelerometer at the top of the transducer assembly, as shown in Figure 1. Such a location resulted in easy access to the

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*g = acceleration due to gravity, taken as 980 cm./sec.^{2} at sea level.

unit with respect to cable attachment, and the temperature at this location was shown to be less than 100°F, even when the test fluid was at 1500°F. Although the acceleration at this location is considerably less than at the horn tip, it was felt that the sensitivity of the accelerometer was large enough to provide a suitable output voltage for measurement. In fact the acceleration at the horn tip is so large (approximately 50,000 g) that an accelerometer mounted in this vicinity would be immediately destroyed upon operation of the unit. Since the transducer assembly had been fitted with a tapped hole (5/8-20) at its top when it was initially constructed, an aluminum adaptor was fabricated which attached to the top of the transducer assembly. The accelerometer was then firmly attached to the aluminum adaptor with a torque wrench. Figure 2 is a photograph of the accelerometer, special cable leading from the accelerometer to the oscilloscope connector, and the aluminum adaptor. Figure 3 is a photograph of the transducer-horn assembly installed in the high-temperature cavitation vessel and furnace. The accelerometer is mounted at the top of the transducer assembly, and the cable leading from the accelerometer to the oscilloscope for measurement purposes is evident. Because of the high frequency of operation and the resultant low impedance of the accelerometer (approximately 20,000 ohms at 20 Kc./sec.), it is possible to feed the signal from the accelerometer directly to an oscilloscope or vacuum tube voltmeter, each of which has an input impedance of several megohms. As a result, in this application, a cathode follower or other similar impedance matching device is not necessary.

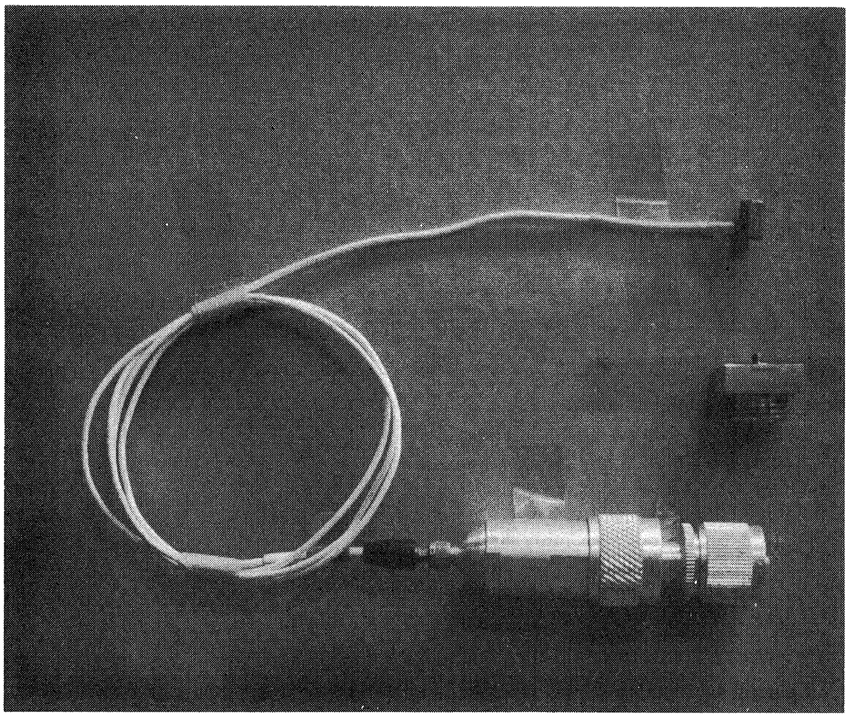

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Figure 2. Photograph of Accelerometer, Cable and Connector, and Aluminum Adaptor

