NSG-4019

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Final Report for
NASA Grant NSG-4019,
"Study of New Flight Test Techniques"

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Final Report for
NASA Grant NSG-4019,
"Study of New Flight Test Techniques"

KU-FRL-407-10

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1. INTRODUCTION

This report describes the final phase of work under NASA Grant No. 4019, a phase which involved modification and testing of a small electromechanical vibrator. The vibrator was designed for the flutter testing of airplane wings and was built to specifications that make it compatible with the X-29 experimental airplane. The unique device uses alternating electromagnetic forces to move a magnetic mass and produce vibration. Its unconventional way of producing vibration avoids the need for complex mechanisms and makes efficient use of space and weight.

The vibrator was developed by the Flight Research Laboratory at the University of Kansas under a series of research grants that began in April 1982. An initial prototype was completed and tested in June 1983.* This report describes an improved prototype and the results of its testing.

2. DESIGN CONCEPT

All self-contained vibrators vibrate by moving mass in a way that produces alternating reaction forces. The amplitude of vibration depends on the size of the reaction forces, which depends on the amount of mass being moved. The frequency of vibration depends on how far the mass moves. Short, alternating motions produce high frequencies. Longer motions produce lower frequencies.

Conventional electromechanical vibrators move mass by eccentric rotation or hydraulic displacement. These devices have been successful, but only a small portion of their overall volume and weight actually produces useful vibration. Much of their size and weight is due to mechanical overhead, like motors, pumps, gears, and shafts.

An electromagnetic vibrator, in which magnetic interaction is the sole source of motion, uses space and weight more efficiently. Such a device needs only two basic components: a wire wound core to produce an alternating electromagnetic field, and a permanently magnetic frame that moves with the alternating field to create vibration. An electromagnetic vibrator is conceptually similar to a loudspeaker or a solenoid. The motion it produces depends entirely on the electrical current supplied to its wire windings.

Figure 1 is a simplified illustration of the electromagnetic vibrator described in this report. The fixed core of the vibrator holds wire windings. The movable frame, which surrounds the core, holds two permanent magnets. Since the frame is steel, it completes a magnetic path between the

*See Reference 1.

magnets and supplies a large source of inertia for reaction forces. Indeed, most of the mass of the device is concentrated in the steel frame and permanent magnets. This gives the device an ability to produce relatively large amplitudes of vibration within a small space. Moreover, since there are no other large components besides the core, the frame has plenty of space in which to move. Only the overall dimensions of the device itself limit movement.

Electrical current applied to the windings of the core interacts with the permanent field of the magnetic frame to produce an electromagnetic force. The direction of this force is perpendicular to both the direction of the current and the direction of the permanent field. Since the core itself is fixed, this force accelerates the frame.

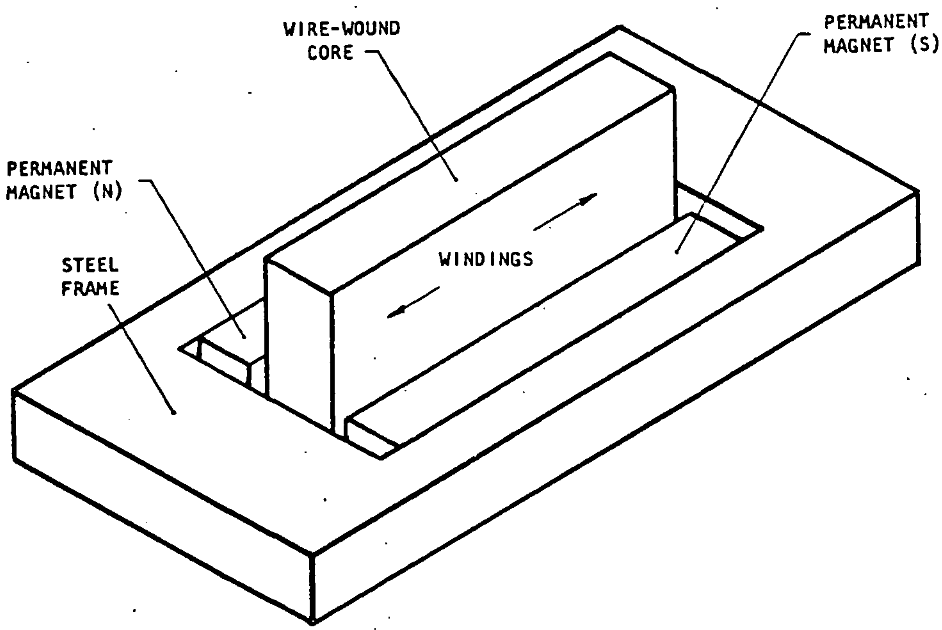

Figure 1. A Simplified Drawing of the Electromagnetic Vibrator.

3. OPERATING PRINCIPLES

The cycle of vibration is an alternating acceleration and deceleration of the magnetic frame. During each cycle, electromagnetic forces accelerate the frame in one direction, decelerate it to a stop, reaccelerate it in the opposite direction, and again decelerate it to a stop. By changing the duration of the alternating forces, one can alter the vibration waveform, the frequency of vibration, or both.

The amplitude of vibration depends on the magnitude of the electromagnetic forces between the core and the magnetic frame. This magnitude depends on the amount of current in the windings of the core, as

$$F = B\ell i, \tag{1}$$

where B is the magnetic flux density of the permanent magnets, ℓ is the length of wire in the permanent magnetic field, and i is the current.

The direction of the current in the windings determines whether the electromagnetic force, F, accelerates or decelerates the magnetic frame. Since each half of a vibration cycle begins and ends with mass at rest, the net energy of motion is zero. Therefore,

$$F_a X_a = F_d X_d, \tag{2}$$

where F_a is the net accelerating force during half a cycle, X_a is the distance of acceleration, and F_d and X_d are the force and distance required to bring the mass to rest. For a symmetrical waveform, $F_a = F_d$ and $X_a = X_d$.

The vibrator has a short operating cycle at high frequencies; thus, for a given amplitude, X_a and X_d are small. But as frequency decreases, the distance of motion must increase to maintain a given amplitude. Below a certain frequency this distance is greater than the thickness of the vibrator, and the amplitude of symmetrical vibration is limited. Figure 2 illustrates this effect.

Low-frequency vibration must be produced by asymmetrical pulses, in which $F_a > F_d$ and $X_a < X_d$. Figure 3 illustrates this kind of pulse waveform. The frequency at which symmetrical vibration must be replaced by pulses depends on the amplitude of the vibration. This transition frequency appears as the sharp break in each curve in Figure 2.

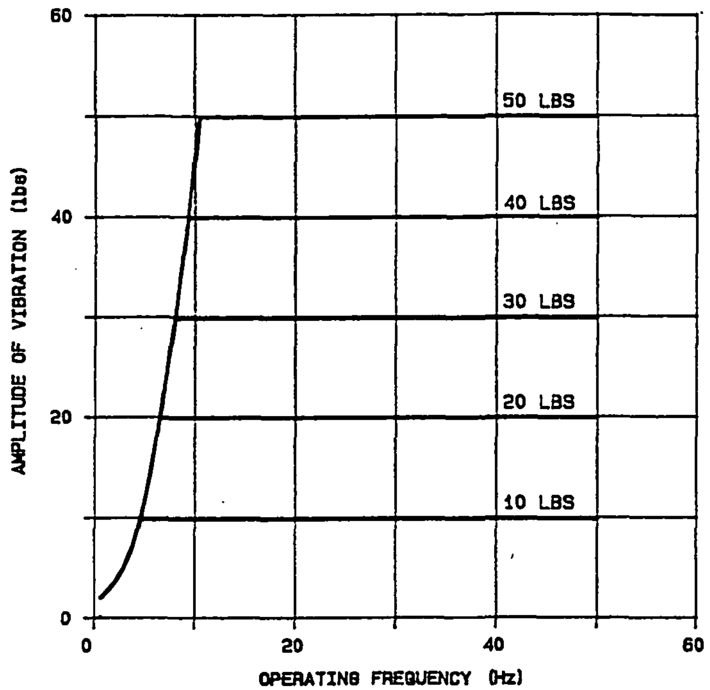

Figure 2. Limits on the Vibrating Movement Restrict the Amplitude of Vibration at Low Frequencies.

