LABORATORY PROJECT NO. 3
DESIGN OF A MICROMOTOR DRIVER CIRCUIT

EE 1000

1.   INTRODUCTION

The following quote from the *IEEE Spectrum* (July, 1990, p. 29) describes a fascinating area of research called microelectromechanical systems (MEMS):

> A mechanical microworld is emerging from the technology developed for integrated circuits. Already, completely assembled mechanisms and motors fractions of a millimeter in size are being made in laboratories around the world. New products and new capabilities for engineering and scientific investigations dot the horizon.

> Surprisingly, these flea-sized mechanical structures might well transform the control of mechanical elephants like automobiles. By the end of this decade, inexpensive yet highly reliable accelerometers and other sensors could revolutionize the design of suspension, braking, and steering systems. These devices are fabricated on silicon substrates using extensions of such IC manufacturing processes as photolithography, thin-film deposition, and chemical and plasma etching. Thus far, the silicon diaphragm pressure sensor has been the main commercial engine, with many uses in the automotive, medical electronics, and process-controlled industries.

> Micromotors and articulated microstructures are more ambitious and might serve as actuators in a range of electromechanical systems. Rapid developments during the past three years by many groups around the world are coalescing into a multidisciplinary research field, described variously as microelectromechanical systems, micromechatronics, microdynamics, and micromechanics. The new field has also spurred basic studies of the physics and chemistry of materials and structures in the micro-scale.

Figure 1 shows a variable-capacitance micromotor with a 100-μm-diameter rotor made at MIT, and Fig. 2 shows a magnetic micromotor made at the University of Wisconsin. For more information about MEMS, read the two articles in the references given in the caption for Fig. 1. Miniature motors have also been developed here at the University of Utah in the Center for Engineering Design in the College of Engineering. In particular, researchers in that group have developed a unique "wobble" motor, which has potential for advantages in robotics and other areas.
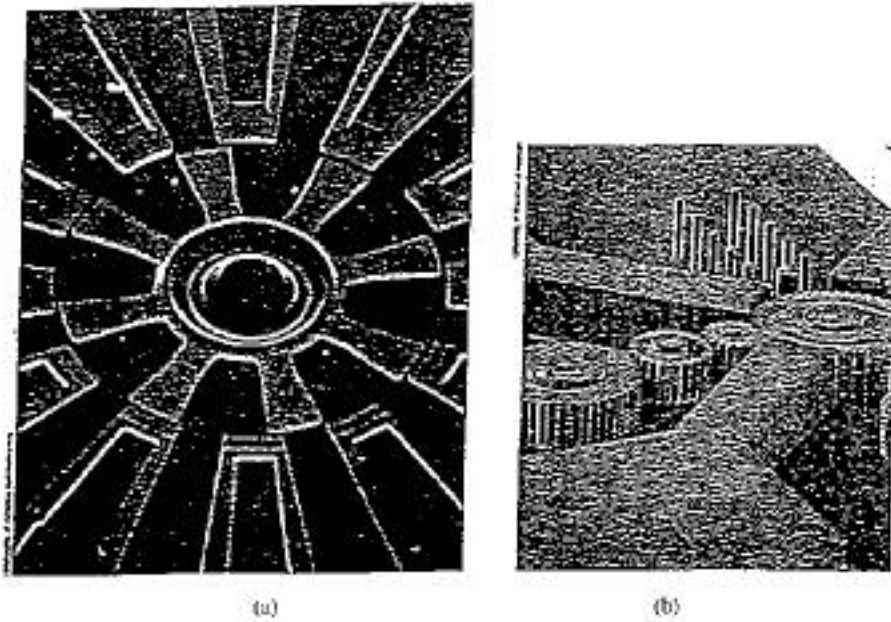
Fig. 1.   (a) Variable-capacitance micromotor made at the Massachusetts Institute of Technology. The eight-pronged rotor rotates at up to 2500 revolutions per minute in response to voltages applied sequentially to the stator poles across a gap of 2 micrometers.   The rotor is 100 μm in diameter. (Taken from the IEEE Spectrum, July, 1990, p. 31) (b) Magnetic micromotor and assorted microgears made at the University of Wisconsin at Madison. The structure is about 300 μm across. (Taken from the *IEEE Spectrum*, May, 1994, p. 24)

Dr. Bruno Frazier and his colleagues at the Georgia Institute of Technology were the first to fabricate metal micromotors.   Dr. Frazier also fabricated a variety of fascinating microstructures here at the University of Utah where he once held joint appointments in Electrical Engineering and Bioengineering.

