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PRELIMINARY CHARACTERIZATION OF A ONE-AXIS ACOUSTIC SYSTEM

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INTRODUCTION

Many useful materials are adversely affected by contamination resulting from contact with container walls during their manufacturing. The microgravity environment that is available in an orbital facility such as Shuttle/Spacelab allows for the positioning of material away from container walls in a relatively simple fashion. One can then process materials in space and avoid many of the problems that limit operations on the ground. Active positioning of the material within the orbiting facility would be required to prevent it from drifting into contact with the walls and to maintain its position relative to any heat sources. Several positioning systems are being developed for use in the microgravity environment. These systems are based upon terrestrial levitation devices and for the present can be grouped into two categories: electromagnetic (EM) positioning systems [1] and acoustic positioning systems [2,3,4].

To completely characterize the material processed in space, the operation of the positioning system and its influence on material properties (e.g., influence of stirring) have to be fully understood. In addition, the capabilities of terrestrial levitation devices have to be documented so that the rationale for conducting containerless experiments in space can be firmly established. Because of the wide usage of EM systems, their limitations appear to be well known, with the most severe being the extreme difficulty in separately controlling the heating of the specimen and the levitation force [5]. Acoustic systems have been used only in a limited fashion to process/manufacture materials on Earth, and little is known of their capabilities.

Various terrestrial levitation and microgravity positioning systems are being characterized at NASA's Marshall Space Flight Center. This report presents some of the initial results characterizing a one-axis acoustic resonance system. This system was chosen in part because it is the basis of an acoustic positioning/furnace facility which has stably positioned specimens at elevated temperatures (~ 1600°C) during short-duration (10 sec) microgravity KC-135 parabolic flight trajectories. In addition, control and understanding of the acoustic fields and acoustic-generated forces are simplified by having only one sound source.

THEORY

The forces acting on a small body (i.e., $kR << 1$ where k is the wave number and R the body radius) in an acoustic field have been derived by several authors [6,7,8]. By time averaging the pressure over the surface, the acoustic radiation force on the body in a plane stationary wave was found to be

$$F_a = 4\pi \bar{E} k R^3 \sin(2kx)\ F(\rho, \rho_o, c, c_o) \tag{1}$$

where $\bar{E}$ = average acoustic energy density, ρ_o = body density, ρ = density of medium, c_o = sound speed in body, c = sound speed in air, and $F(\rho, \rho_o, c, c_o) \sim 5/6$ for a solid body in air to levitate a body in a stationary plane wave against the gravitational force

$$F_a \gtrsim \frac{4}{3} \pi R^3 \rho_o g$$

where g is the gravitational acceleration. The preceding equation can be rearranged to yield

$$\frac{\bar{E}k}{\rho_o g} \sin(2kx) \gtrsim \frac{2}{5} \quad .$$

Seeking the position in the field where the maximum levitation occurs, we have

$$k \bar{E} \gtrsim 0.4 \rho_o g \quad .$$

It is of interest to calculate the acoustic field necessary to levitate a body to help establish the parameters of the one-axis system (e.g., intensity of the sound source). We are interested in studying the fields and forces along the axis because previous results indicated that stable levitation nodes could be found on the axis [4]. The acoustic fields along the axis of the one-axis resonance device should be approximated by a stationary plane wave and, therefore, the preceding derivations should be applicable.

Many materials investigations desire relatively large samples (~ 1 cm dimensions) to be able to measure bulk properties. Therefore, the wave number k of the system should be $\sim 3\ cm^{-1}$. (At diameters $\gtrsim \lambda/2$, the body begins to overlap successive levitation nodes in the standing wave pattern, resulting in a reduction in forces on the body.) Assuming a characteristic body density of $\sim 10\ gm/cm^3$, $\bar{E}$ is determined to be $\sim 100\ J/m^3$. In air at STP, this would result in the acoustic field having an intensity of ~ 165 dB. Higher intensity is needed at the higher temperatures to compensate for the increase in sound speed. Even with the amplification system inherent with a system at resonance, a high-intensity sound source is required. The system discussed in this report is a St. Clair generator which can produce a high-intensity field in a gas [9] and can be easily used in a furnace configuration.