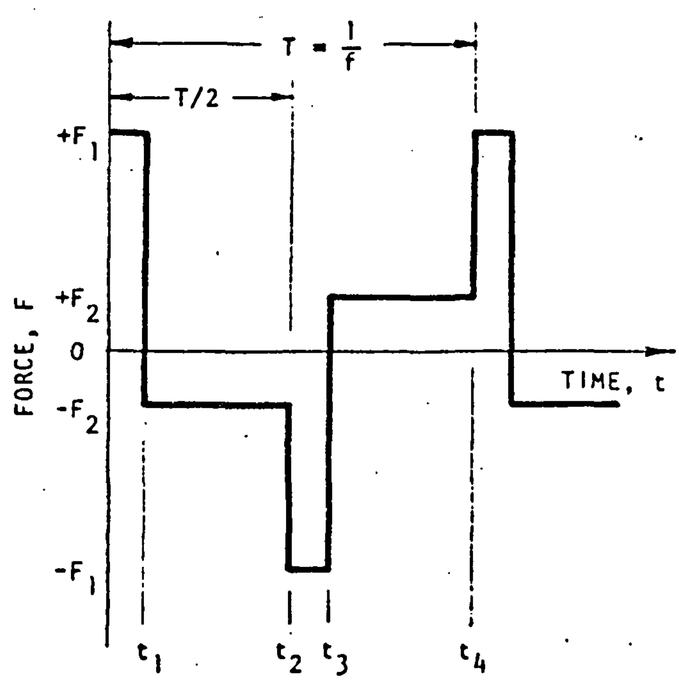

Figure 3. A Pulse Waveform for Generating Low-Frequency Vibration.

4. MECHANICAL DESIGN DETAILS

Development of a prototype revealed the kinds of practical design decisions that must be made to produce a useful vibrator. The following description summarizes important details of the latest vibrator prototype and the important design considerations underlying them.

4.1 Design of the Core

The basic purpose of the vibrator core is to properly orient a large number of energized wire turns in the permanent field of the magnetic frame. The effectiveness of the core therefore depends on the length of wire the core exposes to the field and the number of turns of this length that the core exposes. Electromagnetic efficiency also depends on the magnetic permeability of the core itself. For this reason, a core made of iron or steel works better than one made of some lighter, but less magnetically permeable material, like aluminum.

Dimensions of the core depend on the dimensions of the magnetic frame that surrounds it and the overall size restrictions on the vibrator. The length of the core is the critical dimension because it defines the length of wire exposed to the permanent field of the magnetic frame. The core of the prototype is 4.0 inches long, 1.6 inches high, and 0.7 inches wide.

The sides of the core are notched to hold wire windings. The number and size of the notches maximize the number of windings exposed to the moving magnetic frame at any given time. The core of the prototype has twelve, evenly spaced notches, each containing 25 windings of #28 copper wire. the wire diameter is small enough to allow many windings but large enough to preclude heating problems at high electrical currents.

4.2 Winding Scheme

Figure 4 illustrates the winding arrangement that makes the vibrator produce a linear force effect. The figure illustrates a cross section of the core and a single, idealized winding that represents 25 actual turns.

Consider the winding to be a single, continuous wire beginning at "a_1" on the lower, right side of the figure. Electrical current in this wire would go from "a_1," on the right side, around the core to "a_1," on the left side; then to "a_2," on the left side, and around the core to "a_2," on the right side. From there, current would continue the same way from the "b_1" loop to the "b_2" loop, and so on, until it finally reached "f_2" at the upper right side of the figure. Notice that each loop around the core carries current in one direction on one side of the core and current in the opposite direction on the other side. This arrangement uses wire efficiently, since both sides of the loop can produce a useful force effect. If the core were energized with current in the direction shown, the resulting electromagnetic force would move the magnetic frame upward.

In fact, current does not pass through every loop of the core, as Figure 4 suggests. Actually, pairs of loops, designated by the same letter in the figure, are tapped to form discrete coils. Loops "a_1" and "a_2," for example, form one such coil; loops "b_1" and "b_2" form another. The core windings are thus divided into six, independent coils that can be separately energized. Each coil can carry different currents in either direction. Each can be turned off after the magnetic frame passes, thus reducing power usage.

Figure 5 illustrates how current in the windings changes as the frame moves up and down. In Figure 5A, current in the windings is causing the frame to accelerate upward. In Figure 5B, the frame is moving past the midpoint of its motion as it produces a symmetrical vibration waveform. At this point, the current has switched direction, and a decelerating force is being applied. In Figure 5C this decelerating force has just stopped the frame and is beginning to accelerate it in the opposite direction. Figure 5D is a mirror image of Figure 5B; the frame is again passing the midpoint of its motion, and current has switched direction again to decelerate the frame.

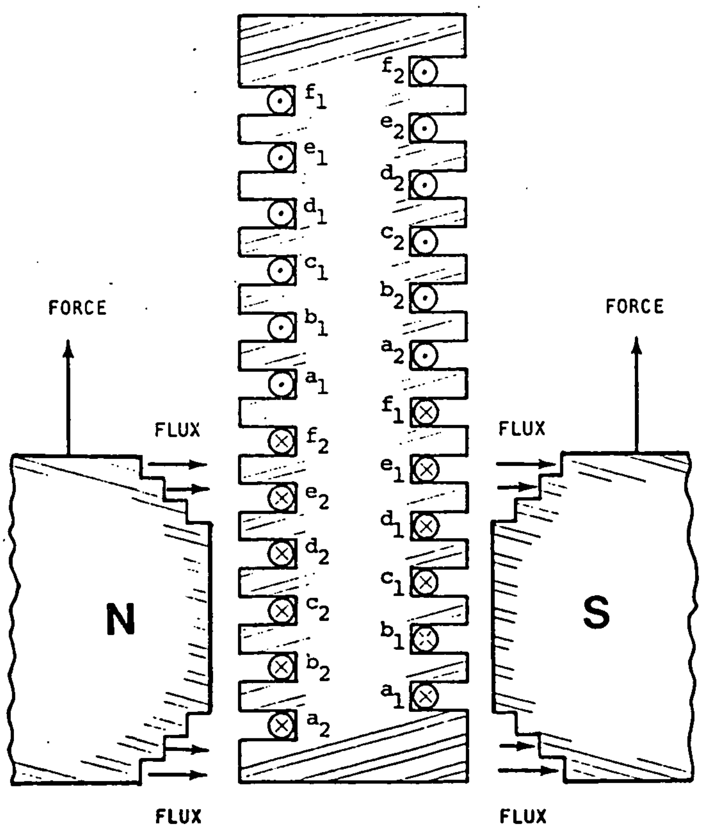

Figure 4. A Section of the Magnets and Core, Showing Current Direction through a Single Wire Winding.
The stairsteps sides of the magnets direct flux.