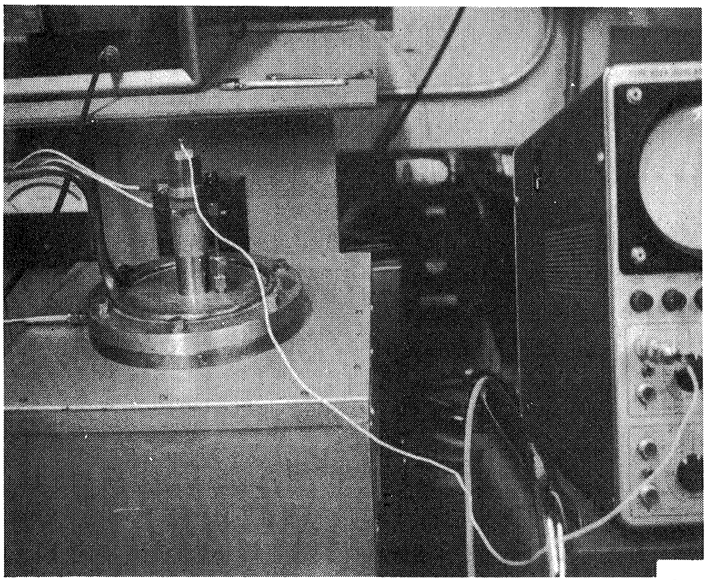

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Figure 3. Photograph of Transducer-Horn Assembly Installed in Vessel with Accelerometer Mounted at Top of Horn

CHAPTER III

ACCELEROMETER CALIBRATION

A. Procedure

As previously noted, it is necessary to calibrate the accelerometer once it is mounted in a fixed position, i.e., determine the relationship between the voltage output from the accelerometer and the amplitude at the horn tip. The necessary calibration was performed in air at 70°F with the transducer-horn assembly mounted in the top plate. The complete assembly was supported so that the axis of the transducer was vertical, corresponding to normal operation of the unit. A Unitron Metallurgical Microscope fitted with an eyepiece which contained a uniformly graduated scale was employed for the absolute amplitude measurements. Previously, the graduated scale had been calibrated by observing a specimen of known dimensions at a magnification of 400. It was found that 8 divisions on the eyepiece scale corresponded to a length of 1 mil, the complete scale having a length of 100 divisions. Since earlier direct amplitude measurements[1] had established that the amplitude of vibration of the horn tip was in the range of 1 to 3 mils, it was felt that the sensitivity obtained at a magnification of 400 would be sufficient for the measurements. The test specimen at the end of the horn was backlighted with a General Radio Company Type 1531-A Strobotac which was adjusted to a suitable frequency so that it was possible to observe the motion of the horn tip as it vibrated between the extremities of travel. For a given test specimen, the voltage applied to the piezoelectric crystals was varied over a wide range (at a fixed frequency of 20 Kc./sec., which corresponds to the resonant frequency of the transducer-horn assembly), and the peak-to-peak amplitude of vibration of the horn tip was observed under the microscope at a magnification of 400. By means of the calibrated eyepiece and stroboscope, it was possible to note easily the number of divisions corresponding to the specimen motion, and hence determine the absolute amplitude, knowing the calibration of the graduated scale. For each value of absolute amplitude observed, the output from the accelerometer was fed to a Ballantine Laboratories, Inc., Model 300-G Vacuum Tube Voltmeter with a scale range from 1 mv. to 1000 volts RMS.* Thus, it was possible to determine corresponding values of the absolute amplitude and voltage output from the accelerometer. The procedure was repeated for three test specimens, one each of stainless steel, aluminum, and a tantalum-base alloy, covering a density range from 2.77 g./cc. to 17.6 g./cc. All specimens weighed 9.4 ± 0.1 grams. After many measurements were made, it was felt that the reproducibility of data was within a tolerance of 1 scale division on the calibrated eyepiece, or approximately 0.1 mils. Also, the visual measurement accuracy was estimated to be within a tolerance of 1 scale division, or approximately 0.1 mils.

For various horn tip amplitudes the output from the accelerometer was also fed directly to a Tektronix, Inc., Type 502A Dual-Beam Oscilloscope for visual display and analysis. Hence, it was also possible to determine the frequency of vibration of the transducer-horn assembly by determining the frequency of the accelerometer voltage waveform.

B. Experimental Results

The results obtained in this investigation are presented in Table 1 which lists corresponding values of variac voltage (proportional to crystal

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*Root-mean-square voltage.