The acoustic standing wave pattern in an open one-axis system should be different from that expected in an enclosure because of the leakage of energy from the sides. To model the fields (and hence the forces) expected in these unique systems, the pres~~re wave generated by the driver was assumed to be reflected from the reflec. /driver several times. The contributions to the pressure at a field point (between the driver and reflector) due to successive reflections were approximated by images of the driver at successively greater distances. This is depicted in Figure 1, where Huygens principle of superposition is used to calculate the total pressure at a field point, $\vec{r}$; i.e.,

$$P_T = \text{Pressure total}\ (\vec{r})\ \alpha \int_{\text{surface of driver}} \frac{e^{i\vec{k}\cdot(\vec{r}-\vec{r}\,')}}{|\vec{r}-\vec{r}\,'|}\, d\vec{r}\,'$$

$$+ \sum_{i=1}^{10} \int_{\text{surface of images } i} \frac{e^{i\vec{k}\cdot(\vec{r}-\vec{r}_i\,')}}{|\vec{r}-\vec{r}_i\,'|}\, d\vec{r}_i\,'$$

where $\vec{r}\,'$, $\vec{r}_i\,'$ are points on the surface of the driver and its images. For the problem of interest the number of reflections was limited to 10. This number of reflections appeared to approximate the completely calculated pressure to within ±15 percent.

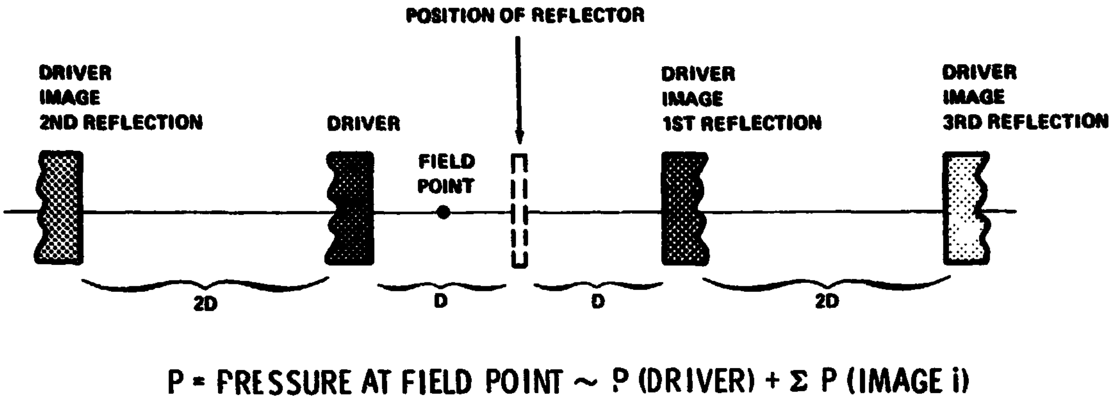

Figure 1. Conceptual schematic depicting the method of calculating the pressure on the axis between the driver and reflector. (The initial pressure pulse produced by the driver is assured to bounce between the reflector/driver several times. The effect of the bounces is approximated by a series of driver images on either side of the field point. Seven images and the driver were used to calculate the pressure.)

APPARATUS

The one-axis acoustic system consists of a sound source and a plane reflecting surface, as shown in Figure 2. The sound source is a St. Clair generator, which consists of a solid aluminum cylinder supported at its mid-section by a flexible aluminum diaphragm and driven at the resonance frequency of the aluminum bar by electromagnetic coupling [10]. This particular device, supplied by Intersonics, Incorporated,[1] has a resonance frequency of ~15 kHz, resulting in a 2.4-cm wavelength in air.