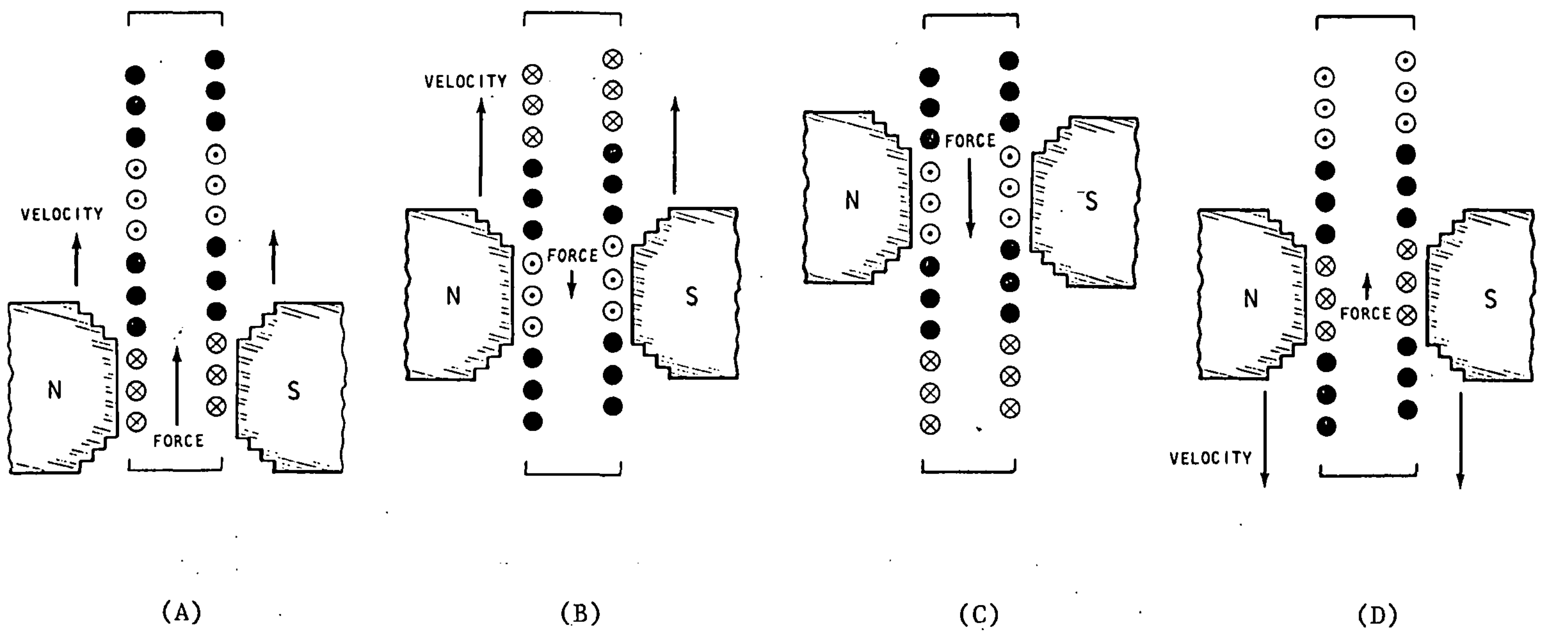

Figure 5. Switching of the Coils as the Magnetic Mass Moves. Black circles represent unenergized coils.

4.3 Design of the Magnetic Frame

The magnetic frame is both a source of inertia and a source of a permanent magnetic field. Its mass determines what reaction force will be produced when the frame moves, thus determining the amplitudes of vibration the vibrator can produce. The field strength produced by its magnets determines, in part, how much force will be generated to move the frame and cause vibration.

The design of the frame balances two important, but conflicting factors. On one hand, the need for a large mass and strong magnetic field suggests the frame should be as large as possible. On the other hand, the need for space in which to vibrate at low frequencies suggests the frame should be as small as possible in the direction of vibration. Together, these two goals require a frame with a large area and a small thickness.

The magnetic frame of the prototype vibrator is about 6.8 inches long, 3.8 inches wide, and 0.8 inches thick. It moves within an enclosed space that is 8.0 inches long, 4.0 inches wide, and 1.6 inches thick.

Figure 6 illustrates the assembled frame. It consists of two samarium-cobalt magnets, two steel pole faces, and a rectangular steel frame with bearings and rollers. Each magnet is bonded to the inside of the steel frame to create a strong, permanent magnetic field. A pole face is attached to each magnet to direct the lines of magnetic force between the magnet and the vibrator core. The corners of the steel frame contain bearings that allow the frame to move on fixed rods in the plane of vibration. The motion is also guided by rollers which prevent the frame from tilting and prevent the bearings from binding. Together, the bearings, rods, and rollers maintain a very small gap between the moving magnetic frame and the vibrator core, thus ensuring high electromagnetic efficiency during vibration.

4.4 Design of the Support Structure

The support structure of the vibrator maintains the orientation of internal components and transmits reaction loads to any structure the vibrator is attached to. The support structure does not enclose internal comonents; it merely supports them. The openness of its structure permits air to circulate, cooling the vibrator when it operates at large electrical currents.

Figure 7 illustrates the assembled prototype with its support structure in place. Large holes in the top and bottom of the structure reduce weight and improve circulation. L-shaped mounting brackets, on the ends of the structure, allow the vibrator to be installed in a cantilever arrangement. A 10-pin connector connects to the windings of the core.

4.5 Special Design Problems

The vibrator prototype revealed two particular design problems that interfered with smooth motion of the magnetic frame during vibration.

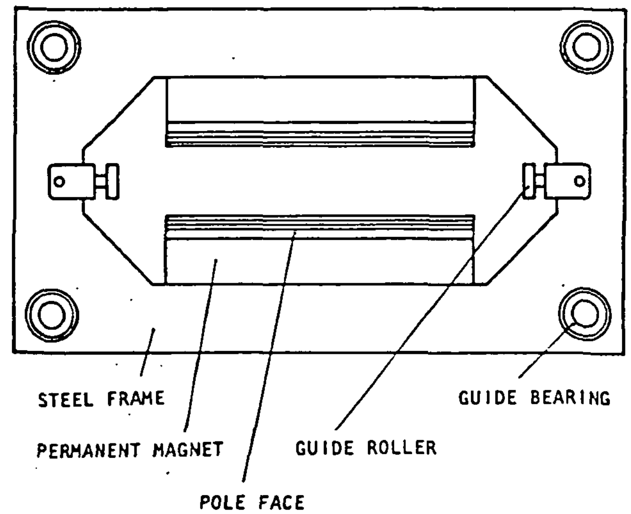

Figure 6. The Magnetic Frame.

