CONTROL OF A FLEXIBLE LINK USING A MICRO-STEPPER MOTOR WITH ACCELERATION FEEDBACK

by

Robert Andrew Simmons

B.S., Kansas State University, 1983

A THESIS

submitted in partial fulfillment of

the requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1985

Approved by:

Major Professor

TABLE OF CONTENTS

Preface.. i

List of Tables.................................... ii

List of Figures...................................iii

Chapter I

1. Introduction................................ 1
2. System Description.......................... 1
3. Dynamic Model............................... 2
4. Stepper Motor Operation..................... 8
5. Model Verification.......................... 11
6. Conclusion.................................. 13

Chapter II

1. Control Strategy............................ 14
2. Simulations................................. 15
3. Implementation.............................. 17
4. Testing and Results......................... 19

Chapter III

1. Introduction................................ 21
2. Theory of Micro-Stepping.................... 23
3. Development of Micro-Stepping............... 25
4. Testing and Results......................... 31
5. Conclusion.................................. 36

Chapter IV

1. Conclusions 37
2. Recommendations............................. 37

List of References................................ 39

Appendix A

1. Hardware.................................... 40

Appendix B

1. Software.................................... 65

Vita.. 80

Abstract.. 82

PREFACE

This thesis describes a procedure for micro-stepping a stepper motor and how it was set up, tested, and verified. It also presents a strategy used to control the movement of a weight on the end of a flexible link. The control strategy seeks to cause the the weight to follow a predetermined movement as closely as possible. The reasons for using a micro-stepper to drive the link are presented. Conclusions and suggestions for further study are presented for both the hardware and the software.

I would like to thank Dr. J. Garth Thompson and Dr. Chi L. Huang for helping me model the system. I would also like to thank Mr. Kent Funk for answers to some late night questions and his help on the hardware aspect of the project. I would especially like to thank my wife, Deborah, for her support.

LIST OF TABLES

Table 1 Full Step Mode Stepping Sequence................ 11

Table 2 Full Step vs. Half Step Stepping Sequence....... 22

Table 3 100 Microsteps per Full Step.................... 24

LIST OF FIGURES

Figure		
1.1	Actuator and Flexible Link With Mass............	2
1.2	System Free Body Diagram........................	3
1.3	Curvature of Beam...............................	4
1.4	Torque vs. Angular Displacement.................	9
1.5	Stepper Motor Model.............................	10
1.6	Fundamental Resonant Frequency..................	12
1.7	Second Mode Resonant Frequency..................	12
2.1	Block Diagram for a Proportional, plus Integral Control with a Derivative Feedback..............	15
2.2	Output Response to a Step Input.................	16
2.3	Output Response to a Ramp Input.................	16
2.4	Wheatstone Bridge and Strain Gauge Conditioner..	18
3.1	Timing Diagram..................................	25
3.2	Basic Micro-Stepper Circuit.....................	28
3.3	Micro Stepping Sequence Method 1................	29
3.4	Micro Stepping Sequence Method 2................	29
3.5	Flow Chart of Micro-Stepper Maintenance Program.	30
3.6a	Side View of Test Set Up........................	32
3.6b	Top View of Test Set Up.........................	32
3.7	Angular Displacement vs. Micro Step.............	34
3.8	Change in Current vs. Micro Step................	35

CHAPTER I

1. INTRODUCTION

The primary purpose of this research is to develop a control system for angular movements of a flexible link with a mass on the end. The secondary objective is to improve the accuracy and resolution of a stepper motor that is used as the actuator of the flexible link.

The goals of this project are as follows:

(1) Produce a micro-stepper logic circuit to improve the resolution of the stepper motor

(2) Configure a computer system for operation of the micro-stepper circuit, control of the link, and data acquisition for the project

(3) Develop signal processing and control algorithms for feedback and control for the movement of the link

(4) Test and evaluate the effectiveness of the control strategy and the micro-stepper

2. SYSTEM DESCRIPTION

The flexible link that is controlled consists of a .292 m strip of spring steel with a .95 cm by .08 cm cross section and with a 200 gm mass attached to one end of the strip. The other end of the strip is connected to the shaft of the actuator (stepper-motor). Figure 1.1 illustrates the system. The reason for using a flexible link is to reduce mass. A manipulator arm on a space craft is an example where mass is a prime concern. For this project, a flexible link with a large period was selected to allow ample time for sampling the feedback signal and to compute the control signal.

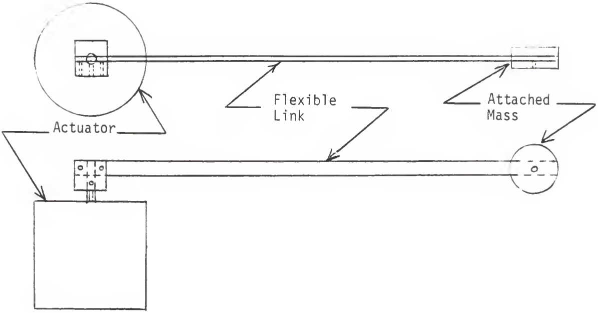


Figure 1.1 Actuator and Flexible Link with Attached Mass

A stepper motor is used to drive the flexible link through an angular displacement. The stepper motor is of the SIGMA series 200 (model #20-2235D200-f3.7). The stepper motor has 200 steps per revolution in the full step mode or 400 steps per revolution in the half step mode. The characteristics of the system to be controlled will be developed in the next section.

3. DYNAMIC MODEL

The deflection of the flexible link during angular displacement is found from the formula for deflection of cantilever beams:

$$\frac{1}{R} = \frac{M}{EI} \quad (1)$$

where:

R is radius of curvature

M is the bending moment and is a function of x

E is the modulas of elasticity, and

I is the cross sectional moment of inertia of the link.

The inertia and flexural rigidity are as follows:

$$I = \frac{hb^3}{12}$$

where:

b = .08 cm

h = .95 cm

$I = 3.9695 \times 10^{-13}\ m^4$

$E = 2.0537 \times 10^{11}\ N/m^2$

$EI = 0.0815\ Nm^2$

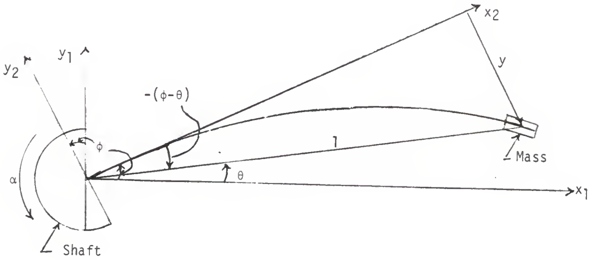


Figure 1.2 System Free Body Diagram

Figure 1.2 shows the coordinate system and the definition of terms. For the development of the model, it is assumed that the deflection of the link is small, thus the small angle theory can be used. Figure 1.3 shows the deflection of a section of the link and the radius of curvature.

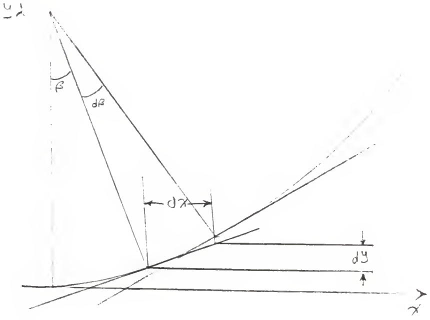


Figure 1.3 Curvature of Beam

From Figure 1.3:

$$\beta \cong \frac{dy}{dx}$$

also,

$$Rd\beta = dx$$

therefore,

$$\frac{1}{R} = \frac{d\beta}{dx} = \frac{d^2y}{dx^2} \; .$$

Substituting for $\frac{1}{R}$ into Equation (1) gives:

$$\frac{d^2y}{dx^2} = \frac{M}{EI}$$

or

$$EI\,\frac{d^2y}{dx^2} = M \quad . \qquad (2)$$

In Equation (2), E and I are constants and M is a function of x. The bending moment is due to the acceleration of the attached mass and the distributed mass of the link. The bending moment due to the attached mass at the end of the link is large compared to the bending moment caused by the distributed mass of the beam. Therefore, the effect of the distributed mass on the fundamental mode of vibration, will be negligible. The attached mass has a translational and rotational motion. The bending moment caused by the rotational acceleration is small compared to that caused by the translational acceleration. The radial component of the inertial force is also neglected. After developing the equation for the fundamental mode of vibration two methods will be used as checks. One method will also be used to evaluate the higher modes of vibration.

From Figure 1.2, the tangential acceleration of the attached mass is $\ell\ddot{\theta}$. The inertial force is $-m\ell\ddot{\theta}$. The bending moment at x is:

$$M = -m\ell\ddot{\theta}\,(\ell - x) \quad . \qquad (3)$$

where m is mass.

Substituting Equation (3) into Equation (2) yields:

$$EI \frac{d^2y}{dx^2} = -m\ell\ddot{\theta} (\ell - x) \tag{4}$$

Integrating from 0 to x yields:

$$EI \frac{dy}{dx} = \int_0^x -m\ell\ddot{\theta} (\ell - x) \, dx$$

$$= -m\ell\ddot{\theta} (\ell x - \frac{x^2}{2}) \tag{5}$$

Since dy/dx = 0 at x = 0.

Integrating Equation (5) from 0 to x yields:

$$EIy = \int_0^x -m\ell\ddot{\theta} (\ell x - \frac{x^2}{2}) \, dx$$

$$= -m\ell\ddot{\theta} (\ell\frac{x^2}{2} - \frac{x^3}{6}) \tag{6}$$

since y = 0 at x = 0.

Equation (6) gives the deflection y of the link at any point x along the link. Of particular interest is the deflection at the end of the link. For $x = \ell$ Equation (6) becomes:

$$y(\ell) = - \frac{m\ddot{\theta}\ell^4}{3EI} \tag{7}$$

From Figure 1.2 the relationship between the deflection $y(\ell)$ and the angles ϕ and θ is:

$$y(\ell) = - \ell(\phi - \theta) \tag{8}$$

Substituting Equation (8) into Equation (7) gives:

$$(\phi - \theta) = \frac{m\ddot{\theta}}{EI}\left(\frac{\ell^4}{3\ell}\right) \tag{9}$$

or

$$\frac{m\ell^3}{3EI}\ddot{\theta} + \theta = \phi \tag{10}$$

or

$$\ddot{\theta} + \frac{3EI}{m\ell^3}\theta = \frac{3EI}{m\ell^3}\phi \quad . \tag{11}$$

The frequency of the fundamental mode of vibration can be seen to be:

$$W_n = \sqrt{\frac{3EI}{m\ell^3}} = 7.03 \text{ rad/sec.} \tag{12}$$

Equation (12) then becomes:

$$\ddot{\theta} + 49.4\theta = 49.4\phi \tag{13}$$

Taking the Laplace transform of Equation (13) yields:

$$S^2\theta(s) + 49.4\theta(s) = 49.4\phi(s). \tag{14}$$

The plant transfer function can be written as:

$$\frac{\theta(s)}{\phi(s)} = \frac{49.4}{S^2 + 49.4} \quad . \tag{15}$$

Equation (15) is the model of the system to be used in developing the control strategy.

The constant $\frac{3EI}{m\ell^3}$ from Equation (11) gives the spring force K_b of the flexible link by the relationship:

$$\frac{K_b}{J} = \frac{3EI}{m\ell^3} \tag{16}$$

where

$$J = m\ell^2 = .0171 \text{ Kgm}$$

therefore:

$$K_b = \frac{3EI}{\ell} \qquad K_b = JW_n^2 = 0.8372 \text{ Nm}$$

A spring constant K_m is associated with the stepper motor and will be dealt with in a later section.

4. STEPPER MOTOR OPERATION

A stepper motor consists of a magnetic armature and four sets of fields which can be energized individually or in combinations of two. Figure 1.5 illustrates the model of the motor. The fields are oriented so that as successive pairs of fields are energized the magnetic force rotates and the armature obtains a set of stable equilibrium positions. If an external torque is applied to the armature, the armature is displaced from the equilibrium position. Figure 1.4 shows the applied torque, $T_{app.}$, versus position relationship. The maximum torque, T_h, is 0.936 Nm with a pair of fields energized at rated current. The 3.6 degree and 7.2 degree positions come from the step size. If a torque is applied which exceeds the holding torque, the shaft will skip to the next stable position, being 7.2 degrees.