A hollow tube was used to suspend the reflector above and parallel to the piston face. The driver-reflector separation was easily adjustable; the driver and reflector diameters are ≈3.5 cm. A small bead was suspended along the axis of the acoustic field on a thin wire extending through a small hole in the reflector and up the tube to the arm of a Cahn balance.[2] This balance operates

1. Intersonics, Inc., 490 E. Ohio, Chicago, Illinois 60611.

2. Cahn Instrument Company, 7500 Jefferson Street, Paramount, California 90723.

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ACOUSTIC LEVITATION

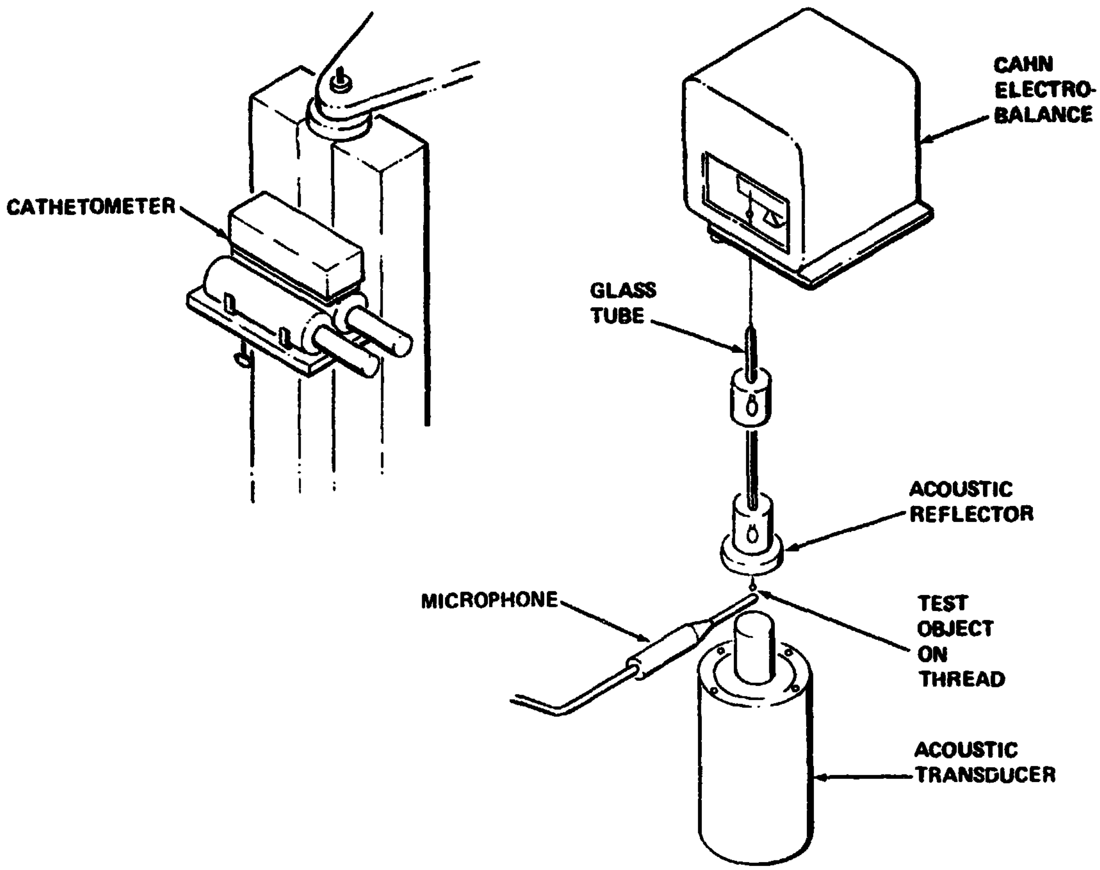

Figure 2. Schematic of the one-axis acoustic system and measuring instrumentation.

on the null-balance principle. Deflection of the balance beam resulting from force changes is opposed by a dc torque motor which quickly restores the beam to its original balance position. Thus, the force is always measured at the desired point in the device.