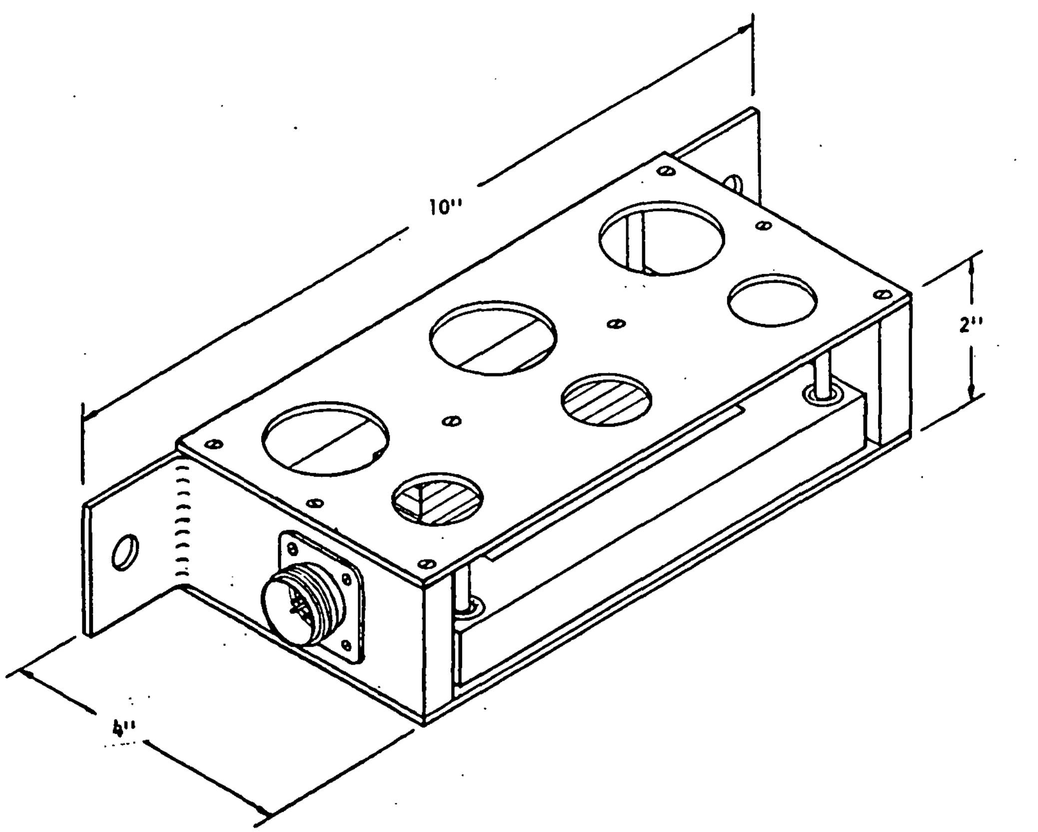

Figure 7. The Assembled Vibrator.

One problem was caused by the linear ball bushings in the corners of the movable, magnetic frame. Linear bushings apparently will not roll freely under torque. Yet torque inevitably results from slight misalignments of the bushing centerlines, from slightly unequal magnetic attraction between the magnetic frame and the sides of the steel core, and from elastic deformation of the vibrator support structure during testing. A roller and track arrangement, like that shown in Figure 8, was designed to alleviate most of the torque on the bushings. The rollers are permanently attached to the movable frame (see Figure 6), and the adjustable tracks are attached to the ends of the core. By adjusting the position of the tracks, one can center the frame with respect to the core. Within each track, the two tandem rollers are offset slightly to permit each to roll on opposite sides of the track. This allows the magnetic frame to move freely despite torques and side forces. The slight offset of the rollers allows the magnetic frame to rotate slightly as it moves, but flexible sleeves around the bushings in the frame prevent binding.

The other significant design problem was caused by the magnetic attraction between each side of the steel core and each permanent magnet of the steel frame. The magnetic attraction is very strong because of the small gaps between the magnets and the core. The force of this attraction complicates assembly, makes adjustment of the position of the frame difficult, and puts large side forces on the bushings and rollers. The forces can be reduced by increasing the gaps between the magnets and the core, but an increased gap size cuts electromagnetic efficiency. Choice of an appropriate gap necessarily requires a compromise between electromagnetic performance and practical, mechanical considerations.

In addition, since the sides of the steel core are notched, the moving magnets of the frame are attracted to a varying volume of steel. The notches are uniform, so the variation in volume is cyclical. The effect produced is a cyclical variation in attraction between the magnets and the core, or a variation in the smoothness of motion. Figure 9 illustrates the problem.

A temporary solution was to replace the stair-step pole faces, shown in Figure 4, with flat steel bars. The flat bars do not direct the magnetic lines of force as well as the original pole faces, but the diffused field produced by the bars does not "lock onto" the steel notches as much. Again, this was a compromise between electromagnetic efficiency and smooth mechanical operation. A better solution perhaps would be to install thin steel plates on each side of the core. This would expose a more constant volume of steel to the magnetic pole faces, while permitting use of the original pole faces to direct the magnetic lines of force.

4.6 Recommendations for Improvement

The ratio of electromagnetic force produced by a given current is a convenient measure of the electromechanical efficiency of the vibrator. This ratio can be defined as

$$\frac{F}{i} = B\ell N, \tag{3}$$

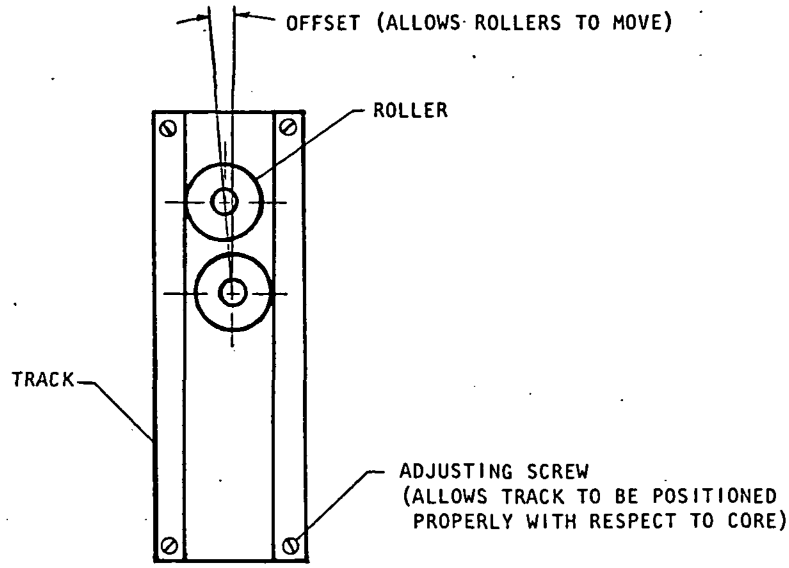

Figure 8. The Roller Guide (looking toward the vibrator core). The rollers are attached to the magnetic frame, and the track is attached to the core.

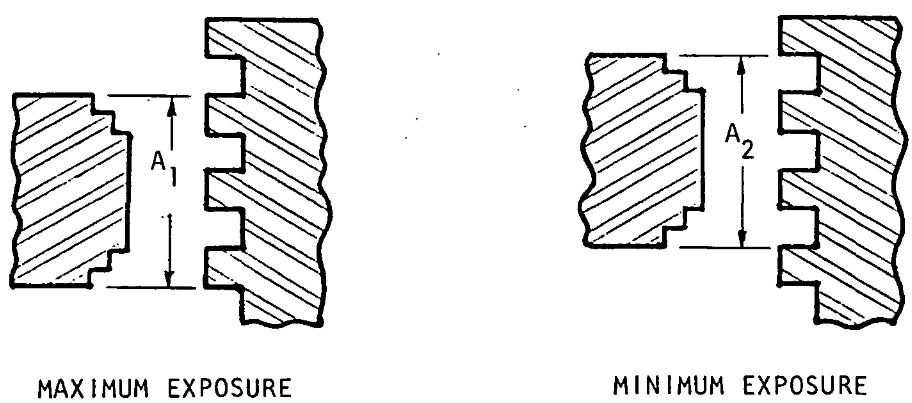

Figure 9. Variation in the Amount of Steel Exposed to the Moving Permanent Magnets.

where F/i is the ratio of force to input current, B is the magnetic flux density of the permanent magnets, ℓ is the length of the wire turns in the permanent magnetic field, and N is the number of such turns. An efficient design will maximize the ratio of force to current and will provide a wide range of vibration amplitudes with reasonably small power requirements. Power requirements are important not only in their own right but also because they influence the amount of heat produced by the vibrator core. Low power usage prevents overheating.