The black, orange, red and yellow motor field lines are connected to four transistors which are switched by the four control lines from the stepper motor driver circuit C_1, C_2,

C_3 and C_4 respectively. When a control line has a logic "1" the transistor is able to sink current, hence, enabling the field to create a magnetic force. Table 1 shows the full step sequence which will be used for this project. When successive sets of fields are energized according to the pattern in Table 1, the magnetic force rotates by 1.8 degrees, providing a torque approximately equal to T_h to move the armature to the next position. The torque displacement relationship will be approximated by a linear function as indicated in Figure 1.4. The motor spring constant is the slope of the torque versus displacement relationship, thus:

$$K_m = \frac{a}{b} = \frac{T_h}{(\frac{3.6}{2})} = 29.0150 \frac{Nm}{rad} \quad .$$

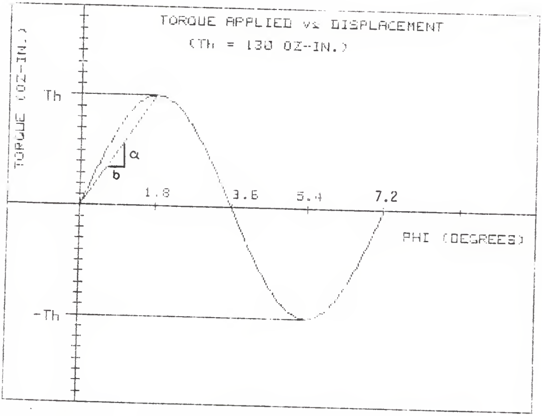


Figure 1.4 Torque vs. Angular Displacement

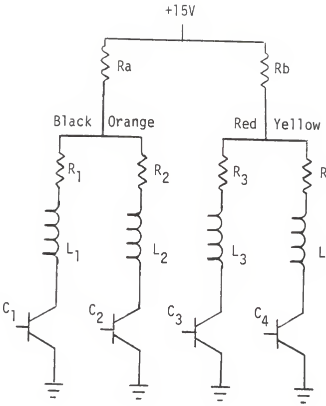


Figure 1.5 Stepper Motor Model

The motor spring constant is much larger then the spring constant due to the elasticity of the link. Also, the armature inertia, Jm, obtained from the manufacturer's literature, is much smaller than the inertia due to the attached mass. The characteristic of the motor produces a fundamental mode of vibration with a frequency of:

$$W_n = \sqrt{\frac{K_m}{Jm}} = 1099 \text{ rad/sec.}$$

where

$$Jm = .24 \text{ Kgcm}^2$$

The fundamental mode of the motor is large compared to that of the link. Thus, the response of the motor may be considered to be instantaneous compared to the response of the link.

STEP	C_1	C_2	C_3	C_4
1	1	0	1	0
2	0	1	1	0
3	0	1	0	1
4	1	0	0	1
5	1	0	1	0
6	0	1	1	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

↓ Clock Wise

↑ Counter Clock Wise

Table 1 Full Step Mode Stepping Sequence

5. MODEL VERIFICATION

Earlier in the chapter, a simplified model of the link was developed and from the dimensions of the link, the fundamental mode frequency was estimated to be 7.03 rad/sec. A check on the fundamental mode frequency was done using Myklestad's method (see reference 1). The first mode from Figure 1.6 is approximately 7.0 radians per second which compares favorably with the simplified model. Myklestad's method also provided a second mode estimate of 194 radians per second and a third mode estimate of 618 radians per second.

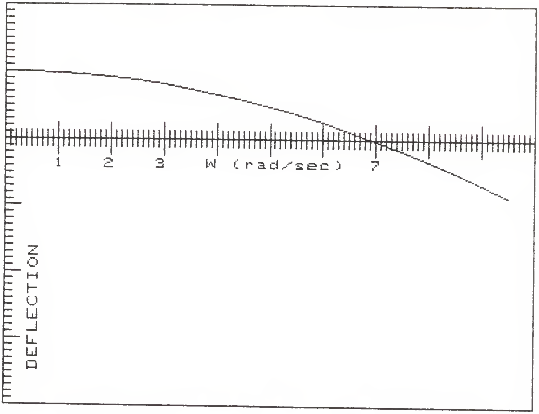


Figure 1.6 Fundamental Resonant Frequency

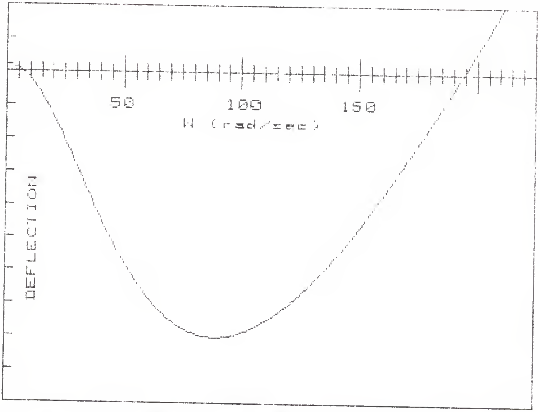


Figure 1.7 Second Mode Resonant Frequency

Another check on the first mode frequency was made using the super position method. The later method uses Dunkerley's general equation of a beam with a continuous load and a massless beam with a concentrated load (see Reference 2). The super position method also gave a first mode frequency equal to 7.0 rad/sec, where:

$$W_b = \frac{3.52}{\ell^2}\left(\frac{EI}{\gamma}\right)^{\frac{1}{2}} \tag{17}$$

$$W_m = \left(\frac{3EI}{m\ell^3}\right)^{\frac{1}{2}} \tag{18}$$

$$W_T^2 = \frac{W_b^2\, W_m^2}{W_b^2 + W_m^2} \tag{19}$$

where:

W_b is the first mode frequency for a uniform beam,

W_m is the frequency of a massless beam with a concentrated load,

W_T is Dunkerley's approximation for the combined frequency,

m is concentrated mass on the beam,

γ is mass per unit length of the beam.

6. CONCLUSION

In this chapter the flexible link has been described and the model of the system has been developed. Also, some characteristics of the stepper motor have been presented. In Chapter II the control strategy will be developed based on the model of the link. The micro-stepper theory and test results will be discussed in Chapter III.

CHAPTER II

In this chapter a control strategy will be developed for controlling the angular displacement of an attached mass at the end of the flexible link. Simulated responses to step and ramp inputs will be plotted so that the performance of the control strategy can be observed. Implementation of the system, both hardware and software, will also be described. Test results for the implemented control strategy will be reported and evaluated in this chapter with conclusions and recommendations given in Chapter IV. In Chapter III a micro stepping concept will be developed, tested and evaluated.

1. Control Strategy

The control strategy implemented is a proportional and integral control with derivative feedback as shown in the block diagram in Figure 2.1. From the general equation:

$$\frac{\text{output}}{\text{input}} = \frac{G(s)}{1 + GH(s)}$$

the transfer function for the system shown in Figure 2.1 is:

$$\frac{\theta}{r} = \frac{W_n^2\,(KpS + Ki)}{S^3 + W_n^2 KpKdS^2 + W_n^2\,(1 + Kp + KiKd)\,S + W_n^2 Ki} \qquad (1)$$

Where

Kp is the proportional gain,

Ki is the integral gain,

Kd is the derivative feedback gain and

W_n is the natural frequency of the link system.

and where

r is the command input to the system which is the desired angular position of the mass.

2. SIMULATIONS

Simulations were performed using the Runge-Kutta method. The Runge-Kutta method makes use of state equations which can be found from Equation (1) using direct decomposition:

$$\dot{X}1 = X2 - W_n^2 KpKdX1 \quad (2)$$

$$\dot{X}2 = X3 + W_n^2 Kpr - W_n^2 (1 + Kp + KiKd)X1 \quad (3)$$

$$\dot{X}3 = W_n^2 Ki (r - X1) \quad (4)$$

where

X1 is θ .

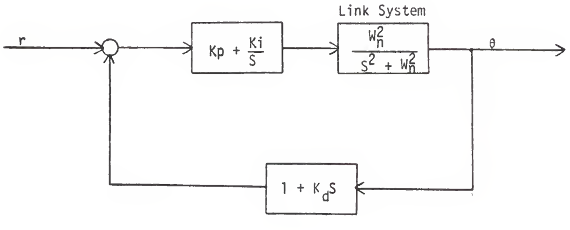


Figure 2.1 Block Diagram for a Proportional Plus Integral Control with Derivative Feedback

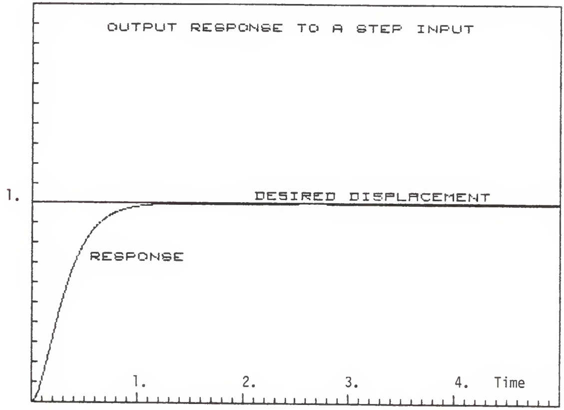


Figure 2.2 Output Response to a Step Input

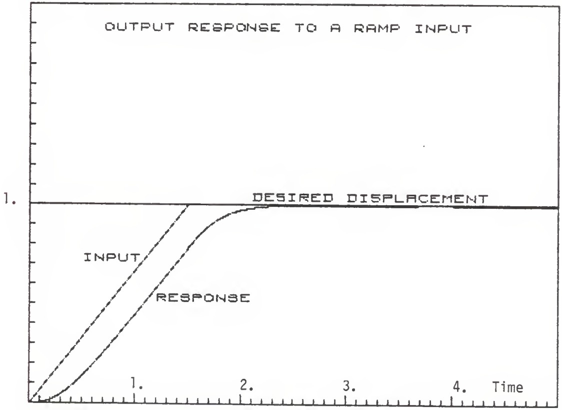


Figure 2.3 Output Response to a Ramp Input

The simulated responses to a step and a ramp input are shown respectively in Figures 2.2 and 2.3 with Kp = 1 , Ki = 50 and Kd = .25. A ramp input will be used in the actual implementation to allow for the inertia and flexibility of the system. The slope of the ramp is determined by R where input r equals Rt.

3. IMPLEMENTATION

The feedback signal comes from a pair of strain gauges placed on either side of the flexible link, close to the base. Error in the signal for strain gauges, due to temperature changes, are canceled out when a pair of strain gauges are used. A Wheatstone bridge is used in connection with a DAYTRONIC (model 2000) strain gauge conditioner (see Reference 3) as shown in Figure 2.4. The 5V DC to 2Hz analog signal is used. An ANALOG DEVICES (model ADC10Z) Analog to Digital Converter is used to digitize the strain gauge signal (see Reference 4). The A/D converts the analog signal to a 2's compliment digital value. The digital value from the A/D is read by the MOTOROLA 68000 microprocessor on a MOTOROLA (model MC68000) single board computer (see Reference 5).

The control strategy is implemented in the MC68000 microcomputer while the control of the stepper motor is implemented in a MOTOROLA (model MEK6802D5) microcomputer which uses a 6802 microprocessor (see Reference 6). Digital values are passed from the MC68000 microcomputer to the

MEK6802D5 microcomputer by an 8 bit latch so the MEK6802D5 microcomputer can read at any time. Also, the MEK6802D5 microcomputer can write to the latch at any time. Thus, the two microcomputers need not be synchronized. The stepper motor control will be discussed in the next chapter along with the micro-stepper theory of operation.

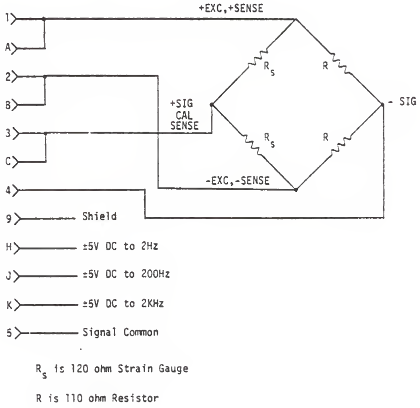


Figure 2.4 Wheatstone Bridge

Figure 2.4 Wheatstone Bridge and Strain Gauge Conditioner

The input to the system, r , is calculated by the MC68000 microcomputer. From Figure 2.1, ϕ is:

(5)

$$\phi = (Kp + \frac{Ki}{S})(r - (1 + K_d S)\ \theta) \qquad (5)$$

or

$$\phi = (Kp + \frac{Ki}{S})(r - (1 + K_d S)\ \frac{\ddot{\theta}}{S^2} \qquad (6)$$

where:

$$\ddot{\theta} = \frac{V}{Kv}\ . \qquad (7)$$

Substituting Equation (7) into Equation (6) yields:

$$\phi = (Kp + \frac{Ki}{S})E \qquad (8)$$

where:

$$E = (r - (\frac{1}{S^2} + \frac{Kd}{S})\ \frac{V}{Kv}).$$

By inspection of Equation (8) the first two integrals of V are needed. The first two integrals of V can be computed by:

Vint1 = Vint1 + V(I)T

Vint2 = Vint2 + Vint1T

where

Vint1 is the first integral of V,

Vint2 is the second integral of V,

V(I) is the present feedback and

T is the sampling period.

The integral of E is also needed. It can be obtained in the same manner as Vint1.

4. TESTING AND RESULTS

The tests were done by implementing the control strategy in the MOTOROLA, MC68000 microcomputer and the micro-stepper maintenance program, to be discussed in Chapter 3, in the MOTOROLA MEK6802D5 microcomputer. The micro-stepper circuit interfaces between the MEK6802D5 microcomputer and the stepper motor is shown in Appendix A.

The control strategy implemented worked as expected. The mass at the end of the link started with a small velocity then increased in the middle and decreased to zero at the end of the move. There are limits imposed on the control strategy by some assumptions made in Chapter 1. The limits will be discussed in Chapter 4, Conclusions and Recommendations. If the operation of the system is not held within the limits, the control breaks down.

