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DEVELOPMENT OF THE SONIC PUMP LEVITATOR

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OBJECTIVE

The general purpose of this research program is to accomplish appropriate experimental measurements oriented toward Materials Processing in Space (MPS), including studying the process and mechanism involved in producing glass microballoons (GMBs) of acceptable quality for laser triggered inertial fusion through use of gas jet levitation and manipulation. The methodology of this effort is to utilize radiative techniques to achieve high levitation furnace temperatures. The validity of the feedback controlled triaxial sonic pump method of air jet levitation is to be tested on the ground and in the KC-135 reduced gravity flight regime. Recommendations are to be made for future research on and applications for the Sonic Pump Levitator.

SUMMARY

A prototype levitating/positioning device termed the Sonic Pump Levitator was designed, built and successfully tested in full gravity and in the reduced gravity of the parabolic flight regime of the KC-135. Positioning is achieved by timely and appropriate application of gas momentum from one or more of six sonic pumps. The sonic pumps, which are arranged orthogonally in opposed pairs about the levitation region, are activated by an electro-optical, computer controlled, feedback system.

The sonic pump is a transducer which is capable of converting sound energy into a directed flow of gas. It consists of a loudspeaker whose face is sealed by a closure perforated by one or more orifices. The diaphragm of the loudspeaker is the only moving part of the sonic pump, no valves being needed. This very low inertia electromechanical device was developed to provide the short response time necessary to keep pace with the demands of computerized position keeping.

Valving is obviated by the fact that the flows of gas into and out of the orifice(s) of the pump naturally follow different paths. The flow during the intake portion of the sonic cycle stems essentially isotropically from the external vicinity of the orifice(s). The exhaust flow on the other hand, proceeds more or less axially from the orifice(s) due to cancellation of the lateral components of momentum of the intake flows in the orifice(s) (a patent has been issued).

Simply by exchanging closures and orifices on the sonic pumps, spheres ranging from a few hundred microns to several centimeters in diameter can be levitated in the prototype sonic pump levitator. In the successful KC-135 test, a closure with a solitary orifice 1.2 cm in diameter accommodated styrofoam and ping pong balls ranging from 2 to 4 centimeters in diameter. In full gravity experiments using much finer, and multiple (collimated hole structure, CHS) orifice closures, the range of diameters which could be levitated was extended down to the region typical of glass microballoons (GMBs), 300-1000 microns.

Tests were carried out to determine whether temperature has an effect upon Sonic Pump Levitation operation. These tests were performed on a simplified single axis version of the Levitator involving the target mounted on a pivotted boom and a single pair of opposed pumps. No effect was found at temperatures up to 720° C.

Preliminary studies indicated that a conical closure was one of the more satisfactory of the simple shapes. It is the one used in the ambient temperature reduced gravity tests. Subsequently it was found that a prolate ellipsoid was much more efficient than the cone (a patent application is in preparation). The ellipsoidal closure was used in the experiments demonstrating the absence of effect of temperature upon sonic pump feedback control.

Studies of sound frequency revealed a slight improvement in performance in the region of the system's resonant frequency. However, the effect is uncritical, performance changing little over as much as an octave.

Turn around time in the feedback loop was kept below two milliseconds by employing an analogue optical sensing device and by programming in machine language. The analogue sensor restricted the optical nature of the target surface to one of diffuse reflection where the centroid of the luminous image corresponds to the projection of the center of gravity. The CCD camera would get around this limitation but could not be used because of budgetary considerations.

Studies were conducted on CHSs and their use in levitating and manipulating GMBs. Perhaps most important, a simple way was found to fabricate high quality CHSs. It was learned that the holes need not be of circular cross-section and that the interstitial spaces in a regular bundle (rectilinear or hexagonal array) of uniform diameter rods or wires will serve as well. The length of hole compared to its effective "diameter," or the aspect ratio, is unlimited and exceeds that attainable by other methods. Aspect ratio is important in achieving laminarity in the issuing streams. (Patent protection has been obtained).

Subdivision of the CHS cross section and separate control of the flow through the subdivisions was examined as a means of shifting the position and controlling the axis of rotation of a levitated object. Experiments with asymmetrically weighted ping pong balls were carried out which suggested that a rotating, levitated, molten shell (e.g., a GMB) will spontaneously shift its axis of rotation in such a way as to achieve uniform wall thickness.

Indirect evidence was found of accelerations of the order of 1/10 gravity in the reduced gravity flight regime of the KC-135.

CONCLUSIONS

1. The Sonic Pump Levitator concept compares favorably with other methods of remote control of position. It is not restricted to electrically conductive materials. Nor is it dependent upon maintenance of an electrostatic charge on the object to be levitated, a task which may present difficulties depending upon the nature of the target material and upon the temperature. Furthermore, single axis levitator tests and other indications suggest that, by contrast with some other types, the Sonic Pump Levitator functions independently of temperature.

2. The rapid response time of the photodiode based optical sensor is available only to those situations, such as the present one, where the centroid of target luminance coincides with the projected center of gravity. The luminance may be incandescence as well as diffuse reflectance. However, in order also to access transparent and opaque targets having specular surfaces as well, and do so in the same time frame, much more sophisticated detectors, such as the CCD camera and associated electronics must be employed.

3. The need for access to the levitated sample (by energy sources, position and other monitors, etc.) places a premium on minimizing the solid angles subtended by the sonic pumps, i.e. increasing the speaker-to-target distance. The high aspect ratio, bundled rod type CHS, with its straight line flow, provides one means to increase this separation. Speaker shroud design may provide another. The effect of elongating the cone may be different from that of elongating an ellipsoid. The effect in both cases deserves further study. Other figures of revolution derived from conic sections, hyperbola and parabola, have not been explored at all. They merit similar scrutiny with respect to elongation.

4. The KC-135 reduced gravity flight regime permits of appreciable residual accelerations. A flight director could be built which would enable the pilot to hold extraneous accelerations down to a small fraction of gravity.

RECOMMENDATIONS

1. Continue optimization of sonic pump output capabilities in terms of weight, power and spatial requirements, and determine and quantify the factors involved in scaling up or down.
2. For operator convenience in a shuttle mid-deck environment, it is essential that the levitator be capable of dynamic self adjustment. Target densities and aerodynamic characteristics will vary not only from sample to sample, but also from thermal expansion phase transformations and other physical changes during processing of a single sample. The software should modify the parameters of the controller equation so that corrections would preclude hunting and preserve the integrity of the feedback loop.
3. Similarly, the luminance properties of the target will change from sample to sample and during the processing of a particular sample. The analogue detection system employed in the successful prototype will handle the two simplest cases, diffuse reflectance and radiant emission. By contrast, specular reflection requires a real time geometric transformation in order to locate target center of gravity. The CCD camera and digital processing will be required throughout in order to assess all three types of light signal and in particular, the specular.
4. Further explore focused radiation for target heating. Demonstrate that target temperatures in excess of 1500°C can be achieved without disrupting levitation.
5. Design and build a sonic pump levitator furnace suitable for containerless processing experiments on the mid-deck of the shuttle. Having achieved the objectives described above, one basic sonic pump levitator would serve in a range of circumstances. It could levitate solid or liquid spheroidal objects from a few microns to a few centimeters in diameter in accelerations up to 0.01 g . With the smaller lighter objects, larger accelerations, could be accommodated. Heating to the region of 1500°C and rapid or slow cooling could be achieved. The furnace, being amenable to hermetic sealing, readily lends itself to control of the gaseous environment including control of gas pressure. Rotation and translation of the levitated object are controllable within limits which may be altered by straight forward design changes.

(4)

With minor modifications, the same basic sonic pump levitating furnace would be adaptable to several missions:

a. Glass melting and freezing studies, requiring only the addition of the desired accessory instrumentation such as optical probes, pyrometers, etc.

b. Controlled melting and freezing of metals, quick quench, nucleation studies, etc.

c. Deposition of very thin uniform polymeric films on pharmaceuticals and controlled thickness polymeric films on glass microballoons (GMB).

d. Combustion studies on fluid droplets.

e. Improving the uniformity of GMB wall thickness by rapid quench coordinated with rapid reduction in ambient pressure. (Achieving such improvements through use of centrifugal forces via the controlled rotation of the GMB would require a next generation funded modification of the levitator. With further effort, irregular shapes could be levitated or positioned, rotated about an axis of choice or maintained irrotational, thus permitting observation for example of the development of a GMB from a frit particle. Glass samples could be shaped into desired figures of revolution, e.g. lenses.)

f. Investigation of the mechanisms involved in the formation of uniform microballoons.

g. Manufacturing of glass and/or polymer microballoons in low-g in sizes that are not possible on earth (i.e., >5 um).

6. Design and build a flight controller to permit the pilot to hold the KC-135 to a true zero gravity parabolic course.

INTRODUCTION

From the outset, a major objective of this project has been the development of a microlevitation furnace which would permit the reworking of molten glass microballoons (GMBs) so as to improve their geometric quality and thereby their serviceability as laser targets for inertial fusion. Particular attention has been paid to centering of the inner and outer surfaces to produce uniform wall thickness. Centering, conceivably, can be achieved centrifugally by spinning the molten GMB or by causing it to expand slightly during a rapid quench regime. The attainment of this objective presupposes control of levitation and of rotation and a means of coordinating these with such operating parameters as temperature and furnace chamber pressure.

At first, the means of levitation were designed to operate in terrestrial gravity. Later, levitation in microgravity, as encountered in an orbital environment, was included. Along with the change in emphasis, the possibility of levitating objects larger and heavier than a GMB, and of containerless processing in general, was also taken into consideration. The sonic pump and the triaxial feedback controlled Sonic Pump Levitator were developed ultimately in response to the emphasis on microgravity.

DISCUSSION

A. Full Gravity Single CHS Levitation

1. General

Work on preceding contracts has shown the practicality of levitating GMBs and other small spherical objects on parallel or collimated jets of air (1 Appendix A). The jets were formed by forcing air through a collimated hole structure (CHS), a regular array of holes formed in a plate, usually of metal. With properly proportioned holes, laminar flow and very steady levitation were achieved. Vertical stability is provided by the diminution of stream velocities with height resulting from the flattening of their velocity profiles and the lateral expansion of the streams.

Lateral stability was attainable in one or more of three ways. The spaces above the CHS interstices, being regions of low flow rate are also regions of minimum levitating force into which levitated GMBs naturally gravitate. This self positioning effect could be augmented by a depression or dimple in the surface of the CHS extending over an area including a number of holes. Finally, the Bernoulli effect tended to keep levitated spheres from wandering outside the cross-section of flow.

Controlled rotation of the levitated sphere had been demonstrated. A centrally located hole was fed a higher velocity stream of gas than the rest of the CHS. The rate of GMB rotation was proportional to the difference in these gas velocities (2).

Two methods of heating levitated GMBs to glass melting temperatures had been demonstrated: resistive heating primarily of the gas supply tubes to the CHS (3) and focused radiant energy (4). Hot wall furnace heating had been rejected because of the concomitant thermal inertia which would interfere with rapid quench regimes.

It had been learned that not only total but partial pressures surrounding a molten GMB would have to be controlled. Not only did temperature induced pressure and volume variations have to be assessed and compensated, but diffusion and counter diffusion of gases through the glass wall must somehow be accommodated (5). Another complication is the effect of temperature upon gas viscosity and aerodynamic properties.

One method of centering a GMB or equalizing its wall thickness was termed quick quench. Thin portions of the wall freeze more rapidly than thick ones. Viscosity differences are enhanced by rapidity of quench. With a simultaneous regime of expansion through reduction of external pressure, the wall attenuates more in the thicker regions and, thereby, approaches wall equalization. The combined effect is to attenuate the thicker portions of the GMB wall relative to the thinner portions. Since wall heat capacities are minute, extremely rapid quench rates are required in order to develop the necessary differences in temperature and viscosity.

Furthermore, the expansion, as by reduction of ambient pressure, must be timed to occur after the differential in wall temperature and viscosity has been established. Premature expansion would cause the thin, instead of the thick portions of wall to attenuate. During this rapid sequence of temperature and pressure reduction, the levitating flow must be kept independent of the decreasing furnace pressure and must be adjusted to compensate for the growing aerodynamic cross-section of the expanding GMB. Because of these and other interrelationships against a background of a need for rapid and precise timing, it had been concluded, prior to this contract, that microprocessor or computer coordination and control would be required.

2. Microprocessor Predictive Control

The first efforts at automated levitation control were aimed at predictive coordination. It was presumed that the CHS gas flow necessary to maintain steady levitation in one G, during varied furnace conditions, could be achieved through real time computation of the combined effects of ambient furnace temperature and pressure. In theory, predictive coordination is possible. In practice, it is difficult.

The rate of momentum transfer to the GMB is influenced by a number of temperature and pressure dependent parameters. The aerodynamic cross-section of a GMB is only approximately proportional to the two-thirds power of the ratio of temperature to pressure. Its drag coefficient is a function of temperature,

pressure and levitating gas velocity. The flow of levitating gas momentum through the CHS is determined by gas temperature, furnace pressure and the pressure differential across the CHS.

The calculation of GMB cross-section deviates from the simple proportionality to the two-thirds power of the temperature/pressure ratio. Aside from Perfect Gas Law aberrations, which are indeed minor, the proportionality is complicated by an additive quantity in the pressure term of the order of 0.1 atmosphere due to surface tension of the molten glass. While the latter varies in minor degree with temperature, it is much more sensitive to glass composition, as well as GMB diameter. Multicomponent glasses and solutions in general, exhibit surface tensions influenced by the tendency of the lower surface tension components to adsorb at the surface. The adsorption through its attendant subsurface concentration gradient may be further influenced by wall thickness in the case of GMBs. The walls are probably too thin to support fully developed concentration gradients. Consequently, the surface tension may become a function of wall thickness as well as composition.

A further complication is the relatively rapid compositional changes undergone by molten GMBs. Precisely those components which are most surface active are also more volatile. Their evaporative loss is compounded by the high surface-to-volume ratio (of the order of 10^2 cm^{-1}) characteristic of the glass volume in GMBs.

Aerodynamic drag is influenced by temperature and pressure in several ways. Gas density upon which it depends, is influenced by both temperature and pressure through the Perfect Gas Law. Gas viscosity, upon which it also depends, is determined by a complex relationship with temperature, perhaps best expressed empirically. The flow of gas through the CHS is governed by density and viscosity parameters, influenced as just described by temperature and pressure.

Measurements of levitating gas temperature and furnace pressure must be converted to appropriate mass flows of levitating gas on a real time basis. Logically, flow would be controlled through the differential pressure across the CHS.

While some of the relationships necessary to do this are straightforward, others are dependent upon information not readily accessible.

B. Reduced Gravity Triaxial Feedback Control

Full appreciation of these difficulties coincided with a shift in operational emphasis from full gravity to reduced gravity, as in Space Lab. In an orbiting situation, such inertial accelerations as were experienced would be from random directions. The need for a unidirectional steady flow of levitating gas would be gone and with it the three mechanisms for lateral positioning heretofore employed: Bernoulli forces, gravitational potential wells over the CHS interstices and the larger gravitational potential well created by the dimple.

It readily became apparent that gas momentum would have to be provided from any direction, in any magnitude, upon demand. Predictive coordination was wholly inadequate. Electrooptical feedback control of multiple jets or flows from orthogonal directions was indicated.

The first efforts in this direction employed an off-the-shelf Vidicon with microscopic optical adaptation to track the GMB. By the use of mirrors, the field of view was split and video information obtained simultaneously from two directions at right angles to one another. Target displacements could be detected along each of the three necessary orthogonal directions, one of two in common, of course, being redundant.

Six CHS streams would be situated orthogonally in opposed pairs aimed inwardly. Position information from the video camera would be a computer processed so as to turn on one or more CHS streams in an appropriate manner.

A problem not fully engaged before abandoning the predictive approach was that of valving the CHS gas flows and bleeding them off with sufficient rapidity. Both the inertia and the bleed off volumes of systems capable of providing the necessary fine control were too large for the requirement of a response time within ten milliseconds. (10 milliseconds would permit a 490 micron displacement in one gravity; 0.5 microns in milligravity),

1. Sonic Pump

It was recognized that a loudspeaker might be employed as a piston because its inertia is low and its response time is fast (low millisecond range). The question was what to do with the return stroke. The problem of finding a low enough inertia check valve was considered for some time until it was recalled that the flow patterns into and out of a simple orifice are quite different.

The flow into an orifice is uniform from all directions, radially or spirally inward. The outward flow, however, tends to be axially aligned, and may exhibit negligible radial components (Figures 2 and 4). In effect, a loudspeaker with its face covered by a perforated closure is a sonic pump. During a sound wave, air is drawn isotropically from the vicinity outside the orifice, then expelled in a more or less straight line. Within the orifice, air flow reverses in synchrony with the sound. A few orifice diameters above the closure it pulsates still in synchrony with the sound, but is unidirectional. Actually, as the steadiness of levitated GMBs shows, even the pulsations damp out quickly. The sonic pump is the fluid analogue of a heavily filtered half wave AC to DC rectifier (Figures 1-5).

Further development and adaptation of the sonic pump are described below under the series of low gravity KC-135 flight test headings.

2. Sonic Pump Levitator

a. Video Camera Sensor

Although at first considered only for lateral control during full gravity experiments, the sonic pump was soon found capable of handling the levitation, as well, of GMBs up to 1 mm in diameter. Sonic pumps were then employed on all six of the C'Ss. The bottom one was larger because when not in a low gravity situation it would have to compensate for full earth's gravity. Each of the CHSs utilized the interstitial concept (see Appendix A) with its capability to achieve stream laminarity.

While the sonic pumps permitted of satisfactory feedback turn around times, other factors prevented realization of times less than the desired ten milliseconds. The framing rate of the commercial video camera was 16.6 milliseconds. Furthermore, the real time data processing required of the order of 100 to 300 millisecond (Appendix B). Periods of time of this order are too large to provide adequate lateral stability in full gravity, though perhaps sufficient to do so in microgravity (in orbit).

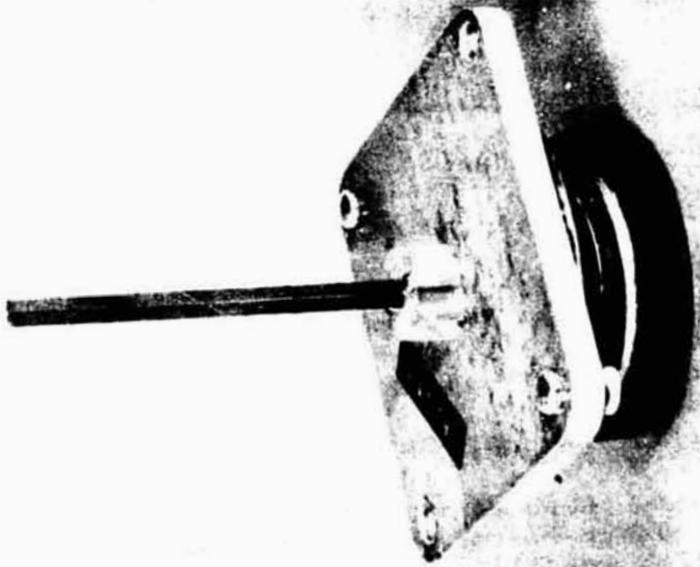


Figure 1a. Sonic Pump With CHS Closure
For Use With GMBs.



Figure 1b. Sonic Pump with Conical Closure
and Simple Orifice (12mm dia.)
for Levitating Larger Objects.

These Two Types of Sonic Pump Are Interchangeable in the Levitator.

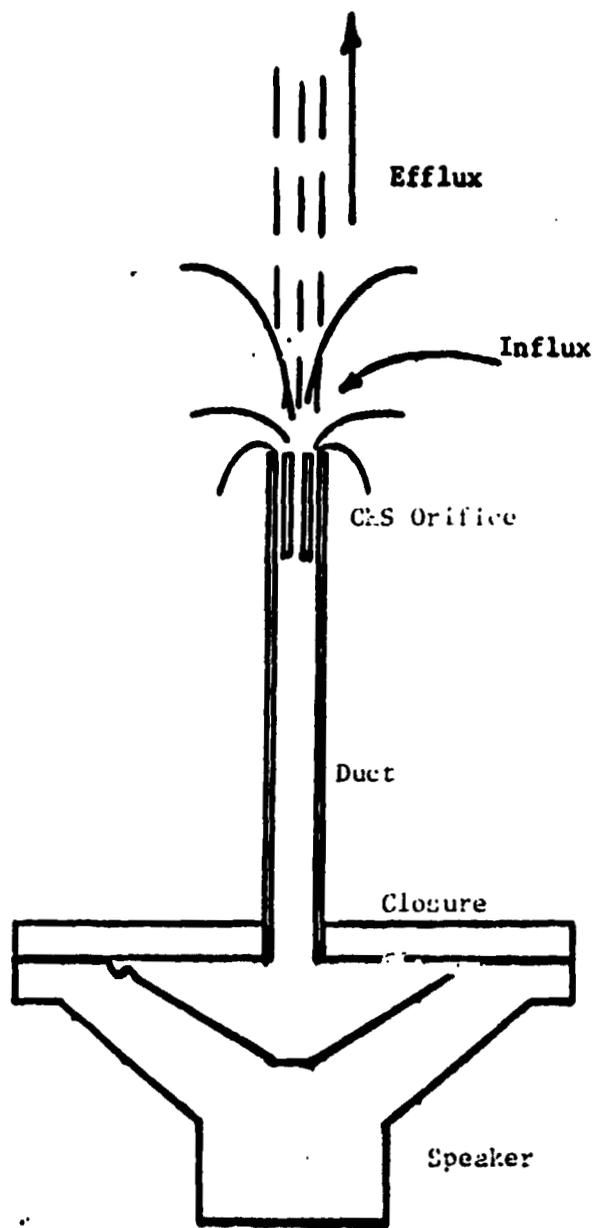


Figure 2. Flow Vectors: Cone Pump with a C&S Orifice Closure.

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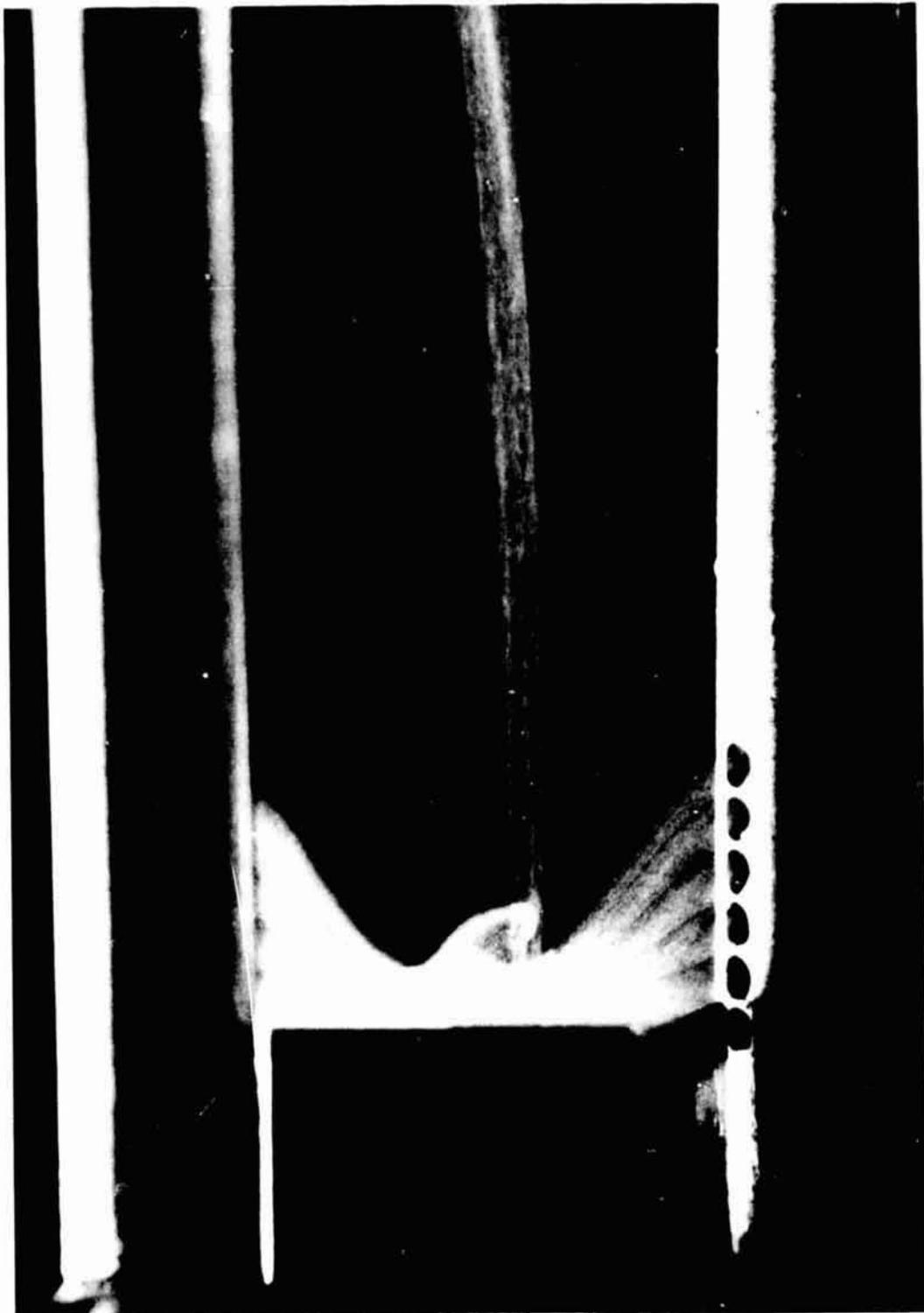


Figure 3. Gas Flow Smoke Pattern: Sonic Pump Having a CHS Orifice (Tubes To Right and Left Are Smoke Supply Ducts.)

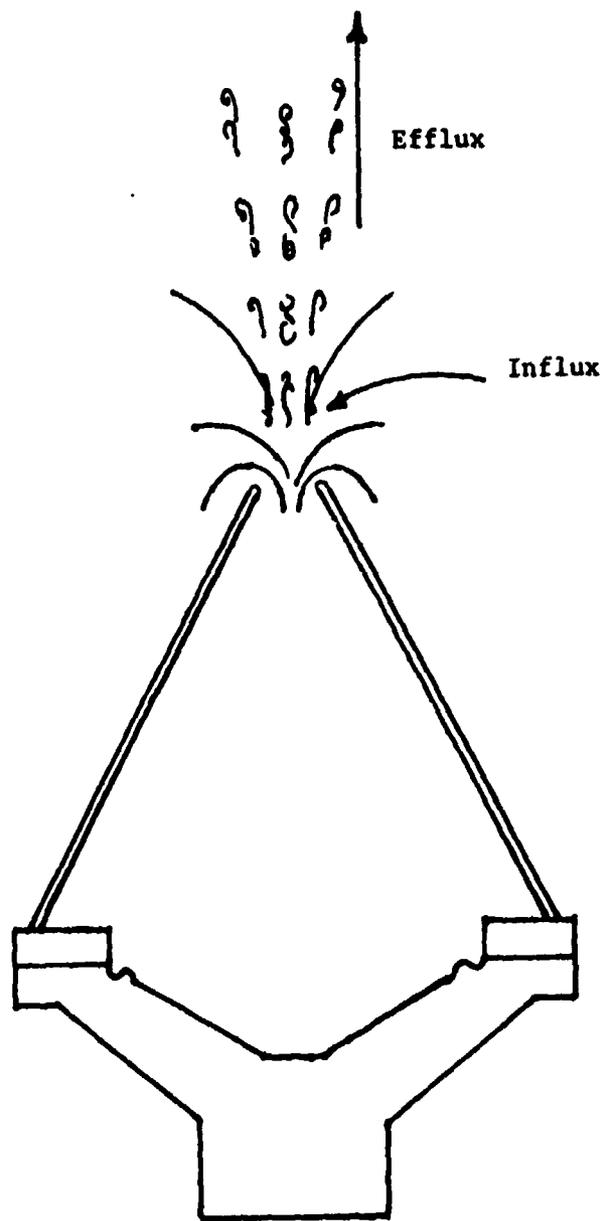


Figure 4. Flow Vectors: Sonic Pump With Conical Closure Having a Simple Apical Orifice.