The following table lists various changes that could be made to increase electromechanical force efficiency in a design like that of the vibrator prototype. The prototype design itself represents a set of rather rough design choices, made within the limited scope of a development grant. An optimal design would require detailed trade studies of the combined effect of the factors listed below.

Table 1. Improving Force Efficiency
($F/i = B\ell N$)

Change	Effect	Limited by
1. Changes to Core		
a. increase no. of slots	increases N	core dimensions wire stacking[1]
b. increase length of core	increases ℓ	dimensions of magnetic frame
c. improve wire stacking[1]	increases N	core dimensions
d. increase depth of slots	increases N	core dimensions wire stacking[1]
e. decrease dia. of wire	increases N	heating of wire[2]
2. Changes to Magnetic Frame		
a. increase size of magnets	increases B	dimensions of magnetic frame length of core magnetic saturation of frame[3]
b. decrease moving friction	reduces losses in F	mechanical design

Notes: 1. The winding scheme requires wire to cross from one slot to another on the ends of the core. The stacked crossover windings produce no useful magnetic field and occupy space that could otherwise be used to lengthen the core. As the number of windings increases, the volume of wasted space also increases.

2. Heat is generated in inverse proportion to the cross-sectional area of the wire.

3. The steel frame carries the magnetic field from one magnet to the other. If the cross-sectional area of the steel is too small, the frame will be magnetically saturated. Beyond the saturation volume, any additional magnetic material will produce no useful effect.

Improvements can also be made in the smoothness of motion. First, the need for troublesome linear bearings could be avoided by using a second set of rollers and tracks installed in the sides of the magnetic frame (see Figure 9). The combination of this set and the existing set would resist all likely side forces and moments without binding. Second, the sides of the notched core could be covered with steel plates to reduce the uneven magnetic attraction, described earlier. Widening the gap between the magnets and the core will also smooth motion of the magnetic frame, although the gap also affects electromagnetic performance. The optimal gap depends on the particular designs and requirements of the core, the magnets, the pole faces, and any bearings or rollers used.

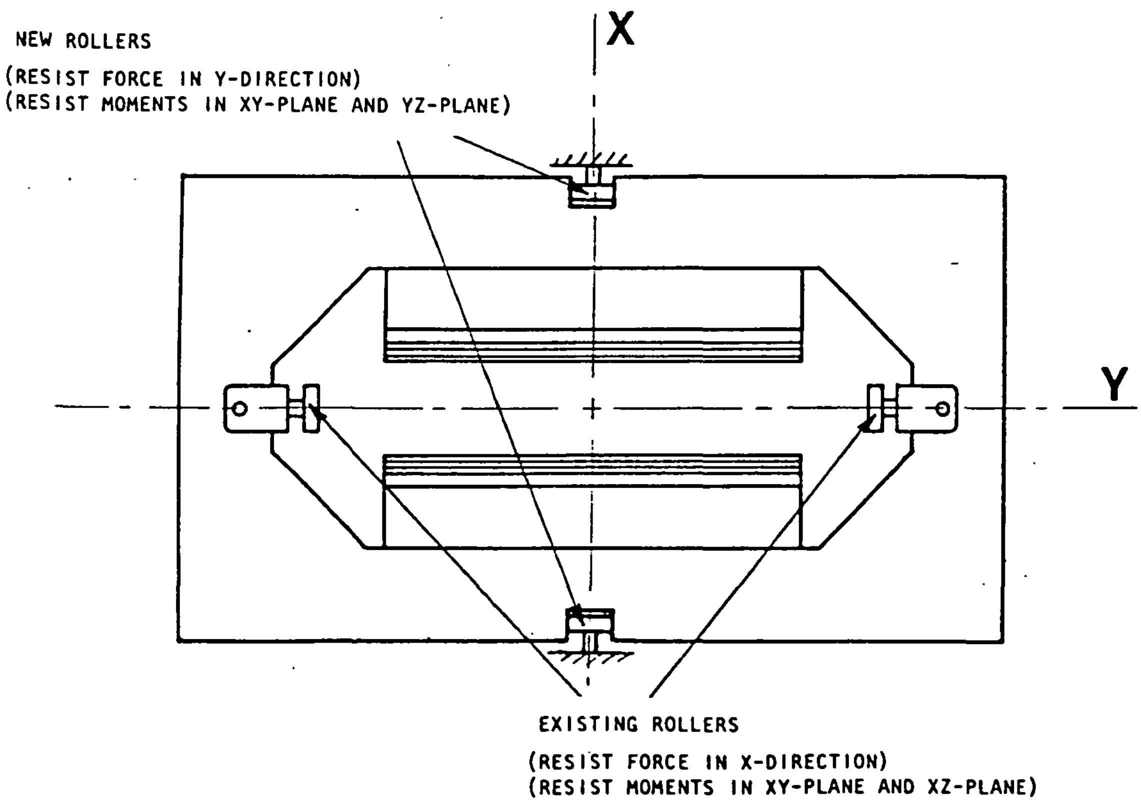

Figure 10. Dual Roller Sets to Guide the Moving Frame.

5. ELECTRICAL DESIGN DETAILS

An electromagnetic vibrator requires some kind of control system to supply and switch electrical current in a way that produces useful vibration. The particular control system for the vibrator prototype was developed merely to demonstrate and test that prototype. Nevertheless, the basic design principles underlying this system would probably work in any control system adapted to use in actual flight testing.

In principle, the control system is simply a digitally controlled switching network, connected to large power amplifiers. Figure 10 is a simplified schematic of this network. The coils shown in the figure correspond to the six independent coils shown in Figure 4: coil "a" represents loops "a_1" and "a_2"; coil "b" represents loops "b_1" and "b_2," and so on. The boxes in Figure 11 represent independent, digitally controlled, switching circuits. Each of these circuits contains a pair of Darlington power transistors which are controlled by digital commands from a microprocessor. These commands determine which coils are energized, how much current is present in these coils, and in which direction the current flows.

Physically, the system consists of four major components: a control computer, a power modulator, a control module, and a power supply. Figure 12 shows how these components connect. Since most test aircraft have their own power supplies and their own on-board computers, the only essential components of the system may in fact be the power modulator and control module. Nevertheless, a general description of all four components used in the test system has been provided here, since design of each component depends on the characteristics of all the others.

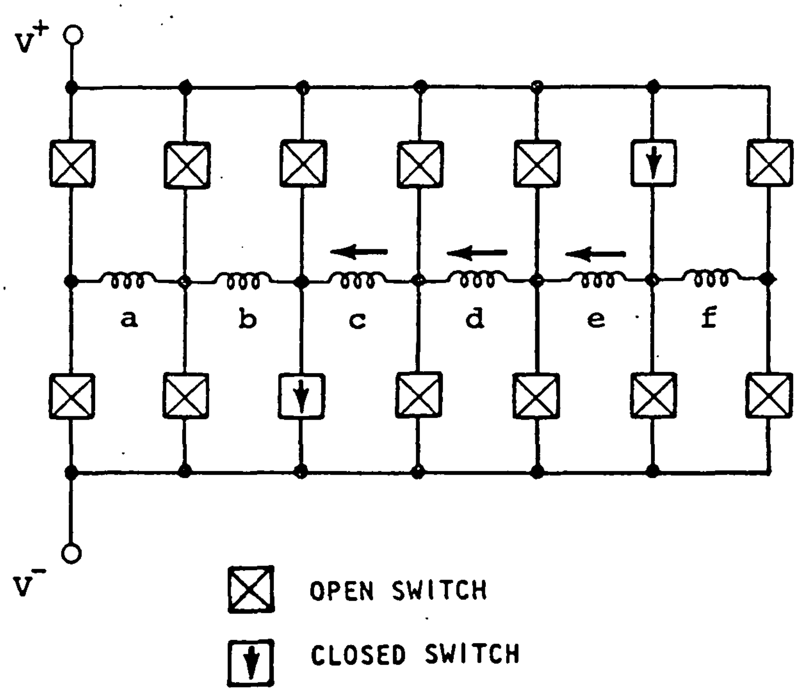

Figure 11. Control System Switching.

