AN ABSTRACT OF THE THESIS OF

UDAYA A. RANAWAKE for the degree of Master of Science in Electrical and Computer Engineering presented on APRIL 10, 1987.

Title: Preliminary Studies on a Magnetic Elevator for Solids (MES)

Abstract approved:

Alan K. Wallace

The thesis describes the preliminary studies on a laboratory model of a magnetic elevator intended as part of a system for circulating magnetic materials in chemical reactors. A multiple coil laboratory model, controlled by computer, was designed and constructed. Current measuring transducers were used to monitor system performance and study system response. Tests were performed on the model to investigate the effect of the following parameters.

1. coil spacing
2. energizing current
3. energizing time
4. particle size

The thesis presents the results of the above tests and gives the design for an adaptive controller as a means of improving system performance by incorporating some closed loop control.
Preliminary Studies on a Magnetic Elevator for Solids (MES)

by

Udaya A. Ranawake

A THESIS
submitted to
OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of
Master of Science

Completed April 10, 1987
Commencement June 1987
APPROVED:

Associate Professor of Electrical and Computer Engineering
in charge of major

Redacted for Privacy

Head of Department of Electrical and Computer Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented April 10, 1987
# TABLE OF CONTENTS

1.0 INTRODUCTION  
1.1 General  
1.2 Purpose of Research and Organization of Thesis  

2.0 THE MES TEST MODEL  
2.1 System Description  
2.2 System Components  
2.2.1 Elevator Coils and Tube  
2.2.2 The Processor Section  
2.2.3 Power Switching Stage  
2.2.4 Switch Driver System  

3.0 EXPERIMENTAL PROCEDURES  
3.1 General Description  
3.2 Measurement of Current  
3.2.1 Operating Principle  
3.2.2 Characteristics of the Current Sensors  
3.2.3 Calibration of Current Sensors  
3.2.4 Measurement of Output Voltage of Current Sensors  
3.2.5 Construction of the Current Waveforms  

4.0 TEST RESULTS  
4.1 The Current Waveforms  
4.2 Data Interpretation  
4.3 Efficiency of MES  

5.0 PROPOSED CONTROL DEVELOPMENTS AND ADAPTABILITY OF USING A MICROPROCESSOR  
5.1 Functional Block Diagram of the Proposed Controller  
5.1.1 The Sensor Section  
5.1.2 Digital Input/Output Port and Microprocessor  
5.2 A Hard Wired Controller for Continuous Motion of Particles  
5.2.1 Implementation of the Timer  

6.0 Concluding Remarks  
Bibliography  
APPENDIX A  
APPENDIX B  
APPENDIX C  
APPENDIX D  
APPENDIX E  
APPENDIX F  
APPENDIX G  
APPENDIX H  
APPENDIX I  
APPENDIX J  
APPENDIX K
LIST OF FIGURES

1.1 Idealized Solid Circulation System 3
1.2 The Concept of MES 3
1.3 Timing Sequence of Voltage Pulses 5
2.1 MES and Control System 9
2.2 Switch Driver System 12
3.1 Calibration of a Current Sensor 17
4.1 I1 and I2 vs. time 21
4.2 Variation of i vs. t 22
4.3 Variation of m vs. D 25
4.4 Variation of m vs. s 26
4.5 Variation of m vs. T 27
4.6 Variation of m vs. TLAP 28
4.7 Variation of m vs. i 29
4.8 Variation of m vs. d 30
5.1 Functional Block Diagram of the Proposed Controller 37
5.2 Functional Block Diagram of UGN 3040T 39
5.3 Characteristics of UGN 3040T Hall Probe 39
5.4 Schematic Diagram of MES with Hall Probes 40
5.5(a) Implementation of the Microprocessor to transfer a block of particles 42
5.5(b) Connection of a Hall Probe to the Microprocessor 43
5.5(c) Connection of Relay Interface to the Microprocessor 43
5.6 A Hard Wired Controller for Continuous Transfer of Particles

5.7 The Timer Circuit

A.1 Resistance Bridge

A.2 Inductance Bridge

B.1 Wiring Diagram of SSR

I.1 The Hall Element

J.1 Variables Affecting the Flux Density of a Solenoid
LIST OF TABLES

3.1 Relationship of Sieve No. to Aperture Wire Diameter 16

4.1 Time (from sampled data) for the current to reach the values corresponding to multiples of $T_c$ 23
PRELIMINARY STUDIES ON A MAGNETIC ELEVATOR
FOR SOLIDS (MES)

1.0 INTRODUCTION

1.1 General:

Magnetic phenomena have been known since ancient times. Lodestones, the mariner's compass and Gilbert's researches on the earth as a giant magnet all date before 1600. However, the connection between electricity and magnetism was not known until the nineteenth century, when Oersted discovered that an electric current affects the orientation of a compass needle. Soon thereafter Biot and Savart, and then Ampere developed the basic laws relating the magnetic flux density (B) to the electric current (I) and this opened up a multitude of applications from the electric motor onward.

One of the more recent applications of magnetism has been in the field of chemical engineering where it has been used to control the downflow of magnetic fine particles, creating a magnetic on-off valve for solids (MVS) or magnetic distributor downcomer for fluidized beds of solids (MDD) [1 - 4].

The object of the present study was to search for the proper way of manipulating the magnetic field to magnetically pump a stream of solids upwards. This new type of pump is to be called the magnetic elevator for solids (MES).

This study could be considered as the complement of
the previous studies on magnetically controlled valves. The MES will lead the way to the development of a complete solid circulation system, from reactor to regenerator and back again, all magnetically driven and electronically controlled, without mechanical valves or pneumatic driving forces and independent of the orientation of the equipment in the gravitational field. Figure 1.1 is an idealized sketch of what such a process could look like. In this system the solids are drawn upwards by MES and then gently lowered from stage to stage in reactor and regenerator under the control of the MVS.

Looking further into the future, this device may find use in the development of compact solar-driven power plants for space stations. With magnetic pumping of solids the orientation of the equipment in the gravitational field is no longer critical. One can pump the solids up and down, left and right, with no difficulty and without carrier gases, valves, pumps and so forth.

Figure 1.2 is a schematic diagram illustrating the concept of the MES which is essentially a vertical tube with a series of coils 1, 2, 3 & 4 etc. Magnetic particles are to be pumped up the tube by sequentially energizing the coils. When coil 1 is activated the solids jump up as shown in sketch (b). If, at just the right time, coil 2 is activated and shortly afterwards coil 1 is deactivated the solids jump up even higher, as shown in sketch (c). If
Figure 1.1: Idealized Solid Circulation System

Figure 1.2: The Concept of MES
this energizing sequence is extended to coils 3, 4 etc, the solids are thereby pumped upward by electromagnetic means only.

To optimize this device, one must answer a number of questions as follows:
1. What is the proper valve spacing and timing sequence?
2. What is the best size of solids to use?
3. What is the minimum energizing current of the coils for stable operation?

The primary aim of this research was to find the answers to the above questions when using a one-inch diameter vertical tube.

Instead of trying to optimize the timing sequence by trial and error one could also optimize this by using solid sensors placed just below each coil. One type of probe that is particularly suitable for this purpose is the Hall probe. When linked by a magnetic field it produces an output voltage, that is proportional to the flux density. When the solids rise the Hall probe will sense the presence of the particles and instruct the computer to energize the coil that is just above the probe making the particles slide further up the tube.

The control section of the MES is responsible for energizing the coils sequentially at the correct instant, for the proper duration of time. Figure 1.3 shows the timing sequence of the voltage pulses applied to three
Figure 1.3: Timing Sequence of Voltage Pulses
adjacent coils. The time duration for which a coil is energized (T) and the time of overlap (TLAP) where two of the adjacent coils are both energized are two of the variables that have to be optimized. An IBM personal computer was used as the processor section of the controller during the experimental stage as it eases the programming and the manipulation of variables. However, once the optimum T and TLAP have been determined the personal computer can be replaced by a dedicated microprocessor as it results in a smaller and cost effective processor section of the controller.

1.2 Purpose of Research and Organization of Thesis:

The objectives of the research are threefold;

1. To investigate the effects of coil spacing, energizing time, size of solids together with the minimum current requirements for stable operation so as to produce an operational device for laboratory control simulations.

2. To investigate the problem of interfacing current measuring transducers and Hall probes to an IBM personal computer as a means of recording performance and controlling the timing sequence.

3. To investigate the possibility of replacing the personal computer by a microprocessor.

The thesis is organized as follows. Chapter 2 provides a description of the MES test model. Experimental
procedures are described in Chapter 3, along with the construction of the current waveforms through two adjacent coils in order to gain an understanding of the response of the coils to applied voltage pulses. The test results are described in Chapter 4. Chapter 5 gives proposed control developments and adaptability of using a microprocessor. Finally, in Chapter 6 some suggestions are made for future work.
2.0 THE MES TEST MODEL

2.1 System Description:

Figure 2.1 is a schematic diagram of the MES and its control section. The MES is essentially a vertical tube with a series of toroidal copper coils. The control system consists of a power switching stage, a switch driver system and a processor section. The characteristics and function of each unit is briefly explained below.

2.2 System Components:

2.2.1 Elevator Coils and Tube:

The elevator of the MES is made up of a vertical, plastic tube of diameter 1 inch. The toroidal copper coils are wound around plastic formers of the same diameter as the tube. The coils have the following characteristics.