The acoustic field was measured using a 0.64-cm (0.25-in.) diameter Bruel and Kjaer condenser microphone and readout. The vertical positions of the vibrator, reflector, and bead were measured with a cathetometer.

RESULTS AND DISCUSSION

Figure 3 is an example of the forces measured on a body positioned on the axis of the system. The body was a sphere 0.8 cm in diameter, and the radiated sound intensity of the driver with the reflector removed was ~ 0.1 W/cm^2. Figure 3 shows two examples of forces on the body: In one example the system was at resonance (i.e., driver/reflector separation = 5.0 cm), and in the other the separation was increased by 0.2 cm to 5.2 cm. The levitation force is proportional to the pressure gradient across the body. As the pressures generated by the vibrator are amplified the most with the system at resonance, the maximum levitation force on a body should occur with the system at resonance. The influence of the resonance mode of operation on the levitation force is clearly indicated in Figure 3. The maximum forces at resonance are ~ 4 times greater than when the separation is increased 0.2 cm.

Data similar to those of Figure 3 were taken for several body sizes and geometries; all other conditions were identical for the system at resonance. Figure 4 shows the forces on these bodies at the position of maximum levitation force (i.e., ~ 1.6 cm). The force is plotted versus body volume with the geometry of the bodies indicated in the figure. These data show that for a range of shapes and sizes the levitation force is roughly proportional to body volume. This relationship holds until the characteristic body diameter reaches $\sim (1/4 - 1/2)\lambda$.

At diameters $>\lambda/2$, the body would begin to overlap successive levitation nodes, resulting in a reduction of the forces on the body. This can be seen in Figure 4, where the force on the 1.2-cm diameter sphere is significantly less than could be expected based on the data for the smaller bodies. The force on a highly irregular body depends to some extent on its orientation in the acoustic pressure field. Figure 4 shows the forces on a 0.5 cm diameter by 0.12 cm thick disc. The lifting force on this disc when oriented with its axis perpendicular to the driver face is twice that experienced when it is oriented with its axis parallel to the driver face. This is in agreement with previous results which indicated that a large levitation force could be obtained on a thin disc whose axis was perpendicular to the driver force [4].

Based on the data of Figure 4, it appears that for bodies of interest to materials scientists (e.g., spheres, right cylinders) the levitation force can be roughly calculated from the body volume. The dependence of this force on the body volume is in agreement with the derivation discussed in theory.