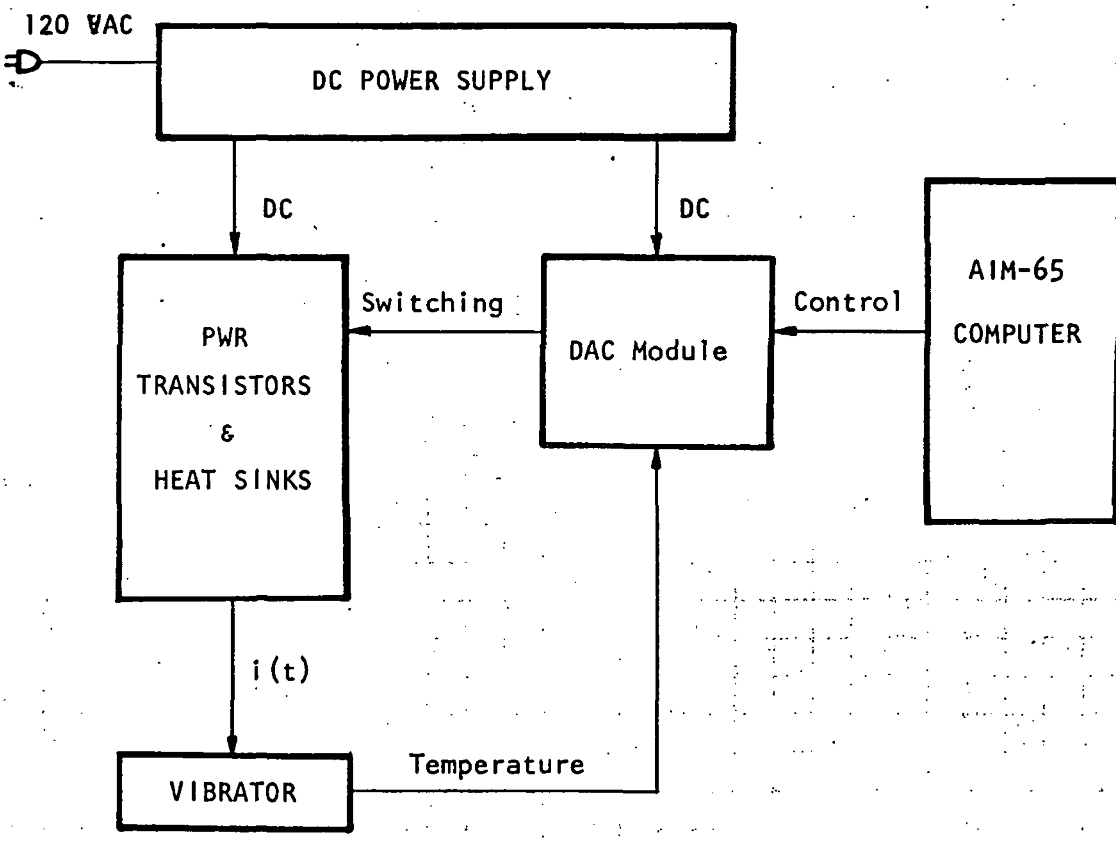

Figure 12. Block Diagram of the Control System.

For the continuation of Section 5, see the Addendum to this report.

6. DEMONSTRATION TESTING

The mechanical operation of this vibrator was demonstrated at Dryden Flight Research Facility on June 30, 1984. This demonstration consisted of a low-power, manually switched cycle, which moved the vibrating mass between fixed points.

A complete, full-power demonstration of the vibrator was not possible because control system components failed during tests. These failures also prevented detailed evaluative testing of the basic design.

7. CONCLUSIONS

Demonstrated operation of this vibrator proves that the concept is sound, although the effectiveness of the design remains unknown. Detailed evaluation of this design should focus on its power requirements to determine how practically suited it is to a given application.

REFERENCES

1. Deam, Dirk; "A Design of an Electromagnetic Vibrator"; Flight Research Laboratory; University of Kansas Center for Research, Inc.; KU-FRL-407-9, June 1983.

ADDENDUM

(Continuation of Section 5: ELECTRICAL DESIGN DETAILS)

Contributed by

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Electrical Engineering Department
University of Kansas

February 1985

5.1 Control Computer

The signals to drive the flutter exciter were produced by a Rockwell AIM-65 microcomputer. This computer was chosen because it was available in house and met the requirements for this project. It was equipped with dual disc drives, a keyboard, a one-line LED display, a small printer, and an expansion chassis to facillitate interfacing the computer to the flutter exciter.

The program was written in 6502 assembly language to operate faster than the interpretative BASIC package with which the computer was equipped. To further speed up the operation of the computer, the digital values which represented the desired waveforms were pre-calculated and stored in tables. A programmable counter generated interrupts to cause the computer program to output the next value to the digital-to-analog converters at the correct time interval to produce the desired force as a function of time. Changing this time interval changed the frequency of the generated signals.

5.2 Power Modulator

The digital signals generated by the control computer are converted to analog voltages by 8-bit digital-to-analog converters (DAC's). These analog voltages are used to control the current flowing in the windings of the flutter exciter by circuitry shown in simplified form in Figure 13.

Because the upper half of the circuitry in Figure 13 is referenced to +72 volts and the lower half of this circuitry is referenced to ground, it is necessary to provide optical isolators between the digital computer parallel output ports and the DAC's. This difference in potential arises because the power transistors, Q02 and Q12, must be connected across the 72-volt DC supply.

The RC network around operational amplifier OA01 serves to increase the voltage swing by approximately a factor of two and also serves to limit the rate of change of voltage applied to the remainder of the circuit. The rate limitation provides for limiting the commutation voltage produced in the exciter windings as the mass moves. This rate limitation is well above the rates programmed to drive the exciter.

Operational amplifier OA02 serves as a voltage-to-current regulator. The voltage V_{01} applied to the input of OA01 is compared to the voltage across resistor R04. Since the voltage across R04 is proportional to the current through transistor Q02, the system functions as a voltage-to-current transducer. The RC network between OA02 and Q01 was needed to eliminate high-frequency oscillations in this circuit. The transistor Q01 serves to shift the voltage level of the signal between the output of operational amplifier OA02 and the base of the Darlington power transistor, Q02. In addition to the voltage level change, Q01 provides additional current gain so as not to overload OA02.

The operation of the lower half of the circuit chosen in Figure 13 is analogous to that described for the upper half of the circuit. The only essential difference is that there is no large shift in voltage level between the output of operational amplifier OA12 and the base of Darlington power transistor Q11.

The complete power modulator is shown in simplified form in Figure 14. Each of the even-numbered blocks represents the upper half of the analog circuitry shown in Figure 13. Each of the odd-numbered blocks represents the analog circuitry of the lower half of Figure 13.