- Number of Turns............700
- Inner Diameter.............1 inch
- Outer Diameter.............3 inches
- Depth.......................1 inch
- Wire Gauge...............22
- Inductance...............17 milli-henrys
- Resistance...............2.85 ohms

(The circuit diagrams of the impedance bridge (Electro Scientific Industries Model 290A) used, for measuring resistance and inductance are shown in Appendix A).
Figure 2.1: MES and Control System
2.2.2 The Processor Section:

An IBM personal computer, equipped with an IBM data acquisition and control adapter and supporting software, is used as the processor section of the MES. The hardware and software facilities of the adapter are briefly described in this section. Further information can be found in the IBM Data Acquisition and Control Adapter Manual [5].

The IBM data acquisition and control adapter contains the following input-output capabilities:
1. Four channels of analog input
2. Two channels of analog output
3. A 16-bit binary input port
4. A 16-bit binary output port
5. A one-channel, 16 bit counter.

In addition the adapter is also equipped with both analog and binary handshaking facilities to communicate with external asynchronous devices. The supporting software is supplied as object modules in several high level languages such as Basic, Fortran and C. The supporting software uses three types of functions as given below:
1. Input Functions - These functions collect input data and move it to memory.
2. Output Functions - These functions move data from memory to an external device.
3. Utility Functions - These control counter/timer and program execution.

The functions also fall into distinct classes according to the rate or frequency at which the adapter performs them:

1. Simple Functions - Functions that execute only once.
2. Multiple Functions - Iterative functions that execute a specified number of times at a specified rate.
3. Scanning Functions - Functions that collect data from a range of consecutively numbered channels.

The programming is made easy by the possibility of using high level languages. The functions can be called like any other external subroutine with variables like the adapter number, device number, channel number, execution rate and the number of times a function executes etc, specified as the arguments of the subroutine.

2.2.3 Power Switching Stage:

The power switching stage employs a set of solid state relays incorporating a power MOSFET as the output device. The specifications of the relays are as listed below:

Manufacturer..................International Rectifier,
Model Number..................D1D20
Control Voltage Range........3.5 to 32 volts d.c.
Input Current...............1.6 to 28 milli-amperes
Maximum Turn On Time........100 micro-seconds
Operating Voltage Range......0 to 100 volts
Maximum Load Current...........20 amperes

The coils are highly inductive and are diode suppressed to prevent damage that could be caused by harmful transient voltages produced by rapid switching of the relays. The maximum on/off rate is limited by the rating of the diode as shown in Appendix B.

2.2.4 Switch Driver System:

The data acquisition and control adapter has only two on board A/D converters. Therefore the solid state relays are driven by the 16-bit digital output port on the adapter. Figure 2.2 is a schematic diagram of the switch driver system which is essentially an interface between the adapter and the power switching stage. It consists of sixteen 2N2222 transistors connected to the digital output port via sixteen 500k resistors. In this circuit the transistor itself is operated as a switch. When a bit
position on the digital output port is at logic '0' the corresponding transistor is cut-off and the relay is turned off. When the bit position is at logic '1' the transistor is driven into saturation. When the transistor is in saturation the collector to emitter voltage (V_{ce}) is nearly zero and the 5 volts drop across the relay turns it on.
3.0 EXPERIMENTAL PROCEDURES

3.1 General Description:

Experiments were conducted with the primary aim of transferring a block of particles up the elevator tube, to the topmost coil at maximum efficiency. The mass of the particles transferred was dependant on a number of variables such as T, TLAP, energizing current, coil spacing and particle type and the effect of each one of these variables were investigated. The elevator tube consisted of a removable lower section which was filled with the magnetic particles to the required level. The coils were energized by a variable, regulated, d.c. power supply via the power switching stage. The power supply voltage could be varied from 0 to 30 volts which corresponded to a variation of 0 to 6 amperes of the energizing current. The particles were transferred up the tube by sequentially energizing the coils. Once the particles were transferred to the top they were held by the top coil to allow sufficient time for the lower section of the elevator coil to be removed and then the coil was deenergized and the mass of the block of particles measured. Each reading was repeated six times and if the readings were not within acceptable limits or if they were not reproducible then that particular state of the MES was rejected as unstable. The coils were
energized by writing a 'one' at the corresponding bit position of the digital output port on the data acquisition and control adapter. The values of $T$ and TLAP were entered as input data from the keyboard of the control computer when executing the program. A listing of the computer program is given in APPENDIX C.

The different sizes of particles were obtained by screening through various test sieves of standard size openings. The screening surface consisted of wedge wire sections of equal-sized, square apertures that constituted a series of go/no-go gauges. The particles were agitated by a sieve shaker which imparted to the sieve both a circular and a tapping motion. Table 3.1 lists sieve number, the sieve opening and the wire diameter of the standard U.S. Sieve Series used for screening the particles [6].

The three particle types investigated corresponded to sieve numbers 25-20, 45-40 and 70-60. (A particle type corresponding to sieve number 25-20 passes through a screen of size 25 but is retained by a screen of size 20). From Table 3.1 the three particle sizes had average diameters of 0.775, 0.385 and 0.230 mm respectively.
Table 3.1: Relationship of Sieve No. to Aperture and Wire Diameter

<table>
<thead>
<tr>
<th>Sieve No.</th>
<th>Sieve Opening (mm)</th>
<th>Wire Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.840</td>
<td>0.420</td>
</tr>
<tr>
<td>25</td>
<td>0.710</td>
<td>0.370</td>
</tr>
<tr>
<td>30</td>
<td>0.590</td>
<td>0.330</td>
</tr>
<tr>
<td>35</td>
<td>0.500</td>
<td>0.290</td>
</tr>
<tr>
<td>40</td>
<td>0.420</td>
<td>0.250</td>
</tr>
<tr>
<td>45</td>
<td>0.350</td>
<td>0.220</td>
</tr>
<tr>
<td>50</td>
<td>0.297</td>
<td>0.188</td>
</tr>
<tr>
<td>60</td>
<td>0.250</td>
<td>0.162</td>
</tr>
<tr>
<td>70</td>
<td>0.210</td>
<td>0.140</td>
</tr>
</tbody>
</table>

3.2 Measurement of Current:
3.2.1 Operating Principle:

The currents through two adjacent coils were measured for various timing sequences in order to study the effect of the energizing current upon the mass of particles lifted by the MES. As the coils were energized for short time durations current measuring devices with fast response times were required. Therefore, the currents were measured by the use of current transducers working on the
principle of Hall effect. The current carrying conductor was passed through a flux collector which concentrated the flux around the conductor at a linear output Hall effect transducer. The amplified output, which is proportional to the current, was fed to a voltage measuring device which was directly calibrated to read the current.

3.2.2 Characteristics of the Current Sensors:
Manufacturer......................MICRO SWITCH
Model Number....................CSLB1AD
Supply Voltage..................10 to 15 volts
Maximum Sensed Current........57 amperes
Response Time...................8 micro-seconds

3.2.3 Calibration of Current Sensors:
The current sensors were first calibrated to obtain the conversion ratio of the output voltage to the current (sensitivity). Figure 3.1 is a schematic diagram of the

![Figure 3.1: Calibration of a Current Sensor](image-url)
circuit used. The offset voltage was first measured by taking the voltmeter reading at zero current and then the output voltage of the sensor was recorded at different currents. This data is tabulated in Appendix D where the calculation procedure for the sensitivity is also shown.

3.2.4 Measurement of Output Voltage of the Current Sensors:

The output voltage of the current sensors were measured by using two of the A/D converters on the data acquisition and control adapter. The output of the sensors were fed to the analog input of the converters and their digital outputs were read by analog input function software and processed to obtain the value of the currents through the coils. The A/D converters had a resolution of 12 bits and a range of -5 volts to +5 volts. The current carried by a coil was computed by the following expression:

\[ I = \frac{|RAWVAL - OFFSET| \times 10 \times s}{2^{12}} \]

where:

- I - current through the coil
- S - scale factor of a current sensor
- OFFSET - number read by the computer at zero current
- RAWVAL - number read by the computer at current I.
3.2.5 Construction of the Current Waveforms:

The current waveforms through two adjacent coils were constructed in order to gain an understanding of the response of the coils to applied voltage pulses. The waveforms for $T=0.3$ seconds and $TLAP=0.1$ seconds were constructed by sampling the two A/D converter channels to which the output of the current sensors were connected at a rate of 1000 samples/second. A more detailed waveform showing the buildup of the current through a coil for $t=0$ to $t=0.012$ seconds was also constructed by the use of a higher sampling rate of 10000 samples/second. The programs for implementing these are listed in APPENDIX E and APPENDIX F.
4.0 TEST RESULTS

4.1 The Current Waveforms:

Figure 4.1 shows the current waveforms through two adjacent coils for $T=0.3$ seconds and $TLAP=0.1$ seconds. As expected the current waveforms through the coils approximate square pulses. The figure also shows how the load is shared between the coils when both coils are switched on during the time interval $TLAP$. It can be seen that the currents are equally distributed as the two coils are nearly identical to one another. The spikes on the current waveforms can be caused by supply voltage variation of the coils. Also, some error is caused by the supply voltage variation of the current sensor and noise generated within the operational amplifier of the sensor due to thermal effects.