Micromotors obviously require electronic circuitry to provide driving voltages for proper operation. One method for producing mechanical rotation with a four-pole stator is to develop a rotating force field that causes the rotor to spin. The force field may be either electric or magnetic. Rotating electric force fields can be produced by pairs of orthogonal electrodes with applied sinusoidal voltages 90° out of phase, and rotating magnetic force fields by pairs of orthogonal coils with sinusoidal currents 90° out of phase. Special circuitry is used to produce the sinusoidal voltages or currents that differ in phase by 90°.

2. YOUR DESIGN PROJECT

Your project is to design circuitry that will produce sinusoidal voltages 90° out of phase that could be used to drive a miniature four-pole motor. The first stage of the driver is an op-amp Wein-bridge oscillator that produces a sinusoid. (See Fig. 2 for a schematic of the basic circuit.) The second stage is an op-amp integrator used to shift a sinusoid by 90°. (Ssee your text for an explanation of op-amp integrators.)

First you will design the Wein-bridge oscillator and get it to work. Then you will design the integrator and get it to work. Then you will display the two sinusoidal voltages on the vertical and horizontal inputs of an oscilloscope and show how they would produce a rotating force field vector. You will also compare calculated and measured values of the two voltages and the rotating force field. Then you will design and construct a minimotor (not micromotor) and drive it with the two sinusoidal voltages produced by the oscillator and phase shifting circuit.
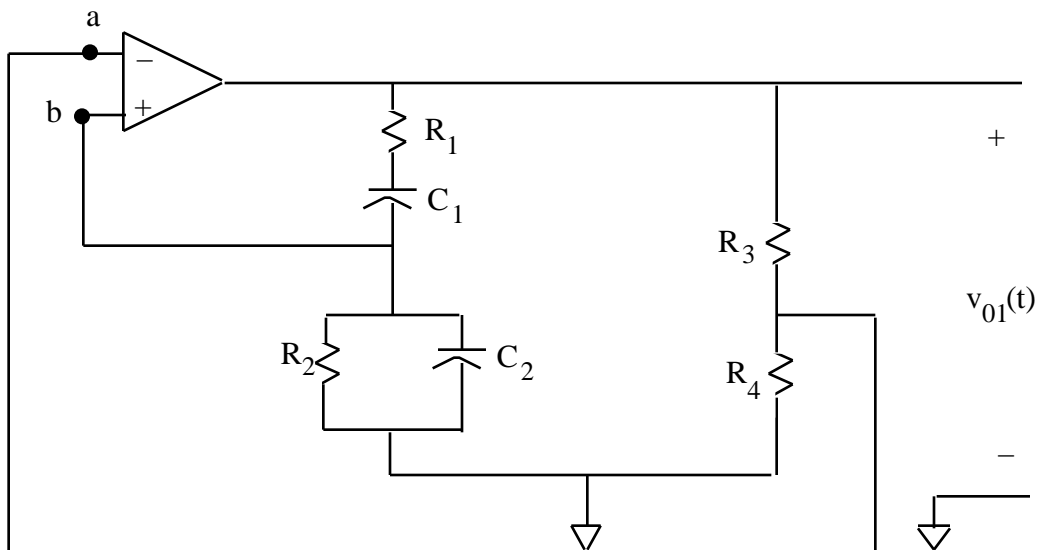

Fig. 2. Schematic diagram of an op-amp Wein-bridge oscillator.

3.   **DESIGN THE OSCILLATOR**

Because the behavior of oscillators includes difficult nonlinear relations, you will use an approximate design procedure that gives the conditions for oscillation to occur and the frequency of oscillation, but does not give an expression for the output voltage of the oscillator.