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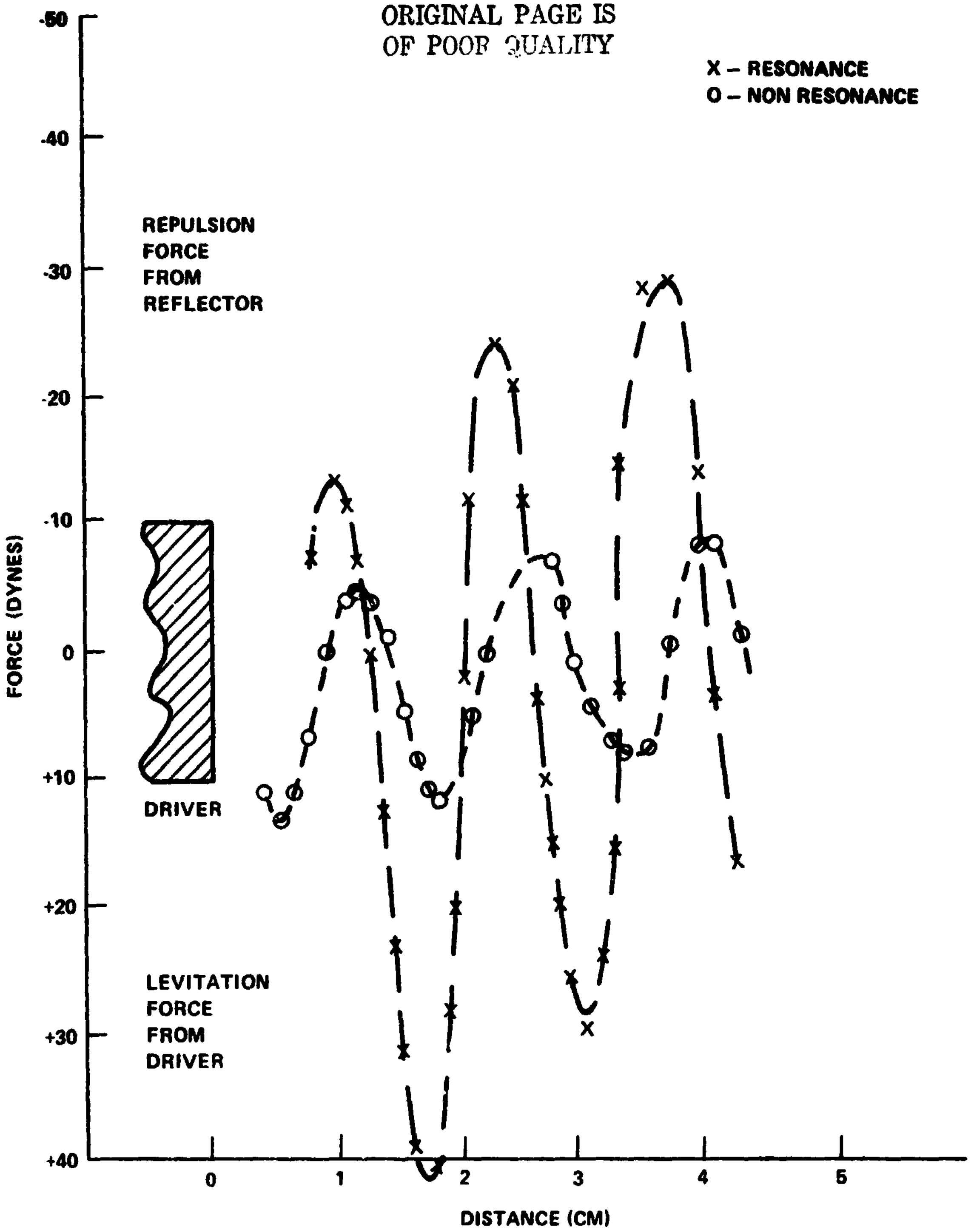

Figure 3. Forces measured on an 0.8-cm diameter sphere along the axis versus distance from the driver. (At resonance the reflector was ~5.0 cm from the driver; for nonresonance, the reflector was ~5.2 cm from the driver.)