A more detailed diagram showing the build-up of current from $t=0$ to $t=0.012$ seconds is shown in Figure 4.2. The time constant ($Tc$) of a coil can be evaluated by using the sampled data used in constructing this current waveforms. Table 4.1 lists the change of current ($i$) (as a percentage of the steady state current) in relation to $Tc$. Time (from sampled data) for the current to reach the values corresponding to multiples of $Tc$ is also shown.
Figure 4.1: I1 and I2 vs. time

T=0.3 s and TLAP=0.1 s
Figure 4.2: Variation of $i$ vs. $t$
Table 4.1: Time (from sampled data) for the current to reach the values corresponding to multiples of Tc

<table>
<thead>
<tr>
<th>Tc</th>
<th>i,%</th>
<th>t (milli-seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>63.2</td>
<td>0.45</td>
</tr>
<tr>
<td>2</td>
<td>86.4</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>95</td>
<td>11.0</td>
</tr>
</tbody>
</table>

From Table 4.1 Tc is the difference between any two adjacent values of the third column. Therefore the values of Tc as given by Table 4.1 are 0.45, 4.05 or 6.50 milli-seconds. The time constant can also be calculated from the experimentally determined values of L and R as follows:

\[
Tc = \frac{L}{R} \text{ seconds}
\]

\[
= \frac{17 \times 10^{-3}}{2.85} \text{ seconds} = 5.96 \text{ milli-seconds}
\]

We observe that the last two values of Tc as obtained from Table 4.1 are in close agreement with the values calculated using the measured values for L and R. The discrepancy in the first value is due to the delay caused by the software overhead of the current measuring subroutine.
4.2 **Data Interpretation:**

Figure 4.3 through 4.8 show the variation of average mass \( m \) with the following parameters.

1. distance between the first coil and particle level \( D \)
2. particle diameter \( s \)
3. energizing time \( T \)
4. time of overlap \( T_{LAP} \)
5. energizing current \( i \)
6. coil spacing \( d \)

Figure 4.3 is the graph showing the ability of coil 1 to capture particles. We observe that \( m \) remains constant for \( D=0.25 \) and \( D=0.5 \) inches and decreases rapidly to zero as \( D \) is increased further. This decrease in \( m \) is in fact due to the large variation of the mass of the particles lifted by the MES at different attempts. We observe from the data in Appendix G that at \( D=0.25 \) inches and 0.5 inches the variation is about 5% while at \( D=0.75 \) inches and 1.0 inches the variation is as high as 100%. Therefore for stable operation the MES should be operated at \( D=0.5 \) inches.

Figure 4.4 shows the variation of \( m \) with particle type. The graphs show that \( m \) decreases with decreasing particle diameter. Since the system performs best with the largest particle type efforts were concentrated on this type of particles only.
$s = 0.775 \text{ mm, } d = 1.0 \text{ inches, } T = 0.7 \text{ s}$

$\text{TLAP} = 0.3 \text{ s, } i = 5.7 \text{ amperes}$

Figure 4.3: Variation of $m$ vs. $D$
Figure 4.4: Variation of $m$ vs. $s$

- □: $i = 5.7$ amperes
- +: $i = 3.5$ amperes
\[ s = 0.775 \text{ mm}, \quad d = 1.0 \text{ inches} \]

\[ \diamond : i = 5.7 \text{ A}, \quad + : i = 5.0 \text{ A}, \quad \odot : i = 3.5 \text{ A} \]

Figure 4.5: Variation of \( m \) vs. \( T \)
Figure 4.6: Variation of \( m \) vs. TLAP

\[ s = 0.775 \text{ mm}, \quad d = 1.0 \text{ inches}, \quad T = 0.7 \text{ s} \]

\( \square : i = 5.7 \text{ amperes} \quad + : i = 3.5 \text{ amperes} \)
Figure 4.7: Variation of \( m \) vs. \( I \)

- \( s = 0.775 \text{ mm}, \quad d = 1.0 \text{ inches} \)
- \( \square: T = 0.7 \text{ s}, \text{TLAP} = 0.3 \text{ s} \)
- \( +: T = 0.1 \text{ s}, \text{TLAP} = 0.05 \text{ s} \)
Figure 4.8: Variation of m vs. d

□: s=0.775 mm, T=0.7 s, TLAP=0.3 s, i=5.7 A
○: s=0.775 mm, T=0.1 s, TLAP=0.05 s, i=5.7 A
+: s=0.775 mm, T=0.7 s, TLAP=0.3 s, i=3.5 A
The variation of \( m \) with \( T \) is shown in Figure 4.5. The graph shows that as \( T \) is gradually decreased, \( m \) remains practically constant until a critical value is reached beyond which it decreases sharply to zero. This critical value of \( T \) is in the range of 0.1 seconds which is representative of the time taken by the particles in the removable lower section of the tube to get magnetized and align themselves along the flux lines when the first elevator coil is energized.

The variation of \( m \) with TLAP is similar to the variation of \( m \) with \( T \) as shown in Figure 4.6. For a given \( T \) the maximum value of TLAP is \( T/2 \). The graphs show that TLAP also has a critical value which is about 0.05 seconds.

When a coil is energized some time is required as determined by the time constant, for the magnetic field to reach its steady state value. The particles will begin to be attracted as current (field) is increasing and align themselves along the lines of magnetic flux. If the coil holding the particles is deenergized before the completion of this transition some of the particles will drop down the elevator tube. The critical value of TLAP is a measure of the minimum time required for a smooth transition of a block of particles from one coil to the other. However, since larger values of TLAP results in larger values of \( m \) and a higher efficiency, TLAP should be selected equal to \( T/2 \).
The variation of $m$ with $i$ for two sets of $T$ and TLAP is shown in Figure 4.7. The minimum current for stable operation is about 3.2 amperes. The figure shows that the average mass increases with increasing energizing currents. However, the analysis is complicated by the fact that the trajectories of the particles are not axial and linear, but tend to move towards the walls of the elevator tube. Further, the effect of friction between the particles and the elevator tube as well as the relative movement of one particle layer about another has to be considered.

Figure 4.8 shows the variation of $m$ with $d$. We observe that $m$ remains constant or increases at a small rate with increasing $d$ until $d$ is about 1 inch. The MES did not operate at all for $d$ greater than 1 inch. Therefore this represents the largest spacing between the elevator coils for a smooth transition of a block of particles from one coil to the other for the given range of excitation currents when the MES is operated in the walking mode.

### 4.3 Efficiency of MES:

The efficiency ($\eta$) of MES is defined as:

$$\eta = \frac{\text{potential energy output}}{\text{electrical energy input}}$$  \hspace{1cm} 4.1$$

The losses come from three mechanisms, namely the copper loss of the elevator coils, the hysteresis loss of
the iron particles as the current is switched on and off and the frictional loss. The frictional loss and hysteresis loss can be neglected compared to the copper loss.

Therefore \( \eta \) is given by:

\[
\eta = \frac{\text{potential energy output}}{\text{potential energy output} + \text{losses}} \quad 4.2
\]

Potential energy output = \( mg \left[ \sum_{i=1}^{N-1} l(i) + L \right] \quad 4.3 \)

Losses = \( \sum_{i=1}^{N} R(i) \left\{ I^2(i) \left\{ T(i) - TLAP(i) - TLAP(i+1) \right\} + ILAPF^2(i) TLAP(i+1) + ILAPR^2(i) TLAP(i) \right\} \quad 4.4 \)

where:

- \( m \) - mass of particles, kg
- \( L \) - distance between the center of the first coil and center of gravity of the block of particles
- \( l(i) \) - distance between the centers of coils \( i \) and \( (i+1) \), meters
- \( I(i) \) - current through coil \( i \), amperes
- \( ILAPF(i) \) - current through coil \( i \) when coils \( i \) and \( (i+1) \) are both energized
- \( ILAPR(i) \) - current through coil \( i \) when coils \( (i-1) \) and \( i \) both energized
- \( R(i) \) - resistance of coil \( i \), ohms
- \( T(i) \) - energizing time of coil \( i \), seconds
- \( TLAP(i) \) - time duration for which coils \( i \) and \( (i-1) \) are both energized
N - number of elevator coils

For identical coils with equal spacing:

\[ R(i) = R \text{ ohms} \]

\[ l(i) = l \text{ meters} \]

The following initial values are used in computing losses.

\[ TLAP(1) = 0, \quad TLAP(n+1) = 0, \quad ILAPR(1) = 0, \quad ILAPF(n) = 0 \]

Further assuming constant energizing current and time duration:

\[ T(i) = T, \quad I(i) = I, \quad ILAPF(i) = ILAPR(i) = ILAP, \]

\[ TLAP(i) = TLAP \]

Then \( \eta \) is given by:

\[
\eta = \frac{mg[L + (N-1)l]}{mg[L + (N-1)l] + I^2 R[N - 2(N-1)TLAP] + 2(N-1)ILAP^2TLAP} \tag{4.5}
\]

Assuming the particles are closely packed the value of \( L \) is given by:

\[
L = \frac{m}{2\pi \rho r^3} + L' \tag{4.6}
\]

where:

\( \rho \) - particle density, \( \text{kg/m}^3 \)

\( r \) - radius of the tube, \( \text{m} \)

\( L' \) - distance between the center of the first coil and particle level

A sample calculation of the efficiency is given in APPENDIX H.
We observe that the efficiency of the MES is very low, being less than even 1%. The main reason for the low efficiency is the high copper loss in the elevator coils. The decrease in efficiency due to copper loss can be compensated by increasing the height to which the particles can be lifted with a given number of coils. This would be possible only if the particles could be made to accelerate as they slide up the elevator tube. The distance between the elevator coils could be gradually increased as the particles gain speed and if the number of coils is large a higher efficiency would result. In order to accelerate the particles it is essential that the coils be energized at the right instant of time so that the magnetic field produced by the current exerts the maximum possible force at the right time and for the minimum duration on the block of particles. The energizing of the coils at the proper instant of time could be achieved by a probe placed just below the coils which detects the presence of particles and instructs the computer to energize the coil.
5.0 PROPOSED CONTROL DEVELOPMENTS AND ADAPTABILITY OF USING A MICROPROCESSOR

In order to attain high efficiency it is essential that the elevator coils be energized at the right time for the minimum duration so that the maximum possible force is exerted on the block of particles sliding up the tube. This necessitates the use of some closed loop control for the detection of the presence of particles and energizing of the elevator coils.