Design the oscillator to produce a sine wave at 10 Hz using the following approximate procedure:

a. Transform the circuit of Fig. 2 to the frequency domain.

b. Add a voltage source $\mathbf{V}_n$ in series with a resistor R_n across the input of the op-amp (a-b in Fig. 2). This is a fictitious voltage source that simulates the noise that starts the oscillations.

c. Using the approximate linear model of the op amp in which the voltage across a-b is zero, derive an expression for the output voltage $\mathbf{V}_{01}$ in terms of $\mathbf{V}_n$, , R_n, and the circuit components.

d. From the expression for $\mathbf{V}_{01}$ obtain an expression for the condition that makes $\mathbf{V}_{01}$ (denominator   0). This condition corresponds to the buildup of oscillation from very tiny amounts of noise. Show that this condition is $Z_1/Z_2 = R_3/R_4$, where Z_1 is the combined impedance of R_1 in series with C_1 and Z_2 is the impedance of R_2 in parallel with C_2.

e. From the condition $Z_1/Z_2 = R_3/R_4$, derive an expression for the frequency of oscillation by solving for the value of   that makes $Z_1/Z_2 = R_3/R_4$. Show that $Z_1/Z_2 = R_3/R_4$ also requires that $R_3/R_4 = (R_1/R_2 + C_2/C_1)$, which is a condition required for oscillation to occur. More advanced analysis shows that the condition for oscillation is $R_3/R_4 > (R_1/R_2 + C_2/C_1)$, but saturation of the op amp occurs when R_3/R_4 is too high, producing clipping of the waveform.

f. Using the equations you derived above, choose component values for the oscillator circuit.

4. DESIGN THE PHASE-SHIFTING CIRCUIT

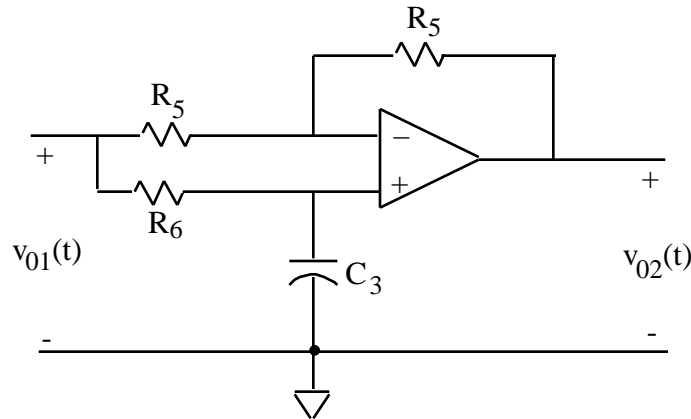The circuit shown in Fig. 3 with properly chosen components will produce a -90° phase shift with unity gain.

Fig. 3. Phase-shifting circuit.

a. Transform the circuit of Fig. 3 to the frequency domain and derive an expression for $\mathbf{V}_{02}/\mathbf{V}_{01}$.

b. Choose R_5, R_6, and C_3 so that at 10 Hz $v_{02}(t)$ has the same amplitude as $v_{01}(t)$, but differs in phase by -90°.

5. PLOT THE VOLTAGES AND THE FORCE FIELD

For micromotors, the force field will be either an electric field or a magnetic field, depending on whether electrodes or coils are used to drive the rotor. In the minimotor that you will construct (Section 8), the force field is produced by a magnetic field $\mathbf{B}$, which is produced by currents in two orthogonal coils. The current in one coil is proportional to $v_{01}(t)$ and in the other to $v_{02}(t)$. Since $\mathbf{B}$ is proportional to current, $\mathbf{B}$ is also proportional to applied voltage. Thus $\mathbf{B}$ is proportional to $v_{01}(t)$ and $v_{02}(t)$. With $v_{01}(t)$ and $v_{02}(t)$ applied to orthogonal coils, the vector magnetic field can be represented as

$$\mathbf{B} = k_1 \, [v_{01}(t) \, \hat{\mathbf{x}} + v_{02}(t) \, \hat{\mathbf{y}} \,]$$

where $\hat{x}$ and $\hat{y}$ are unit vectors in the $\hat{x}$ and $\hat{y}$ directions, respectively, and k_1 is a proportionality constant. The force $\mathbf{F}$ exerted on the paper clip in the motor is proportional to $\mathbf{B}$. Thus, $\mathbf{F}$ can be represented as $\mathbf{F} = k_2 (v_{01}(t) \hat{x} + v_{02}(t) \hat{y})$, where for simplicity we shall assume that the magnitude of k_2 is unity.