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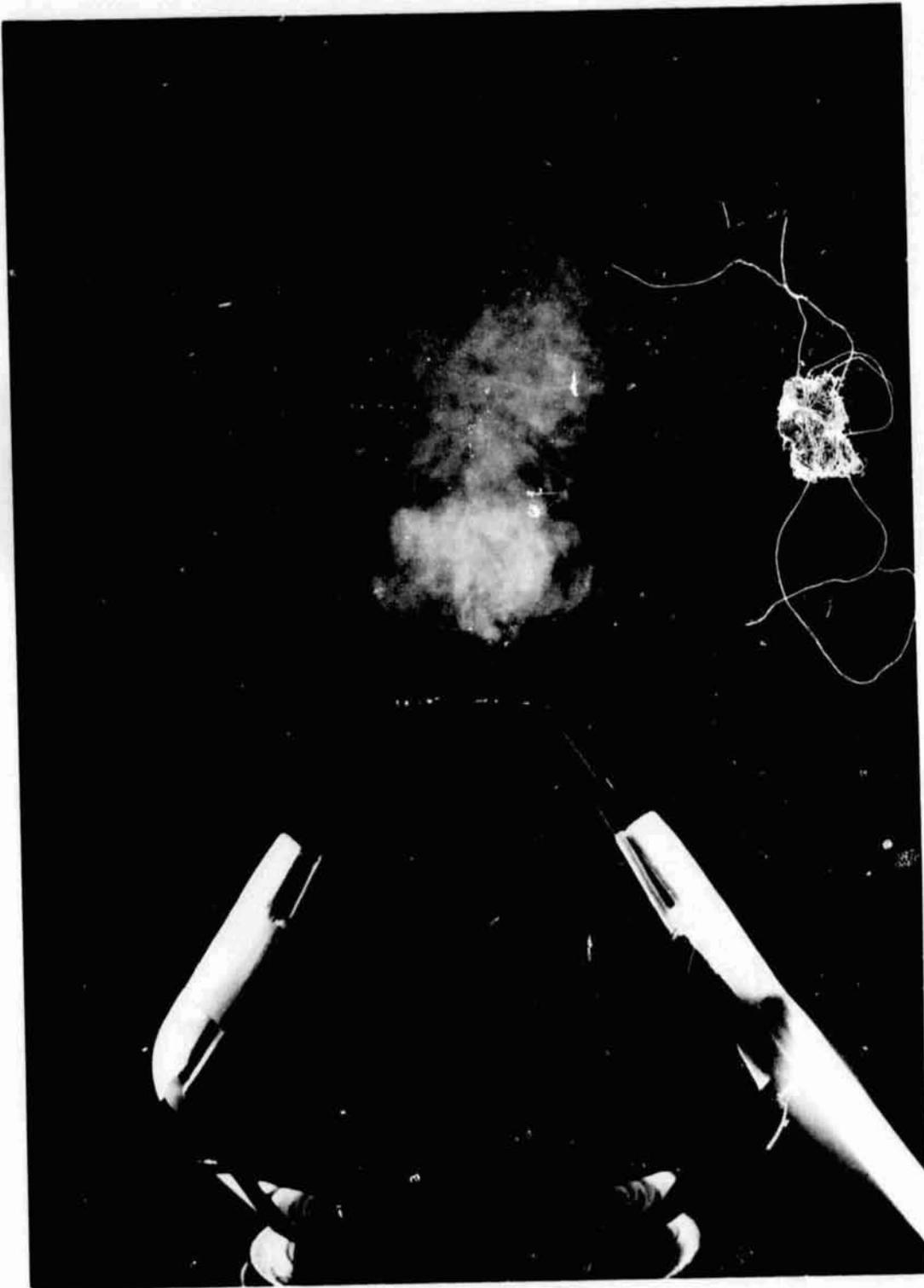


Figure 5. Gas Flow Smoke Pattern: Sonic Pump With Conical Closure Having a Simple Apical Orifice.

For the sake of flexibility, pumps and other functional elements were held in place by a well braced jungle jim of laboratory rods and clamps. The same basic jungle jim was used in all subsequent modifications including the final successful prototype (see Appendix C).

Lateral stability was tested using a bench which could be tilted about two axes, one horizontal and the other perpendicular to it (Figure 6). It was found that a levitated GMB would commence oscillating at three degrees from horizontal, and that it would cease to levitate between five degrees and ten degrees of tilt. The horizontal speakers did not respond rapidly enough to damp out the oscillations which, in each attempt, ultimately removed the GMB from the field of levitation. In full gravity the magnitude of the accelerations in these disruptive oscillations are comparable to unit gravity. In microgravity, they will be proportionately smaller. They will require comparably smaller restoring forces and will tolerate correspondingly longer response times.

1. First Low Gravity KC-135 Test (5/26 & 27/82)

a. Preparations

A number of preparations for the low gravity KC-135 flights were made. A rectangular, aluminum frame reinforced, plexiglass enclosure was constructed for the levitating device itself. Safety of operating personnel dictated the covering of numerous projecting rods, etc. in this way. The cabinet, however, also served three other purposes: a dead black, conductive interior coating minimized extraneous light reflections and shielded against external electrostatic fields; in addition, the cabinet eliminated unwanted external air currents.

This cabinet and several ancillary pieces of equipment, including the computer, were securely fastened to aluminum plates. Provision was then made to bolt these plates to the deck of the aircraft.

Provision was also made to continuously acquire the shipboard accelerometer output as a frequency modulated sound signal recorded on the sound track of the video tape. The capability was not implemented for lack of proper connectors.

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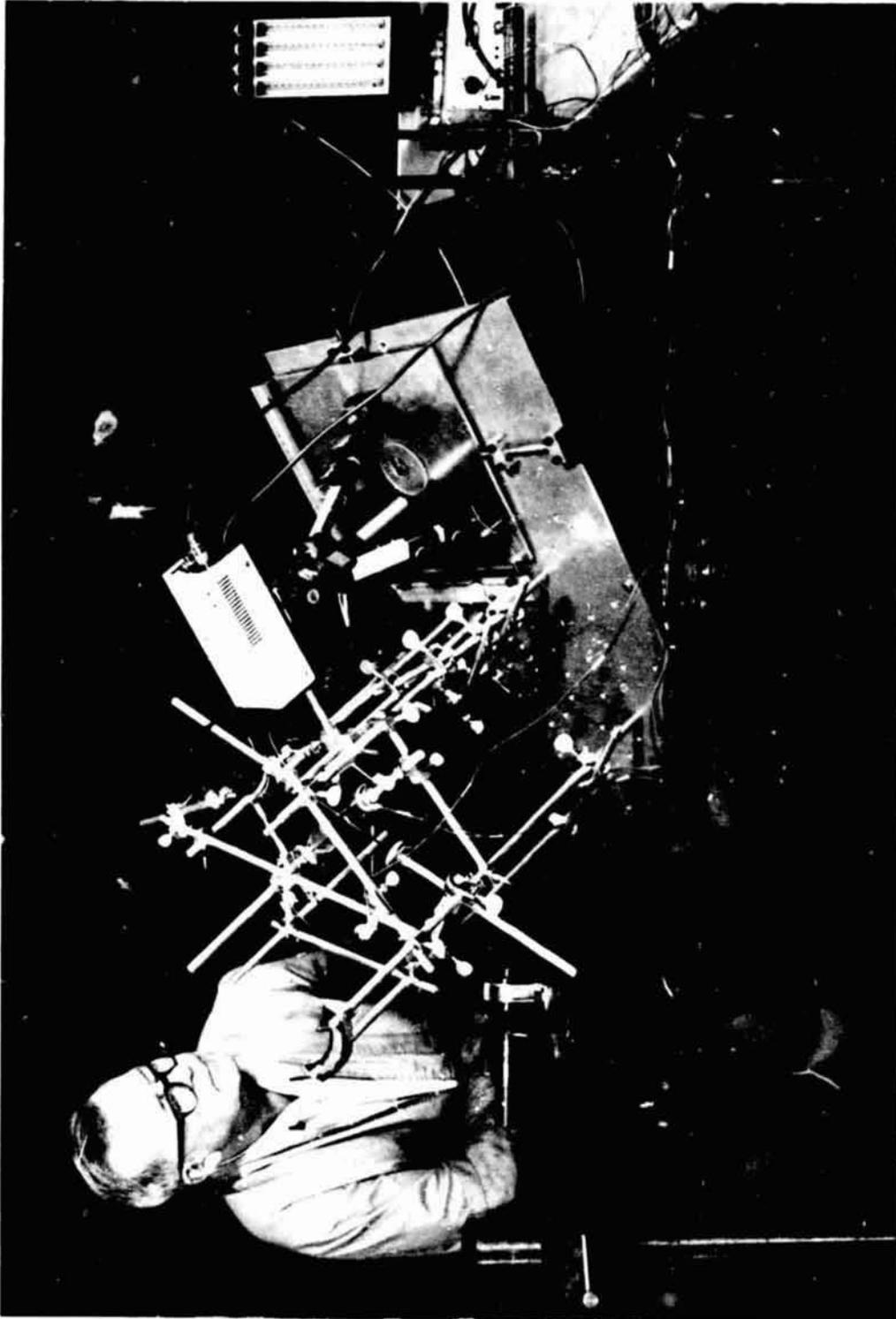


Figure 6. Gimbal Mounted Test Bench and Levitator.

A supply of approximately one millimeter diameter GMBs for the test was obtained through the courtesy of Mr. Jay Fries of Los Alamos Scientific Laboratory and Dr. Ray Downes of KMS Fusion, Inc., the latter providing their proprietary product MSP (R) (Micro Shell Pellets). An assortment of fifty of these were gold plated for use in case electrostatic problems should become severe (see Appendix D).

Rather than risk damage due to mishandling during shipping, the equipment was driven directly to Ellington Air Force Base by Mr. Alan Pomplun of Bjorksten Research Laboratories, Inc. Mr. Pomplun, who constructed much of the equipment as well as operating it, then supervised its installation and handling. Bjorksten Research Laboratories, Inc. is grateful to Mr. Robert Shurney of NASA and Professor Robert Cole of Clarkson College for operation of the equipment during flight.

b. Results

The first low gravity flights in the KC-135 were not entirely successful. They did provide information, however, which contributed toward success in subsequent flights.

Since the duration of each "zero gravity" period was little more than the time required to achieve levitation, provision had been made to levitate the GMB during level flight and to maintain levitation through the intermediate multigravity into low gravity. A manually operated adjustment had been provided to permit assistance in maintaining levitation through these large transitory changes. This provision, however, was not implemented.

While levitation could be maintained stably with the aircraft on the ground, engines off, repeated attempts to do so during taxiing and take-off or to initiate levitation during level flight were unsuccessful. The reason became clear upon analysis of the video tape records after the flights. Typically, the GMB or MSP^R during attempts to levitate would exhibit vibratory behavior having amplitudes of the order of one or two ball diameters (approximately one or two millimeters) and frequencies corresponding roughly to the video framing rate (1/60 hertz). The accelerations corresponding to these vibrations are of the order of full earth gravity, well beyond the established response time capability of this prototype levitator to cope.

Clearly, the remedy for future flights of this particular prototype was to tether and "free float" the levitator system in order to isolate it from these shipboard vibrational accelerations. This solution makes no provision for establishing levitation during level flight, where ample time to do so is available, since "free floating" cannot be commenced prior to the reduced gravity mode.

2. Second Low Gravity KC-135 Test

a. Preparations

Accordingly, the levitator was prepared for the "free float" mode of operation. Handles were installed at each end of the levitator box and an umbilical cord fabricated to make connection with fixed installations, power, computer tape deck, etc.

The decision to levitate only during the brief period of reduced gravity presupposes a means of launching the GMB which is more rapid and precise than the manual method employed heretofore. A GMB holder (launcher) was constructed of stainless steel hypodermic tubing (Figure 7). The GMB, held by vacuum applied through the tube, is manipulated through its holder into the proper location and the holder locked into place. At the appropriate time for launch the vacuum is released and the holder withdrawn rapidly.

The holder must be accelerated at a rate sufficient not only to overcome all attractive forces to the GMB (e.g. electrostatic, Van derWaals, etc.) but also to reduce the impulse therefrom below limits which would appreciably accelerate or disturb the GMP.

Initial experiments indicated that equipment to withdraw the holder electromagnetically would be awkward. Accordingly, the GMB holder/launcher was designed to incorporate a spring steel action. The spring, held in tension and released by a remotely controlled solenoid, has approximately 1/4 inch clearance for acceleration prior to striking the GMB holder. The impact causes the desired rapid acceleration of the holder during its departure from the GMB.

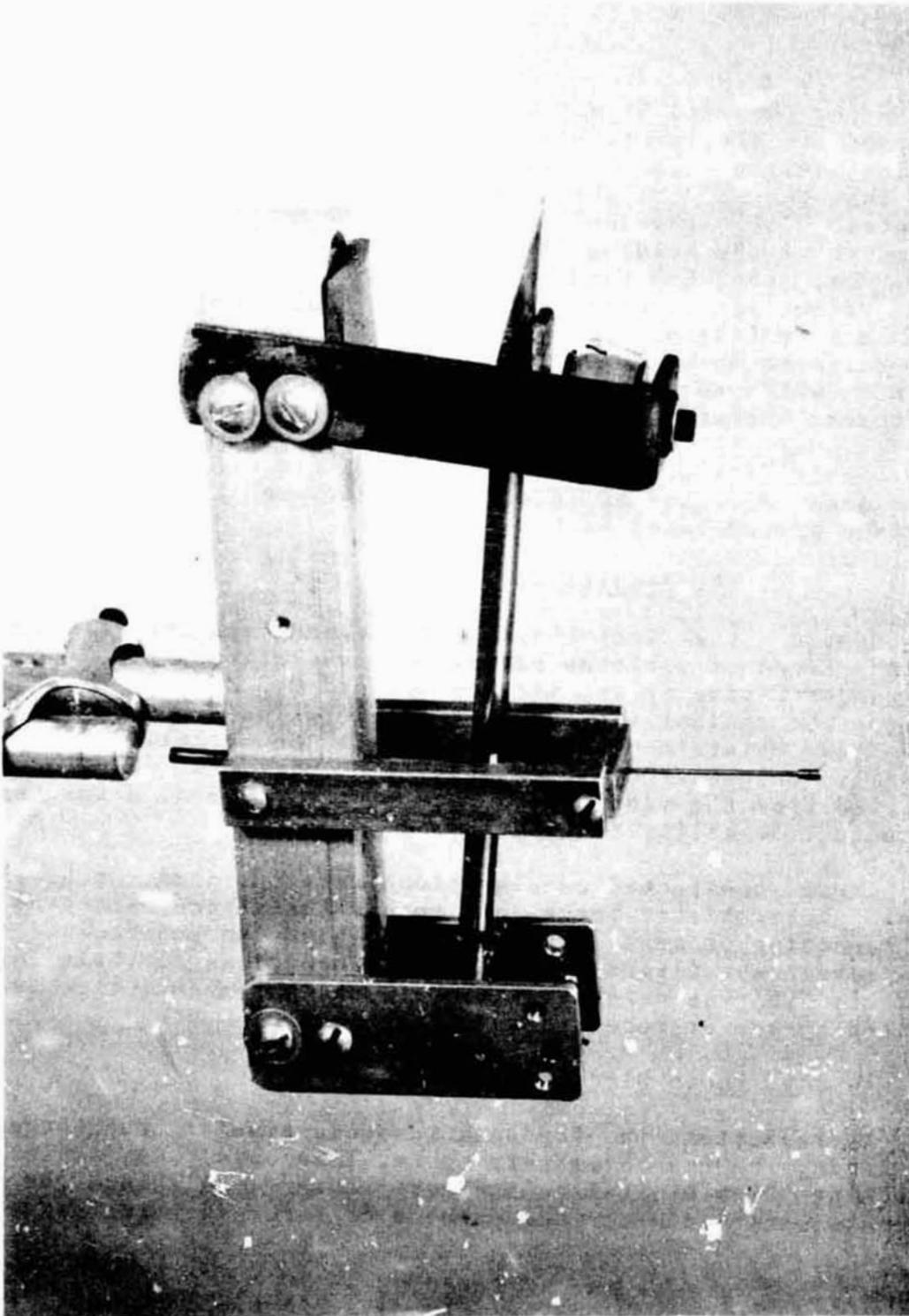


Figure 7. GMB Holder/Launcher, Partially Assembled. Hypodermic Needle Launcher in its Guide (Horizontal Member). Spring Action Striker, Oriented Vertically; Its Pivot and Spring Load in Bottom Horizontal Member; Solenoid Release Upper Horizontal Member.

With the aid of video tape records, GMBs were frequently observed to accelerate slightly forward upon withdrawal of the holding device. This effect appeared to be dependant upon the fact that the I.D. of the tube was a sizeable fraction of the GMB diameter. The spherical surface of the latter protruded inside the mouth of the holding tube. Upon initiation of withdrawal of the tube, the GMB tended to roll forward out of the aperture. This effect was eliminated by covering the aperture of the tube with a fine flat screen. A 100 x 400 micron mesh copper screen was soldered onto the end of the tube, leaving a flat surface against which to vacuum adhere the GMB. The point contact with the screen obviated the forward pitching effect.

Dennis Bahr of Bahr Technologies, Inc. flew the equipment. Mr. Alan Pomplun of Bjorksten Research Laboratories, Inc. provided ground based backup.

b. Results

Despite the fact that the experiment was free floated and thereby freed of airframe vibration, levitation was not achieved. The feedback time cycle, between 0.1 and 0.3 seconds was designed to operate against milligravity accelerations and was much too slow to maintain position against the accelerating forces actually encountered. The magnitude of these accelerations, inferred from the video tape, was of the order of a few tens of cm/sec.sq. or milligravities.

These unexpected accelerations were ascribed, initially, to stray electrostatic forces and to air turbulence attendant upon the launching process. The probable cause was ascertained during the subsequent flight (see below). Regardless of their origin, however, it was determined that feedback response time must be reduced by one or more orders of magnitude.

b. Photo Diode (Analogue) Sensors

A reduction in feedback response time of two orders of magnitude, to approximately two milliseconds, was achieved by switching from digital to analogue sensors. Although the video camera was retained for the purpose of recording progress of the

levitation experiment, its role as a link in the feedback control loop was eliminated. Thus, the time delays associated with its framing cycle (16.7 milliseconds) and with the digital processing of its voluminous tracking data (approximately 100 milliseconds) were simultaneously eliminated.

The field splitting mirror system was dispensed with at the same time. Instead, two position sensing photo detectors, aimed at the target from directions 90 degrees apart, provided photo voltaic output for triaxial position detection (see Appendix C) The optics provided were designed to utilize the entire 10 centimeters field of the sensors.

1. Computer Program

The computer program to control the target in three dimensions was written initially using PID (proportional, integral, differential) equations. The integral term, however, was found to be unnecessary and accordingly, was dropped. The foreground program was written in native machine language to allow a high loop speed. An entire input and output cycle for the three axes can be completed in two milliseconds, two orders of magnitude shorter than the old video system was capable.

A background PL/I-80 program was developed to display the input and output, as well as any calculated data on a CRT terminal. The computer uses is a Z-80, running at 5 megahertz. It employs the CPM 2.2 operating system and is made to function in an auto-boot mode (See Appendix E).

An important factor in implementing photodiode sensors and exploiting their rapid response time was the switch from transparent (GMB) to diffuse reflecting targets (eg., styrofoam, ping-pong ball). The centroid of the target image coincides with the projected center of gravity. Position coordinates are directly related to signal. The edge detection algorithm and associated, real time consuming, digitization process is obviated.

2. Scaleup of Sonic Pump

The perennial problem of unwanted electrostatic forces causing GMBs to stick to the CHS and otherwise misbehave was solved by scaling up to larger sized levitating objects. This modification materially speeded up the process of testing new alterations. It hinged upon the discovery that the levitating power could be greatly increased by opening up the diameter of the orifice(s), no increase in speaker power being required. In essence, the CHS was replaced by a single sharp edged orifice. It was found that the speaker enclosure and crifice could be fabricated conveniently by cutting off a laboratory funnel at the appropriate point near the stem (refer to Figure 1a and to Appendix C).

As expected, flow from the truncated conical closure was turbulent by comparison to that from the CHS. As demonstrated later, however, this turbulence was not sufficient to disturb system stability.

The levitating output was found to be an essentially linear function of signal strength to the speaker except at the lowest values. Levitating force diminishes to negligible values before signal input goes to zero. Accordingly, a manually adjustable control was provided to permit applying a power input bias to the sonic pumps which would assure their operation in the linear region.

3. Full Gravity Tests

Preliminary tests were carried out in full gravity using 2.4 cm diameter styrofoam spheres weighing 0.22 grams as targets. The bottom sonic pump, in addition to its feedback control component and the linearity bias, was provided with a strong constant signal to neutralize the acceleration due to gravity. At first, stable levitation could be achieved for periods of only half a minute or so. Minor misalignments of the sonic pumps produced rotational couples and caused the levitated spheres to spin. As the speed of rotation picked up past a certain point the center of gravity of the sphere would begin to oscillate in a rotary manner. As the ball's rate of spin increased further, the oscillations grew in amplitude until the ball dropped out of levitation.

This pattern of behavior is satisfactorily explained by the Magnus effect (Gustav Magnus, Berlin, 1853, see Royal Society Catalogue), the force which develops at right angles to wind velocity on a rotating body. While this Magnus derived instability could be neutralized by appropriate hardware and software changes, a simpler solution was employed in order to get on with the main objective of establishing feasibility. Rotation was stopped by weighting one side of the sphere. A 1/16" diameter bee-bee shot embedded in the sphere proved adequate. Stable levitations of several hours, until shut-down, were then achieved. The system was capable of effecting recovery from target displacements of the order of a ball diameter from the equilibrium position (Figure 8).

4. Third Low Gravity KC-135 Test (10/4-10/83)

In the interests of ease of operation, the equipment was bolted to the airplane deck, although the previously fabricated accommodations for free float were available. The vibrations encountered during the first flight were deemed of too small magnitude to be a disturbing influence in this much faster acting, much larger scale prototype. Messrs. Dennis Bahr and Brian Vanderwarn flew the experiment.

a. Results

Styrofoam balls as described above, with and without the bee-bee shot counterweight, were repeatedly levitated for the duration (approximately 30 seconds) of the low gravity portion of the parabolic flight regimes. Levitation was stable in either case. Some rotation was experienced, but it was of a degree which did not affect stability. Speaker operating levels were low in correspondence to the reduced inertial accelerations.

Larger styrofoam spheres (3.2 centimeter diameter, 0.64 grams) and ping-pong balls (3.7 centimeter diameter, 1.91 grams) were also successfully levitated. Rotations comparable to those previously mentioned were exhibited.

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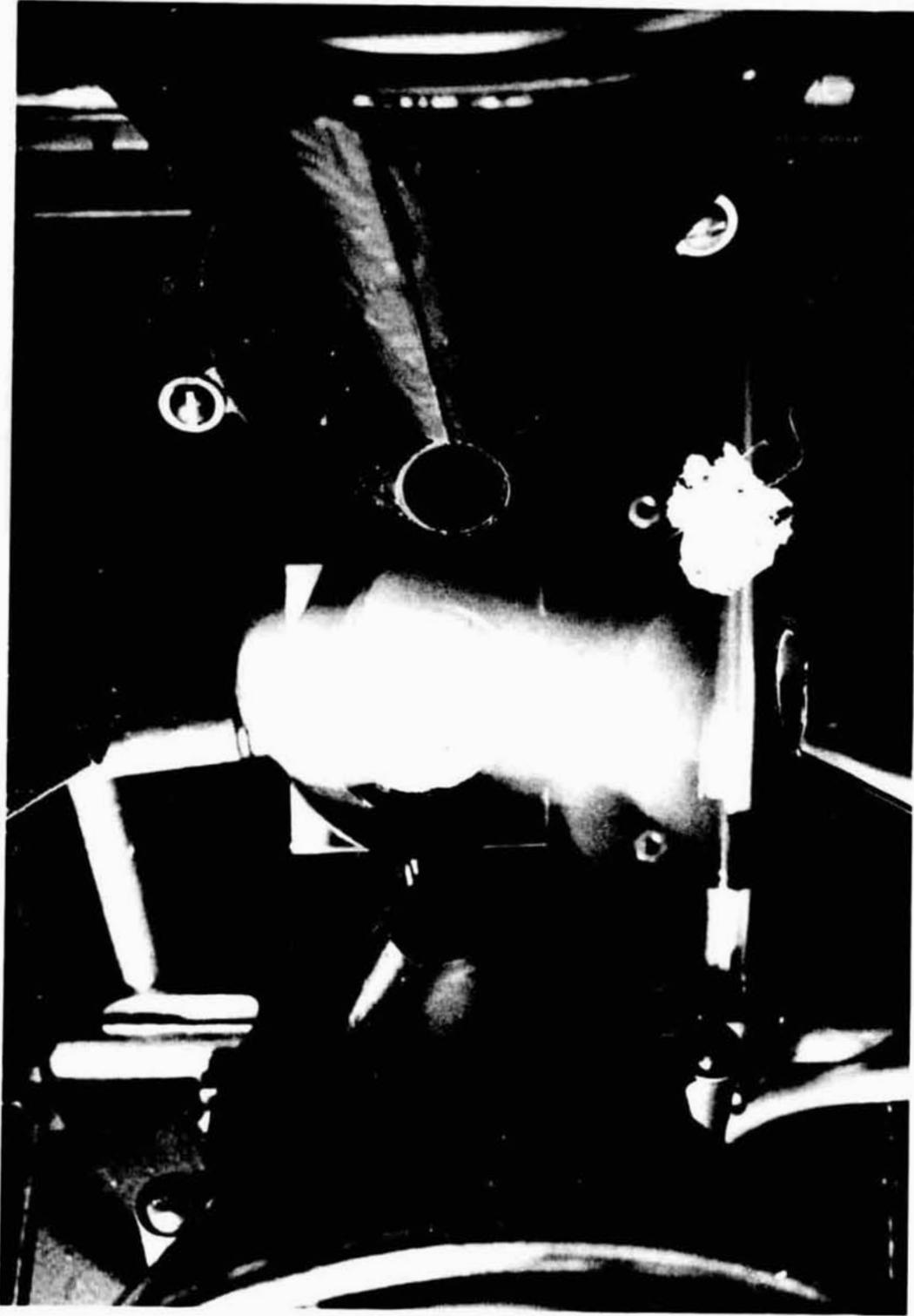


Figure 8. Levitated Styrofoam Sphere. Composite Photo Showing, In Addition to the Stable Equilibrium Position, the Degree of Perturbation from which the System is Capable of Recovering.

A golf ball would not levitate, because it occupied too large a fraction of the field of view of the position sensors. Similarly attempts to levitate a 1.25 centimeter diameter steel ball were unsuccessful. In this case, inadequate target contrast as well as the high inertial loading on the aerodynamic cross-section were undoubtedly the main contributing factors.