TABLE 1

AMPLITUDE MEASUREMENT DATA

Experimental Conditions:

1) Transducer-horn assembly mounted in vessel top plate and held in a vertical position by usual mounting device
2) Surrounding medium is air at 70°F
3) Microscope magnification = 400X
4) Eyepiece calibration: 8 divisions = .001" = 1 mil
5) Stroboscope frequency = 3300 flashes/minute
6) Frequency of vibration of transducer-horn assembly = 20.3 Kc./sec.
7) Test specimens were 304 stainless steel, 2024-T351 aluminum, and T-111 (Ta-base alloy)
8) Accelerometer mounted at top of transducer-horn assembly

	Accelerometer Voltage Output		
Variac Voltage	VTVM(RMS)*	CRO(P-P)**	Amplitude(P-P)
60 V	0 V	0 V	0 mils
70	0.9	3.0	0.5
80	1.8	6.0	1.0
90	2.9	8.0	1.5
100	4.1	10.0	2.0
110	5.2	13.0	2.5
120	6.0	16.0	3.0

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*Voltage measured by vacuum tube voltmeter, root-mean-square.

**Voltage measured by cathode-ray oscilloscope, peak-to-peak.

voltage), accelerometer voltage output (RMS) as measured by the vacuum tube voltmeter, accelerometer voltage output (peak-to-peak) as measured by the oscilloscope, and absolute amplitude (peak-to-peak) of the horn tip. It was found that the results were identical for each of the three specimens employed within the margin of experimental error. Note that the maximum amplitude measured was 3 mils (peak-to-peak), which corresponds to an acceleration of approximately 100,000 g (peak-to-peak) at the horn tip. Equation (3) was used for this computation. At this amplitude the peak-to-peak accelermoter output voltage was 16 volts, which corresponds to an acceleration of approximately 12,000 g (peak-to peak) at the opposite end of the transducer-horn assembly where the accelerometer is mounted. This value of acceleration was computed assuming an accelerometer sensitivity of 1.32 mv./g, which represents a careful calibration supplied by the manufacturer. This calibration should be valid even at the very high values of acceleration involved in this investigation as long as the accelerometer is not damaged, and the frequency of operation (20 Kc./sec.) is a factor of 3 or 4 below the resonant frequency of the accelerometer (138 Kc./sec.) so as to avoid accelerometer resonance effects. It is interesting to note that the acceleration (and hence amplitude) is approximately 8 times greater at the horn tip where the specimen is located than at the opposite end of the horn where the accelerometer is located. This is very reasonable since in an exponential assembly of this type, the amplitude of vibration varies inversely as the cross-sectional areas of the ends of the exponential assembly.[8] In our case, the cross-sectional area at the top of the transducer-horn assembly is approximately 9 times greater than the tip cross-sectional area. Both ends of the horn assembly correspond to antinodal points of the standing waves propagated within the transducer.[1]

In Table 1, values of accelerometer voltage measured by the oscilloscope (peak-to-peak voltage) should be about 2.8 times as great as the values of accelerometer voltage measured by the vacuum tube voltmeter (RMS voltage), if the horn tip describes simple harmonic motion. The ratio of the corresponding voltage values varies from 2.5 to 3.3, which is reasonable, since the measurement error in reading the oscilloscope waveforms is at least 10%, and the motion of the horn tip is not exactly simple harmonic in nature, as discussed later.

A plot of absolute amplitude of vibration of the horn tip in mils (peak-to-peak) versus accelerometer voltage output (as measured by an RMS vacuum tube voltmeter) is presented in Figure 4. Note that the relationship is nearly linear, which corresponds to equation (3). This calibration will make it possible to determine the amplitude of the horn tip during an investigation in any fluid environment by monitoring the output from the accelerometer mounted at the opposite end of the transducer-horn assembly.

Figures 5, 6, and 7 are photographs of oscilloscope voltage waveforms generated by the accelerometer during this investigation. The waveform in Figure 5 has a peak-to-peak amplitude of 6 volts, which corresponds to a peak-to-peak horn tip amplitude of 1.0 mils. The period of the waveform is approximately 50 microseconds, which corresponds to a frequency of 20 Kc./sec., as expected. The waveform in Figure 6 corresponds to a peak-to-peak horn tip amplitude of 2.0 mils, while the waveform in Figure 7 was generated at an amplitude of 2.5 mils. The frequency is 20 Kc./sec. in all cases. It is clear from these waveforms that the motion of the horn tip is not exactly simple harmonic in nature. One would expect a sinusoidal variation in voltage if the motion were simple harmonic.