CHAPTER III

1. INTRODUCTION

In this chapter a problem encountered with the system using conventional stepper motor control will be presented, followed by a discussion of the concept of micro-stepping. Also, the reason that micro-stepping eliminates the problem will be discussed. A scheme to accomplish micro-stepping will be presented. The implementation and evaluation of the micro-stepping operation will be presented.

The maximum stepping rate accepted by the stepper motor used in this project is 600 steps per second in the full step mode. The link with the attached mass is a lightly damped resonant system with first, second and third mode frequencies of 1.11, 30.87 and 98.36 Hz, respectively. If a stepping rate near the resonant frequencies is commanded, the resonant mode will be excited and the link will experience significant oscillations. The first three resonant frequencies lie within the range of the stepping rates being sent to the stepper motor. When the stepper motor operates around the resonant frequencies, the respective modes of vibration are excited, making the response unacceptable.

One potential solution to the problem is to keep the stepping rates away from the resonant frequencies. This solution cannot be used and still obtain satisfactory operation. Another potential solution is to add damping to the system. This is rather difficult to do and would add

	Half Step Mode					Full Step Mode			
Step	1	2	3	4	Step	1	2	3	4
1.	1	0	1	0	1.	1	0	1	0
2.	0	0	1	0					
3.	0	1	1	0	3.	0	1	1	0
4.	0	1	0	0					
5.	0	1	0	1	5.	0	1	0	1
6.	0	0	0	1					
7.	1	0	0	1	7.	1	0	0	1
8.	1	0	0	0					
9.	1	0	1	0	9.	1	0	1	0

Table 2 Full Step vs. Half Step Stepping Sequence

mass to the system which would defeat the purpose of having a low mass link. An alternative would be to stiffen the link, thus raising the resonant frequencies of vibration. Raising the fundamental frequency from 1.11 Hz to a value suitable for stepping rates up to 600 Hz would require increasing the stiffness by about 250,000 times since the resonant frequency is proportional to the square root of the stiffness. This would also add mass to the system.

The method selected was to increase the stepping rate and reduce the step size. This technique is called micro stepping. If 50 microsteps are placed between each full step, the stepping rate for any prescribed motion is increased by a factor of 50. Also the amplitude of the steps would be decreased by a factor of 50.

With 50 microsteps per full step, the stepping rate ranges from 0 to 30 KHz, and the amplitude is .036 degrees. Although it is still theoretically possible to excite the resonant modes, the excitation amplitude is now so small and the prescribed motion so slow that, in fact, the small amount of damping that exists in the system eliminates the resonance problem.

2. THEORY OF MICRO-STEPPING

Micro-stepping works on the same principle as the full step mode. In the full step mode two fields in the motor are energized. This produces two forces on the armature. The armature assumes a position between the two fields. The placement of the armature depends upon which field exerts the strongest force. The force is proportional to the current through the field. Assuming all of the fields have the same characteristics, the position can be directly related to the currents through the fields. If the two fields have the same current, as is the case with the full step mode, the armature would be exactly in the middle. If one field has a higher current than the other field, it would produce a greater force on the armature. The armature would then be closer to the field with more current passing through it. Assuming the amount of current through each field can be controlled, then micro-stepping can be done. By dividing the current into 50 units, 100 microsteps can be placed between each step. This is achieved by letting 0 units of current through field 1 and 50 through field 2. Then increase the units of current in field 1 and decrease the units of current in field 2 in a staggered sequence. This is done in increments of one. Table 3 illustrates the staggered sequence.

By not using the even numbered microsteps in Table 3, 50 microsteps can be placed between each full step. As previously stated, only 50 microsteps per full step will be used. The decision to use 50 instead of 100 microsteps was made based on maximum speed. The maximum speed that can be achieved using 100 microsteps with a 1 MHz clock is 1/2 revolution per second. A higher rotational velocity is desired for this project.

mstep	Units of Current in Phase One	Units of Current in Phase Two
1	0	50
2	1	50
3	1	49
4	2	49
5	2	48
6	3	48
.	.	.
.	.	.
.	.	.

Table 3 100 Microsteps per Full Step

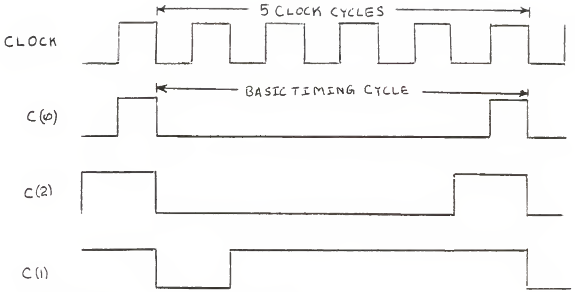


Figure 3.1 Timing Diagram

C(0) is loaded with 5,
C(1) is loaded with 1 and
C(2) is loaded with 4

3. DEVELOPMENT OF MICRO STEPPING

Pulse width modulation is used to divide the maximum current through the fields into 50 units of current. The decision to use pulse width modulation was based on the assumption that the stepper motor filters pulses coming from counters, therefore averaging the current into the stepper motor. Three sixteen bit counters C(0), C(1) and C(2) are used to achieve the pulse width modulation. The three counters all are in a single integrated circuit, a NATIONAL SEMICONDUCTOR INS8253N (see Reference 7). This integrated circuit, IC, is referred to as a programmable, timer-counter. Each of the three counters can be programmed to operate in several different modes. Only the mode and features of the counter used in this project will be described.

Each of the counters is associated with three pins on the IC. One pin is the clock input pin, one is the gate input and the other is the output. Each counter has a buffer register into which a count value can be loaded from the

MEK6802D5 microcomputer. In the operating mode used for this project, when the gate input signal goes from low to high, the value in the buffer register is loaded into the counter, the clock input is enabled, and the output is driven low (one half clock cycle later). Each pulse on the clock input causes the counter to count down one. While the counter is counting down, the output remains low. When a count value of zero is reached, the output goes high and the clock input is disabled until the gate input has another low to high transition.

One counter, C(0), provides the basic cycle timing. A clock signal at 895 KHz is connected to its clock input pin. A value of 50 is loaded into its buffer register and its output is connected to its gate so that it reinitializes itself when it counts out. This counter provides the initialization signal (its output) which is used to gate the other two counters. The 895 KHz clock signal is connected to the clock inputs of all three counters. Values between 1 and 49 are loaded into the buffer registers of counters C(1) and C(2). The outputs of counters C(1) and C(2) will be pulses which are low for the number of clock cycles equal to the value loaded into their buffer registers. The outputs of counters C(1) and C(2) then return high for the balance of the basic timing cycle. Counters loaded with 0 count out the maximum counts of 65,536 (see Reference 7 mode 1). Therefore, the values of 50 and 0 are not used.

By increasing and decreasing the respective counters by increments of 1 from 1 to 49 and 49 to 1, 49 microsteps can be taken in 50 gates. Each microstep will have a spacing of 1 full step divided by 50. The basic configuration of the counters can be seen in Figure 3.2.

To ensure a smooth transition from one full step to the next, caution must be taken to make sure counter C(1) is ANDed with control lines C_1 and C_2 and C(2) is ANDed with control lines C_3 and C_4. A MOTOROLA SAA1042 stepper motor driver determines which control lines are on (see Table 1 and Reference 8). After setting the bias on the MOTOROLA SAA1042 stepper motor driver, C_1 and C_3 are on. Therefore, C_1 must go from full on to full off and C_3 from full off to full on for clockwise operation. To do this, C(1) should be loaded with 1 and incremented to 49 and C(2) loaded with 49 and decremented to 1. The SAA1042 stepper motor driver can then be clocked to the next step. After the stepper motor driver has been clocked, C(1) should then be decremented to 1 and C(2) incremented to 49. A continuation of this process will ensure a smooth transition from one full step to the next.

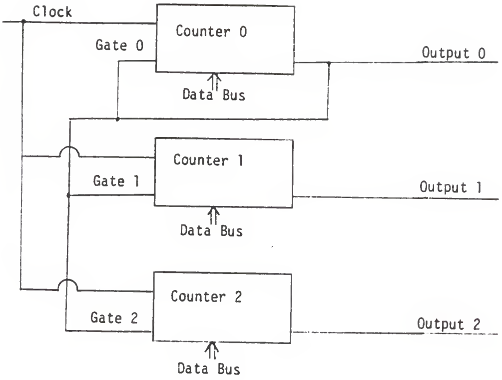


Figure 3.2 Basic Micro-Stepper Circuit

Loading 5 in counter C(Ø) and following the procedure described above will result in a micro-stepping sequence shown in Figure 3.3. The microstep spacing for microsteps 1, 2 and 3 are 1/5 of a full step and microstep 4 is 2/5 of a full step. Again, this is due to the inability to load Ø in the counters. An alternative would be to take 1 microstep at microstep 5. To do this, microsteps 1 and 4 need to be 1/2 of a microstep and microsteps 2 and 3 need to be 1 microstep.

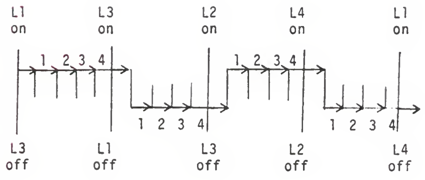


Figure 3.4 Micro-Stepping Sequence Method 1

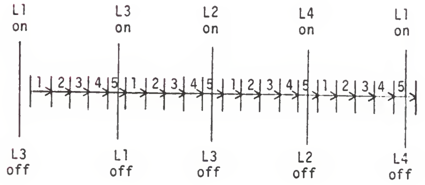


Figure 3.3 Micro-Stepping Sequence Method 2

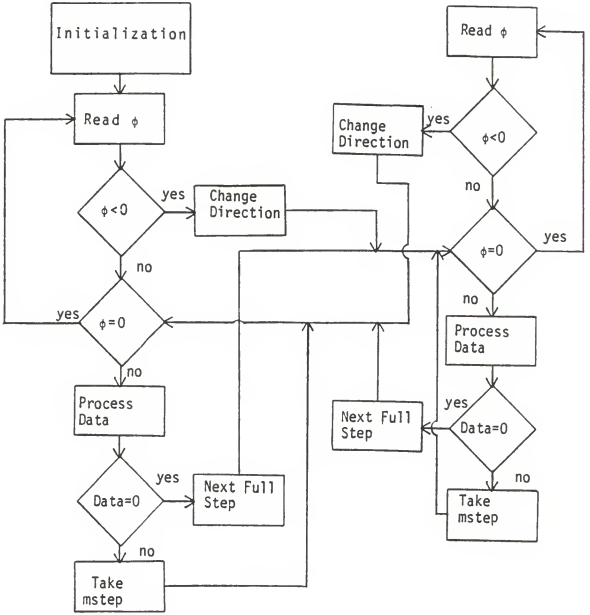


Figure 3.5 Flow Chart of Micro-Stepper Maintenance Program

A half of a step is accomplished by staggering steps as shown in Table 3. This method results in the stepping sequence shown in Figure 3.4. The second method will not be used due to an increase of required logic. Only one microstep can be taken per basic timing cycle, which is determined by the value loaded into counter C(0). If more than one microstep is taken within 50 clock cycles of the basic cycle time, the first microstep loaded into the buffer registers of counters C(1) and C(2) will be skipped. Therefore, caution must be taken with the micro-stepper maintenance program that is implemented in the MEK6802D5 microcomputer, so that no more than one microstep is taken per 50 clock cycles of the MEK6802D5 microcomputer. Figure 3.5 is a flow chart of the micro-stepper maintenance program implemented in the MEK6802D5 microcomputer.

4. TESTING AND RESULTS

Testing of the micro-stepper circuit was achieved by placing a mirror on the flat surface of the motors shaft and directing a laser at the center of the mirror. Using this layout enabled the rotation of the shaft to be measured on a wall 21 feet away (see Figure 3.6a and b).

By having two fields on half the time, .9 degrees can be taken in either direction in .036 degree increments. The distance that the laser beam traveled on the wall was measured to the nearest 1/32 of an inch. Knowing the distance from the wall to the mirror, the angular

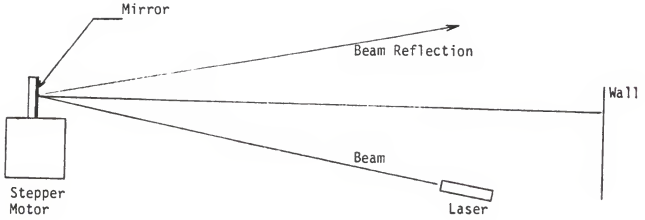


Figure 3.6a Side View of Test Set Up

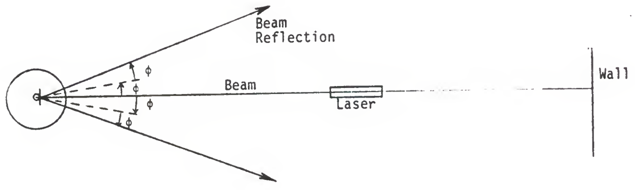


Figure 3.6b Top View of Test Set Up

displacement could then be found. Using the small angle theory, the angular displacement is:

$$\phi = \frac{d}{2r} \qquad (1)$$

where: d is displacement on the wall in inches,

r is distance from the mirror to the wall and is 252 inches.