A one centimeter balsa wood cube fell out of levitation after one or two seconds. The equipment had not been designed either to control target rotation or to deal with the random, lateral aerodynamic forces associated with the changing attitude of an asymmetrical tumbling target or with the random displacements of centroid of the reflected image relative to the projected center of gravity.

Finally, as an afterthought, an attempt was made to levitate a liquid droplet. Surface tension overcame efforts to deliver a drop of milk of magnesia from a hypodermic syringe. At this point, there was insufficient time remaining in the flight series to make the necessary improvements in delivery technique.

b. KC-135 Deviations from the Parabolic Flight Pattern

The visual and sound records revealed evidence of two kinds of accelerations experienced by the KC-135 its passengers and cargo. Hand held movie camera records showed the effects of short duration accelerations with random orientations. Presumably, these had their cause in clear air turbulence (CAT).

The other type of acceleration was more or less constant in magnitude and directed forward along the line of thrust. Its presence could be inferred from two elements of the record. The modest rotation of the levitated balls was uniformly about an axis lying athwart ships in a plane parallel to the deck. Couples to produce rotation about this axis could be derived, through minor misalignment from the opposed pair of sonic pumps lined up vertically to the ship's deck or parallel to its line of thrust.

The sound track on the video tape revealed that the ship's engines were brought to idle upon entry into the ascending leg of the "parabola" and they remained so until pullout. Without the engines, the ship is subject to a decelerating force due to its aerodynamic drag. The force is felt along the line of thrust, objects within the ship being impelled in a forward direction.

The acceleration is a fraction of gravity equal to the sine of the dead stick glide angle for any given velocity. It may amount to 10 to 20% of gravity.

No maneuver, other than matching the engines' thrust to aerodynamic drag, will eliminate this extraneous acceleration. A dead stick parabola cannot do it and no other dead stick flight pattern will even approach a zero gravity condition. An appropriately designed flight controller would enable the pilot to approach zero gravity more closely by an order of magnitude. It would provide appropriate throttle as well as control surface indications.

5. Fourth Low Gravity KC-135 Test 11/13-17/84

The capability of the Sonic Pump Levitator to function at high temperature was tested in full and reduced gravity. A simplified version of the levitator was developed to accommodate budgetary restraints. Improvements were made in the design of the sonic pump.

a. Preparations

In order to handle the higher density refractory bodies capable of withstanding the high temperatures desired, the existing prototype sonic pump levitator would have had to be scaled up in power and otherwise modified at a cost considerably in excess of available funding. A more economical approach, testing only the essential elements, was adopted instead. Accordingly the entire feed back loop of the sonic pump levitator was tested along a single axis rather than all three simultaneously. In addition the necessity of expensive electronics to adapt the position detecting light sensors to the changing luminance of the heated target was eliminated by a simple expedient.

The target was mounted on a boom which swings on a low friction pivot bearing. One pair of opposed sonic pumps move the target between them along the arc of the pivotted boom (Figure 9). The complexity and cost of the feedback control of this essentially uniaxial position keeping set up is greatly reduced relative to the triaxial. Spacing between the pumps, 7.4 cm, is short relative to the boom length, 12.7 cm, so that motion of the target is mainly along the axis of the pumps with very little component along the boom axis and of course none in the direction

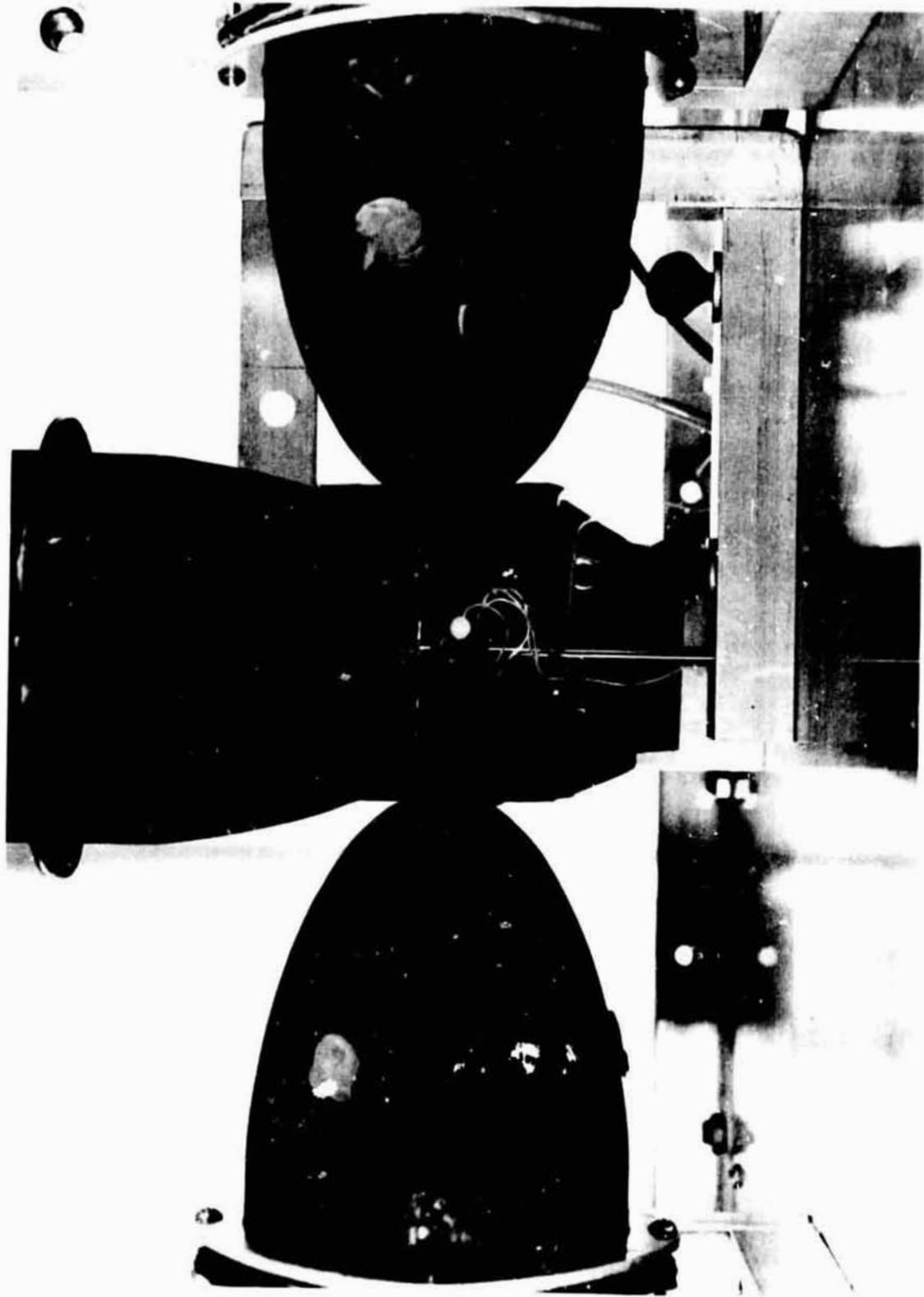


Figure 9.
Target Sphere Mounted on Boom (End On), Single
Pair of Sonic Pumps (Laterally) with Radiant
Heater (Above).

parallel to the pivot axis. In practice, the pumps restricted the motion of the target to a very small fraction of the spacing between them so that the motion along the boom axis was negligible.

The boom was made of stainless steel to withstand the high temperatures at the target end. It was constructed of small diameter thin walled tubing to minimize moment of inertia, which with associated parts amounted to 301 gm cm^2 . The contribution of this moment of inertia toward the effective mass of the target located at the end of the boom is thus 1.87 gm . The entire assembly was balanced so that neither earth gravity nor maneuvers of the KC 135 could influence this effective mass. The boom is mounted in a cylindrical aluminum body suspended between the points of tapered steel shafts, which comprise the pivot (Figure 10).

Hollow alumina spheres ca. 5 mm in diameter were used as targets. Their apparent density, including the effective mass of the boom assembly, is around 30 gm/cm^3 . The spheres were held to the end of the boom by three fine steel wire prongs. The prongs extended into the sphere through a small opening and held it in place by pressing against the walls from within. A Pt-Pt/10%Rh thermocouple was inserted through the same opening.

Instead of focusing the position detecting sensor on the changing intensity target directly, it was trained on a small constant intensity light emitting diode (LED) mounted on the far end of the boom, past the pivot or fulcrum. As the target moves, so also does the LED, tracing its position across the optical sensor. A computer then translates the movement into sonic pump output to maintain a centered target position. The electronics and software required was a simplified version of that presented in Appendix E.

The only drawback to this system was a minor one, namely the spring force on the leads to the LED. These and the leads from the Pt-Pt/10%Rh thermocouple in the target were fed through the boom tube and brought out near the pivot. Together they spring loaded the movement of the boom. The spring load was minimized by using long leads of fine wire and forming them into an open coil about the pivot axis. The restoring force of these wires was shown to be much smaller than that of the sonic pump feed back loop.

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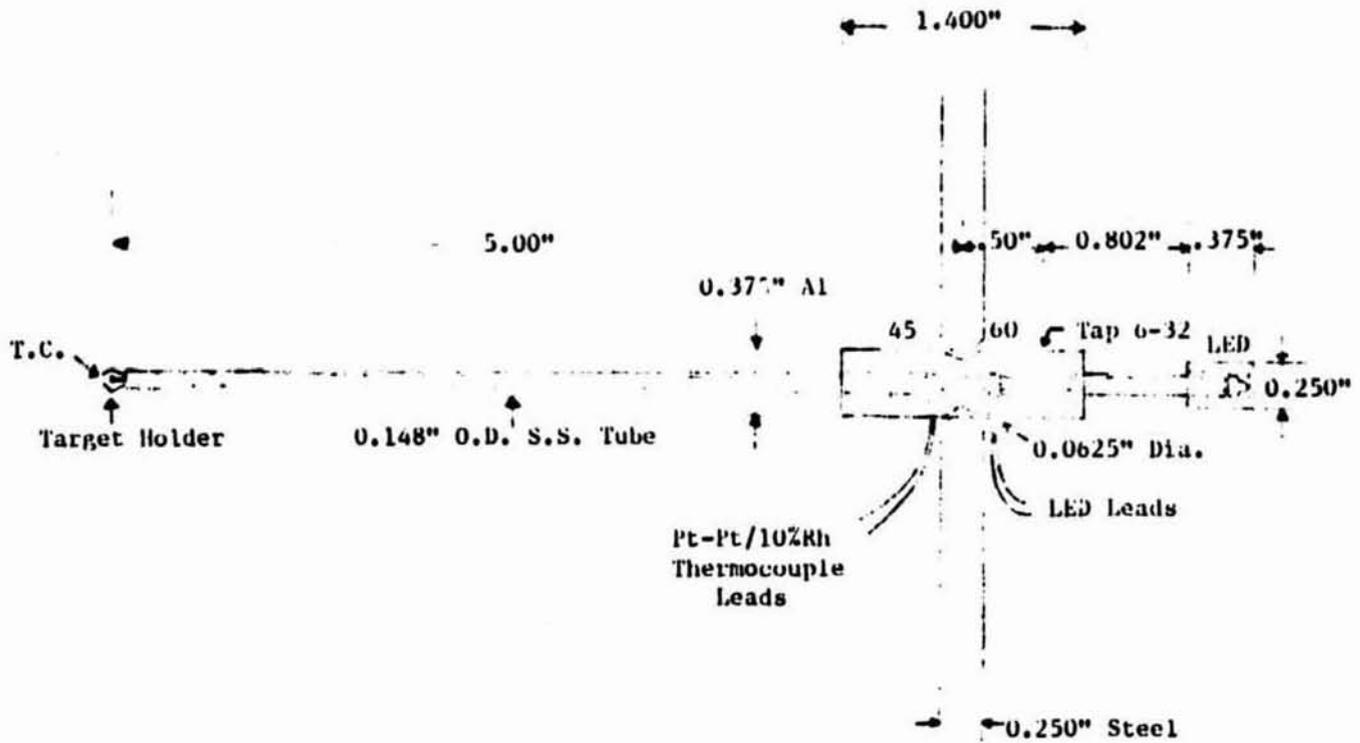


Figure 10. Target Boom and Needle Bearing Pivot.

Several new speaker enclosures were studied in a further effort to improve sonic pump efficiency. These included a 60° taper glass funnel, a 50° taper polypropylene funnel, a polypropylene exponential horn and a spun aluminum ellipsoidal (prolate) reflector hood from an incandescent lamp heater. Comparisons were made on the basis of the power required at 120 hz to levitate a 1" diameter styrofoam ball (0.22 grams) to a height approximately 2" above the enclosure orifice. Tests were run with each enclosure placed over a 4", 18 watt Oaktron speaker. Orifice diameters were approximately 1/2" diameter.

The soft polyethylene 60° taper funnel, the same as used in the 3rd KC 135 flight test, proved to be more efficient than all new designs except for the ellipsoidal hood. The polyethylene funnel enclosed speaker required 0.67 watts to levitate the ball compared to 0.32 watts for the ellipsoidal hood enclosed speaker.

Comparison of smoke flows out of the ellipsoidal hood and the polyethylene funnel orifice show less turbulence with the ellipsoidal hood (Figures 11 and 12). Levitation in one gravity was considerably more stable with the ellipsoidal hood, as would be expected.

It had been reasoned that the wave form from a speaker might be approximately planar and that if so, a paraboloidal shroud might produce a large sound amplitude at the focus, which would be particularly conducive to sonic pump efficiency. A prolate ellipsoidal hood of correct minor diameter was readily available from the ellipsoidal radiant heater (see below). It was tested since it resembled the paraboloid, which was not easily available. The paraboloid is slightly narrower than the ellipsoid and would offer a corresponding advantage of occupying less space. A paraboloid and other related shapes will be tried when funding is available. A patent application is being readied.

A single 750 watt infrared (IR) ellipsoidal heater was tested for use with the one dimensional levitation system. A Pt-Pt/10%Rh thermocouple in a 1 cm diameter hollow alumina sphere indicated 1000° C approximately 45 seconds after being exposed at the focal point of the heater.

The maximum temperatures attained in the final assembly were lower (in the neighborhood of 650° C) for two reasons. The focal point was moved 0.1 inch back from the target to keep the shroud

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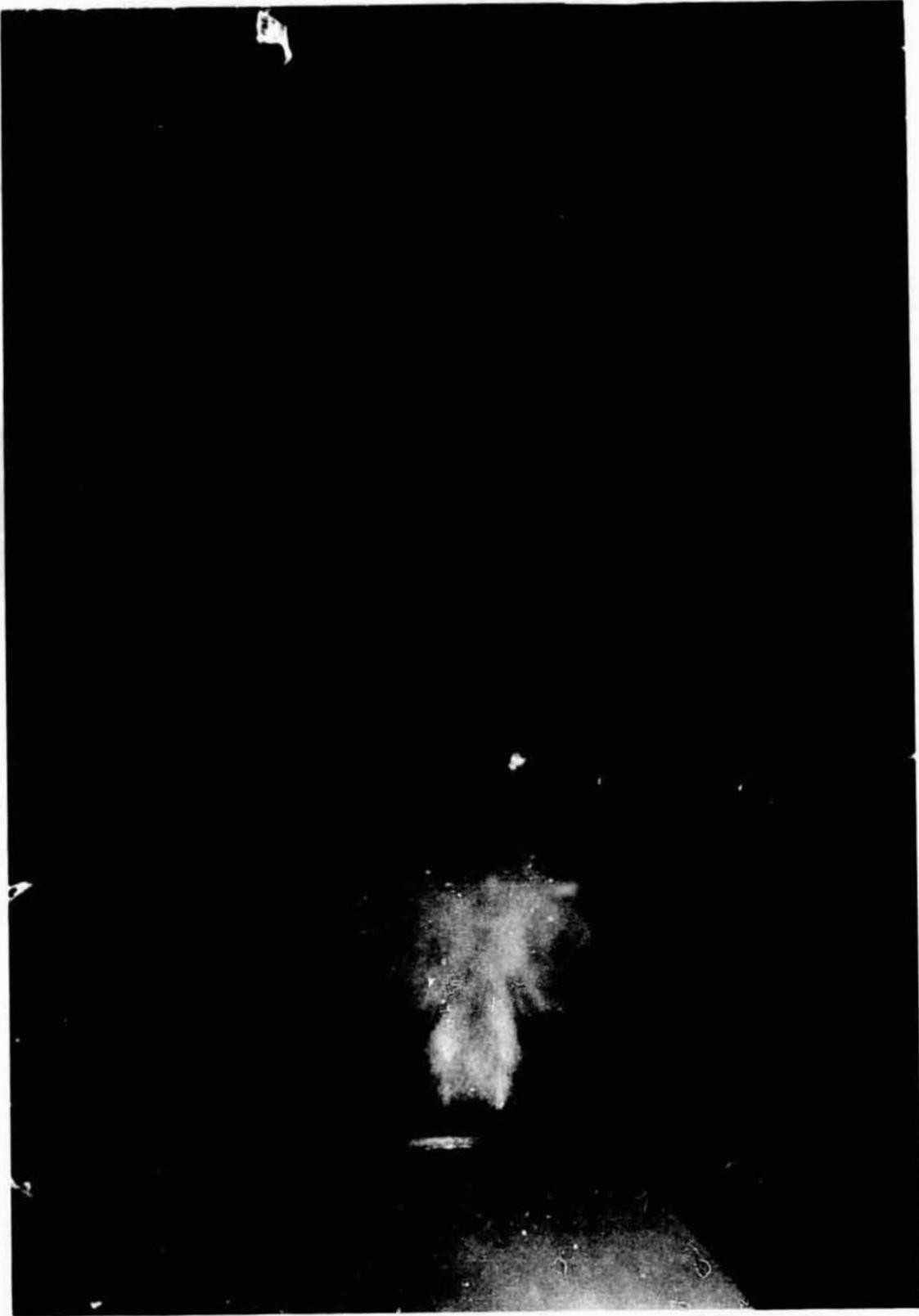


Figure 11. Smoke Pattern of Flow From Ellipsoidal Shroud.

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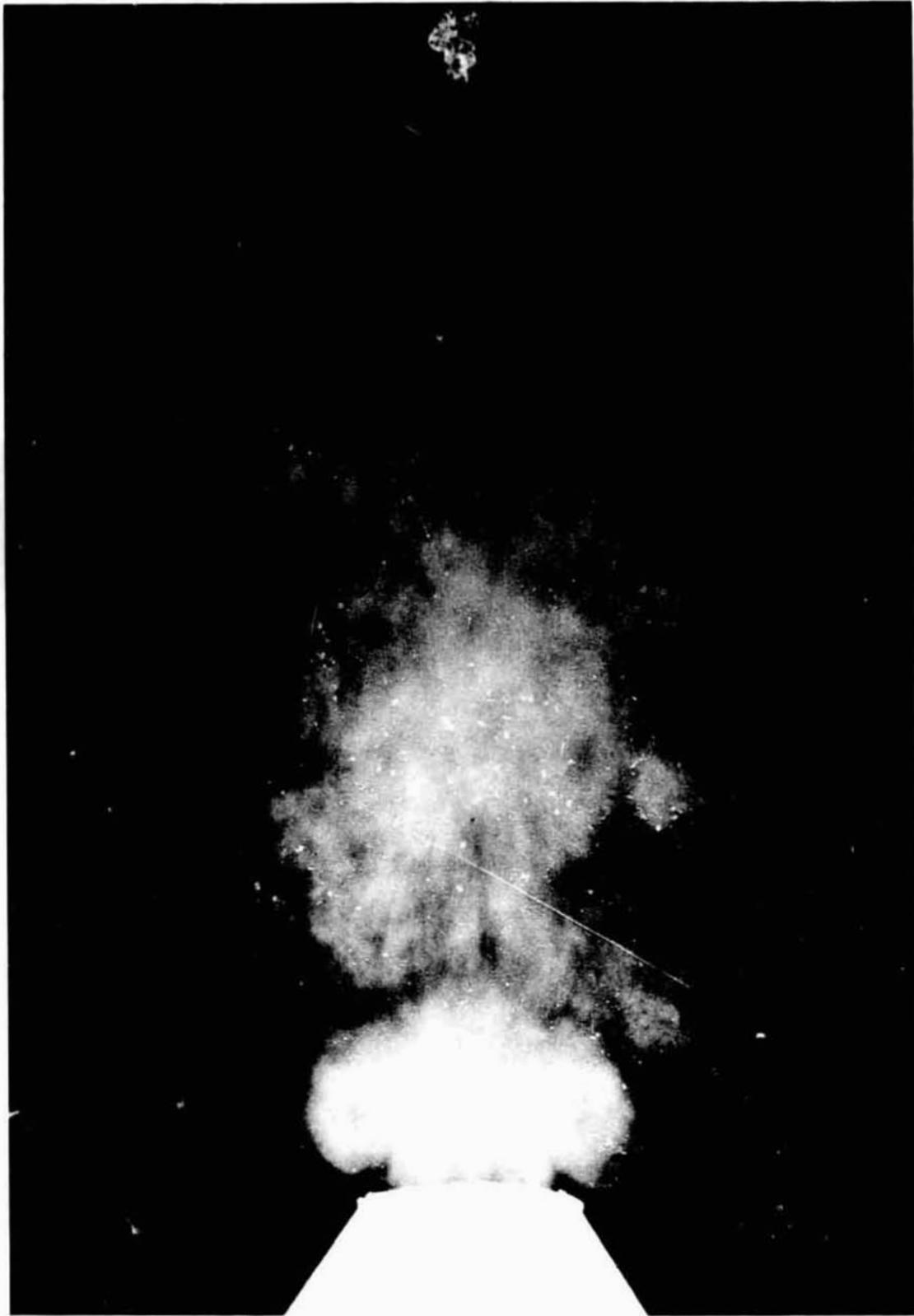


Figure 12. Smoke Pattern of Flow From Conical Shroud.

from interfering with the sonic pump flows. A satisfactory means of cutting the shroud could not be found in time. Also some difficulty was encountered in bringing into coincidence the zero points of the electronic system and the spring load introduced by the lead wires to the LED and the thermocouple. The resulting steady call on one or the other of the sonic pumps caused a further reduction in the temperature of the target.

The equipment rack from the previous sonic pump levitation tests was modified to accept the new computer and amplifier. The sonic pump system was built onto the top plate of the rack and a containment housing was constructed from 1/8" thick aluminum sheet (Figure 13). A video camera positioned 90° off of the Sphere's plane of motion received the image of the heated target from a front surface mirror mounted 45° off the plane (Figure 14). Image intensity was reduced by twin polarizing lenses placed over the camera lens and set to the extinction position. Light transmission was reduced to approximately 0.15%. A small video screen presented continuously updated values of target position and the integral and first derivative of its motion. A videorecorder taped KC-135 flight tests and frame by frame analysis was used to interpret system response time.

b. Results

The feedback loop of the Sonic Pump Levitator appears to function independently of temperature. Artificially induced oscillations are damped out in less than two cycles, despite the abnormally high effective density of the target (ca. 30 gm/cm³) and regardless whether operating under unit or reduced gravity (Figure 15-a). Damping from the combined friction effects in the system is relatively minor (Figure 15-b). The damping factors (ζ) show no significant trend with temperature (Figure 16). The average of the high temperature damping factors is actually slightly higher than the low temperature average though not significantly so.

The target's recovery from a disturbance to its equilibrium position is adequately described by a sine function with an exponential damping term:

$$p = p_0 e^{-t/\tau} \sin wt$$

where τ = period of oscillation / logarithmic decrement
= $T / \ln p_1 / p_2$

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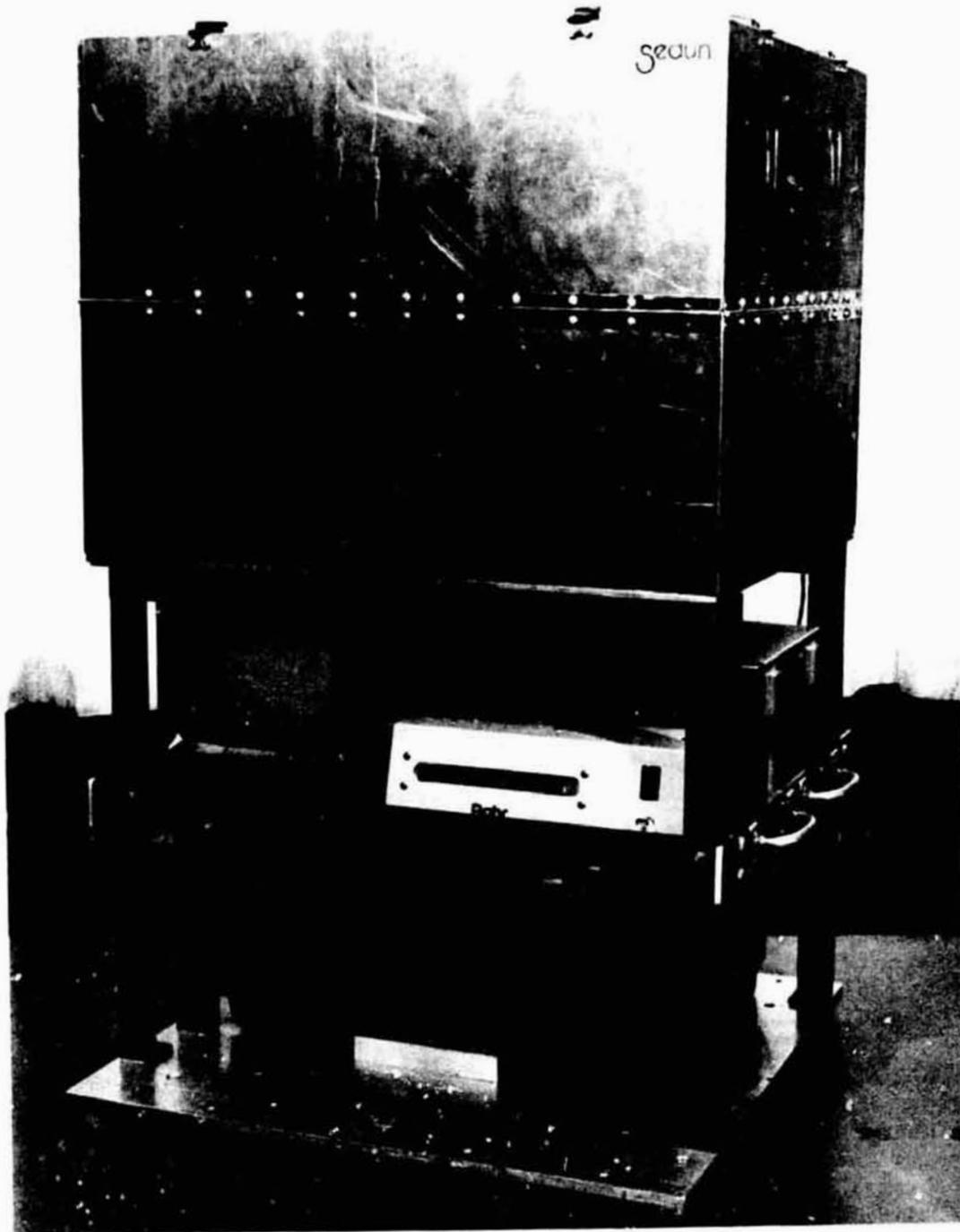


Figure 13. Complete Equipment Package.