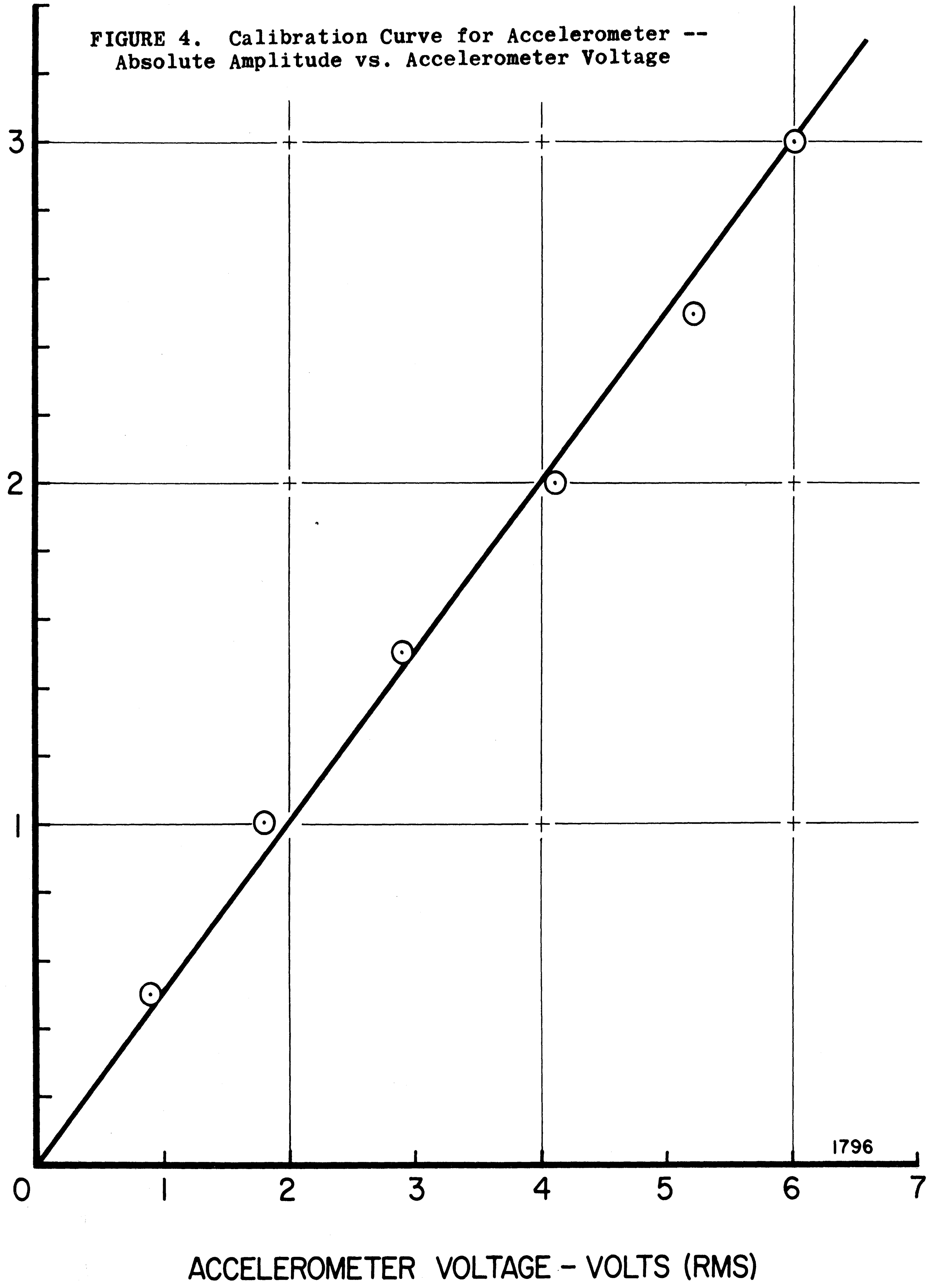

FIGURE 4. Calibration Curve for Accelerometer -- Absolute Amplitude vs. Accelerometer Voltage