The angular displacement of the shaft is also the angle of incidence at which the laser strikes the mirror. The number 2, in the denominator comes from:

$$\theta = 2\phi \qquad (2)$$

where: θ is the angle between the reflection of the laser beam and the laser beam itself (see Figure 3.6b).

Eight tests were done, using 50 microstep spacing on randomly selected full steps. The eight samples were found by rotating the base of the stepper motor. The tests showed that the angular displacement per microstep was not uniform (see Figure 3.7). Each microstep should be .036 degrees for the spacing to be linear. Figure 3.7 shows the average displacement for each separate microstep of the eight tests done. The mean deviation from data in Figure 3.7 is small in comparison, being 0 to 10 percent, of the average angular displacement of each microstep (see Appendix B). The larger deviations were taken from the ends of the graph where the deviation percentage is more sensitive to the error. Therefore, Figure 3.7 accurately depicts the displacement of each microstep for any set of microsteps.

A conclusion to be made from Figure 3.7 is that the current through the fields do not correspond linearly to the change in on and off time of the counters. This conclusion was checked by reading the current meter that is on the LAMBDA done voltage source used. The maximum current that passes through one field when it is on and the other field is off is approximately 1 amp. Data was obtained by changing data in the counters by increments of 5 and measuring the change in current through a field. By inspecting Figures 3.7 and 3.8 it is seen that they are roughly similar. The graph

shows that the conclusion made was correct (see Figures 3.7 and 3.8).

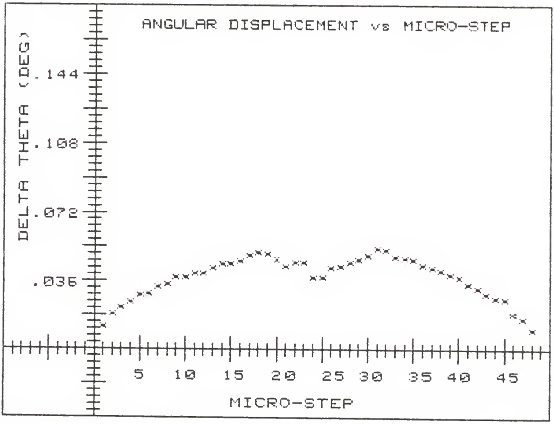


Figure 3.7 Angular Displacement vs. Microstep

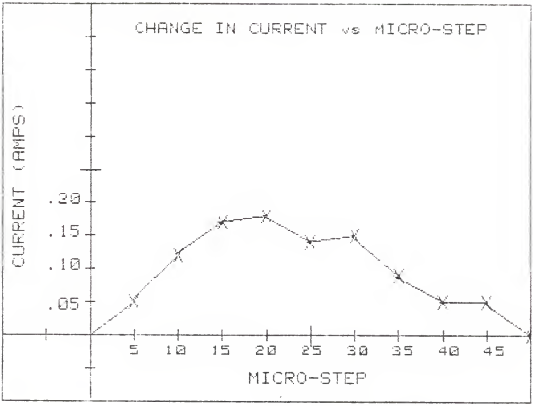


Figure 3.8 Change in Current vs. Microstep

Also, the distance of each full step is not consistent. The average full step size, recorded on the wall, is 508.9/32 inches (see Appendix B). The maximum deviation from the average is 17.9/32 of an inch. The average deviation is 7.6/32 of an inch (see Appendix B). This shows that there is inherent error in the spacing of the motor's fields. The maximum error per microstep is found from:

$$e_1 = \frac{10.4 - 3}{32} = \frac{7.4}{32} \text{ inches}$$

$$e_2 = \frac{.3575}{32} \text{ inches}$$

$$e_T = \sqrt{e_1^2 + e_2^2}$$

e_T = .225 inches = .025 degrees

where:

e_1 is the maximum deviation from all average microsteps

e_2 is the maximum deviation from the average of the eight sets and

e_T is the maximum error

where each microstep should be .036 degrees for uniform microstepping. The error, in percentage form is:

$$e = \frac{e_T}{.036}\ 100 = 71.1\%\ .$$

5. CONCLUSION

The reason the micro-stepper was developed has been discussed. Also, the theory and implementation have been presented. The micro-stepper worked well except for the nonlinearity of displacement verses microstep.

The nonlinearity of the change of current versus microstep could possibly be due to electrical characteristics of the micro-stepper circuit, stepper motor, or even the power supply. Finding the source of the nonlinearity is beyond the scope of this project and will not be dealt with.

CHAPTER IV

1. CONCLUSIONS

The control strategy worked well. Anticipated limits of the system were observed. One limit is imposed on the control strategy by the use of the small angle theory. This puts a limit on the acceleration and the slope of the ramp of the input to the system. Another limit on the acceleration of the micro-stepper is the holding torque of the micro-stepper. The dominating limit is the limit imposed on the system by the use of the small angle theory. When operating over the limit due to the small angle theory, the model of the system used in the control strategy does not accurately describe the characteristics of the system. This can be seen physically.

The microstep spacing of the micro-stepper was not linear as pointed out in Chapter 3. This is due to the current being nonlinear through each set of microsteps. The source of nonlinearity of the change in current versus microstep will not be dealt with, it being beyond the scope of this project.

2. RECOMMENDATIONS

To correct the error in angular displacement versus microstep, a current feedback system could be implemented. The current feedback should force the angular displacement to be linear. Also, a stronger stepper motor should be used so larger angular accelerations could be obtained. To obtain larger speeds, a microcomputer with a faster system should be used.

To obtain more versatility of movement, a control strategy that uses spline functions as inputs could be used. The system could also be expanded into a two degree of freedom link. Combinations of rigid links could be used.

LIST OF REFERENCES

1. Theory of Vibration with Applications, Second Edition, William T. Thomson.

2. Finding Fundamental Natural Frequencies for Common Beam Configurations, Abraham Hassoun.

3. Daytronic Strain Gauge Conditioner Model 3170, 3000 Series Instruments Instruction Manual, February 1983.

4. Model ADC10Z Low Cost General Purpose Analog-To-Digital Converter, Analog Devices Inc.

5. Motorola MC68000 Educational Computer Board Users Manual, Motorola.

6. Motorola MEK6802D5 Microcomputer Evaluation Board Users Manual, Motorola.

7. The 8253 Programmable Counter/Timer, National Semiconductor.

8. Motorola Semiconductors SAA1042, Motorola Specifications and Applications Information.

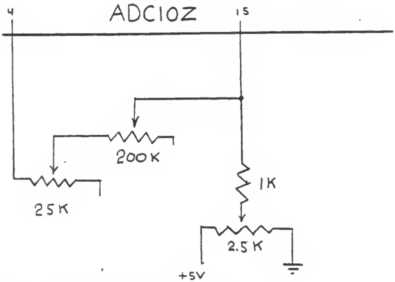
APPENDIX A

HARDWARE

HARDWARE DESCRIPTION

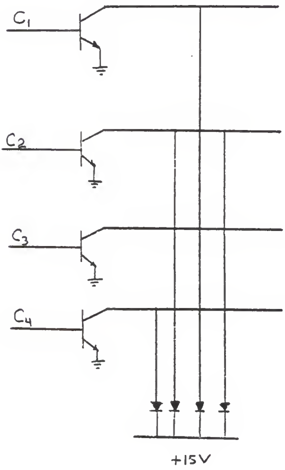
When writting to the 8253 Programmable Counter/Timer from the MEK6802D5 microcomputer, the data becomes invalid before the Read/$\overline{\text{Write}}$ signal does. To correct for this, a 74LS121 Monostable Multivibrator was used to shorten the time that the write cycle is high. The MEK6802D5 microcomputer does not read from the 8253 Programmable Counter/Timer. Also, when the MC68000 microcomputer writes to the latch which contains the control command to the system, or when it reads the feedback signal from the A/D, the Read/$\overline{\text{Write}}$ signal stays valid longer than the data. This problem is also solved by using a 74LS121 Monostable Multivibrator.

The ADC10Z A/D is permanently shifted up, depending on the magnitude of the input, in the bipolar mode. An external bias was added to the A/D to compensate for this. The external bias is illustrated below.



External bias circuit for A/D Converter.

The control lines that come from the 74LS08 AND gates were used to pulse 4 transistors (SK3180's) to allow current to pass through to ground. When a transistor is in the on state the respective electrical field is enegized in the stepper motor. To protect the transistors from possible voltage spikes caused by the electrical field collapsing, diode were placed between the collector of the transistor and the supply voltage to the motor. This can be seen in the figure below.



Diode protection of the switching transistors.

To obtain a better time response from the stepper motor external power resistors were placed in series with the power supply and the stepper motor. The voltage is then raised to get a better response time from the stepper motor. The calculations are as follows:

$$T= \frac{L}{Re+Ri}$$

$$K= \frac{1}{Re+Ri}$$

and

$$I = \left(\frac{K}{Ts+1}\right)V$$

where V is increased so that KV is constant.

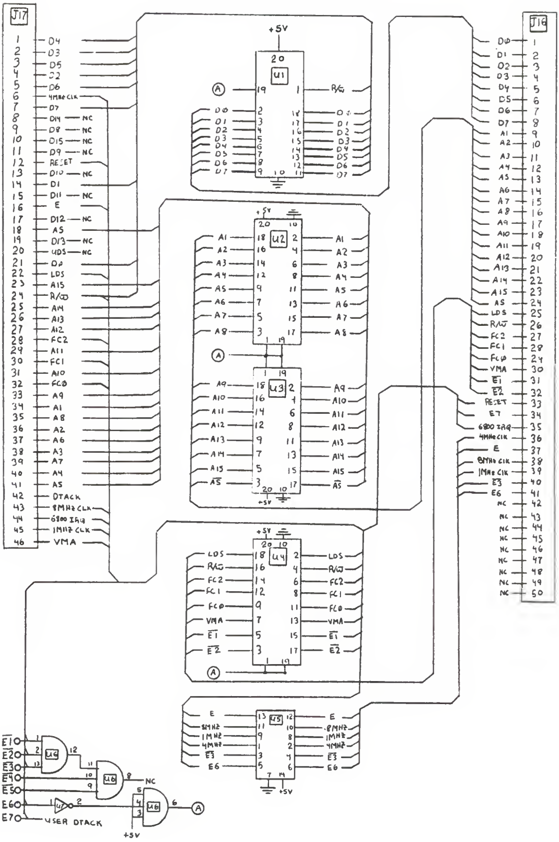
MOTOROLA D5 KIT CABLES

MEK6802D5 Microcomputer

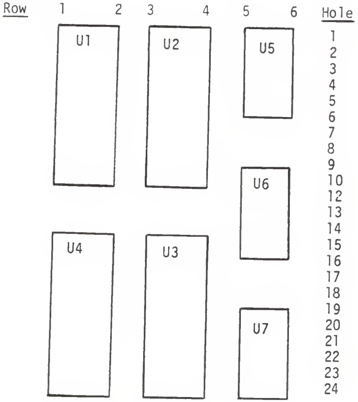
BUS CONNECTOR

J15 DIP PIN NO.	SIGNAL NAME	J14 EDGE CONNECTOR
1		NC
2	(HALT)'	4
3	MR	R
4	(IRQ)'	D
5	VMA	F
6	(NMI)'	E
7	BA	P
8	VCC(+5V)	1,A
9	A0	40
10	A1	V'
11	A2	U'
12	A3	39
13	A4	38
14	A5	T'
15	A6	S'
16	A7	37
17	A8	36
18	A9	R'
19	A10	P'
20	A11	35
21		NC
22	A12	34
23	A13	N'
24	A14	M'
25	A15	33
26	D7	J'
27	D6	L'
28	D5	30
29	D4	32
30	D3	H'
31	D2	K'
32	D1	29
33	D0	31
34	R/W	6
35	-12V	11,M
36	+12V	16,T
37	E(02)	J
38	-5V	25
39	GND	43,Y'
40	(RESET)	5

MC68000 Wire Wrap Region



MC68000 Board Layout for Bus Expansion



U1-74LS245 - Octal Bus Transceiver - Data Bus Buffer D0-D7 (20 pins)

U2-74LS244 - Octal Bus Buffer - Address Bus Buffer A1-A8 (20 pins)

U3-74LS244 - Octal Bus Buffer - Address Bus Buffer A9-A15 & AS (20 pins)

U4-74LS244 - Octal Bus Buffer - Control Line Buffer LDS, R/W, FC2, FC1, FC0, VMA, E1, E2 (20 pins)

U5-74LS07 - Hex Buffer - Nontristate Control Lines E, 8MHz Clk, 4MHz Clk, 1MHz Clk, E3, E6 (14 pins)

U6-75LS11 - Triple Three and Gates - Buffer Enable Logic E1, E2, E3, E4, E5, E6 (14 pins)

U7-74LS04 - Hex Inverters - Buffer Enable Logic E6 (14 pins)

NATIONAL SEMICONDUCTOR 8253 (U8)