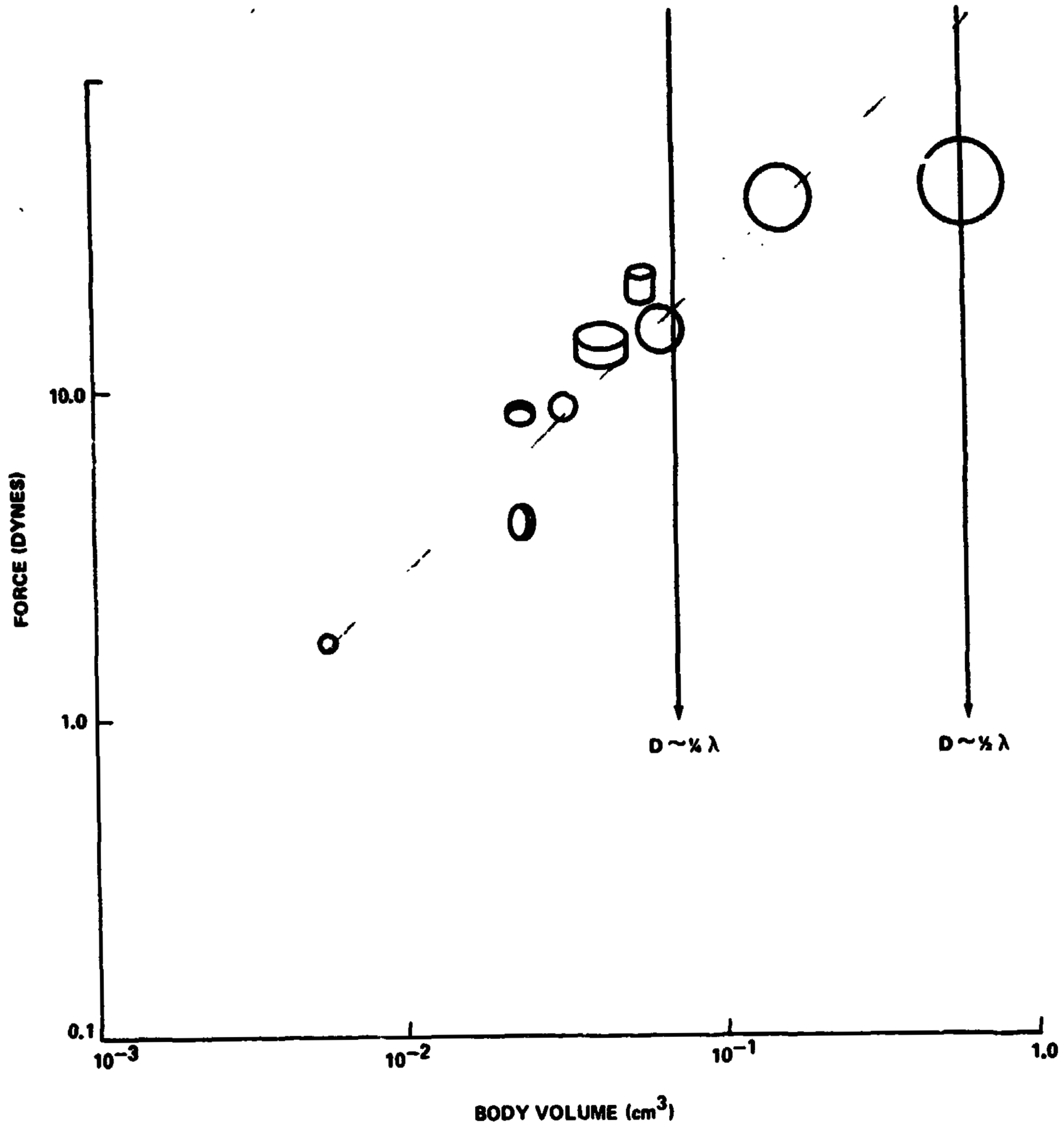

Figure 4. Axial force on body versus body volume. [The system is at resonance (reflector ~5 cm from driver) and the force was measured ~1.6 cm from driver. The body geometry is shown in the figure. The volume of spheres whose diameter (D) equals 1/4 and 1/2 λ (λ = 2.4 cm) is shown. The dotted line is hand drawn to show the "best fit" of the data for D < 1/2 λ.]

It should be noted that the theoretical expressions were derived for $kR << 1$. Figure 4 indicates that under certain conditions, the proportionality holds until $R \approx \lambda/3$ or $kR \approx 2$.