The energizing time sequence of the MES can be controlled by probes placed just below the elevator coils. When a block of particles approaches a coil the probe just below the coil should detect the presence of particles and send a signal to the computer to energize the relay controlling this coil so as to accelerate the particles further up the elevator tube. One type of probe suitable for this application is the Hall probe which works on the principle of Hall effect. APPENDIX I gives a brief description of the Hall principle and Hall probe.

5.1 Functional Block Diagram of the Proposed Controller:

Figure 5.1 illustrates the proposed control section of the MES. It consists of a sensor section, a digital input/output port, a microprocessor, a relay interface and solid state relays.

5.1.1 The Sensor Section:

The sensor section consists of the set of Hall probes
Figure 5.1: Functional Block Diagram of The Proposed Controller
used to detect the presence of magnetic particles. Although probes with both analog and digital outputs are available the latter type is better suited for our application as microprocessors are capable of processing only digital data.

The proposed controller uses a bipolar Hall effect digital switch, UGN 3040T manufactured by Sprague Electric Company [7]. Figure 5.2 shows the functional block diagram of the probe. The transfer characteristics are depicted in Figure 5.3.

Figure 5.4 is a schematic diagram of the MES incorporating Hall probes. To ensure smooth functioning of the system the following factors must be taken into consideration.

1. The optimum distance between the probe and the controlled coil (x) should be experimentally determined to ensure that the coil is activated at the right time so as to exert the maximum possible force on the block of particles.

2. The distance between the probe and the coil immediately below it (y) should be large enough so that the probe is not activated by the magnetic field of this coil.

APPENDIX J gives a sample calculation for the minimum value of y for a given excitation current.

5.1.2 Digital Input/Output Port and Microprocessor:
The function of the microprocessor is to receive signals from the Hall probes and to energize the relay
Figure 5.2: Functional Block Diagram of UGN 3040T

Figure 5.3: Characteristics of UGN 3040T Hall Probe
Figure 5.4: Schematic Diagram of MES with Hall Probes
controlling the coil immediately above this probe to accelerate the block of particles. The digital input/output port acts as the interface between the microprocessor and the outside world (sensor and solid state relays).

The input/output port and the microprocessor can be implemented on a single chip by the use of MCS-51 family of microprocessors [8-9]. For example the 8051 contains an 8-bit CPU, 4Kx8 ROM program memory, 128x8 data memory, four, 8 bit input/output ports and two, 16-bit counters.

Figure 5.5 (a) shows a possible implementation of the controller to transfer a block of particles up the elevator tube for a MES employing 7 elevator coils. The connection of the Hall probes and the transistor interface circuit to input/output ports are shown in Figure 5.5 (b) and 5.5 (c). The probes and coils are numbered starting from the one at the bottom of the elevator coil. Further, since there is no probe below the first coil the total number of probes will be one less than the total number of coils. The controller is implemented by using the multiple source, nested interrupt system of the 8051 microprocessor. The interrupt response latency ranges from 3 μs to 7 μs when using a 12 MHz crystal. In the circuit shown in Figure 5.5 (a) the first four probes are connected to pin INTO and the remaining four to INT1 of the 8051 microprocessor. Port P1 is used as an output port controlling the relays.
Figure 5.5 (a): Implementation of the Microprocessor to transfer a block of particles
Figure 5.5 (b): Connection of a Hall Probe to the Microprocessor

Figure 5.5 (c): Connection of Relay Interface to Microprocessor
The energizing time is controlled by using one of the 16 bit, on board timers of 8051. With a 12 MHz crystal, the input pulse train to the timer has a frequency of 1 MHz as it is obtained by dividing the on chip oscillator frequency by twelve. These timers are started and stopped under software control and can be configured to operate in several modes. For our application, as the energizing time of a coil is in the order of several milli-seconds it is necessary to operate the timer in the 8-bit auto reload mode. This means that with a 1 MHz input pulse train the timer would overflow once in every 256 micro-seconds. The overflow of the timer will cause an interrupt which results in the transfer of control to an interrupt service routine. The interrupt service routine maintains another software counter whose initial value times 256 micro-seconds equals the energizing time of a coil. Whenever the program branches to this interrupt routine this software counter is decremented. Once this counter becomes zero it denotes the elapse of the energizing time of the coil.

It is assumed that the elevator coils have different energizing times ranging up to a maximum of 200 milli-seconds. When started, the program first executes an initializing routine where the registers R1 - R7 of register
banks 1 and 2 are preloaded with values corresponding to the different energizing times of the elevator coils. For example, if the energizing time of coil 1 is 128 mill-seconds the registers R1 of register banks 1 and 2 are loaded with 500 (The two 8 bit registers are considered as equivalent to one 16-bit register). The initializing routine also turns on the timer and energizes the first elevator coil.

A block of magnetic particles approaching a probe causes its output to go high which results in an interrupt. This will result in the transfer of control to an interrupt service routine. This routine first identifies the probe which caused the interrupt by reading Port P0 of the microprocessor. The coil is then energized and the contents of the registers preloaded with the value corresponding to the energizing time of the coil are transferred to registers in register banks 2 and 3. For example, if probe 1 caused the interrupt registers R1 of register banks 2 and 3 are loaded with 500. The registers of banks 2 and 3 function as temporary counters which are decremented with each overflow of the timer.

The timer, controlling the energizing time is programmed to overflow once in every 256 micro-seconds. The program then branches to the timer interrupt service routine. In this routine the registers of banks 2 and 3 (treated as 1, 16 bit register) are decremented if they
contain a positive value, because a register with a positive value corresponds to an energized, elevator coil. Whenever a counter becomes zero the corresponding coil is deenergized.

A program written in 8051 assembly language that implements this function is listed in APPENDIX K.

This idea could be easily extended to design a controller for continuous transfer of particles by periodically energizing coil 1. As each microprocessor can control, a group of elevator coils it is cost effective and easy to implement. However, some error is introduced in the energizing time interval since the interrupt service routine for a probe does not read the current status of the timer. The programming would be more difficult if we were to correct for this error. Further, this error is only about 256 micro-seconds which is acceptable compared to the energizing time of several hundred milli-seconds of a coil. If one needs to reduce this error further it could be done by programming for a smaller timer overflow period by loading the 8 high order bits of the timer with a suitable value.

5.2 A Hard Wired Controller for Continuous Motion of Particles:

Another approach in designing a controller for continuous motion of particles is a hard wired controller which incorporates a simple a logic circuit as shown in Figure 5.6 [10-11].
Figure 5.6: Hard Wired Controller for Continuous Transfer of Particles
In this circuit when a Hall probe is activated it sets the JK flip-flop which is driving the base of the transistor controlling the relay. The output signal of the probe also turns on a timer. The timer can be initialized and preset by external signals. When the timer overflows it gives a DONE signal which resets the flip-flop, deenergizes the coil and initializes the timer for the transfer of the next block of particles. The circuit will begin functioning again on receipt of another signal from the probe.

5.2.1 Implementation of the Timer:

Figure 5.7 shows a possible implementation of a timer to control the timing sequence, where the energizing time could be set to any value from 0 to 99 mS to an accuracy of 1 mS. The energizing time is set via two switch registers. The resistance and capacitor values of the 555 timer are selected to give an output pulse train of period 1 mS. Two mod-10 counters (7490) are used to count the output pulses of the 555 timer. The counters are enabled only when the output of the Hall probe is in the high state. The output of the counters are compared with the contents of the switch registers by the 4 bit comparators (7485). When the counter outputs become equal to the preset value the output lines of the two comparators are set high. The DONE signal is obtained by the logical 'AND' of the two comparator outputs.
Figure 5.7: The Timer Circuit
However, as each elevator is controlled by a separate controller, the high cost involved in building this circuit makes it inattractive compared to a microprocessor controlled controller.
An operational MES suitable for laboratory use consisting of a 1 inch diameter vertical tube and 16 toroidal copper coils was successfully implemented. The device was capable of producing repeatable results in transferring a block of fine, magnetic particles up the elevator tube to the topmost coil. However, the overall efficiency of the MES was very low and therefore further studies are necessary before this device could be successfully incorporated as part of a solid circulation system in chemical reactors. These are explained below.

In order to gain an understanding of the behaviour and predict means for improving performance it is proposed to develop a computer model to simulate the MES. Such a computer model consists of a set of differential equations, one per coil describing the operation of the MES. In developing the model the effect of various parameters such as coil spacing, coil diameter, energizing time, energizing current, type of magnetic particle, tube inclination etc. should be taken into account. The solution to the equations would yield the mass of the particle block and a real time solution to its motion up the elevator tube. Then one would be able to graphically view the motion of the particle block on the computer screen for various values of the set of parameters. The implementation of the model would be
difficult but feasible with the vast amount of computing power of modern computers. Difficulties will be mainly in the determination of the parameters of the set of simultaneous differential equations. Finite element analysis models may prove useful in predicting these parameters.