Programmable Counter/Timer

Pin Number	Designation	Connection Description
1	Data Bit 7	Dip Pin No. 26 from MEK6802D5 Microcomputer (J15)
2	Data Bit 6	Dip Pin No. 27 from MEK6802D5 Microcomputer (J15)
3	Data Bit 5	Dip Pin No. 28 from MEK6802D5 Microcomputer (J15)
4	Data Bit 4	Dip Pin No. 29 from MEK6802D5 Microcomputer (J15)
5	Data Bit 3	Dip Pin No. 30 from MEK6802D5 Microcomputer (J15)
6	Data Bit 2	Dip Pin No. 31 from MEK6802D5 Microcomputer (J15)
7	Data Bit 1	Dip Pin No. 32 from MEK6802D5 Microcomputer (J15)
8	Data Bit 0	Dip Pin No. 33 from MEK6802D5 Microcomputer (J15)
9	Clock for Counter 0	Dip Pin No. 38 from MEK6802D5 Microcomputer (J15)
10	Output for Counter 0	Jumper to Pin 11 of 8253 Programmable Counter/Timer (U8)
11	Gate for Counter 0	Jumper to Pin 10, 14, 16 of 8253 Programmable Counter/Timer (U8)
12	Ground	Ground
13	Output for Counter 1	Pins 12 & 9 on U13 in Micro - Stepper Circuit
14	Gate for Counter 1	Jumper to Pin 11 of 8253 Programmable Counter/Timer (U8)
15	Clock for Counter 1	Dip Pin No. 38 from MEK6802D5 Microcomputer (J15)
16	Gate for Counter 2	Jumper to Pin 11 of 8253 Programmable Counter/Timer (U8)
17	Output for Counter 2	Pins 1 & 5 on U13 in Micro - Stepper Circuit
18	Clock for Counter 2	Dip Pin No. 38 from MEK6802D5 Microcomputer (J15)
19	A0, Register Select	Dip Pin No. 9 from MEK6802D5 Microcomputer (J15)
20	A1, Register Select	Dip Pin No. 10 from MEK6802D5 Microcomputer (J15)
21	Chip Select	Pin 15 on U12 in Micro - Stepper Circuit
22	IOR, Read Control	NC
23	IOW, Write Control	Pin 1 on U14 in Micro - Stepper Circuit
24	Vcc	+5V

MOTOROLA SAA1042 (U9)
Stepper Motor Driver

Pin Number	Designation	Connection Description
1	Control Line 2	Pin 10 on U13 in Micro - Stepper Circuit
2	V_D	+5V
3	Control Line 1	Pin 13 on U13 in Micro - Stepper Circuit
6	Set/Driver Bias	Pin 10 on U12 in Micro - Stepper Circuit
7	Clock	Pin 8 on U11 in Micro - Stepper Circuit with a 30Kohm Pull Down Resistor
8	Full Step/ Half Step	Ground for Full Step Mode
9	Ground	Ground
10	Clock Wise/ Counter Clock Wise	Pin 11 on U11 in Micro - Stepper Circuit
11	Vcc	+5V
14	Control Line 4	Pin 4 on U13 in Micro - Stepper Circuit
15	V_M	+5V
16	Control Line 3	Pin 2 on U13 in Micro - Stepper Circuit

74LS00 Quad. 2 - Input (U10)
Positive - NAND Gates

Pin Number	Designation	Connection Description
1	Input 1A	Dip Pin 9 on J15 and Jumpered to Ground with a 750 Picofarad Cap. & 1Kohm Res.
2	Input 1B	Dip Pin 14 on J15 and Jumpered to Ground with a 1Kohm Resistor
3	Output 1Y	Pin 1 on U20
4	Input 2A	NC
5	Input 2B	NC
6	Output 2Y	NC
7	Ground	Ground
8	Output 3Y	Pin 1 on U19
9	Input 3A	Dip Pin 13 on J16 with a 10Kohm Pull Down Resistor
10	Input 3B	Jumper to Pin 13 on U10
11	Output 4Y	Pin 1 on U18
12	Input 4A	Dip Pin 11 on J16 with a loKohm Pull Down Resistor
13	Input 4B	Pin 6 on U17
14	Vcc	+5V

74LS00 Quad. 2 - Input (U11)
Positive - NAND Gates

Pin Number	Designation	Connection Description
1	Input 1A	Pin 14 on U12
2	Input 1B	Jumper to Pin 11 on U11
3	Output 1Y	Jumper to Pin 12 on U11
4	Input 2A	Pin 12 on U12 with a 360 Picofarad Capacitor to Ground
5	Input 2B	Jumper to Pin 8 on U11
6	Output 2Y	Jumper to Pin 9 on U11
7	Ground	Ground
8	Output 3Y	Jumper to Pin 5 on U11 and Pin 7 on U9
9	Input 3A	Jumper to Pin 6 on U11
10	Input 3B	Pin 11 on U12
11	Output 4Y	Jumper to Pin 2 on U11 and Pin 10 on U9
12	Input 4A	Jumper to Pin 3 on U11
13	Input 4B	Pin 13 on U12
14	Vcc	+5V

TEXAS INSTRUMENT 74LS138 (U12)
3 Line Decoder/Demultiplexer

Pin Number	Designation	Connection Description
1	Select Line A	Dip Pin 24 from MEK6802D5 Microcomputer (J15)
2	Select Line B	Dip Pin 23 from MEK6802D5 Microcomputer (J15)
3	Select Line C	Dip Pin 22 from MEK6802D5 Microcomputer (J15)
4	Enable Line G2A	Ground
5	Enable Line G2b	Ground
6	Enable Line G1	Pin 8 on U15 in Micro - Stepper Circuit
7	Output Y7	NC
8	Ground	Ground
9	Output Y6	NC
10	Output Y5	Pin 6 on U9 in Micro - Stepper Circuit
11	Output Y4	Pin 10 on U11 in Micro - Stepper Circuit
12	Output Y3	Pin 4 on U11 in Micro - Stepper Circuit
13	Output Y2	Pin 13 on U11 in Micro - Stepper Circuit
14	Output Y1	Pin 1 on U11 in Micro - Stepper Circuit
15	Output Y0	Pin 21 on U8 in Micro - Stepper Circuit
16	Vcc	+5V

74LS08 Quad. 2 - Input (U13)
Positive - AND Gates

Pin Number	Designation	Connection Description
1	Input 1A	Pin 17 on U8
2	Input 1B	Pin 16 on U9
3	Output 1Y	This is Control Line 3 to switch the Stepper Motor(C_3)
4	Input 2A	Pin 14 on U9
5	Input 2B	Jumpered to Pin 1 on U13
6	Output 2Y	This is Control Line 4 to Switch the Stepper Motor(C_4)
7	Ground	Ground
8	Output 3Y	This is control Line 2 to Switch the Stepper Motor(C_2)
9	Input 3A	Jumpered to Pin 12 on U13
10	Input 3B	Pin 1 on U9
11	Output 4Y	This is Control Line 1 to Switch the Stepper Motor(C_1)
12	Input 4A	Pin 13 on U8
13	Input 4B	Pin 3 on U9
14	Vcc	+5V

74LS121 Monostable Multivibrator (U14)
with Schmitt - Trigger Inputs

Pin Number	Designation	Connection Description
1	$\overline{Q}$ Output	Pin 11 on U8 in Micro - Stepper Circuit
2	NC	NC
3	A1 Input	Dip Pin No. 34 from J15 with a Pull Up 1Kohm Resistor
4	A2 Input	Jumper to Pin 5 on U14 Which is Connected to +5V
5	B Input	Jumper to pin 4 and 14 on U14
6	Q Output	NC
7	Ground	Ground
8	NC	NC
9	Rint	NC
10	Cext	Jumper to Pin 11, with a 82.5 Picofarad Capacitor, on U14
11	Rext/Cext	Jumper to +5V with a 13Kohm Resistor
12	NC	NC
13	NC	NC
14	Vcc	+5V

74LS04 Hex Inverters (U15)

Pin Number	Designation	Connection Description
1	Input 1A	NC
2	Output 1Y	NC
3	Input 2A	NC
4	Output 2Y	NC
5	Input 3A	NC
6	Output 3Y	NC
7	Ground	Ground
8	Output 4Y	Pin 6 on U12
9	Input 4A	Dip Pin 16 on J15 with a 1Kohm Pull Down Resistor
10	Output 5Y	NC
11	Input 5A	NC
12	Output 6Y	Pin 3 on U17
13	Input 6A	Dip Pin 9 on J16 with 10Kohm Pull Down Resistor
14	Vcc	+5V

74LS121 Monostable Multivibrator (U16)
with Schmitt - Trigger Inputs

Pin Number	Designation	Connection Description
1	$\overline{Q}$ Output	NC
2	NC	NC
3	A1 Input	Dip Pin No. 26 from J16
4	A2 Input	Jumper to Pin 5 on U16 Which is Connected to +5V
5	B Input	Jumper to Pin 4 and 14 on U16
6	Q Output	Pin 11 on U20
7	Ground	Ground
8	NC	NC
9	Rint	NC
10	Cext	Jumper to Pin 11, with a 82.5 Picofarad Capacitor, on U16
11	Rext/Cext	Jumper to +5V with a 15Kohm Resistor
12	NC	NC
13	NC	NC
14	Vcc	+5V

74LS121 Monostable Multivibrator (U17)
with Schmitt - Trigger Inputs

Pin Number	Designation	Connection Description
1	$\overline{Q}$ Output	NC
2	NC	NC
3	A1 Input	Pin 12 on U15
4	A2 Input	Jumper to Pin 5 on U17 which is Connected to +5V
5	B Input	Jumper to Pin 4 and 14 on U17
6	Q Output	Pin 13 on U10
7	Ground	Ground
8	NC	NC
9	Rint	NC
10	Cext	Jumper to Pin 11, with a 82.5 Picofarad Capacitor, on U17
11	Rext/Cext	Jumper to +5V with a 15Kohm Resistor
12	NC	NC
13	NC	NC
14	Vcc	+5V

74LS373 Octal D - Type Transparent Latches
and Edge - Triggered Flip - Flops (U18)

Pin Number	Designation	Connection Description
1	Output Control	Pin 11 on U10
2	Data Bit 1 Out	Dip Pin 1 on J16
3	Data Bit 1 In	Pin 52 on U21
4	Data Bit 2 In	Pin 54 on U21
5	Data Bit 2 Out	Dip Pin 2 on J16
6	Data Bit 3 Out	Dip Pin 3 on J16
7	Data Bit 3 In	Pin 56 on U21
8	Data Bit 4 In	Pin 58 on U21
9	Data Bit 4 Out	Dip Pin 4 on J16
10	Ground	Ground
11	Enable Latch	Pin 33 on U21
12	Data Bit 5 Out	Dip Pin 5 on J16
13	Data Bit 5 In	Pin 61 on U21
14	Data Bit 6 In	Pin 63 on U21
15	Data Bit 6 Out	Dip Pin 6 on J16
16	Data Bit 7 Out	Dip Pin 7 on J16
17	Data Bit 7 In	Pin 65 on U21
18	Data Bit 8 In	Pin 67 on U21
19	Data Bit 8 Out	Dip Pin 8 on J16
20	Vcc	+5V

74LS373 Octal D - Type Transparent Latches
and Edge - Triggered Flip - Flops (U19)

Pin Number	Designation	Connection Description
1	Output Control	Pin 8 on U10
2	Data Bit 1 Out	Dip Pin 1 on J16
3	Data Bit 1 In	Pin 71 on U21
4	Data Bit 2 In	Pin 70 on U21
5	Data Bit 2 Out	Dip Pin 2 on J16
6	Data Bit 3 Out	NC
7	Data Bit 3 In	NC
8	Data Bit 4 In	NC
9	Data Bit 4 Out	NC
10	Ground	Ground
11	Enable Latch	Pin 33 on U21
12	Data Bit 5 Out	NC
13	Data Bit 5 In	NC
14	Data Bit 6 In	NC
15	Data Bit 6 Out	NC
16	Data Bit 7 Out	NC
17	Data Bit 7 In	NC
18	Data Bit 8 In	NC
19	Data Bit 8 Out	NC
20	Vcc	+5V

74LS373 Octal D - Type Transparent Latches
and Edge - Triggered Flip - Flops (U20)

Pin Number	Designation	Connection Description
1	Output Control	Pin 3 on U10
2	Data Bit 1 Out	Dip Pin 33 on J15
3	Data Bit 1 In	Dip Pin 1 on J16
4	Data Bit 2 In	Dip Pin 2 on J16
5	Data Bit 2 Out	Dip Pin 32 on J15
6	Data Bit 3 Out	Dip Pin 31 on J15
7	Data Bit 3 In	Dip Pin 3 on J16
8	Data Bit 4 In	Dip Pin 4 on J16
9	Data Bit 4 Out	Dip Pin 30 on J15
10	Ground	Ground
11	Enable Latch	Pin 6 on U16
12	Data Bit 5 Out	Dip Pin 29 on J15
13	Data Bit 5 In	Dip Pin 5 on J16
14	Data Bit 6 In	Dip Pin 6 on J16
15	Data Bit 6 Out	Dip Pin 28 on J15
16	Data Bit 7 Out	Dip Pin 27 on J15
17	Data Bit 7 In	Dip Pin 7 on J16
18	Data Bit 8 In	Dip Pin 8 on J16
19	Data Bit 8 Out	Dip Pin 26 on J15
20	Vcc	+5V