The table shown in Figure 14 shows how the signals from the computer are connected to the winding of the flutter exciter. As noted earlier in Figure 5, current flows in only a portion of the winding in order to reduce the heating of the winding. In particular only three coils are active at any one time. As the mass moves, the three coils that are active change as shown in this table.

The direction of the force is determined by the direction of the current in the coils. Consider the mass to be in position 0. If the force is to be up, then current control units 0 to 7 are activated and current flows from left to right. On the other hand, if a downward force is desired, then current control units 1 and 6 are activated and the current flows from right to left.

The computer uses information from the position sensor to determine which current control units are active and, hence, the direction of the current in the coils of the flutter exciter. The magnitude of the current is determined by the value read from the table of pre-calculated amplitudes.

The design in phase one of this development project called for one DAC per current control unit. However, in the second phase of this project, we realized that the number of DAC's could be reduced from fourteen to four by sharing one DAC with four control units. The use of four DAC's left open the possibility of programming the commutation of the windings as the mass moved. If the RC networks that limit the rate of change of voltage are adequate to properly commutate the winding, then the number of DAC's could be reduced from four to two. One DAC would operate all even-numbered current control units, and the other DAC would operate all odd-numbered current control units.

The table in Figure 14 shows which DAC's are active as a function of the position of the mass and the direction of the force being produced. This configuration for control assumes that adequate commutation of the winding can be accomplished using only the RC networks around operational amplifiers OA01 and OA11 as shown in Figure 13.

The analog output of the DAC's is switched to the appropriate one of four current control units by means of FET SPDT switches.

5.3 Packaging of the Control System

One DAC together with four of the operational amplifier circuits and FET switches were wire-wrapped on a plug-in card. Four of these cards plugged into a mother board which provided connections to DC power, connections to the parallel output ports of the digital computer, connections to the power modulator unit, and connections to the opto-electric position sensors on the flutter exciter.

The fourteen RC networks to prevent oscillation (R02, R03, and C02; R12, R13, and C12; ...) were mounted together with the level shifting transistors (Q01, Q11, ...), and the power Darlington transistors (Q02, Q12, ...) were assembled into the power modulator unit.

5.4 Power Supply

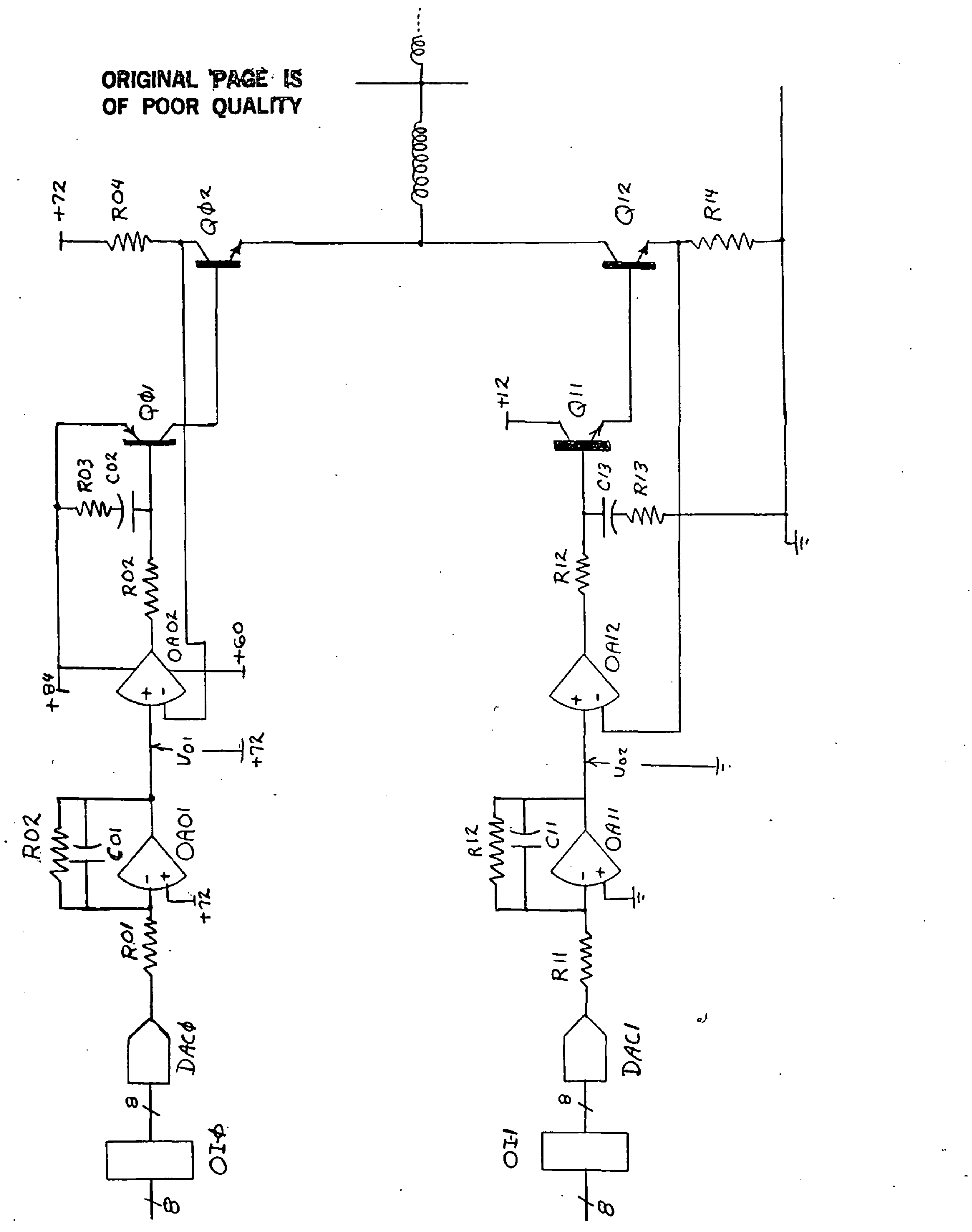
Six regulated DC power supplies rated at 24 volts and 7 amperes were connected in a series-parallel connection as shown in Figure 15. This connection provided 72 volts at 14 amperes to the power modulator for driving the flutter exciter. More than 14 amperes could be drawn for short periods of time for testing as limited by the temperature rise of the regulating transistors. In addition there were two power supplies rated for ±12 volts at 1 ampere. One of these supplies was referenced to ground and the other to +72 volts. These 12-volt supplies provided DC supply voltages for the DAC's and the operational amplifiers. Five volts DC was needed to power the optical isolators and ancillary control logic on the mother board. These power supplies were mounted on a board together with switches, fuses, and a connector strip for connection to the rest of the system.

5.5 Recommendations for Improvement

Based upon the experience with this development to date, and the improvement in power semiconductor devices since this project was started, a system configuration as shown in Figure 16 should be considered.

The programmable power supply would deliver the programmed current as a function of time, proportional to the desired force as a function of time. The commutation unit would consist of a network of 14 power transistors operated in a switching mode, rather than in a current regulating mode. In this mode these transistors would dissipate much less electric power, and hence less heat, than is the case with the current configuration where the current regulation and the commutation are combined into one set of transistors.

The heat dissipation burden is now shifted to the programmable power supply, but it is believed that new products are available which can handle this job. With this design, unregulated DC power would be used to supply the current regulator. Thus the power supply would be simplified.