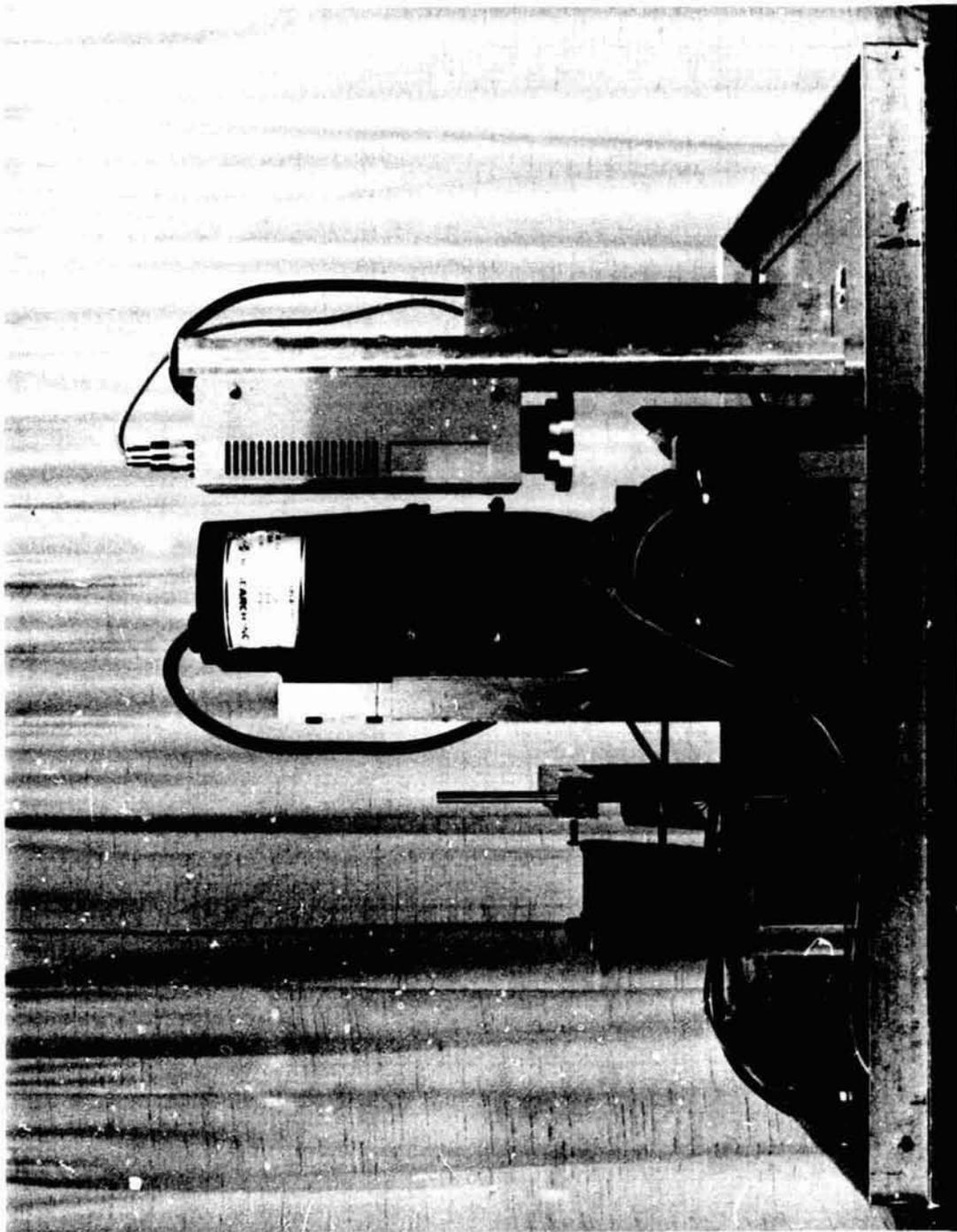
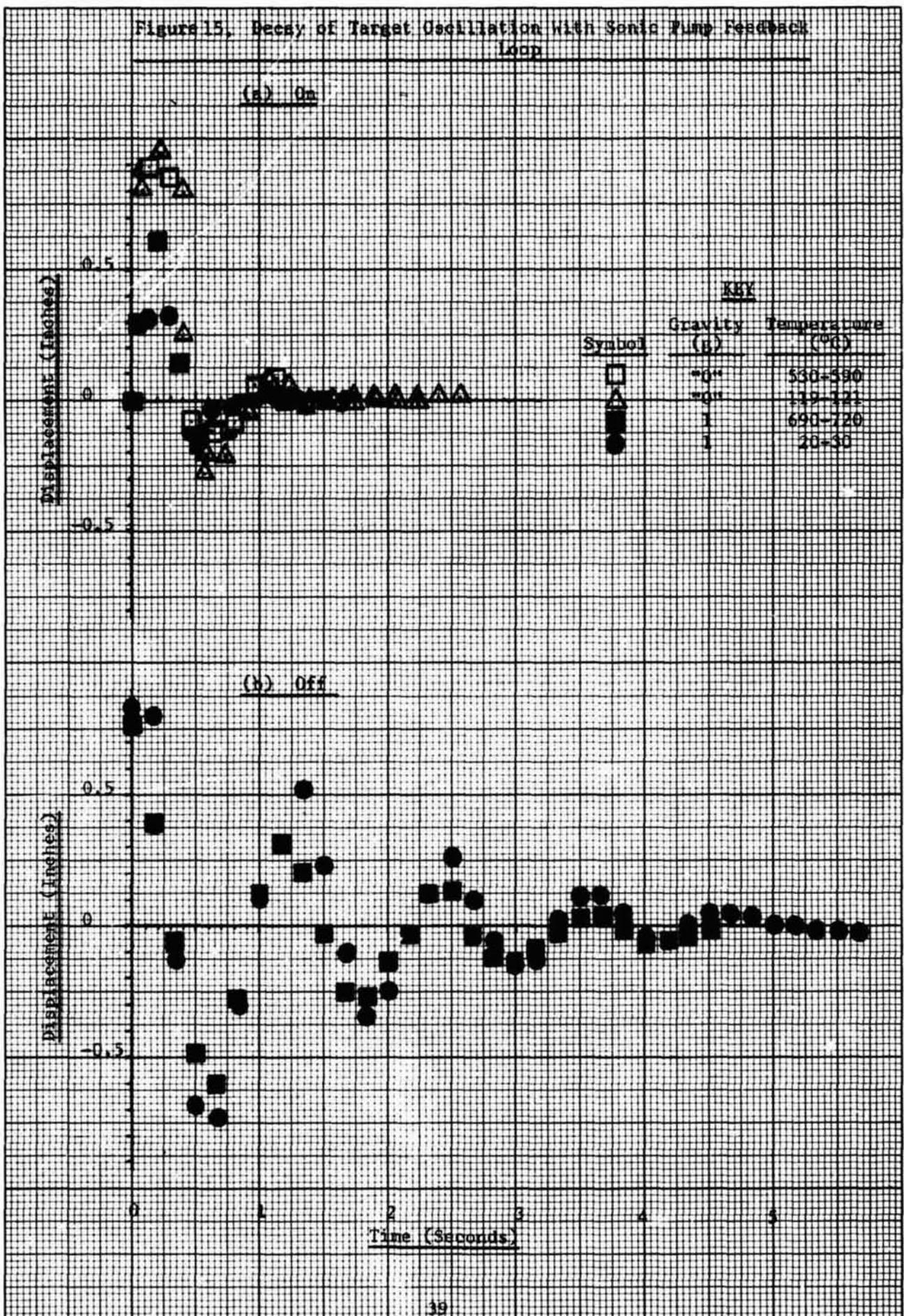


Figure 14. Video Camera and 45 Degree Mirror (To Right),
Pivots and Boom (To Left).

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Figure 15. Decay of Target Oscillation With Sonic Pump Feedback Loop



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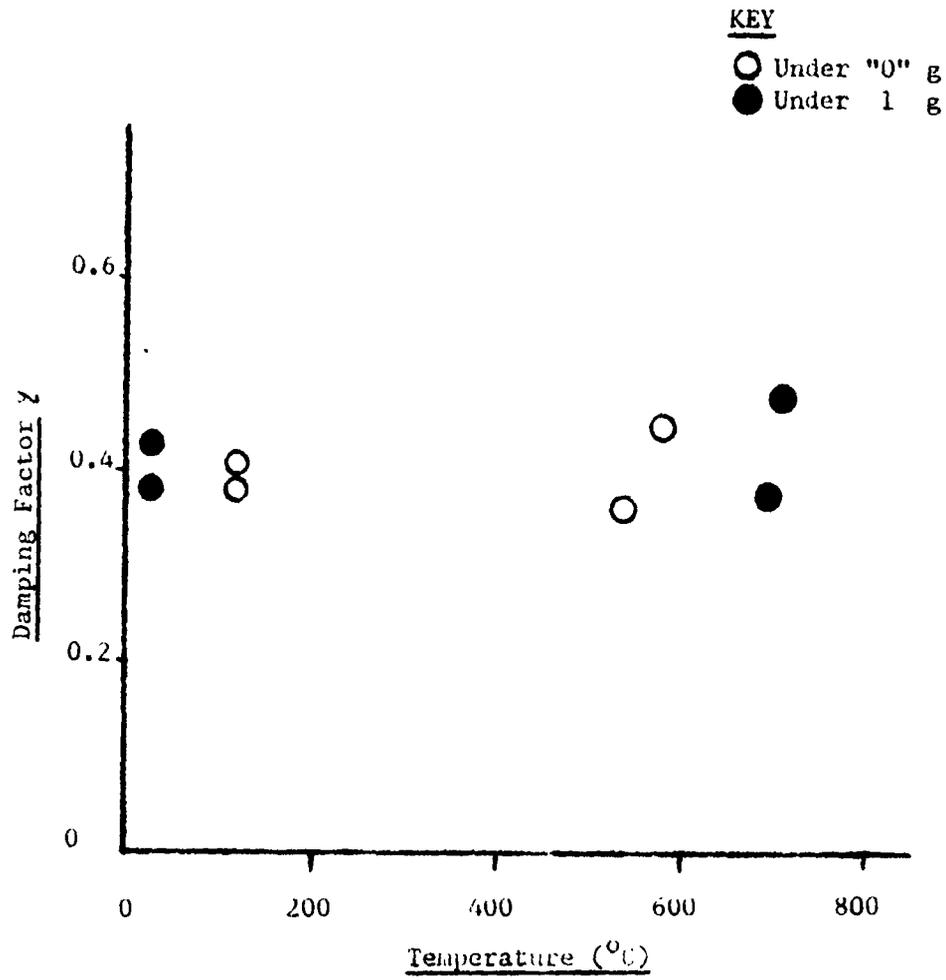


Figure 16. Effect of Temperature Upon Damping Factor

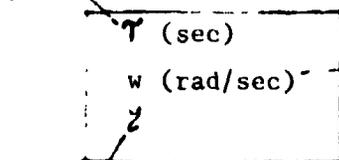
and ω = frequency of oscillations in radians / second.

Values of the equation constants together with their respective damping factors are summarized for representative runs under various sets of conditions (Figure 17).

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		Range of Temperature (°C)				Sonic Pumps	
		22-28	119-121			537-720	
Off	"0"						
	1	1.18				1.19	
On	"0"			0.36	0.33	0.35	0.37
				6.8	6.8	5.9	7.0
	1			0.38	0.41	0.44	0.36
			0.34	0.28			0.26
		7.1	7.6			7.2	8.1
		0.38	0.43			0.48	0.37

Period of time to damping
by a factor of e



Frequency of damped oscillations

Damping factor

Figure 17. Representative Values of Equation Constants for the Damped Oscillatory Recovery Behavior of the Target After Perturbation.

APPENDIX A

COLLIMATED HOLE STRUCTURE (CHS)

1. Fabrication

A: the name indicates, a collimated hole structure (CHS) comprises a collection of parallel channels or tubes. In the embodiments used in levitation, the holes or tubes are taken to be of equal or near equal size unless otherwise noted.

a. Swaging

The earlier levitation work with GMBs employed CHSs with comparatively small sized holes. The first of these had been manufactured from bundles of much larger diameter tubing, often stainless steel, by a drawing process. The tubes were filled with a low melting metal before drawing, to prevent collapse of the tubes. Beside size reduction, the drawing process resulted in the welding of the tubes into a solid structure. The drawn bundle was then sliced like a jelly roll and the low melting metal removed. The physical dimensions of the resulting CHS were determined by easily controlled process parameters. Most importantly, very large aspect ratio holes (the ratio of length to diameter) were easily produced by this process.

Shortly after the utility of the CHS as a levitating device had been recognized, its production by this method was discontinued. The method was profitable only in large volume, for which unfortunately, there was insufficient market.

b. Alternate Methods

Alternate methods of small volume manufacturing were examined on a continuing basis: laser, EDM, electron beam, as well as mechanical drilling. All shared a limitation regarding aspect ratio. For the purpose of this project, mechanical drilling proved most satisfactory. Generally, it was capable of superior hole symmetry. For hole diameters 250 microns and above as required, it compared favorably to the other methods with respect to aspect ratio, up to 3:1 for all but the finest holes. Finally, it seemed to represent the best compromise of cost and speed with the research demand for flexibility.

c. Interstitial

A superior method of fabricating CHSs for levitation purposes was discovered which could produce aspect ratios of any

desired magnitude. It was found that for levitation purposes, holes need not be of circular cross-section. Interstices among rectilinear or hexagonally close packed rods worked quite as well. A CHS could be made by tightly bundling the array of rods in a lateral enclosure. For fabrication of fine hole CHSs the method has the advantages (1) that the interstice-to-rod cross-sectional area ratios are much less than unity (~0.2 rectilinear array, ~0.03 hexagonal) and (2) that rods, wires and fibers of a wide assortment are readily available commercially.

In the first embodiment of this principle of construction, the lateral enclosure was formed by machining out an appropriately sized rectangular groove in one of two mated blocks. The tight fitting rods were clamped in place by bolting the blocks together (Figure 18).

Smoke patterns were used to show the laminar stream stability made possible by the high aspect ratios attainable with interstitial CHS construction. Comparison is made between an interstitial (rectilinear array aspect ratio 50:1) and a mechanically drilled (hexagonal array aspect ratio 3:1) CHS. (Figures 19 and 20).

Subsequently, interstitial CHSs were made more simply by packing appropriately sized rods within the termini of the levitation gas supply lines. The hexagonal symmetry is better adapted to supply tubes of circular cross-section. This convenience is restricted to CHSs comprised of seven rods, of course. The resulting six holes (full size), however, are adequate in many cases. Both square and hexagonal supply tubes will accommodate much larger arrays of the respective packing geometries.

Around the periphery of the array of either symmetry are holes of fractional cross-section. The flows from these are much reduced below those of the interior interstices. They appear to be drawn into the main flows and not to detract from overall levitating performance (Figure 21).

2. Design Features

CHS design was concerned mainly with the levitation and manipulation, particularly rotation, of GMBs. This design study preceded the advent of the interstitial CHS. Consequently, the largest available GMBs were employed in order to permit the use of large hole sized CHSs and thereby reduce hole drilling problems. The design elements discussed here are those other than the dimple or hole aspect ratio, which were covered in the preceding section and elsewhere.

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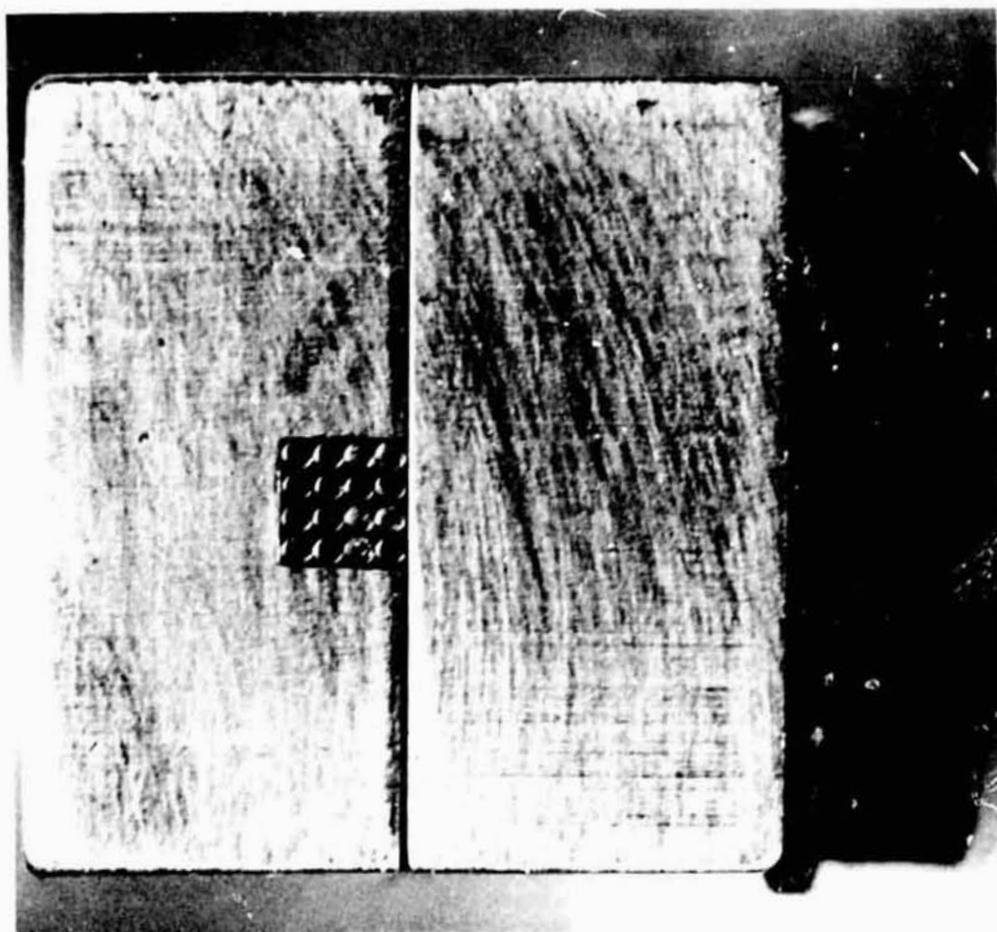


Figure 18. Interstitial CHS. Top Elevation, Above. Grooved, Mated Block with Rods Stacked in Groove, Below. Rods Were 500 μm in Diameter.

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Figure 19. Gas Flow Smoke Pattern (Steady Flow): Interstitial
CHS, Aspect Ratio 50:1.

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Figure 20. Gas Flow Smoke Pattern (Steady Flow): Mechanically
Drilled CHS, Aspect Ratio 3:1.

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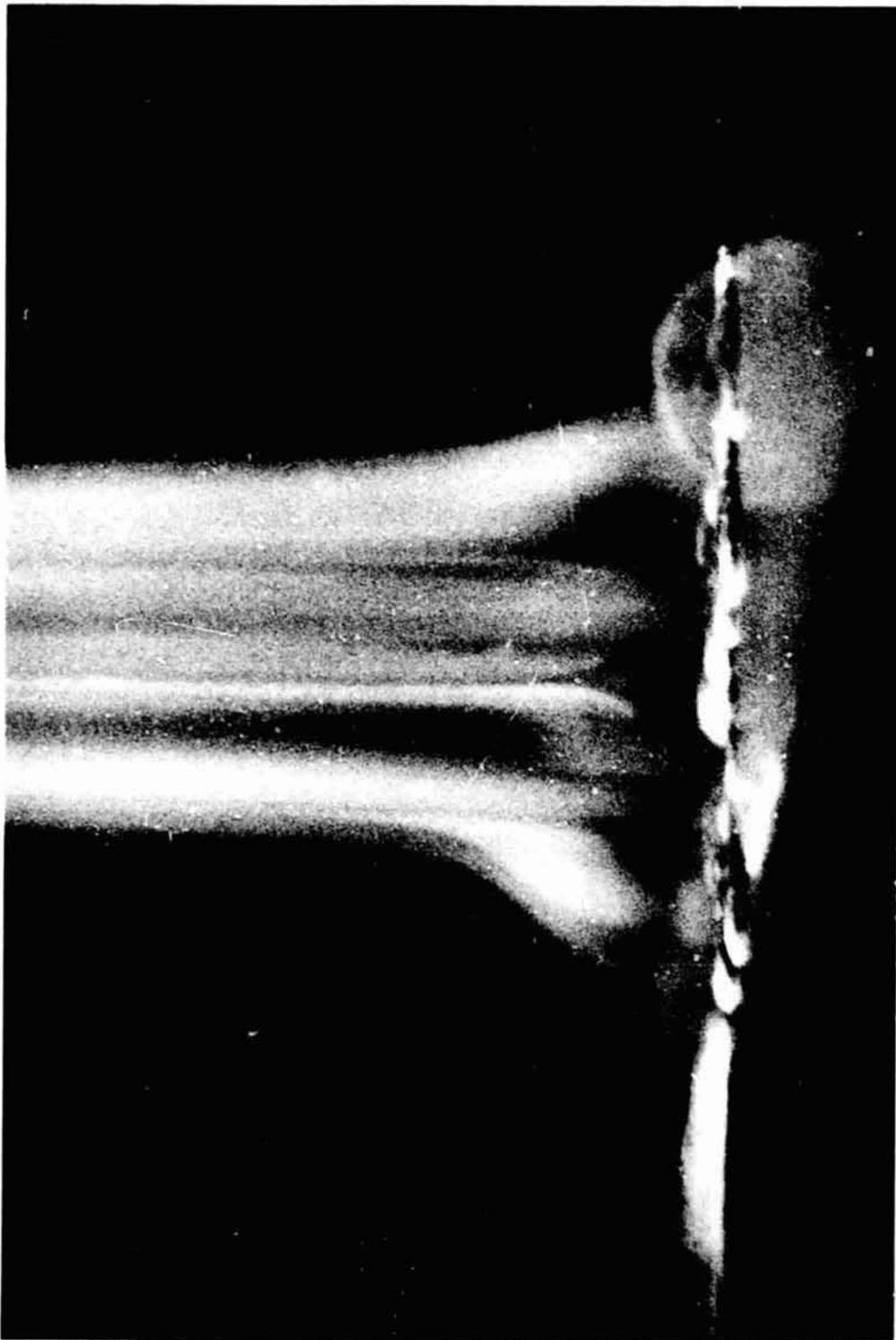


Figure 21. Gas Flow Smoke Pattern (Steady Flow): Showing Peripheral Fractional Flows Being Drawn Smoothly Into the Main Force.

a. Effect of Array Geometry

Much of this design study was carried out before the work on feedback control. Hence it included lateral levitation stability as a major concern in CHS design. It had been known for some time that CHS hole array geometry has an important effect, both qualitatively and quantitatively. The relationship of design elements such as orifice diameter and spacing to each other and particularly to the size and density of the GMB were examined.

1. Glass Microballoons (GMBs)

Repeated observations have indicated that GMBs rarely, if ever, levitate in direct alignment over one hole. At the lowest gas velocities (steady flow) they will commence levitation close to alignment with one hole and equidistant to the next two nearest neighbors. As gas velocity increases, the GMB in addition to gaining altitude, moves away from alignment with its nearest orifice, eventually approaching equidistance among it and the two nearest neighbor holes. Higher velocities slowly push it to a position directly above the webbing between two adjacent holes. With further increase of velocity, the GMB will engage in lateral or vertical oscillations or both, just before levitation ceases to be stable.

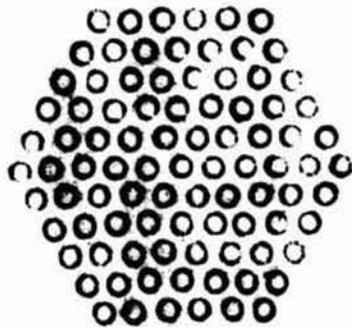
It appeared that the failure to achieve stable or steady levitation in many GMB experiments was related to the ratio of GMB diameter to the hole spacing of the CHS and that stability is enhanced the larger this ratio. Six experiments were performed with hexagonal array CHSs of various center-to-center spacings and hole diameters (Figure 22). The maximum height of stable levitation was determined in each case (Table 1). Whenever possible, the experiments included GMBs of significantly different diameters (Experiments D and F).

Maximum levitation heights were plotted versus the ratios of GMB diameter to interstitial distance (Figure 23). The latter distance was taken along the axis between orifice centers ($S-D$ where S is interorifice spacing on centers and D is orifice diameter), since that is the location over which maximum height of levitation is achieved, as noted above. The heights were normalized by this same interstitial distance for the sake of comparison.

It is seen that beyond a certain point, maximum height of levitation rises monotonically with increase in GMB diameter-to-interstice ratio. Presumably, the maximum height of stable



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Scale 12:1

Figure 27. Scale Drawing of CES Array

Table 1. Maximum Levitating Height as Functions of GMB and CHS Dimensions.

Experiment Designation	CHS Orifice		*GMB Diameter d (μm)	**Maximum Levitating Height h (μm)	$\frac{d}{S-D}$	$\frac{h}{S-D}$
	Diameter D (μm)	Spacing (on centers) S (μm)				
A	508	610	472	804	4.62	7.88
B	254	610	500	0	1.40	0
C	254	356	560	1122	5.49	11.0
D	254	356	262	623	2.57	6.11
E	127	356	490	218	2.14	0.95
F	127	356	280	0	1.22	0

* Measurement Uncertainties: Sphere Diameter: $\pm 25 \mu\text{m}$
 Levitation Height: $\pm 50 \mu\text{m}$

** Levitating Height Measured from CHS to Bottom of GMB

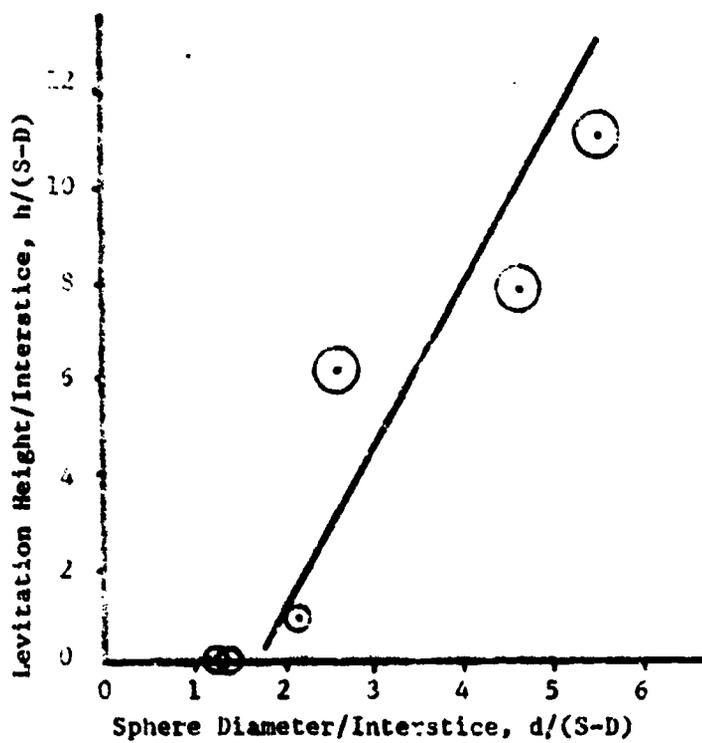


Figure 23. Maximum Levitation Height As A Function of Ratio of Sphere Diameter To Interstitial Spacing Between Orifices.

levitation marks the level at which the GMB is supported primarily by levitating gas whose velocity profile gradient is approaching zero, and whose stream lines are becoming essentially parallel. It is clear from the idealized flow diagram that this region will exist at higher altitudes for those GMBs with diameters which are larger in relation to the interstice (Figure 24).

There are insufficient data to justify any but a linear interpretation in Figure 23. It would seem, however, that the relationship will not extend indefinitely in a linear manner, but will bend over and become essentially horizontal beyond some point. This point should occur when the diameter spans somewhat more than the interorifice spacing.