In your motor, $v_{01}(t)$ and $v_{02}(t)$ applied to the orthogonal coils produces a $\mathbf{B}$ that rotates in space. The $\mathbf{B}$ induces magnetic poles in the paper clip, which then tend to align with $\mathbf{B}$, causing the paper clip to deflect. Thus when $\mathbf{B}$ rotates, it causes the paper clip to rotate.

a.   Calculate $v_{02}(t)$ from $v_{01}(t)$ by using the expression you derived in Section 4 above. Calculate the phase difference between $v_{01}(t)$ and $v_{02}(t)$ for later comparison with the measured value.

b.   Write a MATLAB program to plot the tip of the vector $\mathbf{F}$ as a function of x and y, with t as a parameter ($v_{02}(t)$ vs. $v_{01}(t)$ with $v_{01}(t)$ on the horizontal axis), showing how $\mathbf{F}$ rotates in space with time.

6.   TEST THE CIRCUIT

a.   Construct the oscillator circuit that you designed. Use a potentiometer for R_4, and adjust it so that the R_4/R_3 value makes $v_{01}(t)$ a good sine wave.

b.   Measure the values of the actual resistors and capacitors that you use in the circuit and re-calculate the frequency of oscillation for these component values to get the most accurate calculated value of frequency to compare with the measured value.

c.   Construct the phase-shifting circuit that you designed. Display $v_{01}(t)$ and $v_{02}(t)$ simultaneously on an oscilloscope and measure the phase difference between the two, and measure the frequency.

d.   Connect $v_{01}(t)$ to the horizontal input and $v_{02}(t)$ to the vertical input of an oscilloscope (x-y mode) and display the simulated rotating force field. Record values for comparison with the plot of calculated values that you made in Section 5 above.
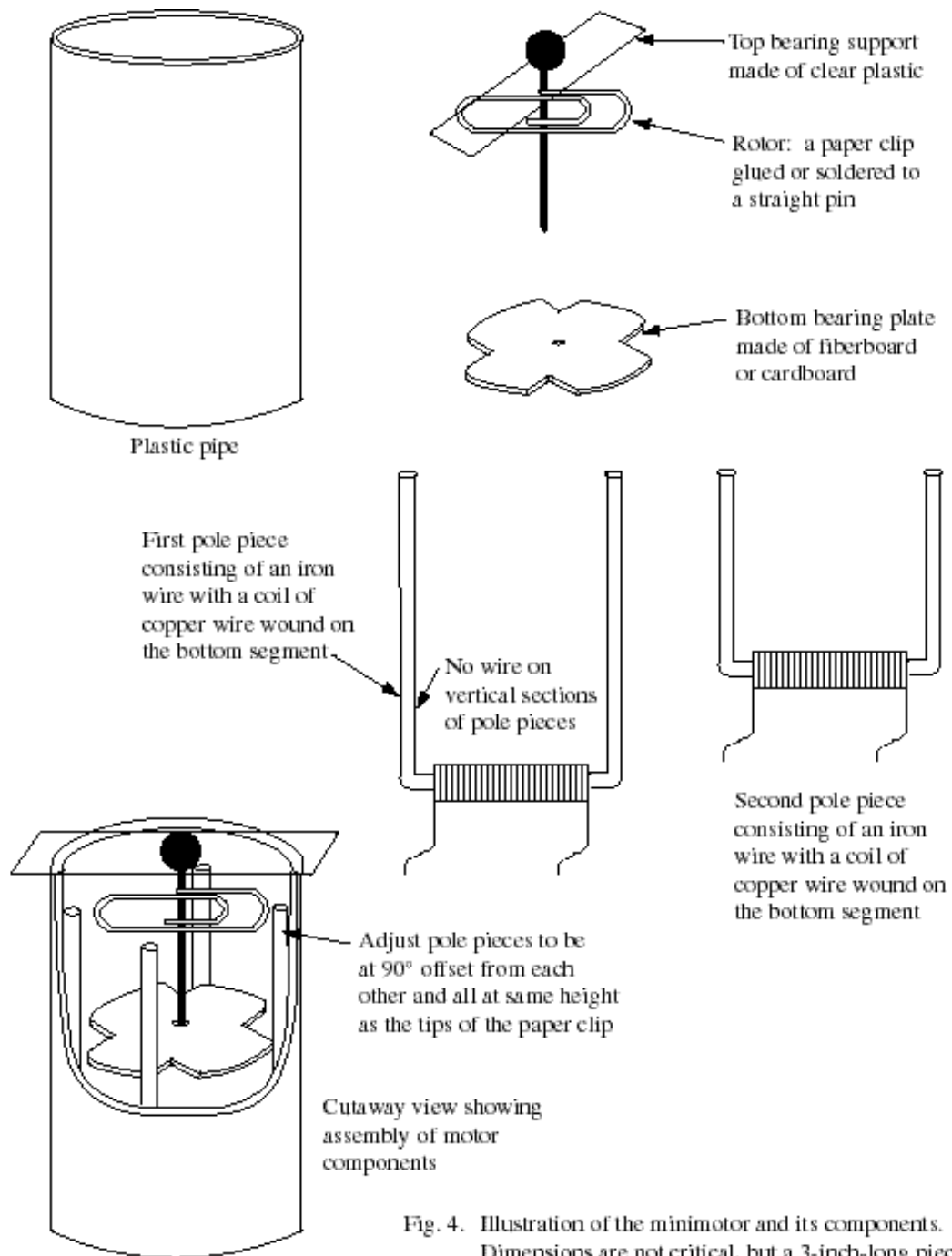
Plastic pipe