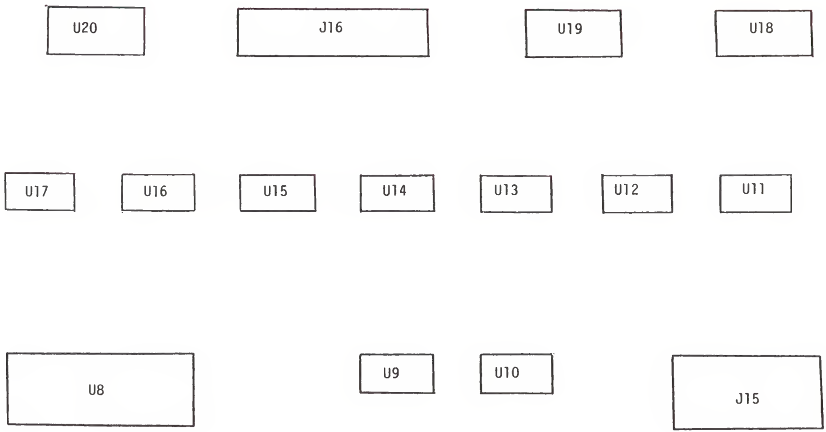
ADC10Z (U21)
Analog - to - Digital
Converter

Pin Number	Designation	Connection Description
2	Buffer Input	Analog Signal from Strain Gauges on the Flexible Link
3	Buffer Ground	Ground
4	Buffer Output	Red on Potentiometer 1
5	+10V or ±10V Input	NC
6	+5V or ±5V Input	NC
15	Direct Input	Red on Potentiometer 2
16	Unipolar	NC
19	Unipolar	NC
20	Zero	-15V
21	Bipolar	Jumper to Pin 22 on U21
22	Bipolar	Jumper to Pin 21 on U21
23	Signal Ground	Ground
25	-15V	-15V
26	Serial Out	NC
27	+15V	+15V
29	+5V	+5V
30	Digital Ground	Jumper to Pin 23 on U21
32	Clock Rate	NC
33	Status	Pin 6 on U16
34	Conversion Command	Pin 11 on U18 and U19
35	Clock in	Jumper to Pin 36 on U21
36	Clock out	Jumper to Pin 35 on U21
37	Clock Inhibit	Jumper to Pin 43 on U21
39	Strobe out	NC

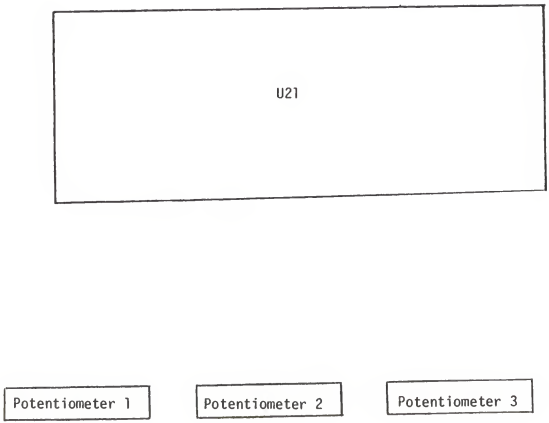
ADC10Z (U21)
Analog - to - Digital
Converter

Pin Number	Designation	Connection Description
43	$\overline{\text{Status}}$	Jumper to 37
52	Data Bit 0 (LSB)	Pin 3 on U18
54	Data Bit 1	Pin 4 on U18
56	Data Bit 2	Pin 7 on U18
58	Data Bit 3	Pin 8 on U18
61	Data Bit 4	Pin 13 on U18
63	Data Bit 5	Pin 14 on U18
65	Data Bit 6	Pin 17 on U18
67	Data Bit 7	Pin 18 on U18
70	$\overline{\text{Data Bit 9}}$ ($\overline{\text{MSB}}$)	Pin 4 on U19
71	Data Bit 8	Pin 3 on U19
72	Data Bit 9 (MSB)	NC

Layout For
Micro - Stepper Circuit
Plus Feedback Latches U18 and U19



Layout For The
Feedback Circuit
Minus Latches U18 and U19



6800 Address Decode Map onto Micro-Stepper Circuit

A15 A14 A13 A12 A11 A10 A9 A8 A7 A6 A5 A4 A3 A2 A1 A0

A14 A13 A12 → A B C: Decoder Logic Select Lines 74LS138

A7 → Chip Select Decoder 74LS138

A1 A0 → A1 A0: Register Select for 8253

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Address Counter 0	X	0	0	0	X	X	X	X	0	X	X	X	X	X	0	0	$0000
Address Counter 1	X	0	0	0	X	X	X	X	0	X	X	X	X	X	0	1	$0001
Address Counter 2	X	0	0	0	X	X	X	X	0	X	X	X	X	X	1	0	$0002
Select Mode for C0	X	0	0	0	X	X	X	X	0	X	X	X	X	X	1	1	$0003
Pulse Clk High	X	0	0	1	X	X	X	X	0	X	X	X	X	X	X	X	$1000
Pulse Clk Low	X	1	1	0	X	X	X	X	0	X	X	X	X	X	X	X	$6000
Shaft Dir. CW	X	1	0	0	X	X	X	X	0	X	X	X	X	X	X	X	$4000
Shaft Dir. CCW	X	0	1	0	X	X	X	X	0	X	X	X	X	X	X	X	$2000
Set Bias S.M.D.	X	1	0	1	X	X	X	X	0	X	X	X	X	X	X	X	$5000
Flag 2 = Flag 1	X	X	X	X	X	X	X	X	1	X	1	X	X	X	X	1	$00A1