It should be noted that the smallest of these maximum heights of stable levitation appeared to occur with the GMB located over the interstice among three adjacent orifices. Hence, in determining this minimax, it would appear that the basis to which GMB diameter should be compared is the diameter of the circle inscribed in the interstitial area among three nearest neighbor CHS orifices rather than the interstitial distance between two of them. The preferability of this comparison can be seen in Experiments B and F, where the GMB failed to levitate. In these instances, the sphere diameter was considerably greater than the interstitial distance between near neighbor orifices; in both cases, however, it was very nearly equal to that of the inscribed circle.

2. Glass Microspheres (GMS)

The higher density solid glass microspheres (GMS) exhibit much different levitation behavior than the GMBs. Their point of levitation is directly over the center hole of the dimple. Regardless of the velocity, the occasional horizontal wandering typical of GMBs has not been observed. Solid spheres do, however, display levitation instabilities at both high and low gas velocities. Whereas GMBs could conceivably be levitated smoothly from rest on the CHS surface (presuming that electrostatic interferences are neutralized), each solid sphere tested had to pass through a low velocity instability range before settling into a smooth levitation. Both the high and low instabilities were marked by violent lateral oscillations. The lower range was further characterized by an absence of rotation.

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CHS

Orifices

Figure 24. Idealized Streamline Flow Over Interstice Between Adjacent Orifices.

The rate of rotation was another major difference between the two types of sphere. The denser spheres rotated at frequencies approaching 250 hertz while the GMBs usually spun at around 1-2 hertz.

The ranges of elevations, and correspondingly of gas velocities, to produce stable levitation were found likewise to be markedly different for the two density spheres. Wider ranges of stable elevations were experienced by the lower density GMBs. The ranges of gas flow velocities which produced these GMB elevations, however, were narrower. Typical sets of stable levitation data, elevations versus flow velocity, are shown graphically for a GMB and a GMS under comparable conditions (Figure 25). In terms of levitating gas velocity the upper boundary between stable and unstable levitation is much sharper for the GMSs, being less than plus-minus 5 cm/second. The corresponding borderline region for GMBs was about plus-minus 25 cm/second wide.

While the above studies were conducted using continuous flows, most of the conclusions appear to apply to the sonic pump mode as well. The exceptions will be with those phenomena occurring in the immediate vicinity of the CHS surface. Here the steady axial efflux typical of steady flow is interrupted by the omnidirectional influxes of sonic pumping. For example, a GMB initially at rest will first hop around on the surface of the CHS as sonic power is gradually turned on before jumping into stable levitation. By contrast, using the continuous flow mode, the GMB can be made to rise smoothly from the CHS as already noted.

b. Subdivided CHS Array

Prior to the sonic pump and feedback control, some studies were conducted on CHSs whose arrays were subdivided into quadrants each quadrant being provided with a separately controlled supply of gas. The purpose was to control rotation and lateral positioning of the levitated GMB. Both rotation and positioning could be affected by this arrangement. Complete control was not achieved in either respect, however, before the line of inquiry was broken off in favor of other matters.

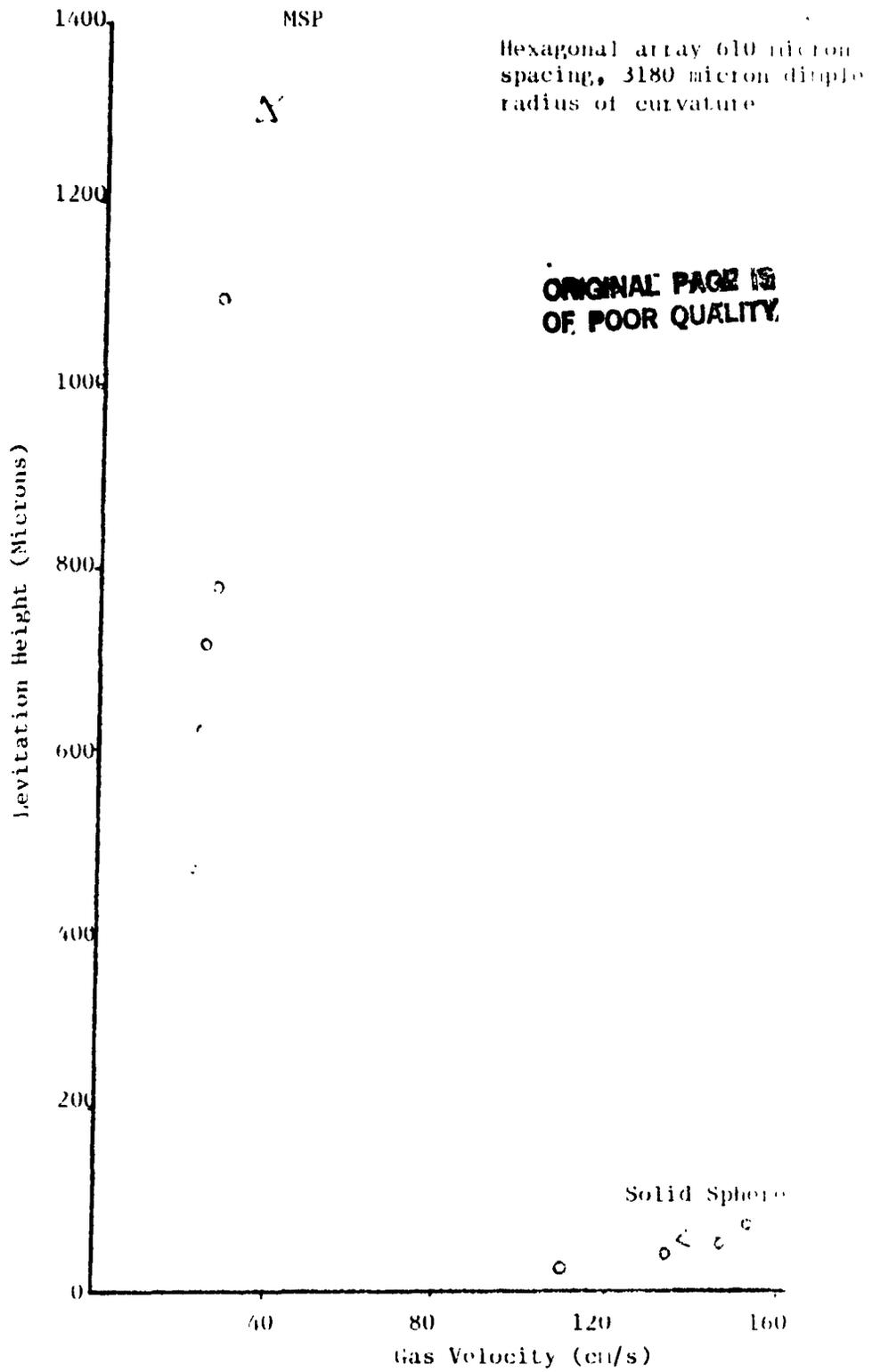


Figure 25. Comparison of the Levitation Range of a 472 Micron MSP ($\rho = 0.18 \text{ g/cm}^3$) with a 490 Micron Solid Sphere ($\rho = 2.58 \text{ g/cm}^3$)

APPENDIX B

FEEDBACK CONTROL BASED ON THE VIDEO CAMERA SENSOR

During this phase of the project the sensing and control equipment consisted of a standard 60 Hz. TV camera connected to a microprocessor with analog control signals to audio amplifiers driving the sonic pumps. The position of the target was placed into the microprocessor memory by a pair of boards connected to the base structure. These boards digitized the signal and placed it in memory using direct memory access cycles. The processor determined the position of the target using a simple edge detection algorithm. The control algorithm was a simple restoring force, with no damping, differentiation or integration of signals. This simple algorithm was made necessary because there was a severe lack of processing time for the microprocessor. This lack of time was caused by the direct memory access action of the position sensor. While each new image was being stored, the processor was in a hold condition. This resulted in the microprocessor having only about 5% of its normal performance. In turn, this meant that the sensor/controller could output a new set of control signals only about 15 times per second, which proved to be too slow.

APPENDIX C

PHYSICAL DESCRIPTIONS OF SONIC PUMP LEVITATORS

1. Video Camera Sensor

The sonic pump levitator which employed the video camera sensor and supporting equipment, as flown on the first KC-135 flight, is pictured (Figure 26). The same black rectangular box was used to house the levitator on all three flights. The video monitor, to the right of center, and the video cassette recorder just visible between, were also used on all flights.

A detail photograph shows the levitation area set up for levitating GMBs, the sonic pumps fitted with CHSs, as it was on the first two flights (Figure 27). Also shown is the GMB launcher used on the second flight. The picture was taken during modifications and does not show the sensing system.

Pumps, mirrors and other functional elements were held in place by standard laboratory bars and clamps mounted in an aluminum plate. The same basic structure was used in the final, successful prototype. It is described in more detail in that connection (see next section).

2. Photo Diode Sensors

An overview of the final and successful prototype sonic pump levitator, employing the more rapid photo diode sensing system, shows the levitator box opened for access to the levitator (Figure 28). A three-quarter view of the levitator outside of the protective box is followed by three orthogonal views of the exposed apparatus (Figures 29 through 32). Three orthogonal views of the protective box follow (Figures 33 through 35). Three similar elevations of the accessory rack are shown in the next three views (Figures 36 through 38). The computer, center shelf, and the auxiliary electronics, top shelf, are described in Appendix E.

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Figure 26. Overview of Sonic Pump Levitator Equipment As Flown
On First KC-135 Flight.

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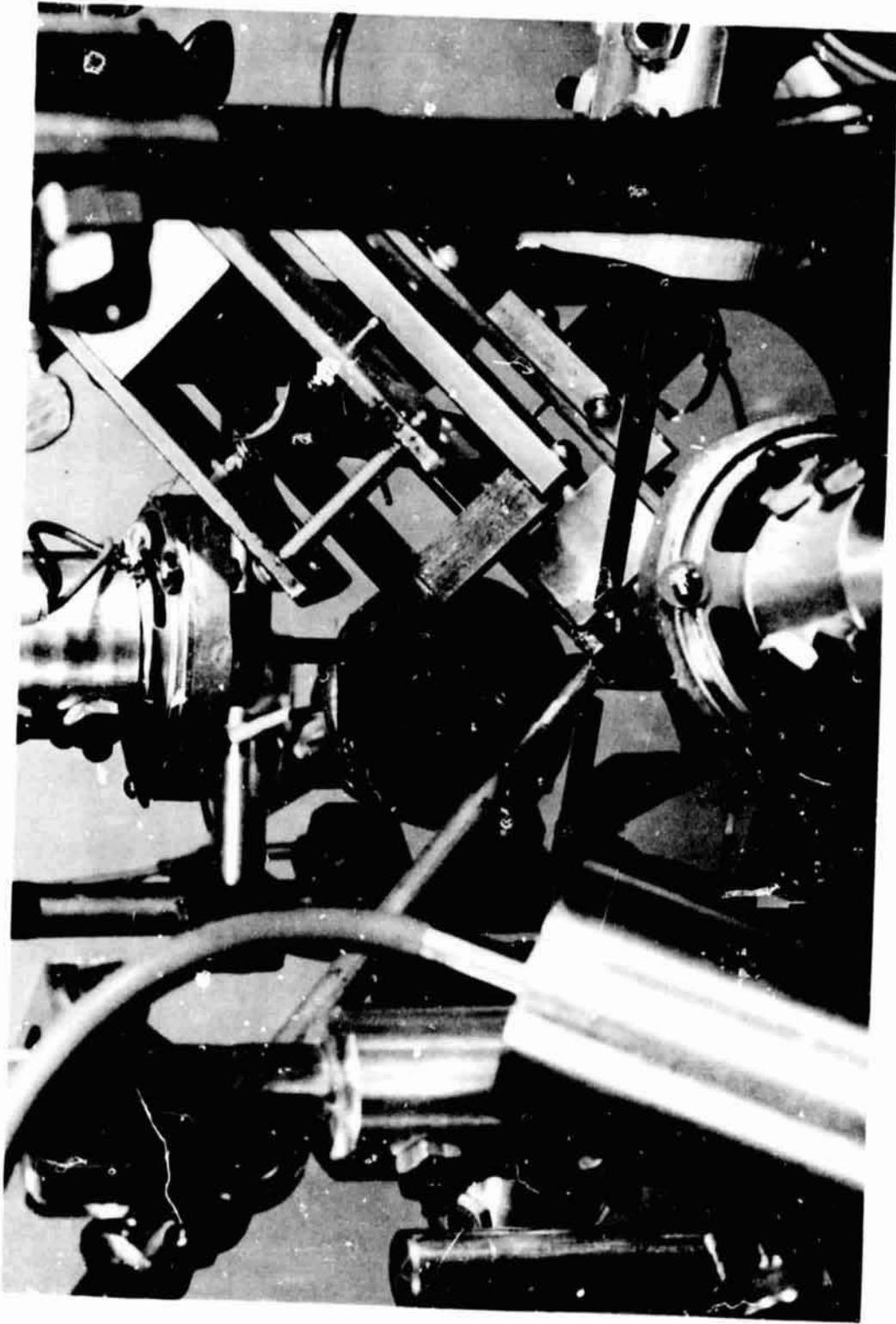


Figure 27. Detail of CHS Modified Sonic Pumps and Levitator.

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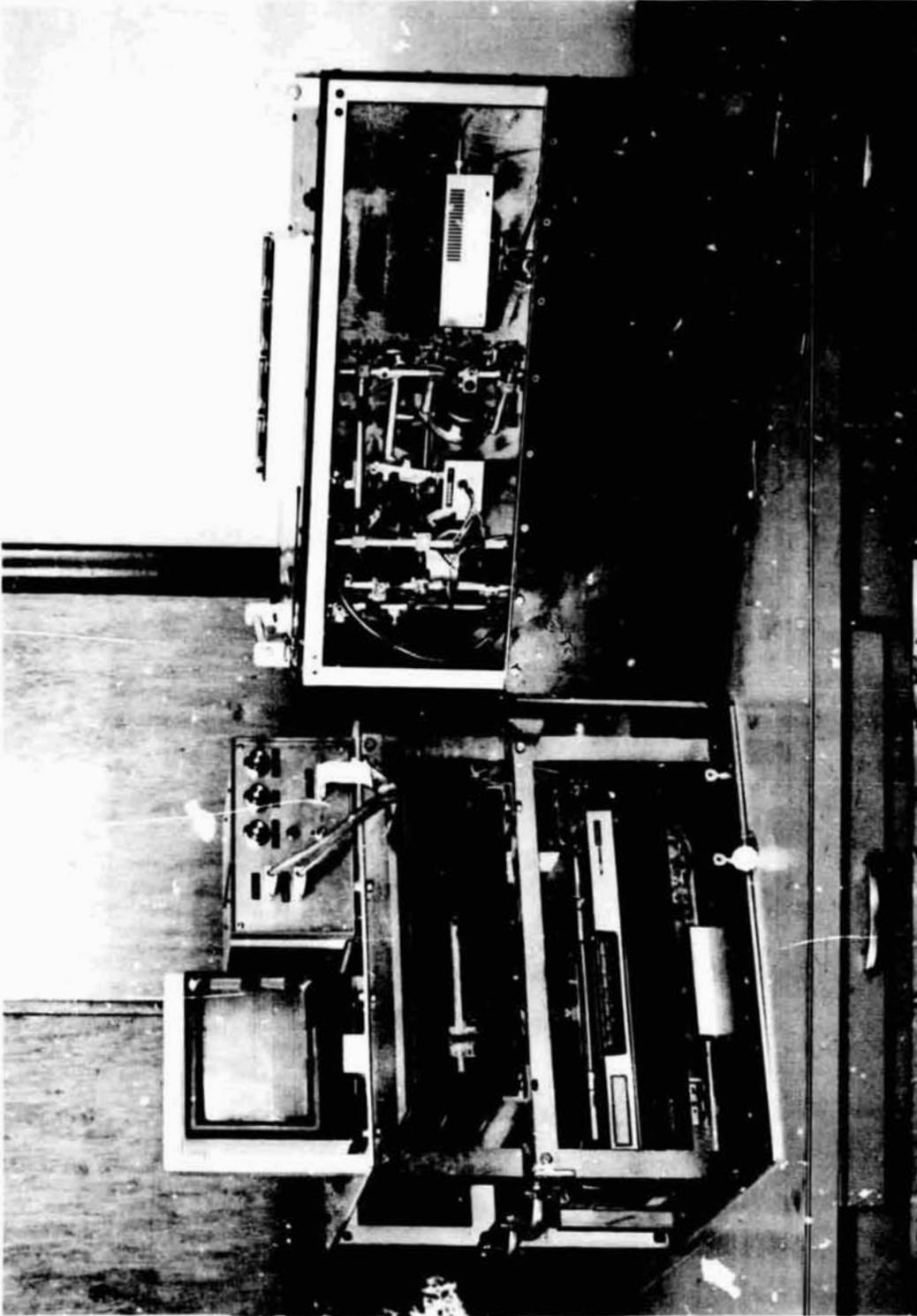


Figure 28. Final, and Successful, Prototype Sonic Pump Levitator,
Utilizing the Rapid Photo Diode Sensing System.

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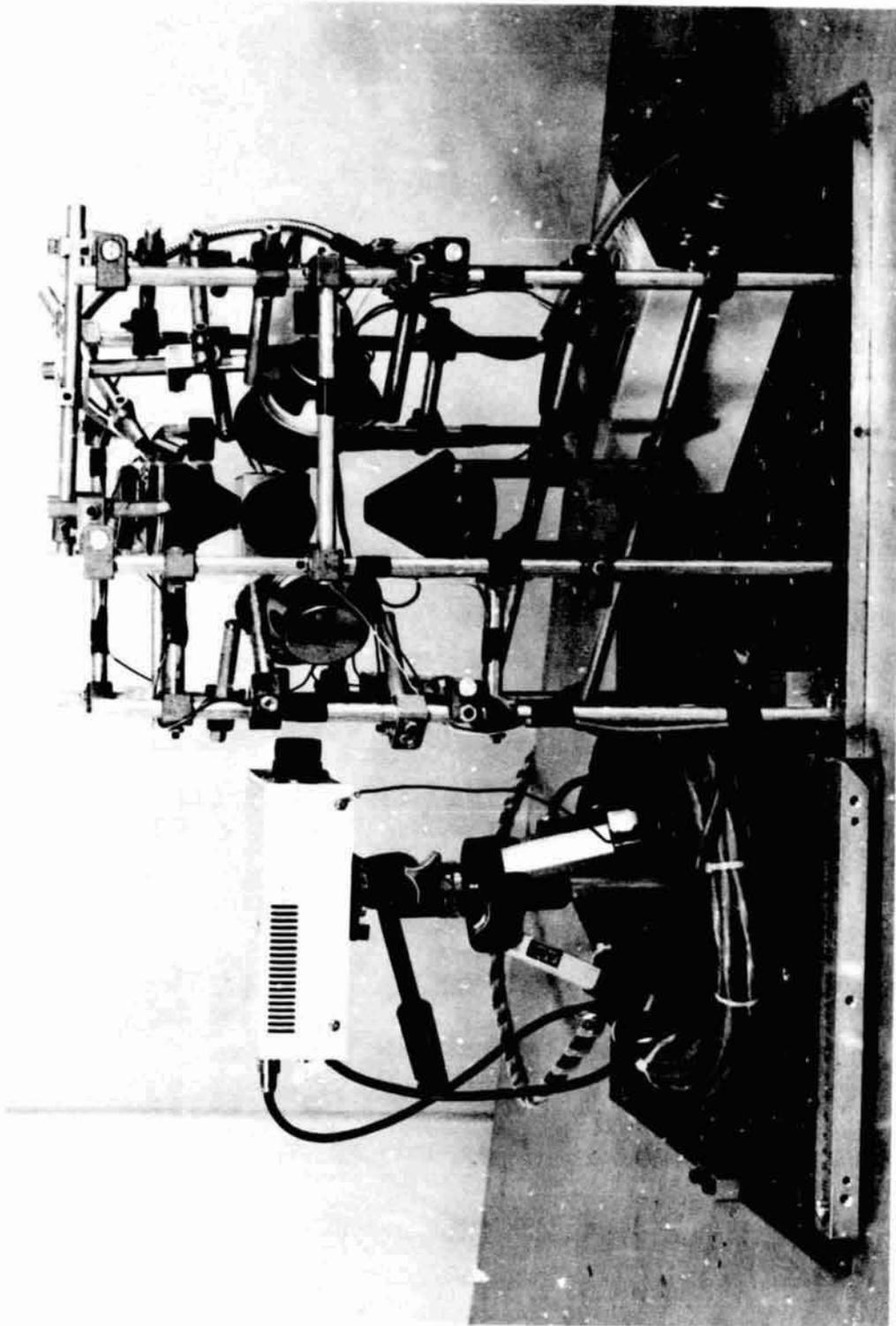


Figure 29. Three-Quarter View of Prototype Levitator. Video Camera is Left, Aircooled Light Source at Lower Right with Shielded Light Pipe Leading Up To Levitation Area.

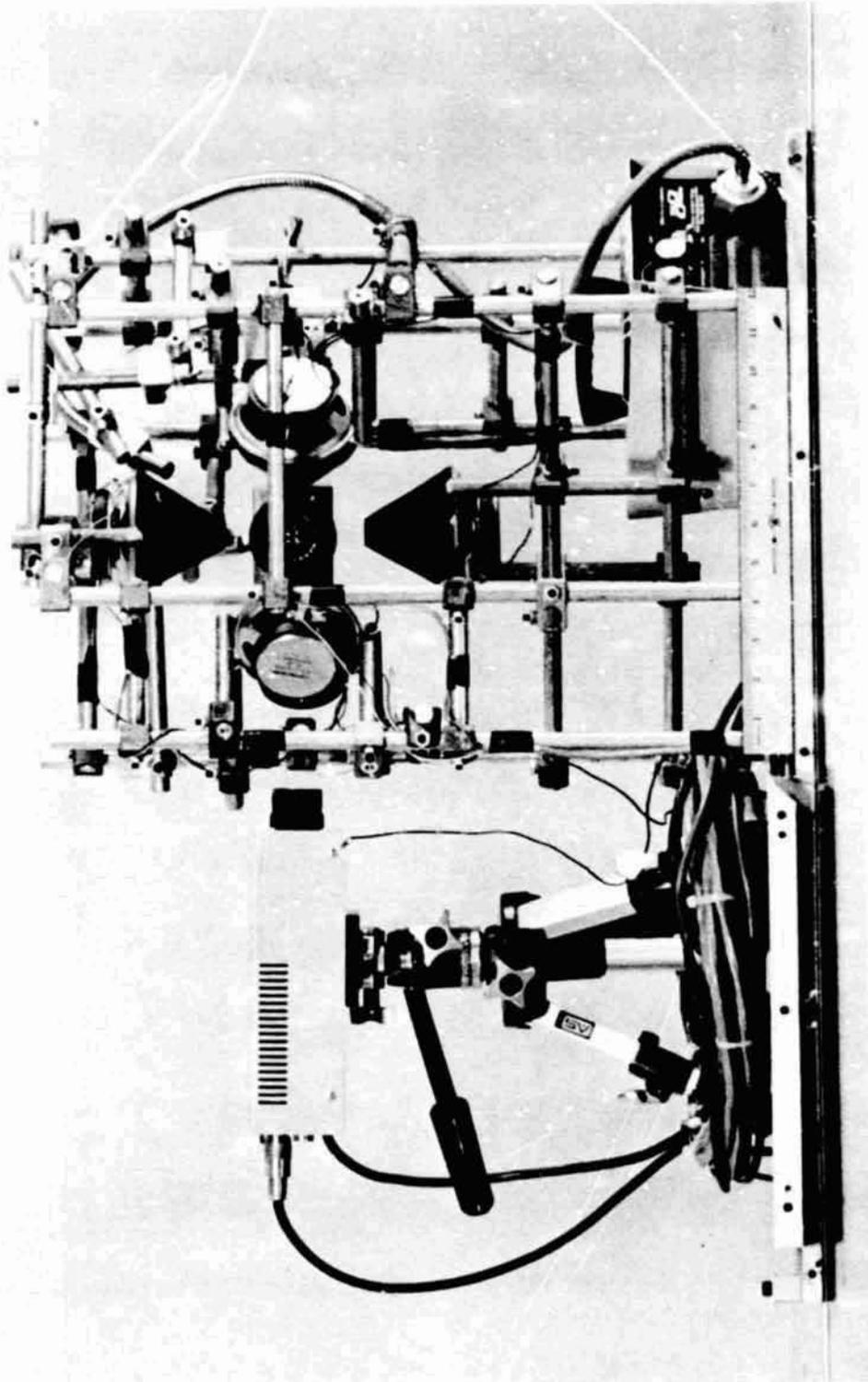


Figure 30. Side Elevation of Prototype Sonic Pump Levitator. At Upper Center the Upper and Lower Sonic Pumps Are Seen in Profile; The Two Nearest Horizontal Pumps Are seen $3/4$ From The Rear. One of the Photo Diode Sensors is Looking at the Viewer.

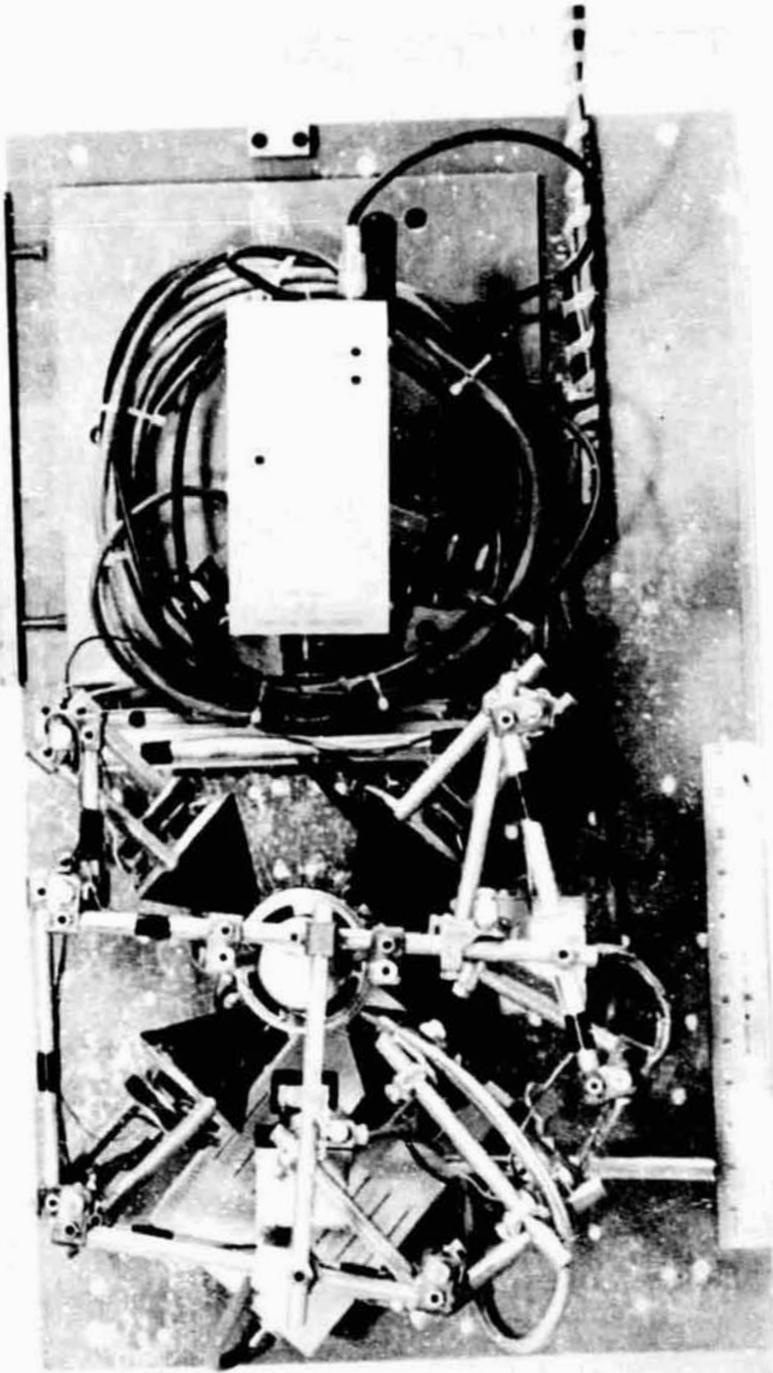


Figure 31. Top Elevation of Prototype Sonic Pump Levitator. The Four Horizontal Sonic Pumps May Be Seen in Profile With the Two Photo Diode Sensors Interleaved Between Three of Them.