It is also necessary to implement the proposed control developments in Chapter 5 to investigate the possibility of improving the MES efficiency by energizing the elevator coils at the right time. The present study concentrated only on the vertical motion of the particles. Further studies are required to investigate the ability of the magnetic particles to slide up inclined tubes and move around corners. It is also important to study the effect of various coil diameters as a commercially built MES will obviously have to incorporate an elevator tube larger than 1 inch.
BIBILIOGRAPHY


APPENDIX
Figure A.1: Resistance Bridge
Figure A.2: Inductance Bridge

(Diagrams obtained from Electro Scientific Industries, Inc.)
APPENDIX B

Calculation of Maximum Switching Rate:

\[ \frac{1}{\text{time from one turn-off to next}} \]

Let:

- \( I_L \) - d.c. load current in amperes
- \( L \) - load inductance in henrys
- \( t_{tr} \) - time from one turn-off to next
- \( I_F \) - rated maximum forward current of diode in amperes
- \( V_F \) - rated maximum forward voltage of diode in volts.

For the NTE5818 diode used:

- \( I_F = 12 \) amperes
- \( V_F = 1.4 \) volts

Then \( t_{tr} \) is determined by the following inequality:

\[ I_F V_F > \frac{I_L}{L} \]

\[ (t_{tr})_{\text{min}} = \frac{I_L}{I_F V_F} \]

For a load current of 6 amperes:

\[ (t_{tr})_{\text{min}} = \frac{6.0 \times 0.017}{12 \times 1.4} = 0.036 \text{ seconds} \]

maximum switching rate = \( \frac{1}{0.036} \) times per second

= 27 times per second
APPENDIX C

Program Listing

This is a generalised program to sequentially energize sets of elevator coils. The coil numbers, T and TLAP of a set are specified in a data file. Each set can contain a maximum of four coils. The program also monitors the currents through two of the coils of the first two sets.

---

```fortran
DIMENSION IVAL(16), IDATA(16), ILAP(16), ITOT(16)
DIMENSION T(16), TLAP(16), T1(16), T2(16)
INTEGER*2 A(20), B(20), C(20), D(20)
INTEGER*2 P, Q, R, S, RAWVAL
INTEGER*2 RAWV1(30), RAWV2(30), RAWV3(30), RAWV4(30)
INTEGER*4 CT1(16), CT2(16), CLAP(16)
INTEGER*4 RT1, RT2, RT3, RLAP
CHARACTER*4 REPLY
WRITE(*,*) 'INPUT NO. OF RECORDS'
READ(*,*) N
WRITE(*,*) 'INPUT NO. OF ITERATIONS'
READ(*,*) ICOUNT
OPEN(20, FILE='DAT1', ACCESS='DIRECT', FORM='FORMATTED', RECL=24)
OPEN(30, FILE='DAT2', ACCESS='DIRECT', FORM='FORMATTED', RECL=5)
DO 10 I=1, N
  READ(20,1, REC=I, END=10) A(I), B(I), C(I), D(I), T(I), TLAP(I)
WRITE(*,*) A(I), B(I), C(I), D(I), T(I), TLAP(I)
10 CONTINUE
DO 15 I=1, 16
  READ(30,2, REC=I, END=15) IVAL(I)
15 CONTINUE
DO 40 I=1, N
  P=0
  Q=0
  R=0
  S=0
  DO 50 J=1, 16
    IF (A(I).EQ.J) P=IVAL(J)
    IF (B(I).EQ.J) Q=IVAL(J)
    IF (C(I).EQ.J) R=IVAL(J)
    IF (D(I).EQ.J) S=IVAL(J)
  50 CONTINUE
IDATA(I)=P+Q+R+S
IVAL(0)=0
DO 70 I=1, N-1
  P=0
  Q=0
  R=0
```

---
S=0
IF((A(I) .EQ. A(I+1)) .OR. (A(I) .EQ. B(I+1)) .OR. (A(I) * .EQ. C(I+1)) .OR. (A(I) .EQ. D(I+1))) P=IVAL(A(I))
IF((B(I) .EQ. A(I+1)) .OR. (B(I) .EQ. B(I+1)) .OR. (B(I) * .EQ. C(I+1)) .OR. (B(I) .EQ. D(I+1))) Q=IVAL(B(I))
IF((C(I) .EQ. A(I+1)) .OR. (C(I) .EQ. B(I+1)) .OR. (C(I) * .EQ. C(I+1)) .OR. (C(I) .EQ. D(I+1))) R=IVAL(C(I))
IF((D(I) .EQ. A(I+1)) .OR. (D(I) .EQ. B(I+1)) .OR. (D(I) * .EQ. C(I+1)) .OR. (D(I) .EQ. D(I+1))) S=IVAL(D(I))
70 ILAP(I)=P+Q+R+S
DO 75 I=1,N-1
75 ITOT(I)=IDATA(I)+IDATA(I+1)-ILAP(I)
ITOT(N)=0
DO 500 I=1,N
WRITE(*,*) IDATA(I), ILAP(I), ITOT(I)
500 CONTINUE
1 FORMAT(4(1X,I2),2(1X,F5.3))
2 FORMAT(I5)
TLAP(N+1)=0
DO 105 I=1,N
T2(I)=T(I)-TLAP(I)-TLAP(I+1)
CLAP(I)=INT(TLAP(I)*1000.)
105 CT2(I)=INT(T2(I)*1000.)
RT1=INT(15./T2(1))
RT2=INT(15./T2(2))
RT3=INT(15./TLAP(3))
RLAP=INT(15./TLAP(2))
WRITE(*,*)RT1,RT2,RT3,RLAP
60 CALL AINS(0,9,2,0,RAWVAL,O)
OFFSE2=RAWVAL
CALL AINS(0,9,3,0,RAWVAL,O)
OFFSE3=RAWVAL
DO 100 II=1,ICOUNT
CALL BOUS(0,8,0,IDATA(1),0)
CALL AINM(0,9,2,0,0,0,15,RT1,RAWV1(1),0)
CALL BOUS(0,8,0,IDATA(1),0)
CALL AINM(0,9,2,0,15,RLAP,RAWV2(1),0)
CALL BOUS(0,8,0,IDATA(2),0)
CALL AINM(0,9,3,0,0,0,15,RT2,RAWV3(1),0)
CALL BOUS(0,8,0,IDATA(2),0)
CALL AINM(0,9,3,0,0,0,15,RT2,RAWV3(1),0)
DO 100 I=3,N
CALL BOUS(0,8,0,IDATA(I),0)
CALL DELAY(0,CT2(I),0)
IF(I.EQ.N)GOTO 100
CALL BOUS(0,8,0,IDATA(I),0)
CALL DELAY(0,CLAP(I+1),0)
100 CONTINUE
WRITE(*,*)'READY?'
270 READ(*,*)REPLY
IF(REPLY.EQ.'YES')GOTO 290
GOTO 270
290 CALL BOUS(0,8,0,0,STAT1)
CUR1 = -(RAWV1(8) - OFFSE2)*.0037
CUR2 = -(RAWV2(15) - OFFSE2)*.0037
CUR3 = -(RAWV2(16) - OFFSE3)*.0040
CUR4 = -(RAWV3(8) - OFFSE3)*.0040
CUR5 = -(RAWV4(8) - OFFSE3)*.0040
WRITE(*,101) CUR1, CUR2
WRITE(*,102) CUR3, CUR4, CUR5
WRITE(*,*)'EXECUTION COMPLETE'
WRITE(*,*)'NEW DATA?'
READ(*,*)REPLY
IF(REPLY.EQ.'NO')GOTO 60
101 FORMAT(2(1X,F5.2))
102 FORMAT(3(1X,F5.2))
STOP
END
APPENDIX D

Calculation of the Sensitivity of Current Sensors:

Characteristics of Sensor 1:
Type: CSLB1AD, MICROSWITCH
Offset voltage = 0.11 volts

Table D.1: Variation of Output Voltage vs. Current

<table>
<thead>
<tr>
<th>Current (amperes)</th>
<th>Output Voltage (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.31</td>
<td>1.63</td>
</tr>
<tr>
<td>2.69</td>
<td>1.87</td>
</tr>
<tr>
<td>3.05</td>
<td>2.11</td>
</tr>
<tr>
<td>3.33</td>
<td>2.29</td>
</tr>
<tr>
<td>3.60</td>
<td>2.46</td>
</tr>
<tr>
<td>4.06</td>
<td>2.78</td>
</tr>
<tr>
<td>4.57</td>
<td>3.09</td>
</tr>
<tr>
<td>4.79</td>
<td>3.24</td>
</tr>
</tbody>
</table>

Characteristics of Sensor 2:
Type: CSLB1AD, MICROSWITCH
Offset Voltage = .03 volts

Table D.2: Variation of Output Voltage vs. Current

<table>
<thead>
<tr>
<th>Current (amperes)</th>
<th>Output Voltage (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.36</td>
<td>1.47</td>
</tr>
<tr>
<td>2.73</td>
<td>1.69</td>
</tr>
<tr>
<td>3.14</td>
<td>1.94</td>
</tr>
<tr>
<td>3.47</td>
<td>2.15</td>
</tr>
<tr>
<td>3.90</td>
<td>2.41</td>
</tr>
<tr>
<td>4.40</td>
<td>2.71</td>
</tr>
<tr>
<td>4.72</td>
<td>2.90</td>
</tr>
<tr>
<td>5.15</td>
<td>3.16</td>
</tr>
</tbody>
</table>
The sensitivity of current sensors were obtained by calculating the gradient of the straight lines that best fit this data, using least square estimates.

When the regression curve of a set of data \( x_i \) (\( i=1,2,..n \)) and \( y_i \) (\( i=1,2,..,n \)) is linear the best straight line that fits this data is given by the following equation:

\[
\bar{y} = m\bar{x} + c
\]

where:
\[
\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}
\]
\[
\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}
\]
\[
m = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}
\]
\[
c = \bar{y} - m\bar{x}
\]

In calculating the sensitivity the 'x' values were taken as the change in output voltage from the offset and the 'y' values were the values of the corresponding currents through the load. The following table lists the calculated values of the sensitivity of the current sensors.