Memory Map

$0000	DFFF	External to ME6802D5
$E000	E3FF	User RAM

APPENDIX B

SOFTWARE

```
10 REM ********************************************************************
20 REM
30 REM    RUNGE-KUTTA SIMULATION FOR CONTROL STRATEGY IMPLEMENTED IN A
40 REM    SYSTEM TO CONTROL THE MOVEMENT OF A FLEXIBLE LINK.  THE CONTROL
50 REM    STRATEGY CONSISTS OF PROPORTIONAL PLUS INTEGRAL CONTROL WITH
60 REM    UNITY PLUS DERIVATIVE FEEBACK.
70 REM
80 REM                 WRITTEN BY BOB SIMMONS   JANUARY 1984
90 REM
100 REM -------------------------------------------------------------------
110 REM
120 REM     THIS PROGRAM SIMULATES A SYSTEM OF DIFFERENTIAL EQUATIONS BY
130 REM  THE FOURTH-ORDER RUNGE-KUTTA METHOD.  THE USER MUST SUPPLY A
140 REM  SET OF EQUATIONS IN STATE-VARIABLE FORM.  THE EQUATIONS ARE
150 REM  ENTERED AS THE SUBROUTINE Funct: AT THE END OF THE PROGRAM.
160 REM
170 REM    AN EULER METHOD SIMULATION IS ALSO DONE USING ONLY THE FIRST
180 REM  ESTIMATE OF THE SLOPE.
190 REM
200 REM    THE RESULTS ARE PRINTED IN THREE COLUMNS -- TIME, THE
210 REM  RUNGE-KUTTA ESTIMATE OF THE SYSTEM OUTPUT, AND THE
220 REM  EULER ESTIMATE OF THE SYSTEM OUTPUT.
230 REM
240 REM  THE VARIABLES USED IN THE PROGRAM ARE:
250 REM
260 REM      N        THE ORDER OF THE SYSTEM.  THIS IS EQUAL TO THE
270 REM                  NUMBER OF STATE VARIABLES.
280 REM
290 REM      X(N)     AN ARRAY HOLDING THE RUNGE-KUTTA ESTIMATE OF
300 REM                  THE STATE VARIABLES.
310 REM
320 REM      Y(N)     A TEMPORARY ARRAY USED TO PASS THE ESTIMATES OF
330 REM                  THE STATE VARIABLES TO THE SUBROUTINE Funct:.
340 REM
350 REM      Z(N)     AN ARRAY USED TO SUM UP THE SLOPE ESTIMATES IN
360 REM                  A WEIGHTED MANNER.
370 REM
380 REM      P(N)     AN ARRAY HOLDING THE EULER ESTIMATE OF THE
390 REM                  STATE VARIABLES.
400 REM
410 REM      H        THE STEP SIZE.
420 REM
430 REM      T        TIME.
440 REM
450 REM      I,J      GENERAL COUNTERS AND ARRAY SUBSCRIPTS.
460 REM
470 REM -------------------------------------------------------------
480 REM
490 REM
500 REM ----------------------------
510 REM
520 REM   SPECIFY N, H, AND INITIAL
530 REM   VALUES OF STATE VARIABLES
540 REM   HERE..
550 REM
560 REM ----------------------------
570 REM
580 COM /Aa/ H,N,X(3),Wn,R,Kp,Kd,Ki
590 INPUT "ENTER KP & KD & KI & K",Kp,Kd,Ki
600 N=3
```

```
610 R=2/3
620 INPUT "ENTER STEP SIZE H =",H
630 X(1)=0
640 X(2)=0
650 X(3)=0
660 P(1)=X(1)
670 REM
680 REM      PRINT HEADINGS
690 REM
700 PRINT "            TIME     RUNGE-KUTTA EST.    EULER EST."
710 PRINT "                          OF X(1)           OF X(1)"
720 PRINT
730 REM
740 REM      TOP OF LOOP
750 REM
760 GINIT
770 GRAPHICS ON
780 ALPHA OFF
790 FRAME
800 WINDOW 0,5,0,2
810 AXES .1,.1,0,0,10,10,5
820 MOVE 0,1
830 DRAW 5,1
840 MOVE 0,0
850 FOR I=0 TO 1/R STEP H       ! LOOP STARTS HERE
860 T=I
870 PRINT USING "DDDDDDDDDDD.DDDD";T,X(1),P(1)
880 REM
890 REM      LOAD Y WITH X TO PASS TO Funct:
900 REM
910 FOR J=1 TO N
920 Y(J)=X(J)
930 NEXT J
940 GOSUB Funct
950 REM
960 REM      START RUNNING SUM IN Z(N) WITH SLOPES FROM Funct:
970 REM
980 FOR J=1 TO N
990 Z(J)=F(J)
1000 NEXT J
1010 REM
1020 REM      CALCULATE EULER APPROXIMATION
1030 REM
1040 FOR J=1 TO N
1050 P(J)=P(J)+H*F(J)
1060 NEXT J
1070 REM
1080 REM    LOAD Y(N) WITH NEW ESTIMATES OF X(N) BASED ON FIRST
1090 REM         SLOPE ESTIMATE.
1100 REM
1110 FOR J=1 TO N
1120 Y(J)=X(J)+H*F(J)/2
1130 NEXT J
1140 GOSUB Funct
1150 REM
1160 REM    ADD WEIGHTED SLOPE TO RUNNING SUM
1170 REM
1180 FOR J=1 TO N
1190 Z(J)=Z(J)+2*F(J)
1200 NEXT J
```

```
1210 REM
1220 REM    LOAD Y(N) WITH NEW ESTIMATES OF X(N) BASED ON NEW
1230 REM        SLOPE ESTIMATE.
1240 REM
1250 FOR J=1 TO N
1260 Y(J)=X(J)+H*F(J)/2
1270 NEXT J
1280 GOSUB Funct
1290 REM
1300 REM    ADD WEIGHTED SLOPE TO RUNNING SUM.
1310 REM
1320 FOR J=1 TO N
1330 Z(J)=Z(J)+2*F(J)
1340 NEXT J
1350 REM
1360 REM   LOAD Y(N) WITH FINAL ESTIMATE OF X(N) BASED ON THIRD
1370 REM        ESTIMATE OF SLOPE.
1380 REM
1390 FOR J=1 TO N
1400 Y(J)=X(J)+H*F(J)
1410 NEXT J
1420 GOSUB Funct
1430 REM
1440 REM    ADD FINAL SLOPE ESTIMATE TO RUNNING SUM
1450 REM
1460 FOR J=1 TO N
1470 Z(J)=Z(J)+F(J)
1480 NEXT J
1490 REM
1500 REM    CALCULATE NEW VALUE OF X(N) USING WEIGHTED AVERAGE
1510 REM         SLOPE.
1520 REM
1530 FOR J=1 TO N
1540 X(J)=X(J)+H*Z(J)/6
1550 NEXT J
1560 DRAW T+H,X(1)
1570 MOVE T,Thc-H*R
1580 DRAW T+H,Thc
1590 MOVE T+H,X(1)
1600 NEXT I
1610 INPUT A
1620 !DUMP GRAPHICS
1630 !GCLEAR
1640 LOAD "CONT51"
1650 STOP
1660 REM
1670 REM         DEFINE STATE EQUATIONS HERE
1680 REM
1690 Funct:Thc=R*T
1700       Wn=7
1710       F(1)=Y(2)-Kp*Kd*Wn*Wn*Y(1)                        ' SYSTEM EQUATIONS IN
1720       F(2)=Kp*Wn*Wn*Thc-Wn*Wn*(1+Kp+Ki*Kd)*Y(1)+Y(3)     '    STATE VARIABLE
FORM
1730       F(3)=Wn*Wn*Ki*(Thc-Y(1))
1740       RETURN
1750       END
```

```
10  COM /Aa/ H,N,X(3),Wn,R,Kp,Kd,Ki
20  PRINT Ze,H,N,X(1),X(2),Wn
30  P(1)=X(1)
40  REM
50  REM      TOP OF LOOP
60  REM
70  FOR I=1/R TO 5 STEP H       ! LOOP STARTS HERE
80  T=I
90  PRINT USING "DDDDDDDDDDD.DDDD";T,X(1),P(1)
100 REM
110 REM      LOAD Y WITH X TO PASS TO Funct:
120 REM
130 FOR J=1 TO N
140 Y(J)=X(J)
150 NEXT J
160 GOSUB Funct
170 REM
180 REM      START RUNNING SUM IN Z(N) WITH SLOPES FROM Funct:
190 REM
200 FOR J=1 TO N
210 Z(J)=F(J)
220 NEXT J
230 REM
240 REM     CALCULATE EULER APPROXIMATION
250 REM
260 FOR J=1 TO N
270 P(J)=P(J)+H*F(J)
280 NEXT J
290 REM
300 REM    LOAD Y(N) WITH NEW ESTIMATES OF X(N) BASED ON FIRST
310 REM         SLOPE ESTIMATE.
320 REM
330 FOR J=1 TO N
340 Y(J)=X(J)+H*F(J)/2
350 NEXT J
360 GOSUB Funct
370  REM
380  REM    ADD WEIGHTED SLOPE TO RUNNING SUM
390  REM
400  FOR J=1 TO N
410  Z(J)=Z(J)+2*F(J)
420  NEXT J
430  REM
440  REM    LOAD Y(N) WITH NEW ESTIMATES OF X(N) BASED ON NEW
450  REM         SLOPE ESTIMATE.
460  REM
470  FOR J=1 TO N
480  Y(J)=X(J)+H*F(J)/2
490  NEXT J
500  GOSUB Funct
510  REM
520  REM    ADD WEIGHTED SLOPE TO RUNNING SUM.
530  REM
540  FOR J=1 TO N
550  Z(J)=Z(J)+2*F(J)
560  NEXT J
570  REM
580  REM   LOAD Y(N) WITH FINAL ESTIMATE OF X(N) BASED ON THIRD
590  REM         ESTIMATE OF SLOPE.
600  REM
```

```
610  FOR J=1 TO N
620  Y(J)=X(J)+H*F(J)
630  NEXT J
640  GOSUB Funct
650  REM
660  REM    ADD FINAL SLOPE ESTIMATE TO RUNNING SUM
670  REM
680  FOR J=1 TO N
690  Z(J)=Z(J)+F(J)
700  NEXT J
710  REM
720  REM    CALCULATE NEW VALUE OF X(N) USING WEIGHTED AVERAGE
730  REM         SLOPE.
740  REM
750  FOR J=1 TO N
760  X(J)=X(J)+H*Z(J)/6
770  NEXT J
780  DRAW T+H,X(1)
790  NEXT I
800  LDIR 0
810  CSIZE 3,1
820  MOVE .50,.7
830  LABEL "INPUT"
840  MOVE 1.20,.5
850  LABEL "RESPONSE"
860  MOVE 2.1,1.01
870  LABEL "DESIRED DISPLACEMENT"
880  MOVE .7,1.85
890  LABEL "OUTPUT RESPONSE TO A RAMP INPUT"
900  INPUT A
910  !DUMP GRAPHICS
920  GCLEAR
930  STOP
940  REM
950  REM         DEFINE STATE EQUATIONS HERE
960  REM
970 Funct: Thc=1
980         F(1)=Y(2)-Kp*Kd*Wn*Wn*Y(1)                        ! SYSTEM EQUATIONS IN
990         F(2)=Kp*Wn*Wn*Thc-Wn*Wn*(1+Kp+Ki*Kd)*Y(1)+Y(3)     !   STATE VARIABLE
FORM
1000        F(3)=Wn*Wn*Ki*(Thc-Y(1))
1010        RETURN
1020        END
```

```
20    ! THIS PROGRAM PLOTS THE MICRO-STEP SIZE vs MICRO-STEP.
30    ! THE NUMBER OF SAMPLES TAKEN FOR THIS PROGRAM IS EIGHT.
40    ! ALSO THE SUM OF THE DISTANCES OF EACH SET OF MICRO-STEPS
50    ! IS FOUND TO FIND THE DEVIATION OF THE SIZE OF EACH SET OF
60    ! MICRO-STEPS.  THE AVERAGE, OF THE SIZES, OF ALL SETS OF
70    ! MICRO-STEPS IS FOUND ALONG WITH THE AVERAGE OF EACH
80    ! INDIVIDUAL MICRO-STEP.  THE DEVIATION OF EACH MICRO 1st,
90    ! 2nd, 3rd ETC. IS FOUND FROM THE EIGHT SAMPLES TAKEN.
100   !
110   !                 written by; BOB SIMMONS
120   !
130   !*****************************************************************
140   OPTION BASE 1
150   DIM Array(48,8),Sums(8),Arr_avg(48),Avg(8),Max_dev(8),Max_dev2(9)
160   DIM Arr_avg1(48,8),Arr_avg3(48),Arr_avg5(48)
170   DATA 3,3,3,4,3,3,4,3,5,5,5,5,5,6,5,5,6,6,7,6,6,6,6,6
180   DATA 7,8,7,7,7,7,6,7,8,8,8,8,8,8,7,8,8,9,8,7,8,8,8,8
190   DATA 9,11,9,8,10,10,9,8,8,11,10,10,9,10,9,9,10,11,11,11,10,10,11,10
200   DATA 9,12,11,12,11,10,10,9,10,13,11,12,10,12,11,10,10,12,12.12,11,11,11,11
210   DATA 11,12,13,13,12,10,13,11,12,14,12,14,11,12,13,12,12,13,13,14,13,11,12,
12
220   DATA 12,14,14,13,12,12,13,14,12,15,15,14,13,14,14,14,12,15,15,15,14,14,15,
14
230   DATA 13,13,16,15,14,13,14,14,13,13,15,12,13,13,14,13,13,13,11,15,11,11,12,
11
240   DATA 13,10,14,14,12,13,13,14,11,13,14,12,12,14,13,13,10,10,10,11,10,10,11,
12
250   DATA 10,12,10,11,10,10,10,12,10,13,12,12,12,12,12,13,12,12,13,12,11,12,13,
12
260   DATA 12,13.11,15,14,11,12,14,13,13,15,12,12.13,13,14,13,13,16,15,14,13,13,
13
270   DATA 14,15,15,15,16,15,14,15,14,15,15,14.15,15,14,14,14,14.14,13,14,14,13,
13
280   DATA 13,13,13,14,13,14,14,13,13,13,13,13,13,13,13,14,12,12,12,12,12,13,13,
12
290   DATA 13,12,12,11,13,12,11,11,12.11,12,11,11,12,12,11,11,10,12,10,11,11,12,
11
300   DATA 11,10,11,9,11,12,11,10,10,10,9,9,10,10,9,9,10,8,9,8,9,9,10,9
310   DATA 9,8,8,8,8,8,8,8,7,8,8,7,9,8,7,7,7,8,7,8,7,8,7,7
320   DATA 6,5,6,4,6,6,5,4,5,4,5,4,5,5,4,4,3,3,3,3,3,3,3,3
330   READ Array(*)
340   PRINT "1st    :    2nd    :    3rd    :    4th    :    5th    :    6th    :    7th    :
   8th"
350   PRINT Array(*)
360   PRINT CHR$(12)
370   PRINT
380   PRINT
390   PRINT "LENGTH OF EACH SET OF MICRO-STEPS IN 32nds OF AN INCH AND THE"
400   PRINT "AVERAGE MICRO-STEP IN THAT SET."
410   PRINT "----------------------------------------------------------------"
420   FOR I=1 TO 8
430   Sums(I)=0
440   FOR J=1 TO 48
450   Sums(I)=Sums(I)+Array(J,I)
460   NEXT J
470   PRINT "SAMPLE ";I
480   PRINT "SUM OF MICRO-STEPS = ";Sums(I)
490   Avg(I)=Sums(I)/48
500   PRINT "MICRO-STEP_AVG = ";Avg(I)
```

```
510   PRINT
520   NEXT I
530   PRINT
540   Summ=0
550   FOR K=1 TO 8
560   Summ=Summ+Sums(K)
570   NEXT K
580   Summ_avg=Summ/8
590   PRINT "AVERAGE OF ALL THE SETS OF MICRO-STEPS = ";Summ_avg
600   PRINT
610   FOR I=1 TO 8
620   Max_dev(I)=ABS(Summ_avg-Sums(I))
630   IF Max_dev(I)>Max_dev1 THEN GOTO 650
640   GOTO 660
650   Max_dev1=Max_dev(I)
660   NEXT I
670   PRINT "MAXIMUM DEVIATION FROM THE AVERAGE SET OF MICRO-STEPS = ";Max_dev1
680   PRINT
690   Max_dev2(1)=0
700   FOR I=2 TO 9
710   Max_dev2(I)=Max_dev2(I-1)+Max_dev(I-1)
720   NEXT I
730   Max_dev3=Max_dev2(8)/8
740   PRINT "AVERAGE DEVIATION FROM THE AVERAGE SET OF MICRO-STEPS = ";Max_dev3
750   PRINT CHR$(12)
760   FOR J=1 TO 48
770   Arr_avg(J)=0
780   FOR I=1 TO 8
790   Arr_avg(J)=Arr_avg(J)+Array(J,I)
800   NEXT I
810   Arr_avg(J)=Arr_avg(J)/8
820   NEXT J
830   PRINT "AVERAGE OF EACH MICRO-STEP FROM LEFT TO RIGHT & TOP TO BOTTOM"
840   PRINT "------------------------------------------------------------------"
850   PRINT Arr_avg(*)
860   PRINT
870   PRINT
880   FOR I=2 TO 49
890   Arr_avg2=0
900   FOR J=1 TO 8
910   Arr_avg1(I-1,J)=ABS(Array(I-1,J)-Arr_avg(I-1))
920   IF Arr_avg1(I-1,J)>Arr_avg2 THEN GOTO 940
930   GOTO 950
940   Arr_avg2=Arr_avg1(I-1,J)
950   NEXT J
960   Arr_avg3(I-1)=Arr_avg2              ! MAX DEVIATION FROM AVERAGE MICRO-STEP
970   NEXT I
980   PRINT "MAXIMUM DEVIATION FROM THE AVERAGE MICRO-STEP FROM LEFT TO RIGHT"
990   PRINT " & TOP TO BOTTOM"
1000  PRINT "------------------------------------------------------------------"
1010  PRINT Arr_avg3(*)
1020  FOR I=1 TO 48
1030  Arr_avg4=0
1040  FOR J=1 TO 8
1050  Arr_avg4=Arr_avg4+Arr_avg1(I,J)
1060  NEXT J
1070  Arr_avg5(I)=Arr_avg4/8
1080  NEXT I
1090  PRINT
1100  PRINT
```

```
1110  PRINT "AVERAGE DEVIATION FROM THE AVERAGE MICRO STEP FROM LEFT TO RIGHT"
1120  PRINT " & TOP TO BOTTOM"
1130  PRINT "------------------------------------------------------------------"
1140  PRINT Arr_avg5(*)
1150  GINIT
1160  GRAPHICS ON
1170  ALPHA OFF
1180  WINDOW -10,50,-10,50
1190  AXES 1,1,0,0,5,5,6
1200  FRAME
1210  Mstep=0
1220  FOR I=1 TO 48
1230  Mstep=Mstep+1
1240  MOVE Mstep-.3,Arr_avg(I)-.3
1250  IDRAW .6,.6
1260  MOVE Mstep-.3,Arr_avg(I)+.3
1270  IDRAW .6,-.6
1280  NEXT I
1290  LDIR 0
1300  MOVE 4.5,-5
1310  LABEL "5  10  15  20  25 30  35 40  45"
1320  MOVE 4,-9
1330  LABEL "         MICRO-STEP"
1340  MOVE -7,8.5
1350  LABEL ".036"
1360  MOVE -7,18.5
1370  LABEL ".072"
1380  MOVE -7,28.5
1390  LABEL ".108"
1400  MOVE -7,38.5
1410  LABEL ".144"
1420  LDIR PI/2
1430  MOVE -7,10
1440  LABEL "   DELTA THETA (DEG)"
1450  INPUT X
1460  PRINT CHR$(12)
1470  DUMP GRAPHICS
1480  GCLEAR
1490  END
```

LENGTH OF EACH SET OF MICRO-STEPS IN 32nds OF AN INCH AND THE AVERAGE MICRO-STEP IN THAT SET.