K.U. Electrical Engineering

TITLE	SHEET
Figure 13: Simplified Schematic for Digital to Analog Current Conversion	1 OF 1

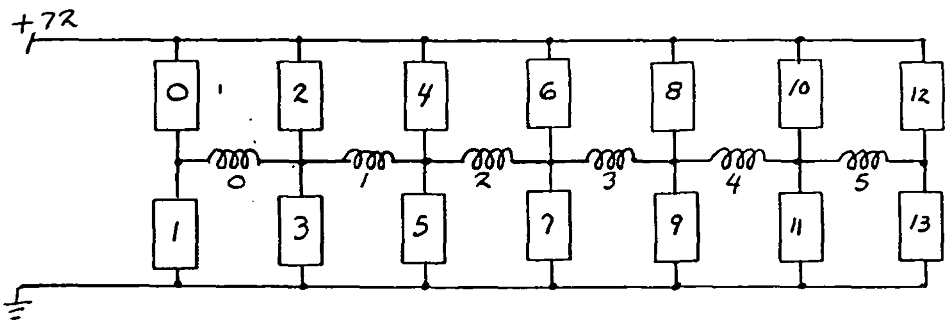
MODULE	CLASS	PAGE
		A-5 OF

DATE	DESIGN	DRAWN	DOCUMENT	REVISION

REV	ECO NO	DATE	BY

CURRENT CONTROL UNIT

□ REPRESENTS ONE-HALF OF ANALOG CIRCUIT OF FIGURE 13.



MASS POS.	COILS ACTIVE	FORCE UP CONTROL	FORCE UP DAC	FORCE DOWN CONTROL	FORCE DOWN DAC
Ø	Ø 1 2	Ø, 7	Ø, 3	1, 6	1, 2
1	1 2 3	2, 9	1, 2	3, 8	Ø, 3
2	2 3 4	4, 11	Ø, 3	5, 10	1, 2
3	3 4 5	6, 13	1, 2	7, 12	Ø, 3

K.U. Electrical Engineering

TITLE Figure 14: Simplified Schematic of Power Modulator Unit	SHEET 1 OF 1
MODULE	CLASS	PAGE A-6 OF
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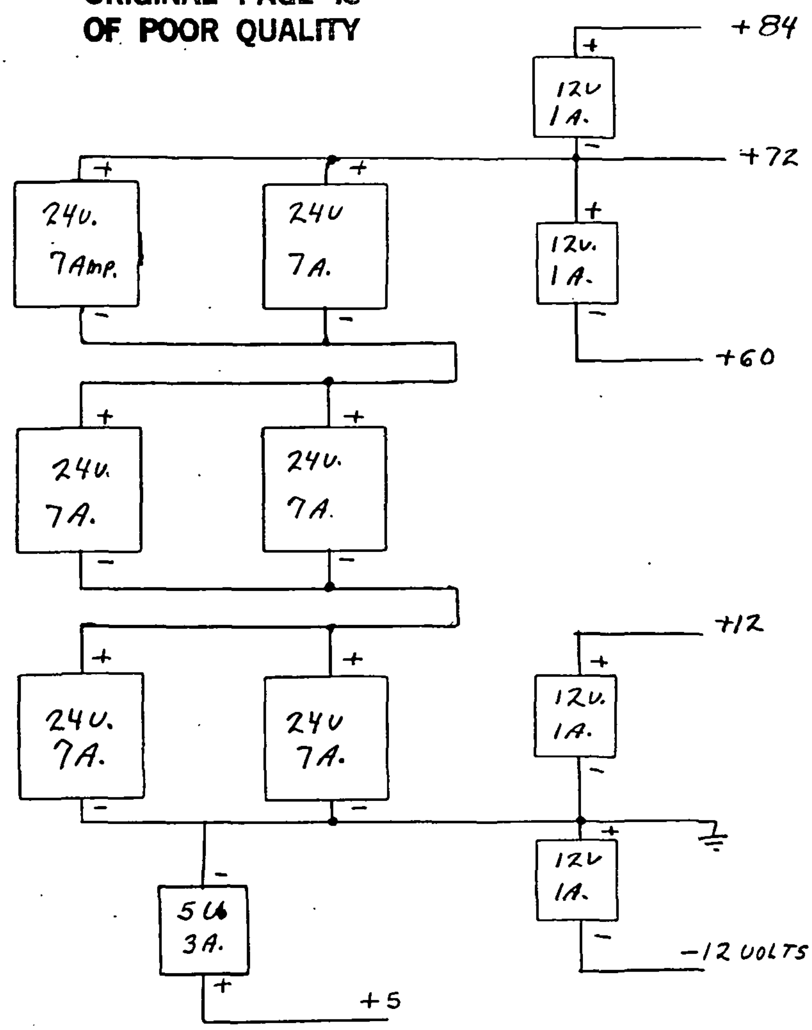

<u>NOTE</u>: 120-volt line to each power supply fused for overload protection.

K.U. Electrical Engineering	TITLE Figure 15: Power Supply Connections	SHEET 1 OF 1
	MODULE	CLASS	PAGE A-7 OF
	DATE	DESIGN	DRAWN	DOCUMENT	REVISION

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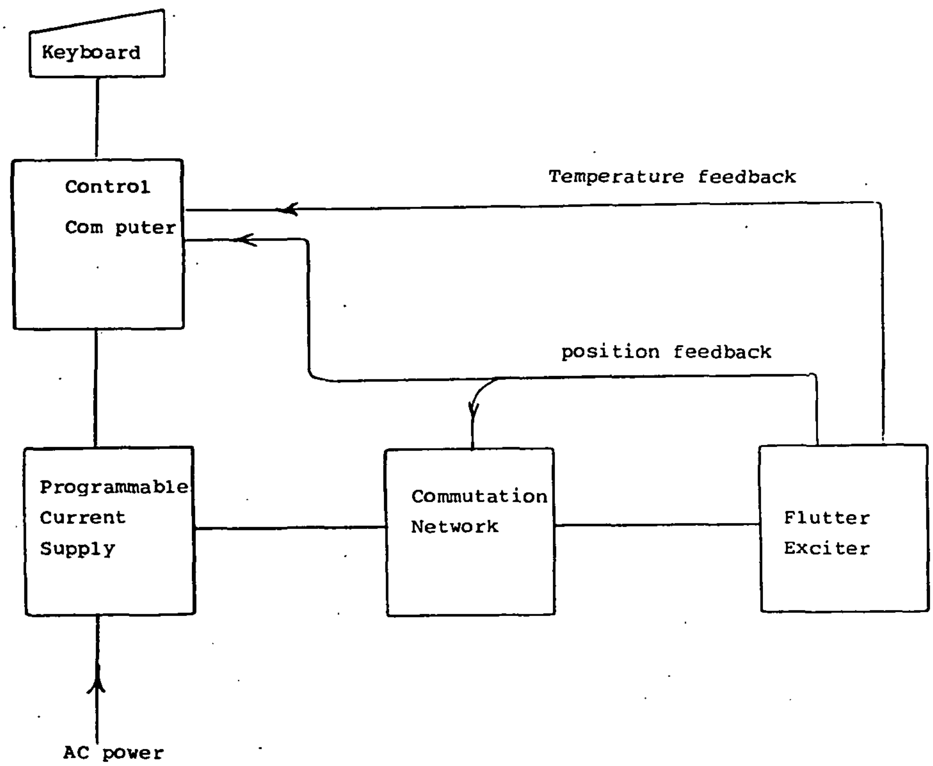

K.U. Electrical Engineering

TITLE Figure 16, Suggested Alternate Configuration for Improved Design

SHEET 1 OF 1

MODULE

CLASS

PAGE A-8 OF

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