Figure 5 shows the pattern of rms sound pressures (p) measured along the axis for conditions similar to that of Figure 3 (resonance). The pressure is normalized to the free piston pressure measured ~1 cm above the driver ($\sim 0.64 \times 10^4$ dyne/cm^2). The pattern is similar to that expected in a "plane wave" resonance device. A comparison of Figures 3 and 5 shows that the zero force point for stable levitation occurs at the pressure nodes as predicted by theory. It was of interest to compare the measured forces with that predicted from the theoretical treatments of the acoustic forces in a stationary plane wave. The body used in this instance was the 0.42-cm diameter sphere which, from the data of Figure 4, experiences a force of ~9.5 dynes at ~1.6 cm from the driver. Taking the expression for the maximum acoustic-generated forces from equation (1) [i.e., $\sin(2kx) = 1$] and using the appropriate acoustic field parameters (i.e., $p = 10^4$ dyne/cm^2 and $\lambda = 2.4$ cm), the force is calculated at ≈ 25 dynes. This force was also calculated from the axial gradient of the acoustic radiation energy [i.e., $F \alpha \ d/dx(\bar{p}^2 - \rho^2 c^2 \bar{V}^2)$], where $\bar{V}$ is the rms particle velocity. Assuming that $V = -1/i\omega\rho \ dp/dx$, the force can be calculated from the experimental data of Figure 5 (e.g., dp/dx and p at 1.6 cm). These calculations yield a force of 8 dynes.

The assumption that a plane standing wave can describe the acoustic fields along the device should be considered only an approximation. The force calculated from the gradient of the acoustic radiation energy is in closer agreement with the measurement than the force calculated from equation (1), which is derived for a plane wave system. The relative discrepancies between the calculated values of the forces would indicate the limitations of using a plane wave approximation.

Figure 4 also shows a computer calculation of the rms pressures produced along the axis of the one-axis system. The pressure wave generated by the driver was assumed to reflect off the reflector/driver several times, and Huygens principle of superposition was used to calculate the pressure at a point (Fig. 1). The theoretical pressures were normalized to the free driver pressure modeled at 1 cm on the axis above the face. There is general agreement between the measured and modeled pressures shown in Figure 5, giving some degree of confidence in using this approach to predict the acoustic fields under other conditions (e.g., off-axis and at high temperatures when the piston diameter < λ).