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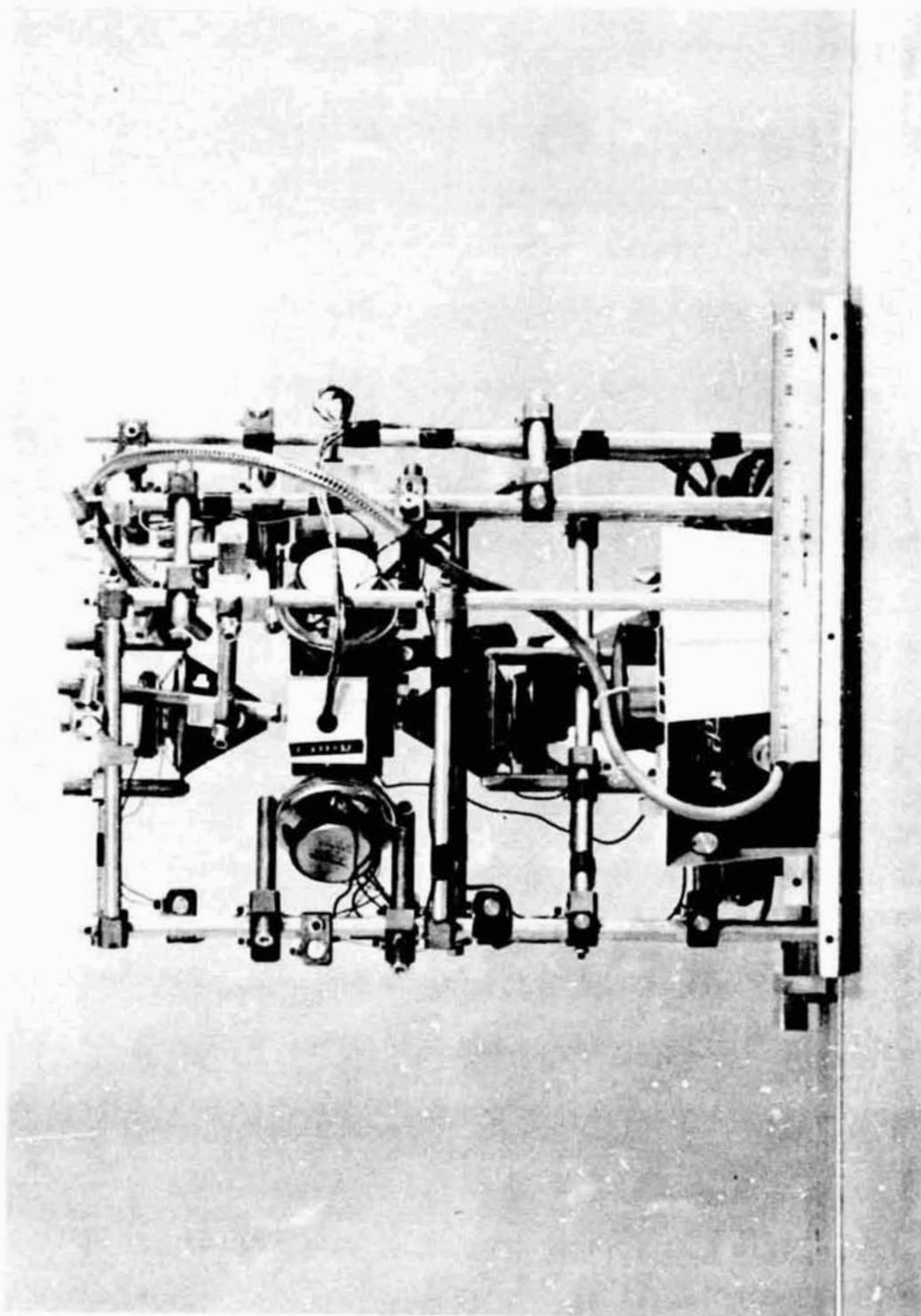


Figure 32. End Elevation of Prototype Sonic Pump Levitator. A Rear View of One of the Photo Sensors is Seen Upper Center.

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Figure 33. Front Elevation of Levitator Box.

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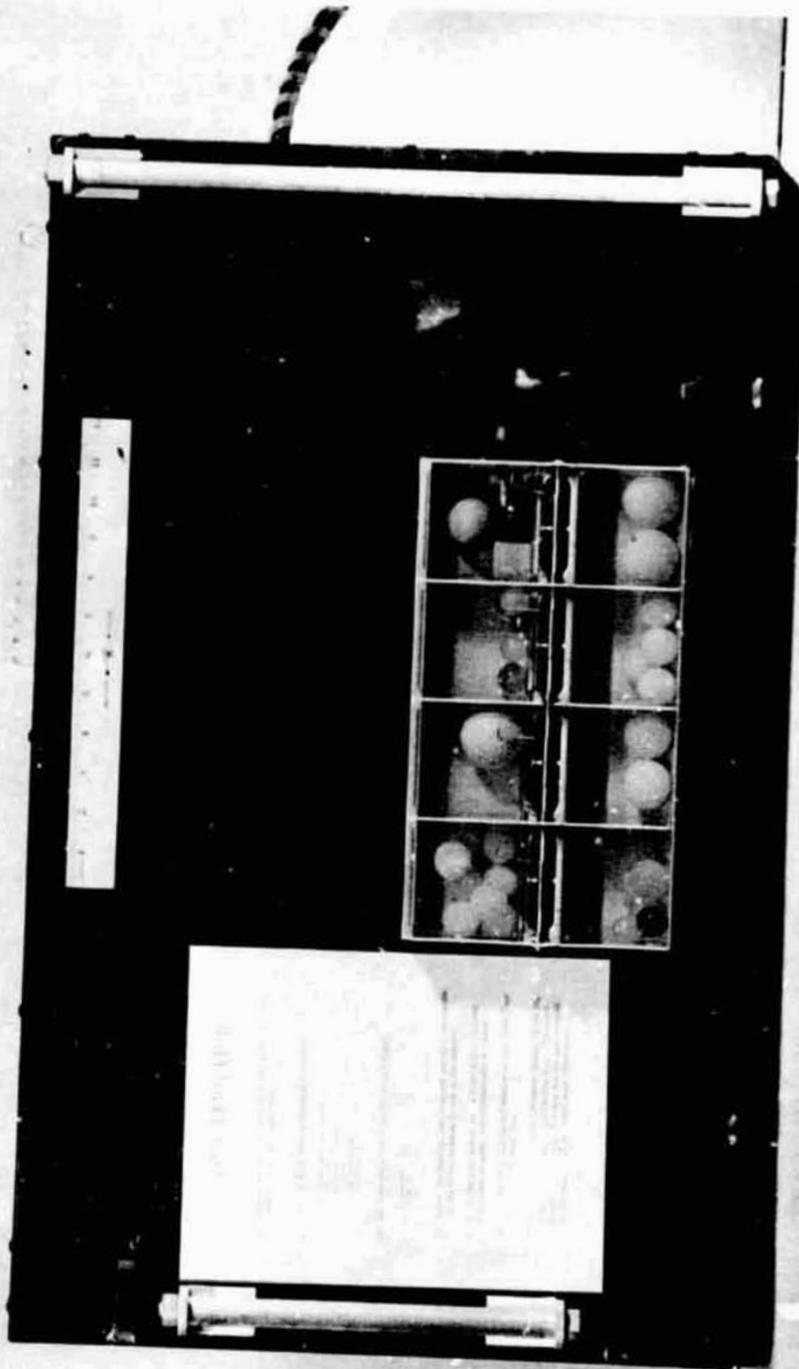


Figure 34. Top Elevation of Levitator Box. Handles at Either End Were Used For Free Float During Second Flight Only. Box With Separate Spring Loaded Lids Contains Various Targets On Which To Attempt Levitation.

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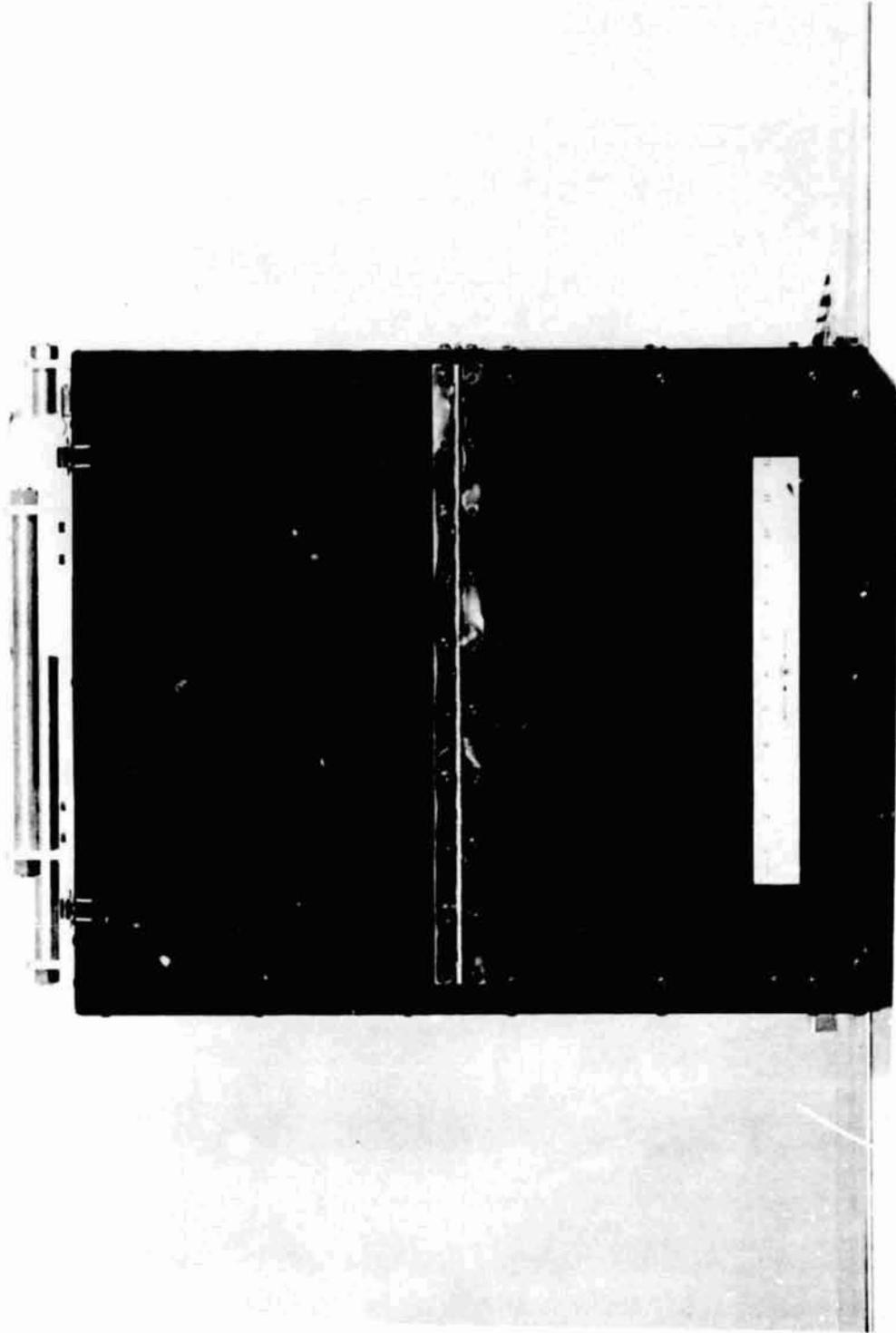


Figure 35. End Elevation of Levitator Box.

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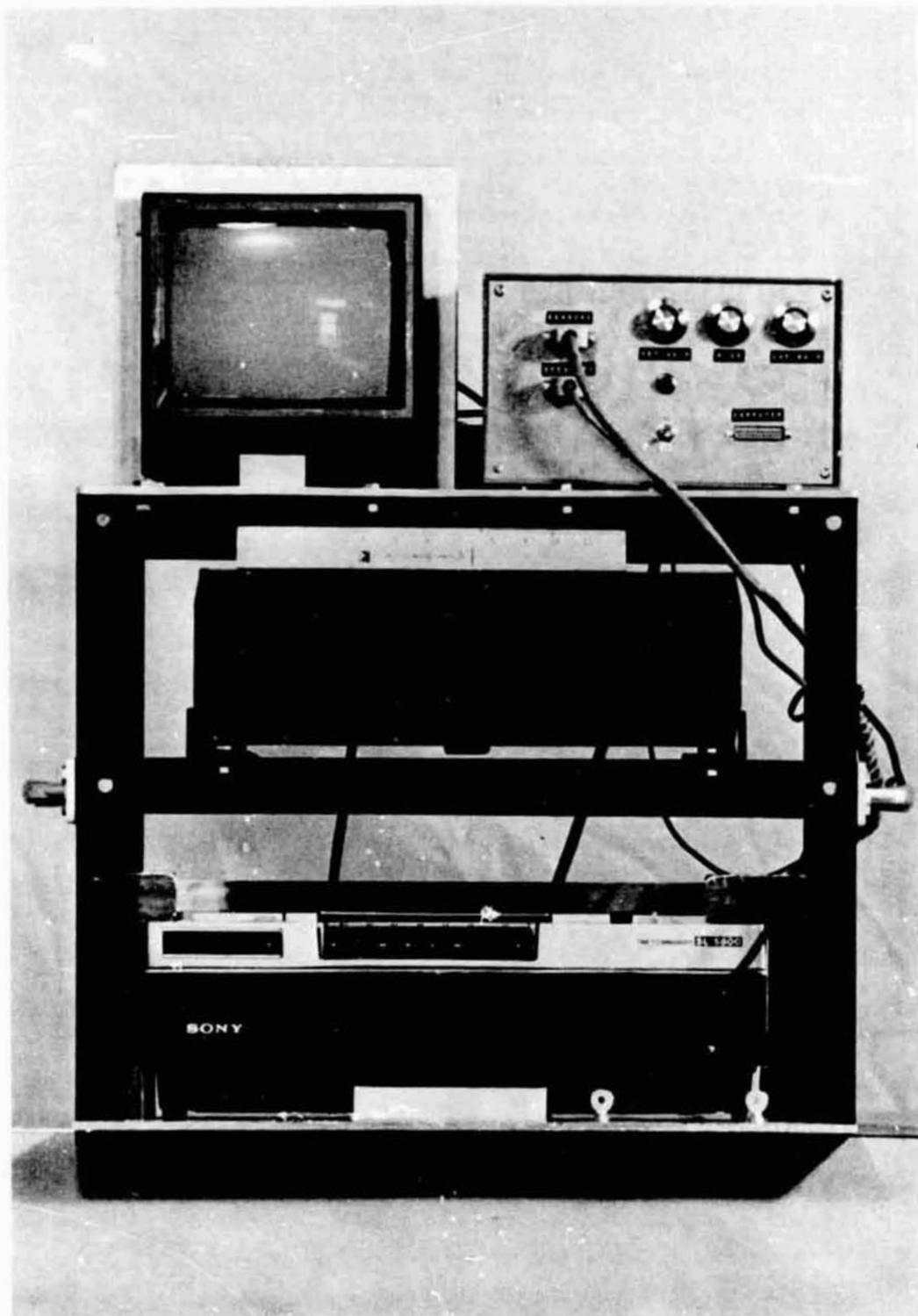


Figure 36. Front Elevation Auxillary Equipment Rack For Proto-
type Sonic Pump Levitator. Manual Controls on Unit
Upper Right.

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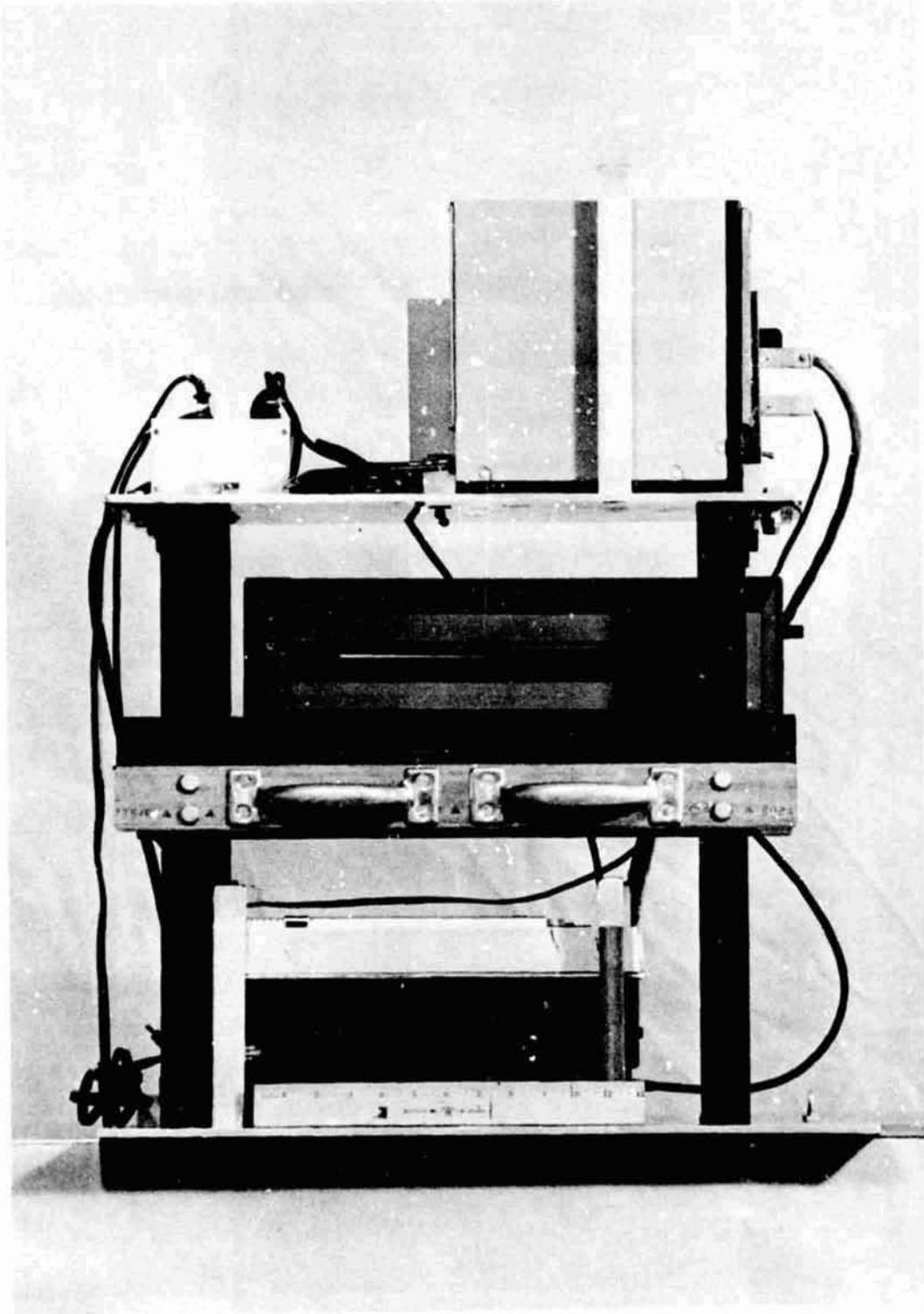


Figure 37. Side Elevation Auxillary Equipment Rack for Prototype
Sonic Pump Levitator. 70

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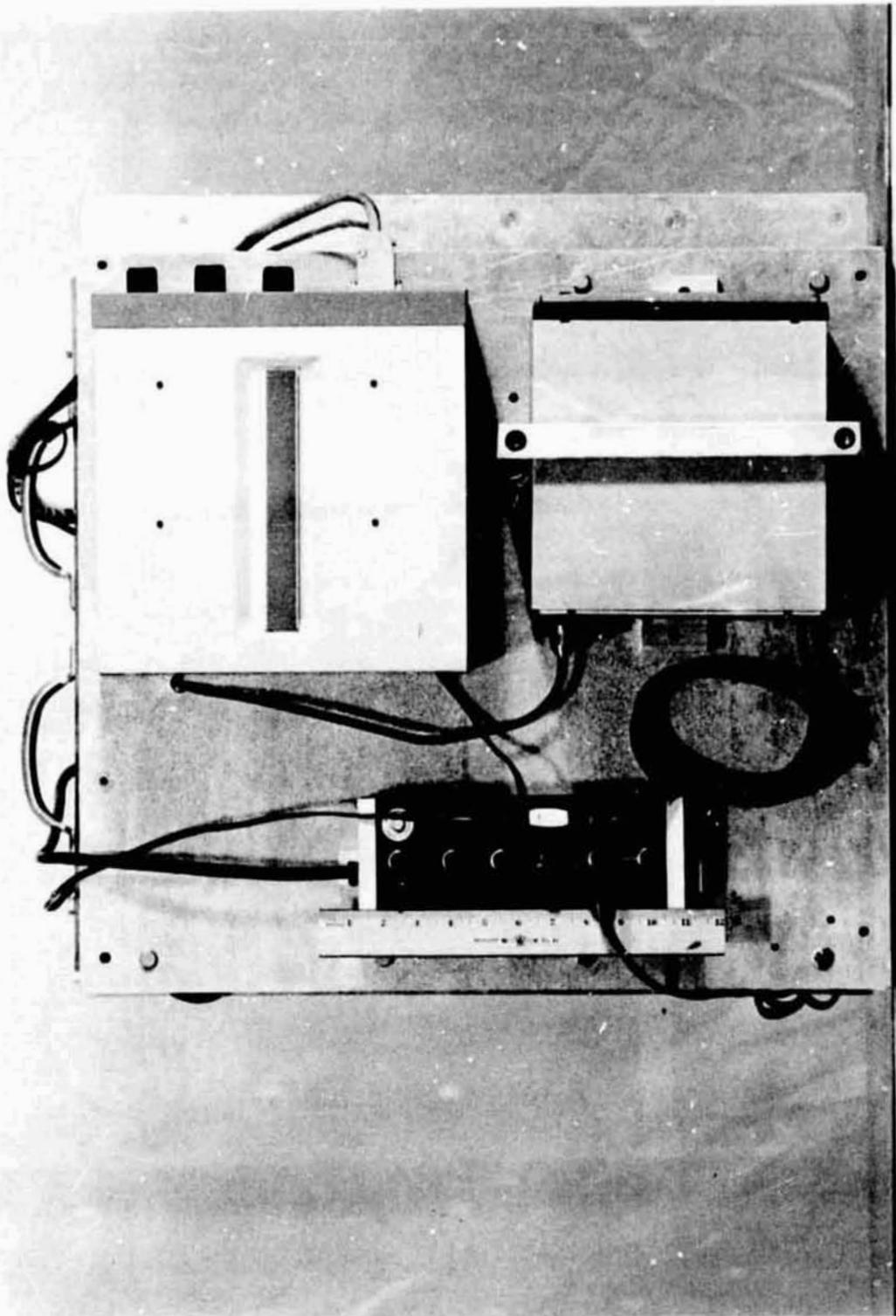


Figure 38. Top Elevation Auxillary Equipment Rack For Prototype Sonic Pump Levitator.

(4.)

APPENDIX D

SPURIOUS ELECTROSTATIC ATTRACTIONS

The problem of unwanted electrostatic attraction of GMBs was reviewed in conjunction with testing of the commercial antistatic device (the Simco Static Bar). The device conveniently provides positive or negative D.C. potentials up to 6500 volts. Unfortunately, it was found to be without effect in GMB levitation in a variety of application configurations.

As had been found in past work, some GMBs are afflicted with electrostatic sticking, while others are not. The effect usually appears to be associated with one particular spot on the GMB and/or on the surface upon which it rests. High humidity sometimes helps. Gold coating is more effective; but even it does not work 100% of the time.

The effect would seem to be due to electrets frozen into the glass surface of the GMB and/or present in oxide coatings on the metal operating surface. In the ultimate levitating furnace when GMBs are melted and reprocessed these electrets will become unfrozen. They may then disappear, shift or new ones may form. At that time, it may be more appropriate to explore the possibilities of removing them and preventing their reappearance. For the present, in order to get on with the more pressing objectives of the project, the policy was adopted of selecting those GMBs with minimum electrostatic proclivities and of gold plating them for use in levitation studies.

APPENDIX E

DIGITAL CONTROL SYSTEM BASED ON THE PHOTO DIODE SENSORS

This Appendix is taken from the University of Wisconsin, Master of Science, thesis of Brian Vanderwarn, dated December 12, 1983, with minor editing by the Principal Investigator.

1. Introduction

The control loop, which is used to hold the position of the object, includes several major elements (See Figure 39). Two optical sensors are used to determine the position of the target in three dimensional space. The sensors are positioned so that their fields of view are at right angles to one another. Thus, each sensor has the capability to determine a lateral and vertical position for the object. With this information, the computer is able to determine the position of the target in three dimensions.

The next element in the loop is the computer system. It is composed of a single board, micro-processor based, computer. The micro-processor used on the board is a Z-80 running on a five megahertz clock. The board contains the support hardware for the micro-processor. This includes a half megabyte of memory and all necessary input/output hardware for use with a video terminal and floppy disk drive. The computer board also carries part of the hardware necessary to interface it with the optical sensors and sonic pump system. In addition to executing the actual control algorithm in the system, the computer was also used to do the software development required by the project.

The sonic pumps are the next major element in the control loop. They represent the block in the loop which does the actual positioning of the target in the control field. The pumps act as the interface between the electrical domain of the control system and the mechanical domain.

The last element of the control loop is the target itself. It closes the loop through the optical sensors which detect the target's position in the control field. The dynamics of the target, or how it reacts to air flows from the sonic pumps, become an integral part of the entire control system and must be accommodated in the control algorithm executed by the computer.