**Table D.3 : Sensitivity of Current Sensors**

<table>
<thead>
<tr>
<th>Sensor Number</th>
<th>Sensitivity (amperes/volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5375</td>
</tr>
<tr>
<td>2</td>
<td>1.6446</td>
</tr>
</tbody>
</table>
APPENDIX E

Program Listing

This program constructs the waveforms of the * currents through two adjacent coils of MES.T and TLAP are inputs from the keyboard. The program energises a coil by writing a '1' at the output port. Then, it collects data by sampling the A/D converter channels at 1000 samples/second. The sampled data is stored in a data file and the waveforms are constructed later by using the graphic capabilities of Symphony and Lotus software.

DIMENSION CUR1(600), CUR2(600), TIME(600)
INTEGER*2 RAWVAL
INTEGER*2 RAWD1(250), RAWD2(200), RAWD3(500)
RAWD4(200), RAWD5(250)
INTEGER*4 CT1, CT2, CTLAP
WRITE(*,*) 'INPUT T, TLAP'
READ(*,*) T, TLAP
T1=T-TLAP
T2=T-2.0*TLAP
CTLAP=INT(TLAP*1000.)
CT1=INT(T1*1000.)
CT2=INT(T2*1000.)
WRITE(*,*) CT1, CT2, CTLAP
CALL AINS(0,9,2,0, RAWVAL, 0)
OFFSE2=RAWVAL
CALL AINS(0,9,3,0, RAWVAL, 0)
OFFSE3=RAWVAL
CALL BOUS(0,8,0,1,0)
CALL AINM(0,9,2,0,0,0, CT1, 1000, RAWD1(1), 0)
CALL BOUS(0,8,0,3,0)
CALL AINSC(0,9,2,3,0,0,0, CTLAP, 2000, RAWD2(1), 0)
CALL BOUS(0,8,0,2,0)
CALL AINSC(0,9,2,3,0,0,0, CT2, 2000, RAWD3(1), 0)
CALL BOUS(0,8,0,6,0)
CALL AINM(0,9,3,0,0,0, CTLAP, 1000, RAWD4(1), 0)
CALL BOUS(0,8,0,0,0)
CALL AINM(0,9,3,0,0,0, CT2, 1000, RAWD5(1), 0)
WRITE(*,*) CT1
DO 10 I=1, CT1
CUR1(I+1)=-(RAWD1(I)-OFFSE2)*0.0037
10 CUR2(I+1)=0.0
DO 20 I=1, CTLAP
J=CT1+I+1
CUR1(J)=-(RAWD2(2*I-1)-OFFSE2)*0.0037
20 CUR2(J)=-(RAWD2(2*I)-OFFSE3)*0.0040
DO 30 I=1,CT2  
   J=CT1+CTLAP+I+1  
   CUR1(J)=-(RAWD3(2*I-1)-OFFSE2)*0.0037  
30 CUR2(J)=-(RAWD3(2*I)-OFFSE3)*0.0040  
DO 40 I=1,CTLAP  
   J=CT1+CTLAP+CT2+I+1  
   CUR1(J)=0  
40 CUR2(J)=-(RAWD4(I)-OFFSE3)*0.0040  
DO 90 I=1,CT2  
   J=CT1+CT2+2*CTLAP+I+1  
   CUR1(J)=0  
90 CUR2(J)=-(RAWD5(I)-OFFSE3)*0.0040  
K=CT1+CT2+3*CTLAP+1  
WRITE(*,*)'K=',K  
TIME(1)=0.0  
CUR1(1)=0.0  
CUR2(1)=0.0  
DO 50 I=1,K  
50 TIME(I+1)=TIME(I)+0.001  
DO 80 I=1,K+1  
80 WRITE(*,1)TIME(I),CUR1(I),CUR2(I)  
OPEN(60,FILE='DATA.PRN',STATUS='NEW',ACCESS='DIRECT',FORM='FORMATTED',RECL=17)  
DO 70 I=1,K+1  
70 WRITE(60,1,REC=I)TIME(I),CUR1(I),CUR2(I)  
CONTINUE  
1 FORMAT(1X,F6.3,1X,F4.1,1X,F4.1)  
STOP  
END
APPENDIX F

Program Listing

C ******************************************************************************
C *This program constructs the waveform of current *
C *from t=0 to t=0.012 seconds. *
C ******************************************************************************
DIMENSION CURT(150), TIME(150)
INTEGER*2 RAWVAL
INTEGER*2 RAWDT(150)
CALL AINS(0,9,3,0,RAWVAL,0)
CALL BOUS(0,8,0,1,0)
CALL AINM(0,9,3,0,0,0,120,10000,RAWDT(1),0)
CALL BOUS(0,8,0,0,0)
DO 10 I=1,120
10 CURT(I+1)=(RAWDT(I)-RAWVAL)*0.00370
  CURT(1)=0.0
  TIME(1)=0.0
  DO 50 I=1,120
50 TIME(I+1)=TIME(I)+0.0001
  DO 80 I=1,121
80 WRITE(*,1)TIME(I),CURT(I)
OPEN(60,FILE='B:TCON.PRN',STATUS='NEW',ACCESS='DIRECT',
  *FORM='FORMATTED',RECL=15)
DO 70 I=1,121
70 WRITE(60,1,REC=I)TIME(I),CURT(I)
1 FORMAT(1X,F6.4,1X,F7.4)
STOP
END
APPENDIX G

The experimental data is tabulated below, with:

- $s$ - particle size, mm
- $d$ - spacing between coils, inches
- $D$ - distance to first coil from the particle level, inches
- $T$ - energizing time, seconds
- $TLAP$ - time of overlap, seconds
- $I$ - energizing current, amperes
- $m$ - mass of solids, grams

Subscripts 1 through 6 refer to reading numbers.

1. Variation of $m$ with $D$

$s=0.775 \quad d=1.0 \quad T=0.7 \quad TLAP=0.3 \quad I=5.7$

<table>
<thead>
<tr>
<th>$D$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>46.88</td>
<td>48.91</td>
<td>49.22</td>
<td>46.56</td>
<td>48.51</td>
<td>49.56</td>
</tr>
<tr>
<td>0.5</td>
<td>46.11</td>
<td>47.97</td>
<td>48.61</td>
<td>48.75</td>
<td>47.26</td>
<td>49.21</td>
</tr>
<tr>
<td>0.75</td>
<td>44.97</td>
<td>18.85</td>
<td>49.25</td>
<td>51.52</td>
<td>17.31</td>
<td>40.28</td>
</tr>
<tr>
<td>1.00</td>
<td>40.35</td>
<td>16.93</td>
<td>50.06</td>
<td>17.15</td>
<td>20.38</td>
<td>18.56</td>
</tr>
</tbody>
</table>

2. Variation of $m$ with particle type

2.1 \ $T=0.7 \quad TLAP=0.3 \quad I=5.7 \quad d=1$

<table>
<thead>
<tr>
<th>$s$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0306</td>
<td>47.15</td>
<td>46.50</td>
<td>46.41</td>
<td>47.75</td>
<td>48.39</td>
<td>48.81</td>
</tr>
<tr>
<td>0.0152</td>
<td>38.88</td>
<td>36.13</td>
<td>37.62</td>
<td>38.49</td>
<td>35.59</td>
<td>37.55</td>
</tr>
<tr>
<td>0.0091</td>
<td>37.78</td>
<td>38.17</td>
<td>34.81</td>
<td>37.07</td>
<td>35.57</td>
<td>36.26</td>
</tr>
</tbody>
</table>
2.2 \ T=0.7 \ TLAP=0.3 \ I=3.5 \ d=1

<table>
<thead>
<tr>
<th>s</th>
<th>m1</th>
<th>m2</th>
<th>m3</th>
<th>m4</th>
<th>m5</th>
<th>m6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.775</td>
<td>38.56</td>
<td>34.60</td>
<td>35.50</td>
<td>37.00</td>
<td>40.40</td>
<td>35.79</td>
</tr>
<tr>
<td>0.385</td>
<td>32.35</td>
<td>25.16</td>
<td>30.77</td>
<td>33.37</td>
<td>32.35</td>
<td>32.18</td>
</tr>
<tr>
<td>0.230</td>
<td>32.57</td>
<td>32.15</td>
<td>30.26</td>
<td>31.52</td>
<td>26.78</td>
<td>29.18</td>
</tr>
</tbody>
</table>

3. Variation of \( m \) with TLAP

3.1 \( s=0.775 \) \( d=1.0 \) \( T=0.7 \) \( I=5.7 \)