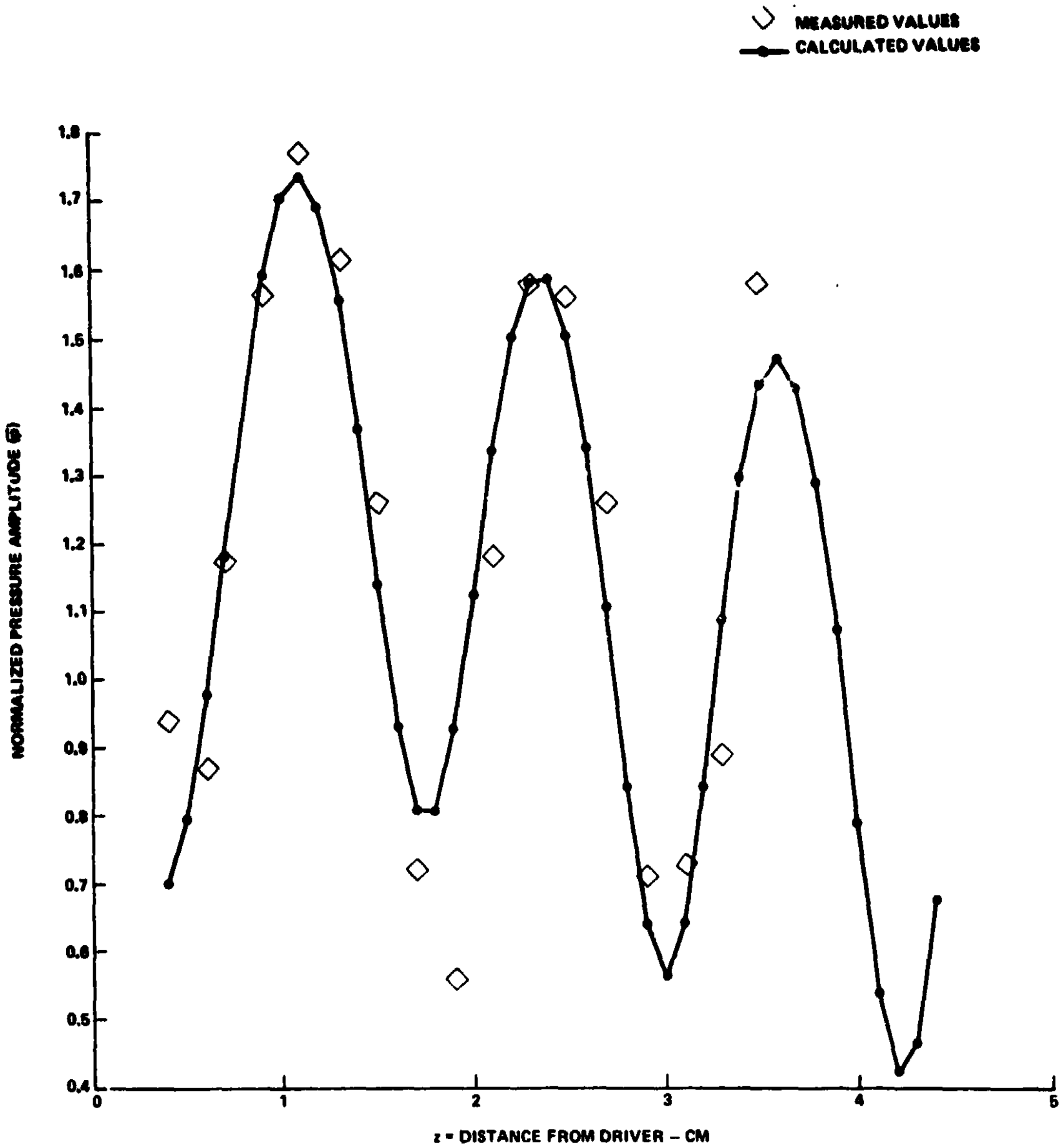

Figure 5. rms pressure along the axis of the device for the system at resonance (driver/reflector distance ~5 cm). [The experimental data were normalized to the pressure produced by the free-standing driver 1 cm from its face (~0.64 × 10^4 dyne/cm^2). The calculated pressures were normalized independently to that of a free-standir driver theoretically modeled 1 cm from its face.]

In the future the computer code of the pressure will be expanded to completely describe the accustic field in the device (i.e., the axial and radial variations). Also, the acoustic fields and forces will be experimentally mapped and compared with the modeled fields to better understand phenomena such as: (1) the shape and strength of the levitation points, (2) the influence of drivers and reflectors of different sizes, and (3) the limitation of such devices at high temperatures.

SUMMARY

The acoustic fields and acoustically generated forces were characterized in a one-axis resonance acoustic system consisting of a flat piston-type sound source and a planar reflector. These measurements were made as part of a program to determine the capabilities of various ground-based levitation systems.

Measurements of the acoustic force were made on bodies of various sizes and geometries suspended from the arm of a sensitive electrobalance. The force was determined to be roughly proportional to body volume until the characteristic body diameter reached $\sim(1/4 - 1/2)\lambda$. This indicated that the body density is an important parameter in determining whether a material can be processed in an acoustic levitator on the ground.

A simple one-dimensional model of the acoustic field (based on Huygens principle and taking into account multiple reflections between the driver and reflector) was used to calculate the pressure pattern on the axis of the device. These axial pressure variations were also measured and found to be in agreement with the theoretically modeled values of pressure variation.

One of the objectives of the present program is to determine the capabilities of terrestrial acoustic processing systems, and future work will investigate (theoretically and experimentally) the acoustic fields and forces on and off axis to characterize a one-axis device. This effort will also involve studying the operation of a one-axis system in an enclosed furnace at elevated temperatures as well as analyzing these devices at room temperature.

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APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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