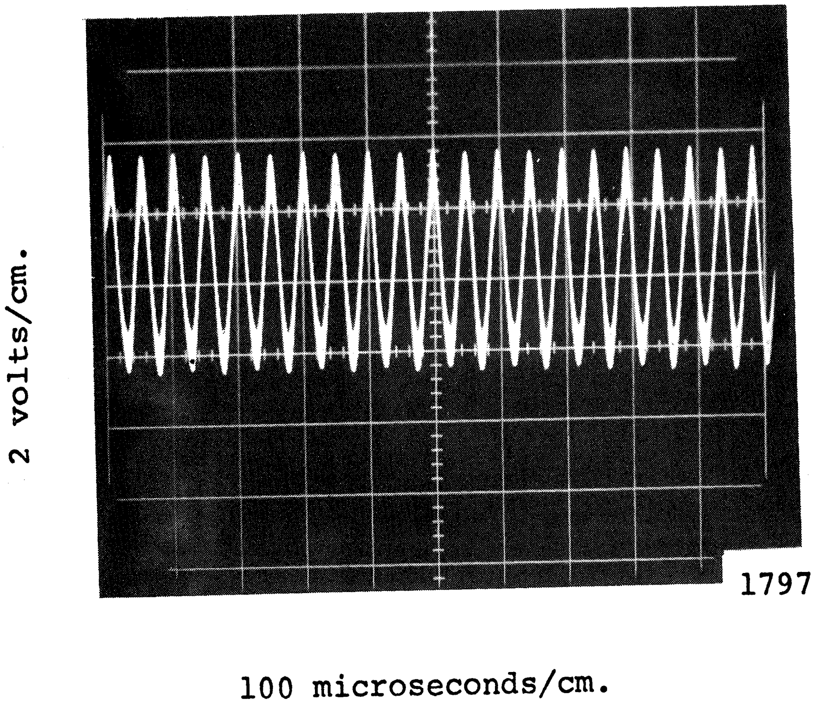

Figure 5. Accelerometer Voltage Waveform at Amplitude of 1.0 Mils

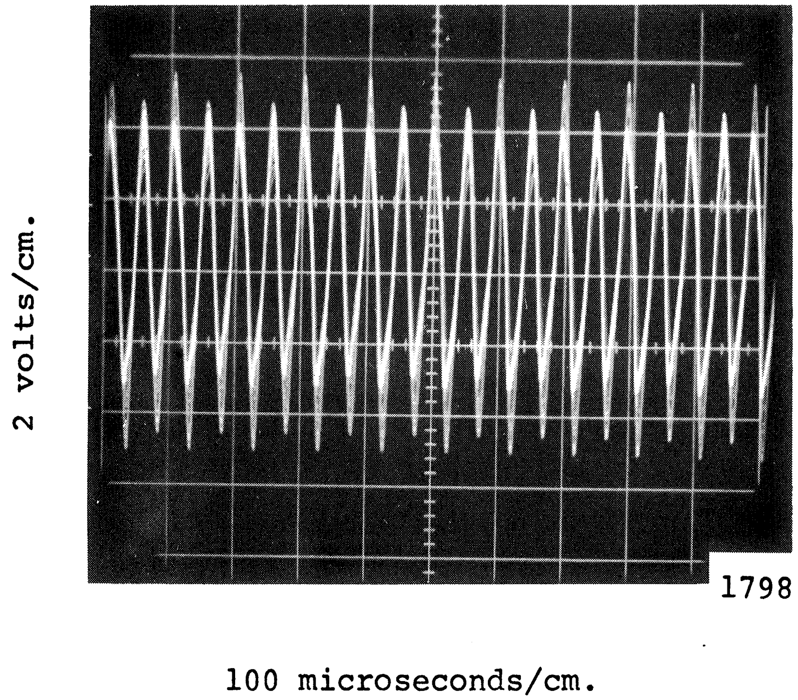

Figure 6. Accelerometer Voltage Waveform at Amplitude of 2.0 Mils

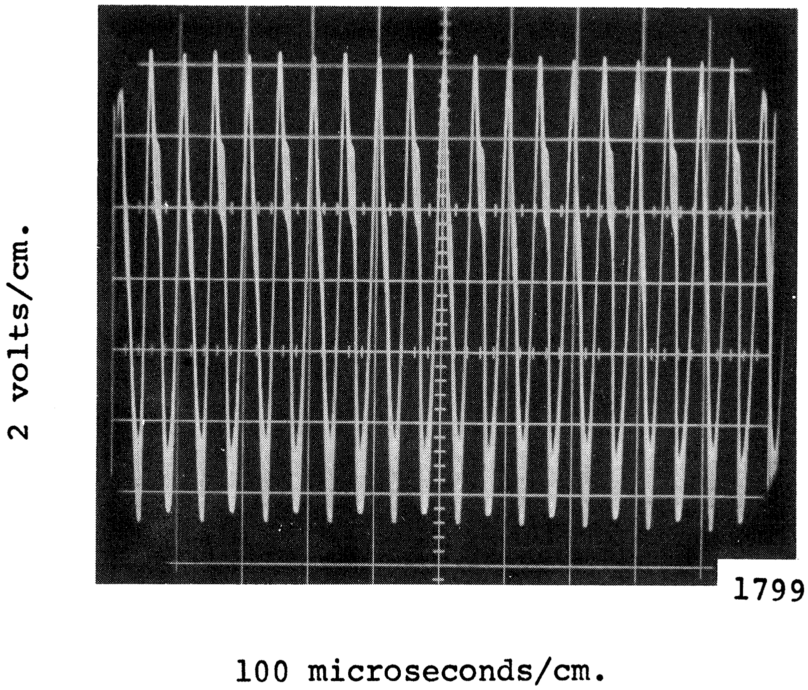

Figure 7. Accelerometer Voltage Waveform at Amplitude of 2.5 Mils

CHAPTER IV

SUMMARY AND CONCLUSIONS

An accurate method for measuring the amplitude of vibration at the tip of an ultrasonic transducer assembly has been developed. The method consists of monitoring the voltage output from a GLENNITE accelerometer, Model #CA260502, which responds to changes in acceleration. The accelerometer is mounted at the top of the transducer assembly where it is readily accessible during any investigation. The absolute amplitude of vibration at the opposite end of the horn assembly to which test specimens are attached is desired. A calibration of absolute amplitude at the horn tip versus the voltage output from the accelerometer makes it possible to determine the desired amplitude during any investigation. The major features of this system are as follows:

1) The accelerometer is able to operate at frequencies in the vicinity of 20 Kc./sec.
2) The accelerometer has a sensitivity of 1.32 mv./g, which makes it ideal for amplitude measurements in the range 1-3 mils.
3) The accelerometer is mounted at the top of the transducer horn assembly where it is easily accessible and at a point where the temperature never exceeds 100°F, even when the test specimen is immersed in a fluid at 1500°F. Hence, the accelerometer is never exposed to a severe environment, thus insuring relatively trouble-free operation.
4) The voltage output from the accelerometer is proportional to the acceleration to which it is subjected, and hence the amplitude at the point of mounting. Thus, the output is also proportional to the amplitude at the tip of the transducer, since the system is acoustically coupled.

The major observations made during the investigation are as follows:

1) The maximum amplitude measured at the horn tip was 3 mils (peak-to-peak), which corresponded to an accelerometer voltage of 6 volts RMS.

2) The relationship between absolute amplitude and accelerometer voltage was nearly linear (Figure 4).

3) The ratio of peak-to-peak accelerometer voltage to RMS accelerometer voltage varies from 2.5 to 3.3 for this investigation.

4) The calibration obtained is independent of the three test specimens used.

5) The oscilloscope waveforms of voltage output from the accelerometer confirm the frequency of vibration of the transducer-horn assembly, namely 20 Kc./sec. (Figures 5, 6, and 7).

6) The acceleration at the horn tip is approximately 100,000 g (peak-to-peak), whereas it is only about 12,000 g (peak-to-peak) at the point where the accelerometer is mounted, as expected, due to the difference in cross-sectional area at the two locations.

7) The absolute amplitude of vibration can be determined visually within a tolerance of ± 0.1 mils.

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