<table>
<thead>
<tr>
<th>TLAP</th>
<th>m1</th>
<th>m2</th>
<th>m3</th>
<th>m4</th>
<th>m5</th>
<th>m6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>47.15</td>
<td>46.50</td>
<td>46.41</td>
<td>47.75</td>
<td>48.39</td>
<td>48.81</td>
</tr>
<tr>
<td>0.25</td>
<td>43.40</td>
<td>47.04</td>
<td>46.77</td>
<td>48.45</td>
<td>47.92</td>
<td>44.85</td>
</tr>
<tr>
<td>0.2</td>
<td>44.83</td>
<td>46.47</td>
<td>43.97</td>
<td>47.95</td>
<td>45.72</td>
<td>46.34</td>
</tr>
<tr>
<td>0.15</td>
<td>47.86</td>
<td>44.93</td>
<td>46.52</td>
<td>47.07</td>
<td>46.53</td>
<td>48.62</td>
</tr>
<tr>
<td>0.1</td>
<td>43.19</td>
<td>38.72</td>
<td>44.40</td>
<td>43.39</td>
<td>43.17</td>
<td>40.10</td>
</tr>
<tr>
<td>0.05</td>
<td>43.02</td>
<td>41.55</td>
<td>41.70</td>
<td>41.24</td>
<td>41.70</td>
<td>43.66</td>
</tr>
<tr>
<td>0.03</td>
<td>37.70</td>
<td>39.15</td>
<td>19.52</td>
<td>36.50</td>
<td>16.08</td>
<td>30.19</td>
</tr>
<tr>
<td>0.01</td>
<td>15.44</td>
<td>16.04</td>
<td>16.51</td>
<td>16.85</td>
<td>15.30</td>
<td>12.42</td>
</tr>
</tbody>
</table>

3.2 \( s=0.775 \) \( d=1.0 \) \( T=0.7 \) \( I=3.5 \)

<table>
<thead>
<tr>
<th>TLAP</th>
<th>m1</th>
<th>m2</th>
<th>m3</th>
<th>m4</th>
<th>m5</th>
<th>m6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>38.56</td>
<td>34.60</td>
<td>35.50</td>
<td>37.00</td>
<td>40.40</td>
<td>35.79</td>
</tr>
<tr>
<td>0.25</td>
<td>33.98</td>
<td>37.61</td>
<td>35.26</td>
<td>36.21</td>
<td>40.23</td>
<td>38.10</td>
</tr>
<tr>
<td>0.2</td>
<td>32.61</td>
<td>38.52</td>
<td>35.62</td>
<td>35.41</td>
<td>36.33</td>
<td>38.93</td>
</tr>
<tr>
<td>0.15</td>
<td>38.93</td>
<td>34.61</td>
<td>33.82</td>
<td>36.58</td>
<td>37.21</td>
<td>36.23</td>
</tr>
<tr>
<td>0.1</td>
<td>32.81</td>
<td>33.53</td>
<td>34.21</td>
<td>36.23</td>
<td>34.62</td>
<td>35.98</td>
</tr>
<tr>
<td>0.05</td>
<td>28.53</td>
<td>30.83</td>
<td>31.85</td>
<td>29.31</td>
<td>32.56</td>
<td>30.16</td>
</tr>
</tbody>
</table>
4. Variation of $m$ with $T$

4.1 $s=0.775$  $d=1.0$  $I=5.7$

<table>
<thead>
<tr>
<th>$T$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>47.15</td>
<td>46.50</td>
<td>46.41</td>
<td>47.75</td>
<td>48.39</td>
<td>48.81</td>
</tr>
<tr>
<td>0.5</td>
<td>47.20</td>
<td>48.49</td>
<td>48.59</td>
<td>44.80</td>
<td>44.73</td>
<td>45.70</td>
</tr>
<tr>
<td>0.3</td>
<td>47.80</td>
<td>50.73</td>
<td>44.02</td>
<td>44.82</td>
<td>45.17</td>
<td>48.33</td>
</tr>
<tr>
<td>0.2</td>
<td>42.16</td>
<td>42.02</td>
<td>42.25</td>
<td>39.20</td>
<td>44.74</td>
<td>40.91</td>
</tr>
<tr>
<td>0.1</td>
<td>41.89</td>
<td>40.99</td>
<td>41.56</td>
<td>41.25</td>
<td>40.16</td>
<td>39.40</td>
</tr>
<tr>
<td>0.06</td>
<td>30.41</td>
<td>28.40</td>
<td>29.03</td>
<td>27.58</td>
<td>28.20</td>
<td>27.69</td>
</tr>
<tr>
<td>0.04</td>
<td>19.12</td>
<td>20.16</td>
<td>14.25</td>
<td>18.16</td>
<td>16.14</td>
<td>18.91</td>
</tr>
</tbody>
</table>

4.2 $s=0.775$  $d=1.0$  $I=5.0$

<table>
<thead>
<tr>
<th>$T$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>40.79</td>
<td>42.18</td>
<td>45.05</td>
<td>43.03</td>
<td>42.68</td>
<td>42.86</td>
</tr>
<tr>
<td>0.5</td>
<td>41.28</td>
<td>43.15</td>
<td>44.28</td>
<td>44.32</td>
<td>42.18</td>
<td>43.00</td>
</tr>
<tr>
<td>0.3</td>
<td>42.70</td>
<td>43.36</td>
<td>40.34</td>
<td>43.28</td>
<td>39.87</td>
<td>42.70</td>
</tr>
<tr>
<td>0.2</td>
<td>38.56</td>
<td>39.18</td>
<td>37.56</td>
<td>36.81</td>
<td>38.91</td>
<td>39.26</td>
</tr>
<tr>
<td>0.1</td>
<td>37.48</td>
<td>38.37</td>
<td>36.96</td>
<td>35.70</td>
<td>36.02</td>
<td>36.44</td>
</tr>
<tr>
<td>0.06</td>
<td>25.30</td>
<td>24.55</td>
<td>24.88</td>
<td>26.38</td>
<td>25.25</td>
<td>24.16</td>
</tr>
<tr>
<td>0.04</td>
<td>16.97</td>
<td>16.78</td>
<td>18.51</td>
<td>10.26</td>
<td>18.68</td>
<td>18.17</td>
</tr>
</tbody>
</table>
5. Variation of m with I

5.1 \( s=0.775 \quad d=1.0 \quad T=0.7 \quad TLAP=0.3 \)

<table>
<thead>
<tr>
<th>I</th>
<th>m1</th>
<th>m2</th>
<th>m3</th>
<th>m4</th>
<th>m5</th>
<th>m6</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7</td>
<td>47.15</td>
<td>46.50</td>
<td>46.41</td>
<td>47.75</td>
<td>48.39</td>
<td>48.81</td>
</tr>
<tr>
<td>5.0</td>
<td>40.79</td>
<td>42.18</td>
<td>45.05</td>
<td>43.03</td>
<td>42.68</td>
<td>42.86</td>
</tr>
<tr>
<td>4.2</td>
<td>42.07</td>
<td>41.21</td>
<td>42.77</td>
<td>38.96</td>
<td>39.76</td>
<td>37.82</td>
</tr>
<tr>
<td>3.5</td>
<td>38.56</td>
<td>34.60</td>
<td>35.50</td>
<td>37.00</td>
<td>40.40</td>
<td>35.79</td>
</tr>
<tr>
<td>3.2</td>
<td>29.79</td>
<td>28.56</td>
<td>35.12</td>
<td>0</td>
<td>29.30</td>
<td>0</td>
</tr>
</tbody>
</table>

5.2 \( s=20 \quad d=1.0 \quad T=0.1 \quad TLAP=0.05 \)

<table>
<thead>
<tr>
<th>I</th>
<th>m1</th>
<th>m2</th>
<th>m3</th>
<th>m4</th>
<th>m5</th>
<th>m6</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7</td>
<td>41.89</td>
<td>40.99</td>
<td>41.56</td>
<td>41.25</td>
<td>40.16</td>
<td>39.40</td>
</tr>
<tr>
<td>5.0</td>
<td>37.48</td>
<td>38.37</td>
<td>36.96</td>
<td>35.70</td>
<td>36.02</td>
<td>36.44</td>
</tr>
<tr>
<td>4.2</td>
<td>33.19</td>
<td>29.89</td>
<td>32.31</td>
<td>31.50</td>
<td>30.08</td>
<td>31.18</td>
</tr>
<tr>
<td>3.5</td>
<td>26.53</td>
<td>29.49</td>
<td>29.05</td>
<td>26.93</td>
<td>28.00</td>
<td>26.27</td>
</tr>
</tbody>
</table>
6. Variation of $m$ with $d$

6.1 $s=0.775 \quad T=0.7 \quad TLAP=0.3 \quad I=5.7$

<table>
<thead>
<tr>
<th>$d$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.15</td>
<td>46.50</td>
<td>46.41</td>
<td>47.75</td>
<td>48.39</td>
<td>48.81</td>
</tr>
<tr>
<td>0.75</td>
<td>41.84</td>
<td>44.60</td>
<td>46.53</td>
<td>42.89</td>
<td>45.85</td>
<td>44.75</td>
</tr>
<tr>
<td>0.50</td>
<td>45.46</td>
<td>43.49</td>
<td>42.86</td>
<td>44.54</td>
<td>42.72</td>
<td>47.64</td>
</tr>
</tbody>
</table>

6.2 $s=0.775 \quad T=0.7 \quad TLAP=0.3 \quad I=3.5$

<table>
<thead>
<tr>
<th>$d$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.56</td>
<td>34.60</td>
<td>35.50</td>
<td>37.00</td>
<td>40.40</td>
<td>35.79</td>
</tr>
<tr>
<td>0.75</td>
<td>35.94</td>
<td>36.17</td>
<td>36.39</td>
<td>34.84</td>
<td>36.45</td>
<td>35.37</td>
</tr>
<tr>
<td>0.50</td>
<td>34.72</td>
<td>32.87</td>
<td>35.27</td>
<td>33.77</td>
<td>34.57</td>
<td>33.80</td>
</tr>
</tbody>
</table>

6.3 $s=0.775 \quad T=0.1 \quad TLAP=0.05 \quad I=5.7$

<table>
<thead>
<tr>
<th>$d$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.89</td>
<td>40.99</td>
<td>41.56</td>
<td>41.25</td>
<td>40.16</td>
<td>39.40</td>
</tr>
<tr>
<td>0.75</td>
<td>41.16</td>
<td>38.41</td>
<td>39.33</td>
<td>40.70</td>
<td>40.07</td>
<td>40.85</td>
</tr>
<tr>
<td>0.50</td>
<td>42.02</td>
<td>42.78</td>
<td>39.38</td>
<td>42.00</td>
<td>40.00</td>
<td>42.75</td>
</tr>
</tbody>
</table>
APPENDIX H

Sample Calculation of MES Efficiency:

From APPENDIX G, section 5.2:

\[ s = 0.775 \text{ mm} \]
\[ d = 1.0 \text{ inches} \]
\[ T = 0.1 \text{ seconds} \]
\[ TLAP = 0.05 \text{ seconds} \]

\[ m = \frac{37.48 + 38.37 + 36.96 + 35.70 + 36.02 + 36.44}{6} \]

\[ = 0.0368 \text{ kg} \]

\[ I = 5.0 \text{ amperes} \]

Also it was observed that for \( I = 5.0 \text{ A} \), \( ILAP = 4.8 \text{ A} \).