SAMPLE 1
SUM OF MICRO-STEPS = 491
MICRO-STEP_AVG = 10.2291666667

SAMPLE 2
SUM OF MICRO-STEPS = 519
MICRO-STEP_AVG = 10.8125

SAMPLE 3
SUM OF MICRO-STEPS = 526
MICRO-STEP_AVG = 10.9583333333

SAMPLE 4
SUM OF MICRO-STEPS = 516
MICRO-STEP_AVG = 10.75

SAMPLE 5
SUM OF MICRO-STEPS = 504
MICRO-STEP_AVG = 10.5

SAMPLE 6
SUM OF MICRO-STEPS = 507
MICRO-STEP_AVG = 10.5625

SAMPLE 7
SUM OF MICRO-STEPS = 507
MICRO-STEP_AVG = 10.5625

SAMPLE 8
SUM OF MICRO-STEPS = 501
MICRO-STEP_AVG = 10.4375

AVERAGE OF ALL THE SETS OF MICRO-STEPS = 508.875

MAXIMUM DEVIATION FROM THE AVERAGE SET OF MICRO-STEPS = 17.875

AVERAGE DEVIATION FROM THE AVERAGE SET OF MICRO-STEPS = 7.609375

AVERAGE OF EACH MICRO-STEP FROM LEFT TO RIGHT & TOP TO BOTTOM

3.25	5.125	6.125	7	7.875	8.25	9.25	9.5
10.5	10.5	11.125	11.25	11.875	12.5	12.5	13
13.875	14.25	14	13.25	12.125	12.875	12.75	10.5
10.625	12	12.125	12.75	13.125	13.75	14.875	14.5
13.625	13.375	13.125	12.375	11.875	11.5	11	10.625
9.5	9	8.125	7.625	7.375	5.25	4.5	3

MAXIMUM DEVIATION FROM THE AVERAGE MICRO-STEP FROM LEFT TO RIGHT & TOP TO BOTTOM

.75	.875	.875	1	.875	.75	1.75	1.5
.5	1.5	1.875	1.25	1.875	1.5	1.5	1
1.875	2.25	2	1.75	2.875	2.875	1.75	1.5
1.375	2	1.125	2.25	1.875	2.25	1.125	.5
.625	.625	.875	.625	1.125	.5	1	1.625
.5	1	.875	1.375	.625	1.25	.5	0

AVERAGE DEVIATION FROM THE AVERAGE MICRO-STEP FROM LEFT TO RIGHT & TOP TO BOTTOM

.375	.21875	.21875	.25	.21875	.375	.8125	.75
.5	1	.90625	.5625	.90625	.875	.75	.75
.6875	.75	.75	.625	1.15625	.9375	.8125	.625
.78125	.5	.4375	1.25	.6875	.9375	.4375	.5
.46875	.46875	.21875	.46875	.65625	.5	.5	.71875
.5	.5	.21875	.625	.46875	.75	.5	0

Eight Sets of Data for Testing

Operation of Micro - Stepper

1st	2nd	3rd	4th	5th	6th	7th	8th
3	3	3	4	3	3	4	3
5	5	5	5	5	6	5	5
6	6	7	6	6	6	6	6
7	8	7	7	7	7	6	7
8	8	8	8	8	8	7	8
8	9	8	9	8	8	8	8
9	11	9	8	10	10	9	8
8	11	10	10	9	10	9	9
10	11	11	11	10	10	11	10
9	12	11	12	11	10	10	9
10	13	11	12	10	12	11	10
10	12	12	12	11	11	11	11
11	12	13	13	12	10	13	11
12	14	12	14	11	12	13	12
12	13	13	14	13	11	12	12
12	14	14	13	12	12	13	14
12	15	15	14	13	14	14	14
12	15	15	15	14	14	15	14
13	13	16	15	14	13	14	14
13	13	15	12	13	13	14	13
13	13	11	15	11	11	12	11
13	10	14	14	12	13	13	14
11	13	14	12	12	14	13	13
10	10	10	11	10	10	11	12
10	12	10	11	10	10	10	12
10	13	12	12	12	12	12	13
12	12	13	12	11	12	13	12
12	13	11	15	14	11	12	14
13	13	15	12	12	13	13	14
13	13	16	15	14	13	13	13
14	15	15	15	16	15	14	15
14	15	15	14	15	15	14	14
14	14	14	13	14	14	13	13
13	13	13	14	13	14	14	13
13	13	13	13	13	13	13	14
12	12	13	12	12	13	13	12
13	12	12	11	13	12	11	11
12	11	12	11	11	12	12	11
11	10	12	10	11	11	12	11
11	10	11	9	11	12	11	10
10	10	9	9	10	10	9	9
10	8	9	8	9	9	10	9
9	8	8	8	8	8	8	8
7	8	8	7	9	8	7	7
7	8	7	8	7	8	7	7
6	5	6	4	6	6	5	4
5	4	5	4	5	5	4	4
3	3	3	3	3	3	3	3

```
10     PRINT "*****************************************************************"
20     PRINT "****                                                         ****"
30     PRINT "****   THIS PROGRAM DETERMINES THE RESONANCE FREQUENCY       ****"
40     PRINT "****   OF THE DIFFERENT MODES OF VIBRATION FOR A             ****"
50     PRINT "****   UNIFORM BEAM WITH A LUMPED MASS AT THE FREE           ****"
60     PRINT "****   END OF A CANTILEVER BEAM.  THIS PROGRAM USES A        ****"
70     PRINT "****   LUMPED MASS ANALYSIS DEVELOPED BY MYKLESTAD's.        ****"
80     PRINT "****            written by: BOB SIMMONS                      ****"
90     PRINT "****                                                         ****"
100    PRINT "*****************************************************************"
110    PRINT
120    PRINT
150    OPTION BASE 1
160    DIM Am(20),Al(20),V(20,2),Bm(20,2),Th(20,2),Y(20,2),Thi(2)
170    DIM Yi(2),Sm(20),Sv(20),Dv(20),Slop(20)
171    GINIT
173    GRAPHICS ON
174    ALPHA OFF
175    WINDOW 0,10,-4,2
176    AXES .1,.1,0,0,10,10,8
180    !*****************************************************************
190    REM  V(I,J)= SHEAR AT SECTION I DUE TO INITIAL CONDITION J
200    REM  BM(I,J)= BENDING MOMENT AT I DUE TO INIT. COND. J
210    REM  TH(I,J)= SLOPE AT I
220    REM  Y(I,J)= DEFLECTION AT I
230    !*****************************************************************
240    Thi(1)=0.         ! INITIAL SLOPE
250    Thi(2)=1         ! INITIAL SLOPE
260    Yi(1)=1          ! INITIAL DEFLECTION
270    Yi(2)=0.          ! INITIAL DEFLECTION
280    H=.2921           ! LENGTH OF BEAM (METERS)  11.5 INCHES
290    N=9               ! NUMBER SECTIONS
300    Ws=0              ! STARTING W
310    Dw=.5             ! DELTA W
320    Wf=10             ! ENDING W
330    PRINT " mass                 1/EI                1^2/EI                 I^3/
EI"
340    CALL Vib(Am(*),Al(*),Ei,N,Ws,Wf,Dw,Sm(*),Sv(*),Dv(*),H)
350    W=Ws
360    PRINT " W                 DEFL"
370    !****************  LOOP FOR INIT. COND    **********************
380    FOR J=1 TO 2
390    Th(1,J)=Thi(J)
400    Y(1,J)=Yi(J)
410    V(1,J)=0.
420    Bm(1,J)=0.
430    !***************   LOOP FOR LUMPED MASSES    ********************
440    FOR I=2 TO N
450    V(I,J)=V(I-1,J)-Am(I-1)*W*W*Y(I-1,J)
460    Bm(I,J)=Bm(I-1,J)-V(I,J)*AI(I-1)
470    Th(I,J)=Th(I-1,J)+Bm(I,J)*Sm(I-1)+V(I,J)*Sv(I-1)
480    Y(I,J)=Y(I-1,J)+Th(I-1,J)*A1(I-1)+Bm(I,J)*Sv(I-1)+V(I,J)*Dv(I-1)
490    NEXT I
500    NEXT J
510    Slope=-Th(N,1)/Th(N,2)
520    Defl=Y(N,1)+Y(N,2)*Slope
530    !  PRINT W,DefI
531    DRAW W,Defl
540    W=W+Dw
550    IF W<Wf THEN 370
```

```
551   FRAME
553   DEG
554   CSIZE 4,.8
555   MOVE .9,-.5
556   LABEL "1    2    3    W (rad/sec)    7"
557   LDIR 90
558   MOVE .7,-3.5
559   LABEL "DEFLECTION"
560   INPUT A
561   PRINTER IS 701
562   DUMP GRAPHICS
563   GCLEAR
564   END
570   SUB Vib(Am(*),Al(*),Ei,N,Ws,Wf,Dw,Sm(*),Sv(*),Dv(*),H)
571   !****************************************************************
572   REM Am's ARE THE LUMPED MASSES STARTING FROM THE FREE END
573   REM Al's ARE THE LENGTHS OF THE SECTIONS OF THE BEAM
574   !****************************************************************
580   M=N-1
590   FOR K=1 TO M
600   Am(1)=.2+.021/((N-1)*2)
610   FOR Q=2 TO N-1
620   Am(Q)=.021/(N-1)
630   NEXT Q
640   Al(1)=H/(N-1)
650   FOR Q=2 TO N-1
660   Al(Q)=H/(N-1)
670   NEXT Q
680   Ei=.08207*10^0
690   Sm(K)=Al(K)/Ei
700   Sv(K)=Sm(K)*Al(K)/2.
710   Dv(K)=Sv(K)*Al(K)*2./3.
720   PRINT USING "K,12X,SD.5DE,7X,SD.5DE,10X,SD.5DE";Am(K),Sm(K),Sv(K),Dv(K)
730   NEXT K
740   PRINT
750   PRINT
760   !**************************************************************
770   REM   SM= SLOPE DUE TO MOMENT
780   REM   SV= SLOPE DUE TO SHEAR
790   REM   DV= DEFLECTION DUE TO SHEAR
800   !**************************************************************
810   SUBEND
```

```
*****************************************************************
****                                                        ****
****   THIS PROGRAM DETERMINES THE RESONANCE FREQUENCY      ****
****   OF THE DIFFERENT MODES OF VIBRATION FOR A            ****
****   UNIFORM BEAM WITH A LUMPED MASS AT THE FREE          ****
****   END OF A CANTILEVER BEAM.  THIS PROGRAM USES A       ****
****   LUMPED MASS ANALYSIS DEVELOPED BY MYKLESTAD.         ****
****              written by: BOB SIMMONS                   ****
****                                                        ****
*****************************************************************
```

mass	l/EI	l^2/EI	l^3/EI
.2013125	+4.44895E-01	+8.12211E-03	+1.97706E-04
.002625	+4.44895E-01	+8.12211E-03	+1.97706E-04
.002625	+4.44895E-01	+8.12211E-03	+1.97706E-04
.002625	+4.44895E-01	+8.12211E-03	+1.97706E-04
.002625	+4.44895E-01	+8.12211E-03	+1.97706E-04
.002625	+4.44895E-01	+8.12211E-03	+1.97706E-04
.002625	+4.44895E-01	+8.12211E-03	+1.97706E-04
.002625	+4.44895E-01	+8.12211E-03	+1.97706E-04

W	DEFL
0	1
.5	.994738793761
1	.97895976911
1.5	.952676699333
2	.915912510247
2.5	.868699235823
3	.811077956281
3.5	.743098718877
4	.664820441674
4.5	.576310800637
5	.477646100439
5.5	.368911129462
6	.250198999479
6.5	.121610970583
7	-.0167437380219
7.5	-.164748150729
8	-.322277751043
8.5	-.489200709171
9	-.665378120936
9.5	-.850664257216
10	-1.04490662312
10.5	-1.24794722603
11	-1.4596208517
11.5	-1.67975734756
12	-1.90818091226
12.5	-2.14471059074
13	-2.38916057382
13.5	-2.64134050151
14	-2.90105576915
14.5	-3.16810783554
15	-3.44229453226

VITA

Robert Andrew Simmons

Canidate for the Degree of

MASTER OF SCIENCE

Thesis: Control of a Flexible Link Using a Micro Stepper Motor with Acceleration Feedback

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Ft. Worth, Texas, March 1, 1961, the son of Dayton J. and Marguerite E. Simmons.

Education: Graduated from Shawnee Mission West High School, Overland Park, Kansas in May of 1979. Received a Bachelor of Science degree in Mechanical Engineering from Kansas State University in December, 1983. In July, 1985 the requirements for a Master of Science in Mechanical Engineering were completed at Kansas State University.

CONTROL OF A FLEXIBLE LINK
USING A MICRO STEPPER MOTOR
WITH ACCELERATION FEEDBACK

by

Robert Andrew Simmons

B.S., Kansas State University, 1983

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of

the requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1985

CONTROL OF A FLEXIBLE LINK
USING A MICRO STEPPER MOTOR
WITH ACCELERATION FEEDBACK

ABSTRACT

A low mass flexible link is one requirement of a manipulator arm for use in space investigations. A control system, consisting of a stepper motor, a stepper motor circuit, and strain gauges, was developed to control the angular displacement of a low mass flexible link. The control strategy was a proportional plus integral control with unity plus derivative feedback. The position of the flexible link was determined by a set of strain gauges which provided an acceleration feedback signal to the MC68000 microcomputer. In addition, a micro stepper circuit was developed to improve the resolution and smoothness of the motion of the flexible link. This was achieved by regulating the current through the stepper motor fields. Pulse width modulation using three programmable counters, provided 1 to 50 usec. pulses to the stepper motor. The electrical features of the stepper motor filtered these pulses to provide a regulated current to the electrical field and therefore, generated a proportional force to the armature of the stepper motor. The magnitude of the force determined the placement of the flexible link. The control system permitted the flexible link to be positioned within ± 0.076 degrees.