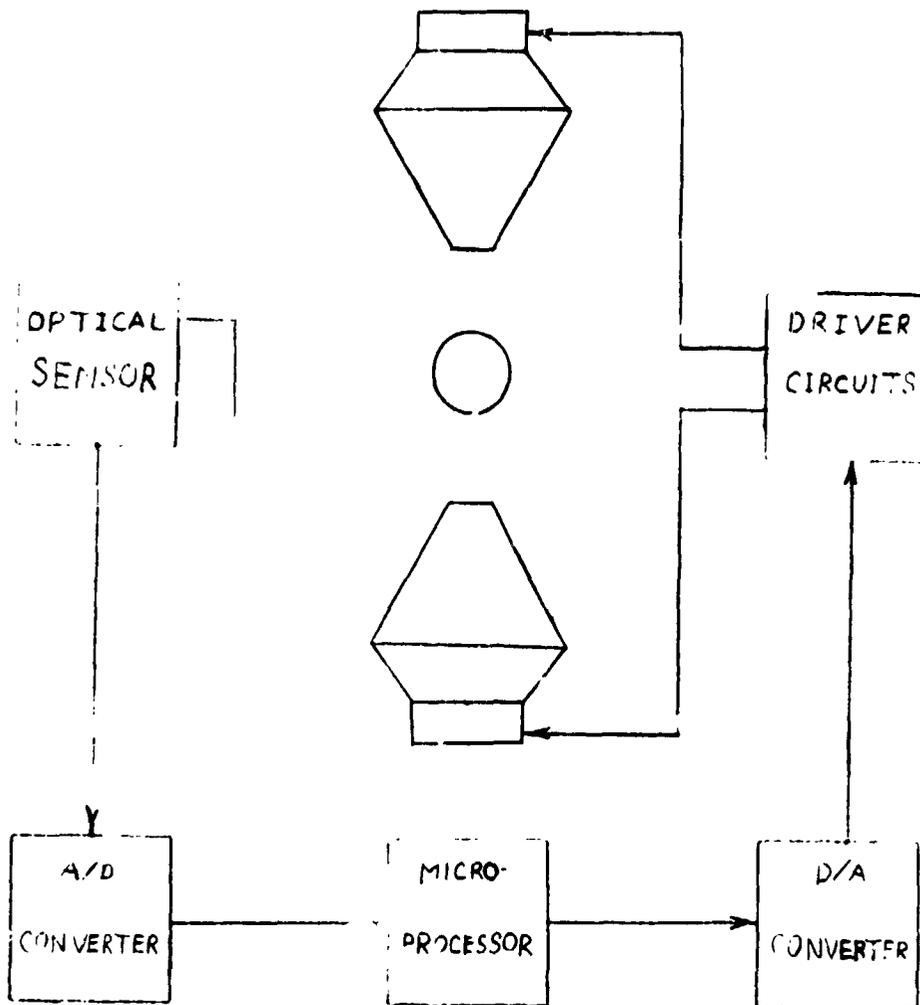


Figure 39. Control Loop.

2. Detailed Hardware Description

a. The Computer System

The computer system which is used as the main control element in the control loop is a single board Z-80 micro-processor based system. The board operates at a five megahertz clock rate. The board also contains a half megabyte of dynamic RAM memory and the input/output interface circuitry (See Figure 40). The I/O facilities included ports for a terminal and floppy disk drive as well as a port for communication with special purpose interface hardware. The large memory and the added I/O capabilities are included on the board because the computer was used for software development as well as a control element in the over all system.

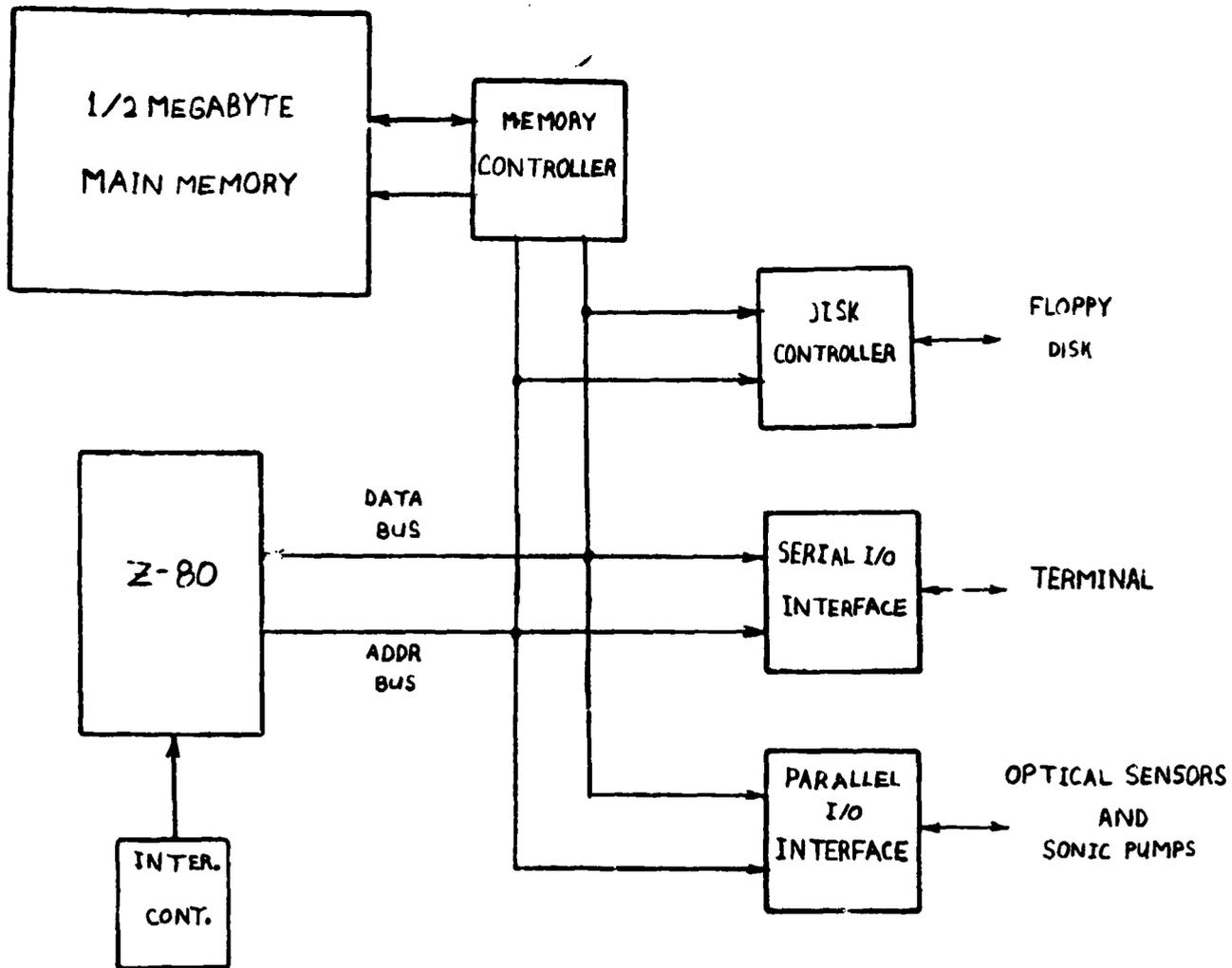


Figure 40. Computer System.

b. The Interface Hardware

A special purpose interface box is used in the project to aid in the transfer of information into and out of the computer from the rest of the system. The interface box contains three major elements: a digital-to-analog converter, an analog-to-digital converter, and driver circuitry for the sonic pumps (See Figure 41).

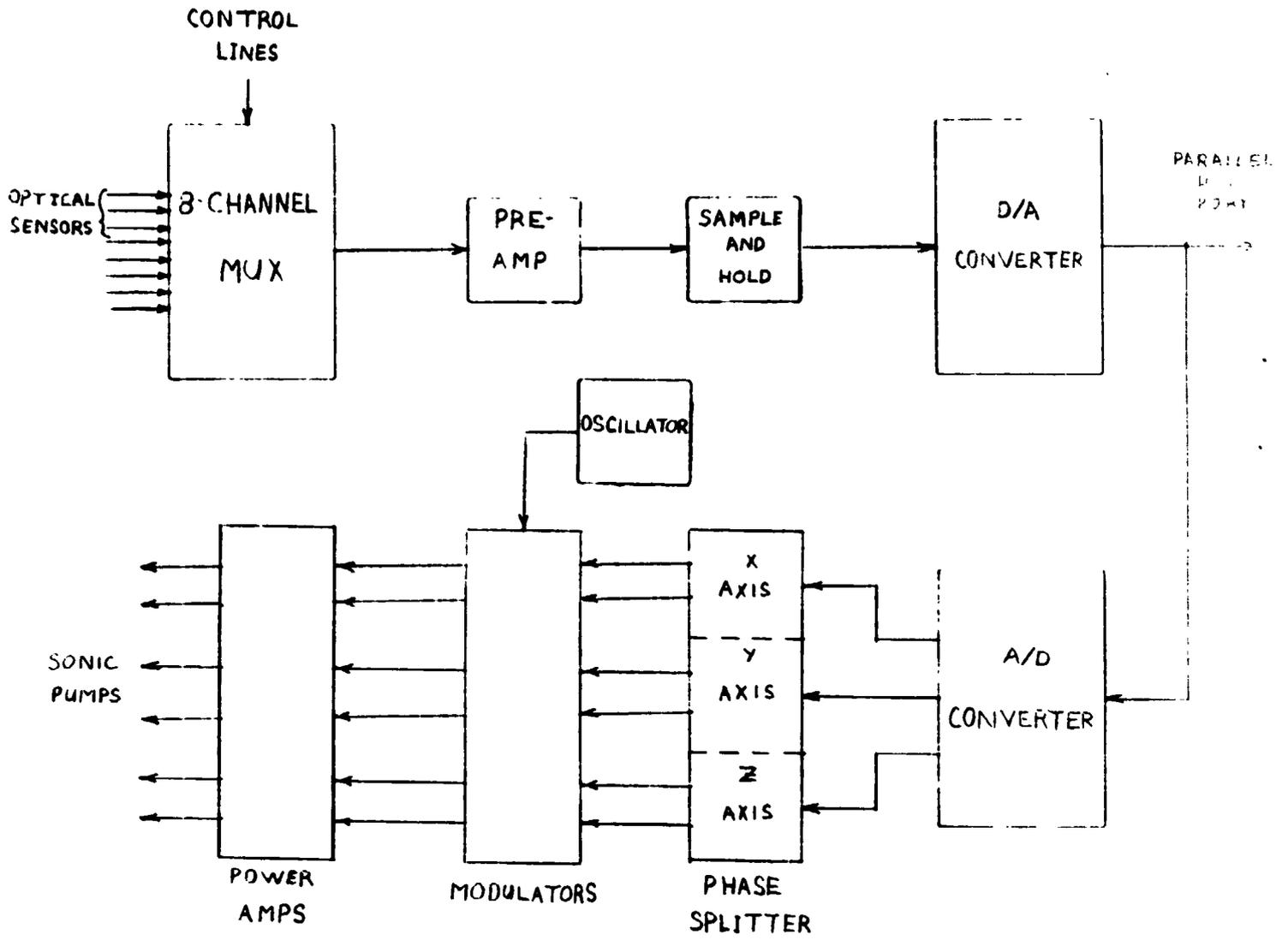


Figure 41. Interface Hardware.

The analog-to-digital converter is used in the detection of the targets position. Three analog signals are received from the optical sensors. Each signal is in the range of -10 volts to +10 volts corresponding to the target at the edges of the optical sensors' field of view. Zero volts represents the desired position of the target along one axis. An EI508 eight channel analog multiplexer is used to bring the three signals into a buffer amplifier and sample and hold circuit (See Figure 42). The multiplexer is controlled directly by the computer so that the programmer can decide which of the three signals is to be sampled and converted.

The three signals are multiplexed into an HS574 analog to digital converter chip. This chip was chosen for the project because of its very fast conversion time. Each eight bit conversion can be performed in 35 microseconds. The HS574 also has the capability to perform twelve bit conversions. However, only eight bit conversions were required for the purposes of this project. Each conversion was initiated by the computer under software control. The resulting binary number could then be transferred into the computer's memory for storage and used at a later time. The binary numbers generated by the HS574 as a result of a conversion were coded in an excess 128 format. These numbers were converted to standard two's complement format before storage.

The second element in the interface box performs the digital to analog operation necessary to convert digital control signals from the computer into analog signals for the sonic pumps (See Figure 43). This section consists of two AD7528 eight bit digital-to-analog converters chips. Each converter contains two separate D/A sections. Once the computer has calculated an error correction signal for an axis, the resulting number is first converted into an excess 128 format. This conversion is necessary to be compatible with the format required by the AD7528. The number is then loaded into the appropriate D/A converter for that axis. This initiates a conversion and a subsequent change in an analog output. The analog signals which are generated by this process are in the range of +10 volts to -10 volts.

The third element in the interface box is responsible for generating the amplitude modulated sine wave signals which actually drive the sonic pumps (See Figure 44). Each of the analog output signals from the D/A converters controls a pair of opposing sonic pumps oriented along one of the three axes. Each output signal is first processed by a signal splitter which rectifies it into two signals. When the control signal swings positive, it causes one of the rectified signals to change

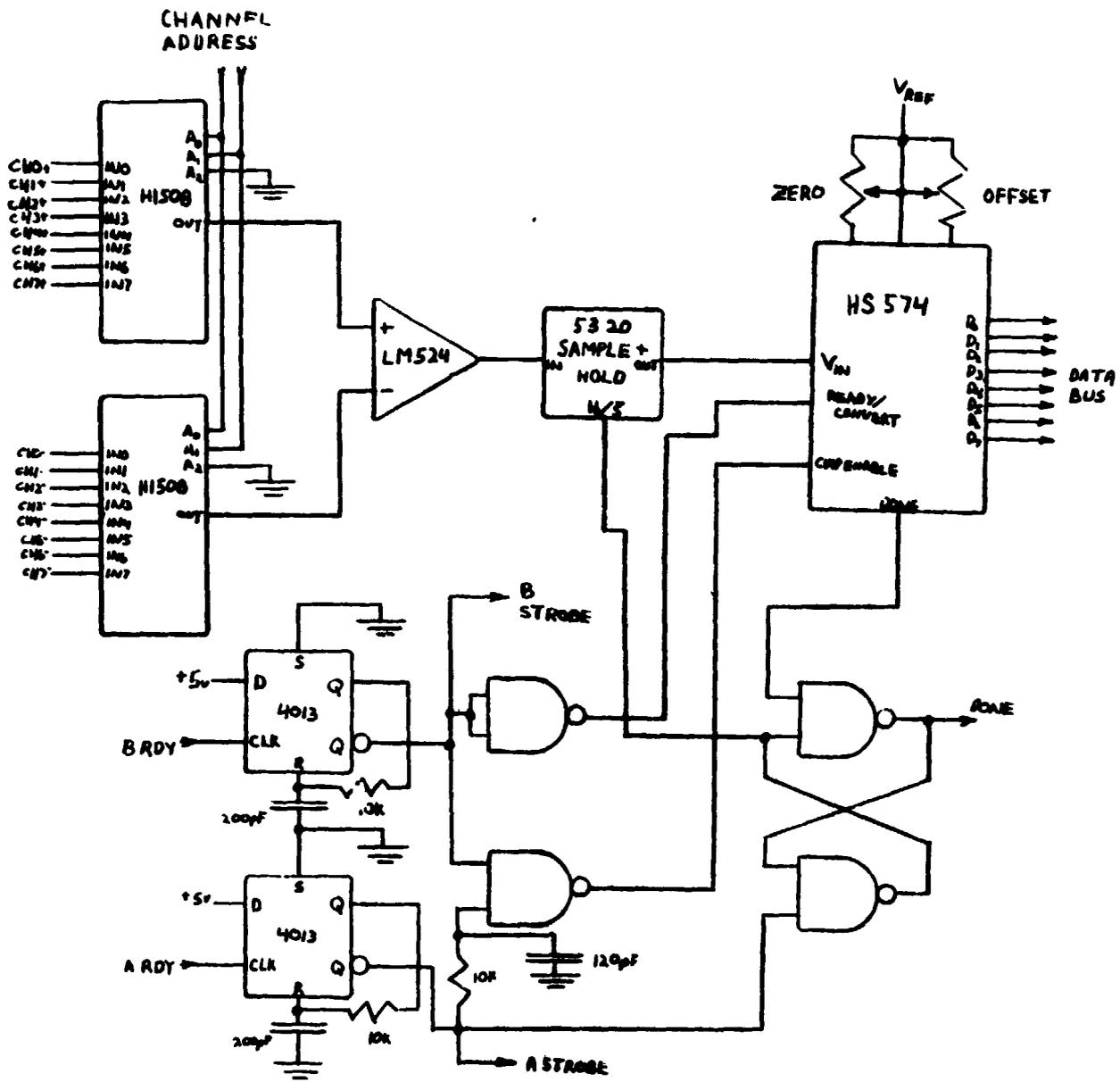


Figure 42. Multiplexer, Buffer Amplifier, Sample and Hold Circuit.

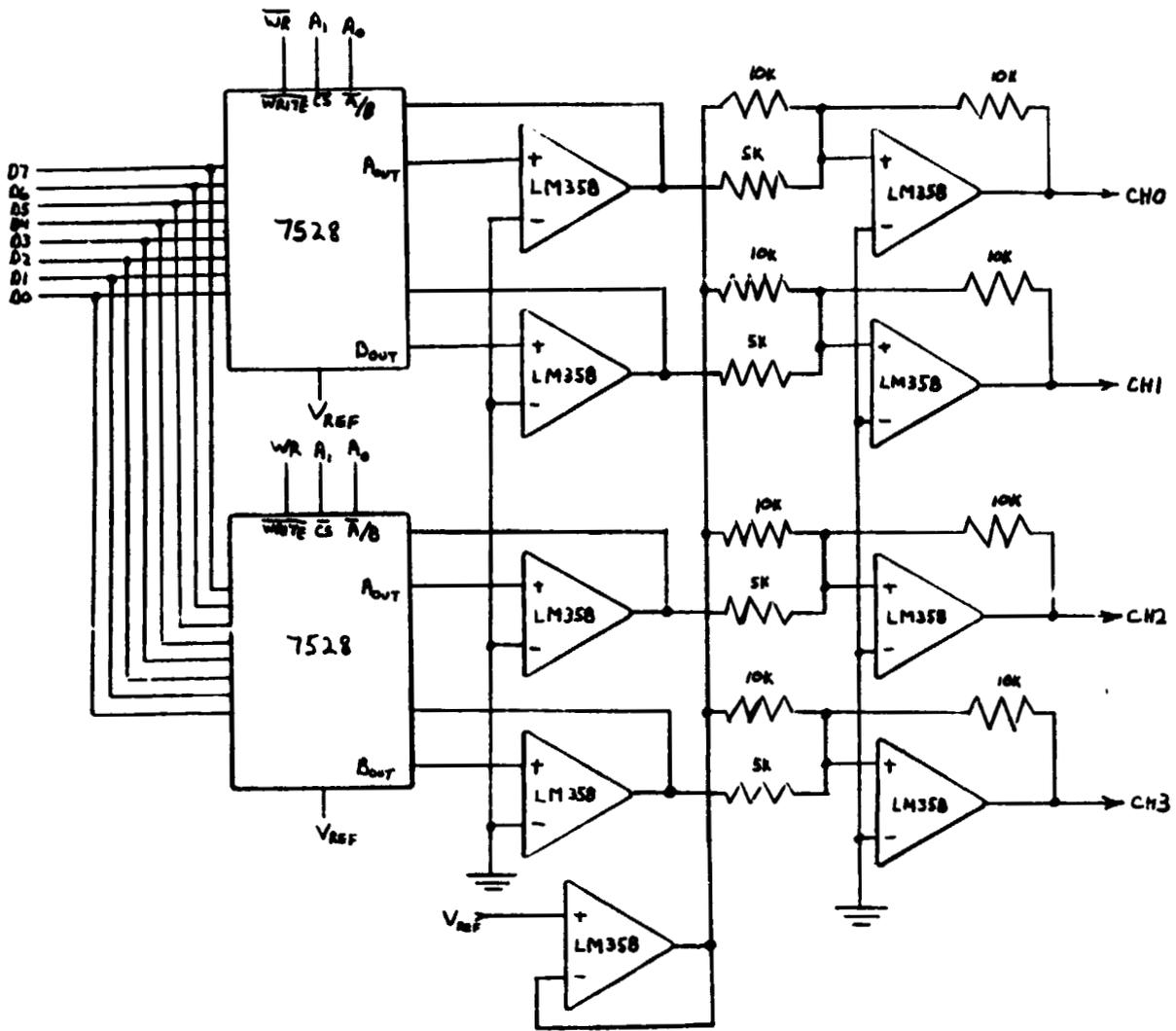


Figure 43. Digital-to-Analogue Converter.

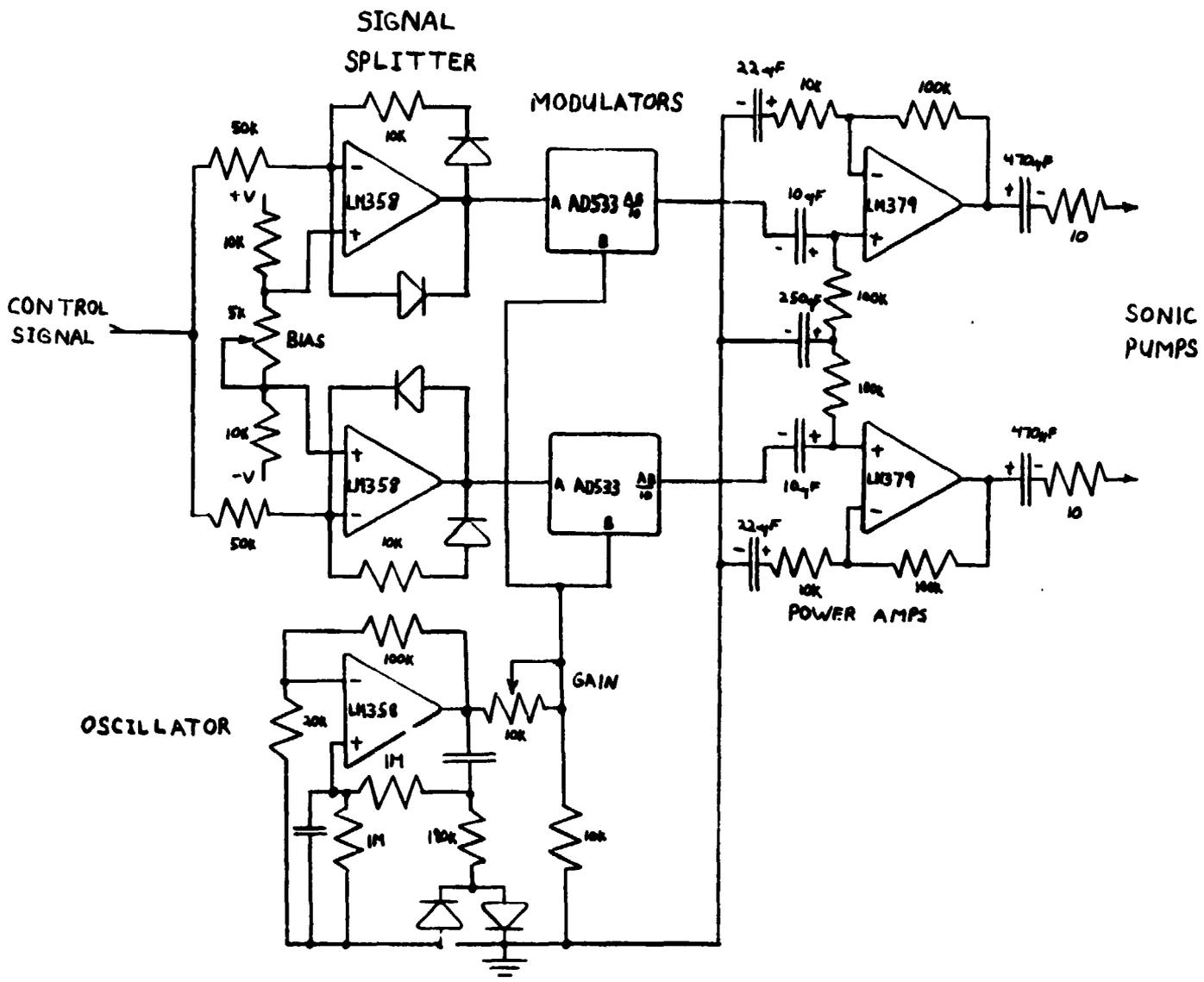


Figure 44. Oscillator, Signal Splitter.

proportionately while the other remains at zero. If the control signal swings negatively, then the rectified signals change roles. The signal that was zero on the positive swing begins to change proportionately with the control signal (See Figure 45). The signal splitting operation makes it easier to control both sonic pumps on one axis with a single D/A output. This is feasible because the opposing sonic pumps on one axis will never be operating simultaneously. The two signals which are generated through this operation are used to modulate the amplitude of a sine wave output which drive the sonic pumps.

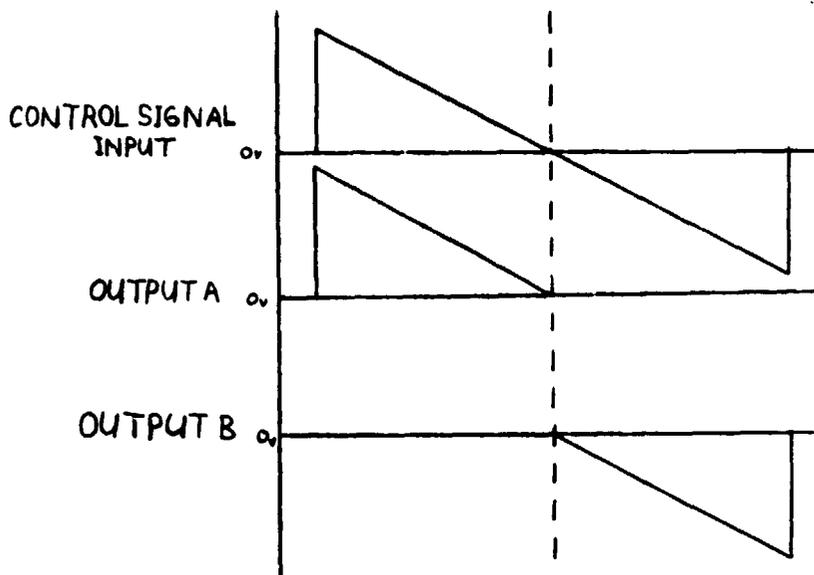


Figure 45. Signal Splitting

A set of six AD533 analog multiplier chips are used to modulate the signals driving the sonic pumps. These multipliers are wired as voltage controlled amplifiers with the split analog output signals from the computer as the controlling voltage. A 200 Hz sine wave is the controlled input to the amplifier. The six resulting signals are amplified with fixed gain power amplifiers and then fed into the sonic pumps (See Figure 44).

Three manual adjustments were added to the front panel of the interface box. Two of these controls allowed manual adjustment of the final loop gain. This is accomplished by regulating the amplitude of the sine wave being fed into the modulators. These gain adjustments were used to fine tune the loop gains in the axes while course gains were set in the software. Initially only one control was used. However, it was later found to be useful to be able to control the gain of the vertical axis separately from the two lateral axes. This feature was used only in one gravity testing. Under actual low gravity conditions, these gain settings were the same.

A third adjustment was added to the front panel of the interface box to add a bias to all six of the sonic pumps. It was discovered in testing that at low amplitude signals, the sonic pumps did not perform in a linear fashion. Therefore, a slight bias was added which turns on all six sonic pumps at once and thus causes a more linear performance. The bias is introduced into the system by adding a bias circuit to the signal splitter. This caused the modulators to give some amplitude to the driving signals even though the output from the computer may be zero for that axis.

c. Optical Sensors

Determining position of the target was an important aspect of the project. Initially, a standard video camera was used to give information about the position and motion of the target. However, the slow frame rate of the camera was unacceptable for sampling position. The camera was replaced by two PIN-SC/10D photo-diode devices. These diodes were capable of generating a voltage differential between two output leads which depends on the centroid of a spot of light falling on the active surface of the diode. Each device has a ground lead and two pairs of output leads. The two sets of output leads make it possible to determine the position of the light spot in two dimensions on the surface of the active area of the diode.

The signal levels generated directly from the diode were on the order of +100 mv to -100 mv for a target moving across the sensors field of view. These low signal levels, along with the need to transmit the signals over 30 feet of cable to the computer interface, made it necessary to add pre-amplifiers at the sensors. The pre-amplifiers also made it possible to align the physical center of the system with the optical center of the system. This was accomplished with offset adjustments in the pre-amplifiers circuitry. The pre-amplifiers consisted of a LM363 instrumentation amplifier with a fixed gain of 100 (See Figure 46) This brought the signal level at the input of the A/D up to approximately the +10v to -10v range.