The values of \( N, l, L, R, r \), for the calculation of efficiency are as follows.

\[ N = 10 \]
\[ l = d + \text{thickness of a coil} \]

\[ = 2 \text{ inches} \]

\[ = 0.05 \text{ meters} \]

\[ R = 2.85 \text{ ohms} \]
\[ r = 0.5 \text{ inches} = 0.013 \text{ meters} \]
\[ L' = 1 \text{ inch} = 0.025 \text{ meters} \]
\[ \rho = 1390 \text{ kg/m}^3 \]

\( L \) is evaluated by equation 4.3 as follows:

\[ L = \frac{0.0368}{2 (1390)(0.013)} + 0.025 \text{ meters} \]

\[ = 0.049 \text{ meters} \]
η is evaluated by equation 4.5:

\[ \eta = 0.6423\% \]
APPENDIX I

The Principle of Hall Effect:

When a current carrying conductor is placed at right angles to a magnetic field, an electric potential is developed in a direction transverse to the magnetic field. This transport phenomena is called the Hall effect.

The Hall Element:

The Hall element is a thin strip of a semiconductor with input and output terminals as illustrated in the Figure. The semiconductor material can be GaAs, InAs or InSb. The output voltage across the Hall element (V) is given by:

\[ V = K R I B \]

where:
- \( K \) - specific sensitivity
- \( R \) - internal resistance
- \( I \) - control current
- \( B \) - magnetic flux density

The Hall Probe:

The output of the Hall element as a function of the magnetic flux, is a low level linear output and therefore must be modified to accomplish a switching function. This may involve additional circuitry to improve the linearity, temperature and voltage compensation or signal amplification and modification to provide either a digital or pulse output depending on the application. The Hall element with these additional circuitry is termed the Hall probe.
Figure I.1: The Hall Element
Sample Calculation for the Minimum Distance:

As explained in section 5.4.1 the distance between a probe and the coil immediately below the probe should be large enough to ensure that the probe is not activated by the magnetic field of this coil. An elevator coil can be regarded as a solenoid of radius $r$ and length $l$. The figure shows the variables which affect the magnetic flux density at the axes of a solenoid.

![Figure J.1: Variables Affecting the Flux Density of a Solenoid](image)

Referring to the figure the magnetic field intensity at any point $P$ along the axis of the coil is given by

$$B = \frac{\mu_0 NI (\cos \alpha - \cos \beta)}{2l}$$

where:

- $N$ - number of turns
- $I$ - excitation current (amperes)
- $\mu_0$ - permeability of free space
\[
\cos \alpha = \frac{y}{\sqrt{r^2 + y^2}} \quad \cos \beta = \frac{(y-1)}{\sqrt{r^2 + (1-y)^2}}
\]

Substituting for \(N, I, \mu_0, l\) and \(r\):

\(N = 700\)

\(I = 5.0\) amperes (say)

\(\mu_0 = 4\times10^{-7}\) Henry/metre

\(l = 1\) inch = 0.025 meters

\(r = 0.5\) inch = 0.013 meters

\(B\) is given by:

\[
B = 0.0880 \left[ \frac{2y}{\sqrt{1+4y^2}} - \frac{2(y-1)}{\sqrt{1+4(1-y)^2}} \right]
\]

\[
= 0.1760 \left[ \frac{y}{\sqrt{1+4y^2}} - \frac{(y-1)}{\sqrt{1+4(1-y)^2}} \right]
\]

\(y\) should be selected such that:

\(B < 0.01\) Tesla

Further \(y\) will be negative. Substituting \(y = -d\) where \(d\) is positive gives:

\[
B = 0.1760 \left[ \frac{(d+1)}{\sqrt{1+4(1+d)^2}} - \frac{d}{\sqrt{1+4d^2}} \right]
\]

The following Table lists \(B\) for three values of \(d\):

<table>
<thead>
<tr>
<th>(d) (inches)</th>
<th>(B) (Tesla)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.021</td>
</tr>
<tr>
<td>0.75</td>
<td>0.011</td>
</tr>
<tr>
<td>1.00</td>
<td>0.006</td>
</tr>
</tbody>
</table>
Therefore, assuming that the distance can be varied in steps of 0.25 inches we observe that for an energization current of 5.0 amperes, the minimum distance from a coil to the point on its axes at which the flux density is less than the threshold value is 1 inch. Since the flux density at any point on the axes of the coil is greater than that at any point on the same horizontal plane, we can safely assume that if the vertical distance between a probe and a coil is 1 inch the probe will not be turned on by the magnetic field of the coil for an energization current of 5 amperes. The minimum distance between a probe and the coil immediately below for different energization currents can be similarly calculated.
APPENDIX K

Main Programme:

BEGIN: ACALL INIT ;jump to sub. INIT.
MOV A, #1 ;load acc.
MOV P1, A ;energize coil 1
MOV 21H, 1H ;load counter
MOV 29H, 9H

WAIT: NOP ;no operation
SJMP WAIT

INIT: MOV PSW, #00H ;select register bank 0
       MOV R1, #20H ;load registers
       MOV R2, #BCH
       MOV R3, #58H
       MOV R4, #F4H
       MOV R5, #90H
       MOV R6, #2CH
       MOV R7, #8CH
       MOV PSW, #08H ;select register bank 1
       MOV R1, #03H ;load registers
       MOV R2, #02H
       MOV R3, #02H
       MOV R4, #01H
       MOV R5, #01H
       MOV R6, #01H
       MOV R7, #00H
       MOV A, #FFH ;load acc.
MOV P0, A ; initialize PORT0
MOV IP, #08H ; set interrupts
RET ; return

TIMER: MOV TMOD, #20H ; set TMOD
MOV TH1, #0 ; initialize timer
MOV TL1, #0
MOV TCON, #40H ; turn on timer
RET ; return

External Interrupt Routine:
ROUTINE: MOV A, P0 ; identify probe
MOV P1, A ; energize coil
MOV PSW, #00H ; switch register banks
MOV R0, #0 ; reset counter
LABEL1: INC R0 ; increment counter
RR A ; rotate right acc.
JNB ACC.0 LABEL1
ACALL TRANS ; load low bits of counter
MOV A, R0 ; load acc.
CLR C ; clear carry
SUBB A, #8 ; point to register bank
MOV R0, A ; save pointer
ACALL TRANS ; load high bits of counter
 RETI

TRANS: MOV 20H, @R0 ; save data
MOV A, R0 ; load acc.
ADD A, #16 ;point to transfer address
MOV R0, A ;save address
MOV @R0, 20H ;transfer data
RET ;RETURN

Interrupt Routine For Timer:

ITIMER: MOV PSW, #00H ;select bank 0
MOV R0, #10H ;point to low byte
MOV PSW, 08H ;select bank 1
MOV R0, #18H ;point to high byte
MOV 20H, #0 ;init. counter
LABEL2: INC 20H ;increment counter
MOV PSW, #00H ;select bank 0
CJNE @R0, #0, LABEL3 ;jump if counter of timer non zero
MOV PSW, #08H ;select bank 1
CJNE @R0, #0, LABEL4 ;jump if high byte non zero
LABEL4: DEC @R0 ;decrement high byte
MOV PSW, #00H ;select bank 0
MOV @R0, #FFH ;update low byte
AJUMP LABEL5 ;goto label5
LABEL3: DEC @R0 ;decrement counter
CJNE @R0, #0, LABEL5 ;goto label5
MOV PSW, #08H ;select bank 1
CJNE @R0, LABEL5 ;goto label5
MOV 21H, #1 ;init. counter
MOV 22H, #1 ;point to pin 1 of P1
MOV A, 21H ;load acc.
LABEL6  CJNE A, 20H, LABEL7 ;compare acc.
    MOV A, 22H ;point to pin of P1
    CPL A ;complement acc.
    ANL P1, A ;deenergize coil
    AJMP LABEL5 ;goto label 5

LABEL7  MOV A, 22H ;load acc.
    RL A ;point to next pin
    MOV 22H, A ;save acc.
    MOV A, 21H ;load acc.
    INC A ;increment counter
    MOV 21H, A ;save counter
    AJMP LABEL6 ;goto label 6

LABEL5  CJNE 20H, #7, LABEL8 ;select bank 0
    AJMP LABEL9 ;point to next low byte

LABEL8  MOV PSW, #00H ;select bank 1
    INC R0 ;point to next high byte
    MOV PSW, #08H ;jump to label2
    INC R0
    AJMP LABEL2

LABEL9  RETI ;return