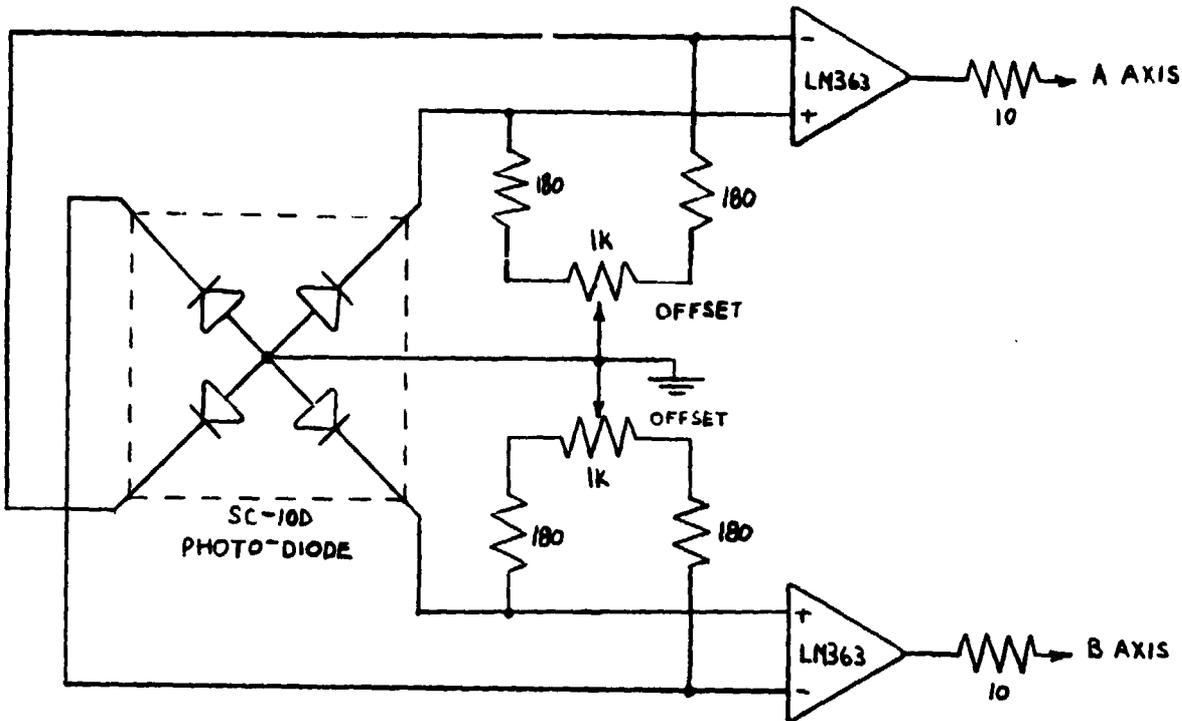


Figure 46. Diode Sensor and Preamplifier.

Each diode was mounted behind a wide angle camera lens. The lens focused reflected light from the target onto the active area of the diodes while giving the widest field of view possible (See Figure 47). Due to the relatively low voltage levels generated by the diodes, a high wattage incandescent light source was necessary to achieve good signal levels from the diodes initially. Due to space limitations, the light source was mounted away from the target area. The light was directed onto the target with a light pipe.

Some care had to be taken in the actual construction of the sensors and their cabling. It was discovered that noise, in the form of radio interference, could be introduced into the system. Because the project was to operate in an environment where there would be a great deal of RF equipment, this was an important concern. Each of the sensors was built into a closed metal box and all cabling to the sensors was done with grounded shielded cable. These precautions were successful in eliminating any radio frequency interference to the point where it did not adversely affect the performance of the system.

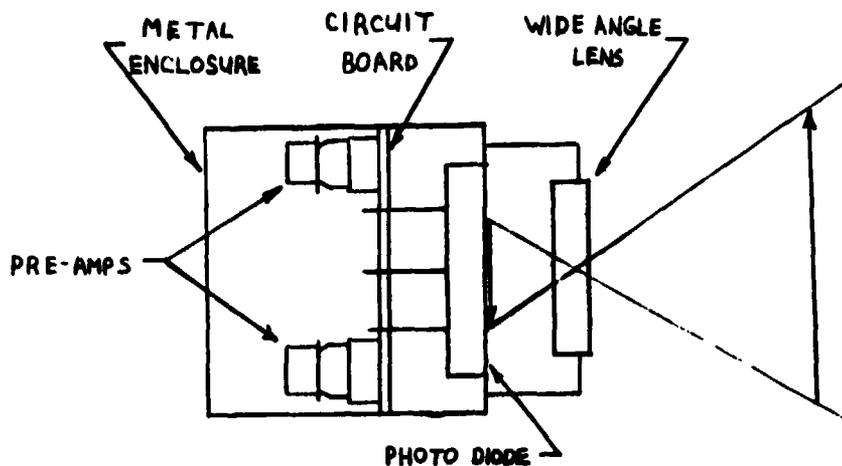


Figure 47. Arrangement of Optical Sensor Components.

d. Sonic Pumps

Each of the six sonic pumps used as positioners in this system was comprised of a five watt, 8 ohm audio speaker with a perforated, conical closure, as described elsewhere. The perforation or orifice located at the apex of the cone is 12 millimeters in diameter. When the speaker is driven with a sine wave, a flow of air is driven out of the orifice at the apex of the cone. A variation in the amplitude of the signal driving the speaker caused a change in the force of the flow of air leaving the orifice of the pump.

This design for an actuator was found to be significantly better than schemes using valves to control the flow of compressed gases. Valves are too slow. The advantage of the sonic pump is realized in the ease and speed with which electrical commands from the computer can be converted into physical reactions in the system. Through experimentation, a 200 hertz signal was found to give the most air flow at a particular amplitude for the size speaker and closure being used. With different size components in the pump, a different frequency may be found to give the best results.

3. Software Description

The computer added a great deal of flexibility to the system as a control element because of its programmability. With the computer in the loop, system dynamics could easily be changed by modifying the software which generated the control algorithm. The algorithm used in the system described a first order linear differential equation of the form:

$$E(t) = PG * P(t) + DG * dP(t)/dt$$

where

t	= Time
E(t)	= Error signal at time t
PG	= Position gain
P(t)	= Position of the target at time t
DG	= Differential gain
dP(t)/dt	= Derivative of position at time t

Because the system is a discrete time sampled system, this equation is transformed to a discrete form expression:

$$E(n) = PG * P(n) + DG * (P(n) - P(n-d))$$

where

n	= Sample number
E(n)	= Error signal at sample n
PG	= Position gain
P(n)	= Position at sample n
DG	= Differential gain
d	= Sample interval

This expression lends itself to being implemented on a computer. Each of the three axes is controlled by one of these equations. Thus, after the position of the target has been determined, three of these equations are formed by the computer. The results of these calculations become the signals which reposition the target if necessary.

Most of the actual software which implements the control algorithm is written in Z-80 assembly language. The decision to program in assembly language verses a high level language, such as PL/I, was prompted by the need for fast execution. While a higher level language would have made the actual writing of the program easier, the algorithm had to be executed in real time. This meant that the calculations that were performed by the processor had to be made fast enough to keep up with the movements of the target. Using assembly language made this possible.

The entire operation, from sampling position in all three axes to taking corrective action on the target, could be performed in approximately 2 ms. This fast turn around time was found to be very important in the operation of the system. At slower sample rates the target would become increasingly more unstable until the target could not be maintained in the operational field of the positioner.

The program was organized into a series of modules to make the software easier to read and trouble shoot. Each module had a specific task to perform and was confined to that task. A list of the main modules in the program and short explanation of each follows:

a. Hardware Initialization - This module sets up the I/O ports and initialized the interrupt clocks to their correct settings.

b. Analog to Digital - This module carries out the communication with the A/D converter. The information returned by this module represents positional information of the target.

c. Digital to Analog - This module drives the hardware necessary to convert digital control information to analog form. The information passed out of the computer, through this module, is the result of the control algorithm.

d. Position - This module is responsible for retrieving the correct positional data on the target when the control equations are being formed. It then does the multiplication with the positional gain constant. This data comes from a shift register structure which holds a series of past data samples.

e. Derivative - This module calculates a backward difference for the control equation. This analogous to a derivative in the continuous form of the control equation. This calculation is accomplished by taking the difference between the most current position sample and a sample delayed by a constant interval of samples. The result is then multiplied by the derivative gain constant. This scheme was found to be as effective as a more complex algorithm which calculates an actual derivative over several samples. The backwards difference, however, was easier and faster to implement in the program.

f. Overflow Check - All of the data representations in this program are eight bit two's compliment. However, all arithmetic operations are performed using sixteen bit operations. The results are then checked by this module for values out of the range of +127 to -128. If there is an eight bit overflow, this module will return +127 or -128 depending on the sign of the original result. This algorithm is analogous to an amplifier being driven into saturation in an analog control loop.

g. Variable Output - This is the only module not written in Z-80 assembly language. Because the purpose of the module is to display selected variables during operation of the system, it is not speed critical. The module's only purpose is for trouble shooting of the program. Therefore, it was written in PL/I to simplify its development. This module is run in the background. This means it is only executed after all other modules have completed their tasks.

The mainline portion of the software ties together all of the functional modules in the program (See Figure 48). The mainline starts a sampling cycle by collecting target position information from all of the sensors. This information is then rotated 45 degrees in one plane. Due to space limitations, the optical sensors are placed between the sonic pumps. This causes their respective horizontal axes to be displaced from each other

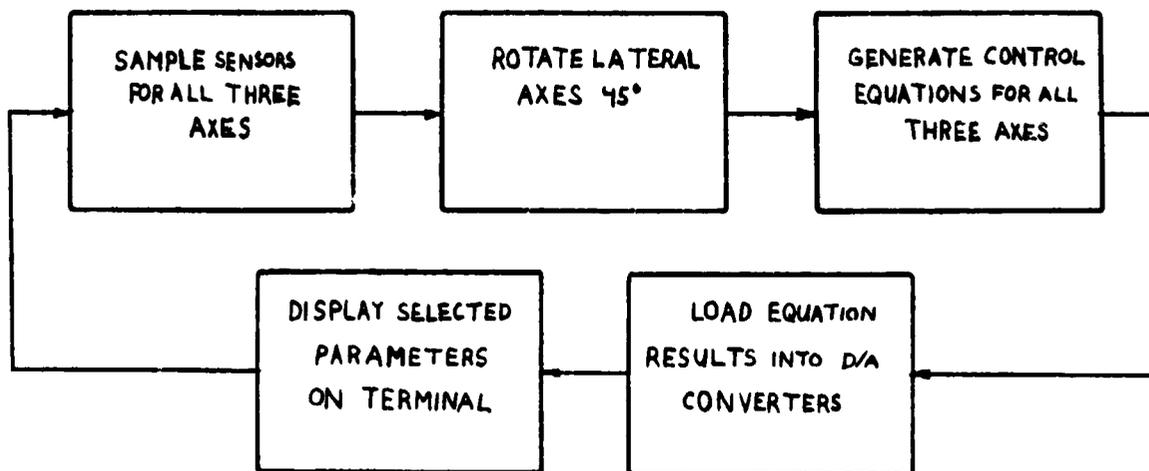


Figure 48. Functional Relationships of Software Modules.

by 45 degrees and makes the rotation necessary (See Figure 49). The equation to perform this rotation is:

$$X = P \cdot \sin(45) + Q \cdot \cos(45) \quad Y = P \cdot \cos(45) - Q \cdot \sin(45)$$

Because the sine and cosine portion of each term is a constant, they simply become part of the gains in the loops of each axis. This simplified the rotation calculation to:

$$X = P + Q \quad Y = P - Q$$

The X and Z axes are the same for both the pumps and the sensors and do not need to be transformed.

Once the position of the target has been determined, the information is stored in to a shift register with previously sampled data points. Using the position and derivative modules, the control equations for each of the three axis are formed to determine the error signal for each axis. The results of these calculations represented a signal amplitude to be output to each of the sonic pump sets. The mainline uses the digital to analog module to output the results, thus, affecting a change in the target's position and velocity.

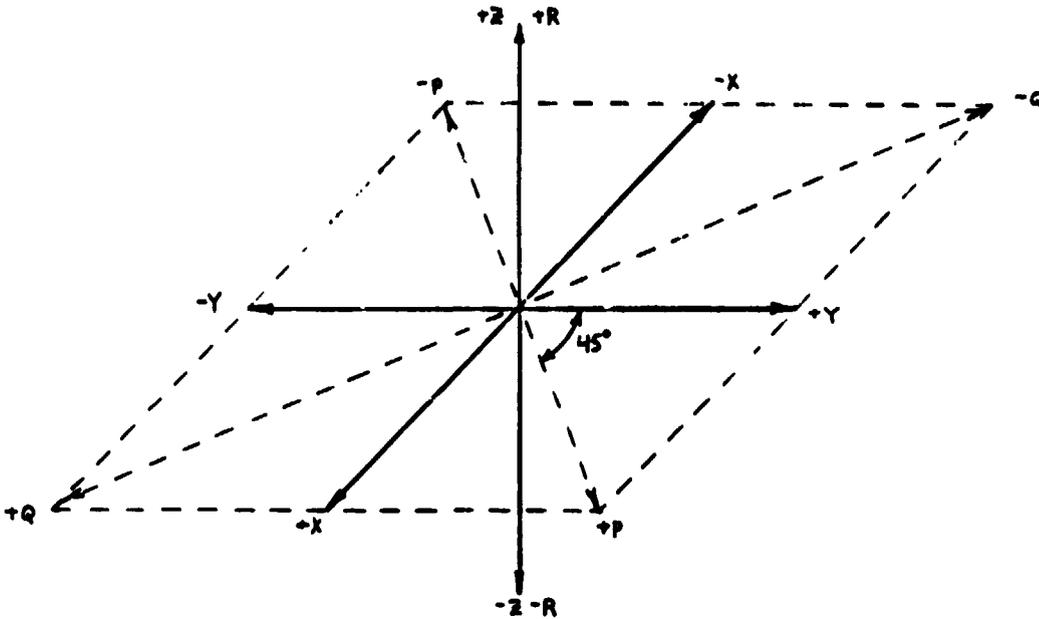


Figure 49. Sensor/Pumps Angular Relationship.

4. Testing and Evaluation

The initial testing of the system occurred under normal one gravity conditions. To compensate for the effects of the one gravity environment, the software in the system was modified. An offset was added to the control equation of the vertical axis so that the bottom sonic pump of that axis was operating continuously while still being modulated. Under these conditions, the dynamics of the system could be experimented with in the ground level laboratory.

The targets in these initial trials were styrofoam spheres of approximately 3/4 to 1 1/4 inches in diameter. Levitation was stable longer than with a solitary sonic pump, 10 seconds as opposed to 2 or 3. After around 10 seconds, however, minor pump misalignments would cause rotation of the target. The associated Magnus effect grew to the point of interfering with the position keeping algorithm and instability resulted. The option to modify the algorithm to take the Magnus effect into account was discarded for lack of funds and time. Instead, the problem of rotation was solved by loading a small brass pellet into one side of the styrofoam sphere. This virtually eliminated the rotation and the Magnus effect disturbance. Levitation could now be achieved for periods lasting up to a half hour or more, thus establishing the levitating capability of the Sonic Pump Levitator.

With the system operational in one gravity, different parameters of the system were experimented with. The parameters that were adjusted for optimum performance included the algorithm gain coefficients in the software, the delay constant in the derivative module, the fine gain adjustments, and the bias control. Settings for all of these parameters were established as a starting point for zero gravity experiments.

The system was tested under the reduced gravity conditions available in the parabolic flight regime of the KC-135. With the parabolic pattern flown, the KC-135 could achieve a low gravity condition for approximately 30 seconds. This was sufficient to test the system.

During the KC-135 reduced gravity flights, the equipment was subject to an operating environment approaching that with which it would have to deal on actual space flights. The testing included experimenting with the different system parameters and attempting to control different diameter and mass targets. As reported elsewhere, the results from these flights were excellent. The styrofoam targets, for example, that were levitated in one gravity could also be controlled in reduced gravity.


```

#####
;# initialization module #
#####
false equ 0
true equ not false
;
gravity equ true ;false if zero gravity
position equ true ;true if included in equation
derivative equ true ; " " " " "
;
basevec equ OFB00h ;location of interrupt vectors
pio_base equ 10h ;port base address
data equ pio_base ;port A data address
control equ pio_base+1 ;port B data address
a_cntrl equ pio_base+2 ;port A control address
b_cntrl equ pio_base+3 ;port B control address
;
begin: di ;disable interrupts
ld a,0ffh ;set port B strobes off
out (control),a
ld a,08fh ;bidirectional mode
out (a_cntrl),a ;output to port A
ld a,0cfh ;bit mode
out (b_cntrl),a ;output to port B
ld a,8 ;set bit 3 as input
out (b_cntrl),a
;
call clk_on ;initialize the ctc
call adc_set ;initialize the adc
call dac_set ;initialize the dac
ei ;enable interrupts
jp NASA ;go to pli background
;
save macro ;macro to save registers and flags
push af
push bc
push de
push hl
endm
;
restore macro ;macro to restore registers and flags
pop hl
pop de
pop bc
pop af
endm
;

```

```

#####
;#
;#                               Main Process Module                               #
;#
;#   This module processes the sampled data and forms the control #
;#   signals using the equation: #
;#
;#                               Output = PG*x(i) + DG*deriv(x(i)) #
;#
;#   Where:  PG = proportional gain #
;#           DG = derivative gain #
;#
#####
process:save                ;save the registers
        ei                  ;enable the interrupts
        xor                a
        ld                 (channel),a      ;set channel address to zero
        call               adc
        ld                 (p_sense),a     ;distance (p sensor)
        ld                 e,a
        ld                 d,0             ;sign extend to 16 bits
        bit                7,a             ;is the number positive?
        jr                 z,procl         ;jump if yes
        dec                d
procl:  call               adc
        ld                 (q_sense),a     ;distance (q sensor)
        ld                 c,a
        ld                 b,0             ;sign extent to 16 bits
        bit                7,a             ;is the number positive?
        jr                 z,proc2        ;jump if yes
        dec                b
proc2:  ld                 l,c              ;distance (q sensor)
        ld                 h,b
        add                hl,de           ;x = p + q
        push               de              ;save (p sensor)
        push               bc              ;save (q sensor)
        call               ovftest        ;test for overflow
        ld                 hl,shift_x     ;x shift register
        call               register
        pop                bc              ;return (q sensor)
        pop                hl              ;return (p sensor)
        xor                a               ;clear carry flag
        sbc                hl,bc          ;y = p - q
        call               ovftest        ;test for overflow
        ld                 hl,shift_y     ;y shift register
        call               register
        call               adc
        ld                 (r_sense),a    ;distance (r sensor)
        ld                 hl,shift_z     ;z shift register
        call               register
;

```

```

;*****
;* calculate 1st order functions for x *
;*****
ld      hl,shift_x      ;set up for position of x
call    posit
ld      (x_posit),hl    ;store position
;
ld      hl,shift_x      ;set up for derivative of x
call    deriv
ld      (x_deriv),hl    ;store derivative
;
;*****
;* calculate 1st order functions for y *
;*****
ld      hl,shift_y      ;set up for position of y
call    posit
ld      (y_posit),hl    ;store position
;
ld      hl,shift_y      ;set up for derivative of y
call    deriv
ld      (y_deriv),hl    ;store derivative
;
;*****
;* calculate 1st order functions for z *
;*****
ld      hl,shift_z      ;set up for position of z
call    posit
ld      (z_posit),hl    ;store position
;
ld      hl,shift_z      ;set up for derivative of z
call    deriv
ld      (z_deriv),hl    ;store derivative
;
;*****
;* generate the control equation for x *
;*****
pid_x: ld      c,0        ;set dac channel to zero
;
      If      position
      ld      hl,(x_posit)
      Else
      ld      hl,0
      Endif
;
      If      derivative
      ld      de,(x_deriv)
      Else
      ld      de,0
      Endif
      add     hl,de        ;hl = pos(x) + der(x)
;

```

```

call    ovftest      ;test for overflow
ld      (x_speak),a

call    dac          ;out to dac
;
;*****
;* generate the control equation for y
;*****
pid_y:  inc          c          ;increment to next channel addr
;
      If            position
      ld            hl,(y_posit)
      Else
      ld            hl,0
      Endif
;
      If            derivative
      ld            de,(y_deriv)
      Else
      ld            de,0
      Endif
      add           hl,de          ;hl = pos(y) + der(y)
;
      call          ovftest      ;test for overflow
      ld            (y_speak),a
      call          dac          ;out to dac
;
;*****
;* generate the control equation for z
;*****
pid_z:  inc          c          ;increment to next channel addr
;
      If            position
      ld            hl,(z_posit)
      Else
      ld            hl,0
      Endif
;
      If            derivative
      ld            de,(z_deriv)
      Else
      ld            de,0
      Endif
      add           hl,de          ;hl = pos(z) + der(z)
;
      If            gravity
      ld            de,100        ;offset for gravity
      xor           a
      sbc           hl,de        ;gravity offset constant
      Endif
;

```

```

call    ovftest          ;test for overflow
ld      (z_speak),a
call    dac              ;out to dac
;
in      a,(15h)          ;console input port
cp      27               ;escape ?
jr      nz,exit         ;jump if no char
call    clk_off         ;turn the ctc off
call    dac_set         ;turn dacs off
restore ;clean up stack
ld      hl,0             ;cp/m entry address
ex      (sp),hl         ;put entry address on stack
reti                    ;return to cp/m
exit:   restore         ;restore the registers
reti                    ;return from interrupt
page

```

```

#####
;#                               #
;#           Counter Timer Initialization Module                       #
;#                               #
;#   The CTC is set up with channel #1 connected as a counter        #
;#   and as a timer. The baud rate frequency of 307,692 Khz         #
;#   is connected to the counter input and the clock frequency      #
;#   of 5 Mhz is divided by 16 internally for a timer frequency     #
;#   of 312,500 Khz. Channel #1 has been initialized with a        #
;#   count of 4. Channel #0 is set up in the counter mode and      #
;#
;#   has its input connected to the output of channel #1. The      #
;#   equation describing the sample rate is as follows:              #
;#
;#           sample rate = 307,692 / (ctc_one*ctc_two)              #
;#                           (counter)                               #
;#
#####

```

```

ctc_one:db    205          ;500 Hz sample rate
ctc_two:db    3            ;" " " "
ctcbase equ   4            ;ctc base address
ctc_vec equ   basevec+30h  ;ctc interrupt vector addr
;
clk_on: ld    hl,process   ;main process module
ld      (ctc_vec),hl     ;ctc interrupt vector
ld      a,01000011b      ;ctc reset
out     (ctcbase),a      ;counter # 0
ld      a,11000111b      ;counter mode with interrupts
out     (ctcbase),a
ld      a,(ctc_one)      ;counter period
out     (ctcbase),a
ld      a,01000011b      ;ctc reset

```

```

out    (ctcbase+1),a    ;counter # 1
      ld      a,0100011b    ;counter mode without interrupts
      out    (ctcbase+1),a
      ld      a,(ctc_two)    ;counter period
      out    (ctcbase+1),a
      ret

```

```

;*****
;*          Module to reset ctc's and disable interrupts          *
;*****

```

```

clk_off:di    ;disable interrupts
          ld      a,01000011b    ;reset ctc control code
          out    (ctcbase),a
          out    (ctcbase+1),a
          ei          ;enable interrupts
          ret
          page

```

```

;#####
;#          Analog to Digital Converter Module          #
;#          #                                           #
;#          input:  This module gets 8 bit data in a round robin fashion #
;#                   advancing through channel numbers 0,1,2 each time it #
;#                   is called                                           #
;#          #                                           #
;#          output: The 8 bit data is returned in the accumulator in #
;#                   2's complement notation                             #
;#          #                                           #
;#####
;

```

```

adc_set:ld    a,0f8h    ;all chip selects off
          out    (control),a    ;port B control word
          ret

```

```

;*****
;*          do the conversion and read in the data          *
;*****

```

```

adc:   push    bc
      ld      a,(channel)    ;current channel number
      or      0e0h    ;select 8 bit conversion
      out    (control),a
      out    (data),a    ;start conversion
adcl:  in     a,(control)    ;port B control word
      bit    3,a    ;is conversion complete?
      jr     z,adcl    ;jump if not yet done
      res    5,a
      out    (control),a
      in     a,(data)    ;get the previous data
      in     a,(data)    ;get the new data
      ld     b,a    ;save the data

```



```

posit:  ld      de,24          ;point to most current data byte
        add     hl,de         ;point to the current byte
        ld     l,(hl)
        ld     h,0           ;2's complement sign extend
        bit    7,l
        jr     z,posit1
        dec    h
posit1: sra    h
        rr     l
        ret
        page

```

```

#####
;#                                     Module to find the derivative #
;#                                     #
;#      input:      A pointer in reg's HL pointing to the least #
;#                  current of 25 data points                    #
;#                                     #
;#      output:     One byte in the accumulator and in reg L #
;#                  with reg H sign extended representating #
;#                  the backward difference between the most #
;#                  recent data point and a data point #
;#                  by a constant value. #
;#                                     #
;#      The algorithm used is:   $x'(i) = x(i) - x(i-delay)$  #
;#                                     #
#####

```

```

deriv:  ld      de,24          ;point to the most current byte
        add     hl,de
        ld     e,(hl)
        ld     d,0           ;2's complement sign extend
        bit    7,e
        jr     z,deriv1
        dec    d
deriv1: ld      bc,5          ;point to delayed byte
        xor    a
        sbc   hl,bc
        ld     l,(hl)
        ld     h,0           ;2's complement sign extend
        bit    7,l
        jr     z,deriv2
        dec    h
deriv2: ex     de,hl
        xor    a
        sbc   hl,de         ;hl = x(i) - x(i-1)
        ld     d,h
        ld     e,l
        add   hl,hl
        add   hl,de
        call  ovftest       ;test for 2's comp ovf
        ret
;

```



```

and    00010111b    ;select dac channel
      or            c
      out          (control),a
      ld          a,b    ;return data
      out          (data),a    ;output data to channel
      in          a,(control)    ;port B control word
      or          0f8h    ;all chip selects off
      out          (control),a
      ret

;
get_p: ld          hl,(p_sense)
      ret
get_q: ld          hl,(q_sense)
      ret
get_r: ld          hl,(r_sense)
      ret
get_a: ld          hl,(x_speak)
      ret
get_b: ld          hl,(y_speak)
      ret
get_c: ld          hl,(z_speak)
      ret
;

;#####
;#          Program Data Storage Area          #
;#####
p_sense:dw        0    ;p sensor data
q_sense:dw        0    ;q " "
r_sense:dw        0    ;r " "
x_posit:dw        0    ;position of x
y_posit:dw        0    ; " " y
z_posit:dw        0    ; " " y
x_deriv:dw        0    ;derivative of x
y_deriv:dw        0    ; " " y
z_deriv:dw        0    ; " " z
x_speak:dw        0    ;speaker x output
y_speak:dw        0    ; " y "
z_speak:dw        0    ; " z "
sum_x: dw        0    ;sum of x
sum_y: dw        0    ; " " y
sum_z: dw        0    ; " " z
channel:db        0    ;multiplexer channel
shift_x:ds        25   ;x shift register
shift_y:ds        25   ;y shift register
shift_z:ds        25   ;z shift register
;
      end          begin    ;declare begin as the first exec statement

```

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