Top bearing support made of clear plastic

Rotor: a paper clip glued or soldered to a straight pin

Bottom bearing plate made of fiberboard or cardboard

First pole piece consisting of an iron wire with a coil of copper wire wound on the bottom segment

No wire on vertical sections of pole pieces

Second pole piece consisting of an iron wire with a coil of copper wire wound on the bottom segment

Adjust pole pieces to be at 90° offset from each other and all at same height as the tips of the paper clip

Cutaway view showing assembly of motor components

Fig. 4. Illustration of the minimotor and its components. Dimensions are not critical, but a 3-inch-long piece of 2-inch plastic pipe works well.

7.   **COMPARE CALCULATED AND MEASURED VALUES**

   a.   Compare calculated and measured values of frequency and phase difference.

   b.   On the same set of axes, plot calculated and measured values of the tip of the vector force field **F** with time as a parameter.

8.   **CONSTRUCT AND TEST A MINIMOTOR**

Construct a minimotor, as illustrated in Fig. 4, above. All the component parts are available for purchase in the stockroom. Use about 6 m of 26-gauge copper wire for each coil. Construct the rotor-bearing supports carefully so that the motor turns freely.

For a typical minimotor of this kind, the peak value of the current in each coil must be hundreds of milliamps to deflect the rotor. Because the op-amps will furnish at most only tens of milliamps, a power amplifier is needed to drive the motor. When you take the electronics courses, you will learn how to design power amplifiers using transistors, but for now, check out from the stockroom a power amplifier that has been designed and constructed for this project.

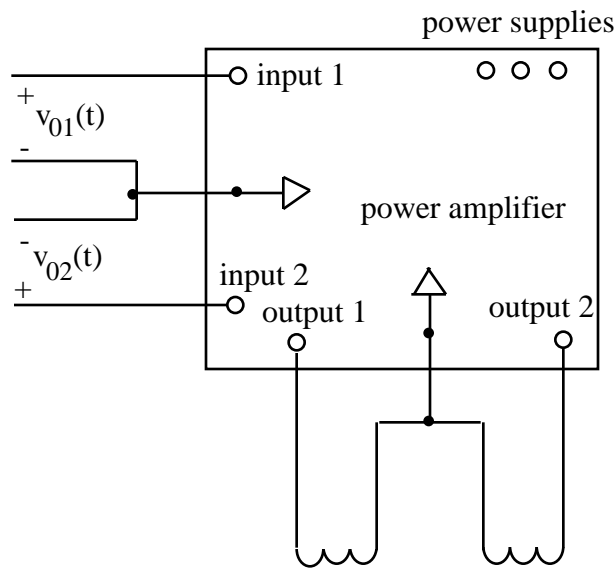Connect the power amplifier as shown in Fig. 5 and record a description of the performance of the motor.

Fig. 5. Connections for the power amplifier.

9. **WRITE A FORMAL REPORT**

Write a formal report describing your work on this project. See instructions in "Course Procedures" about how to write the report. Include at least the following in your report:

a. A short introduction. You may include this handout as an appendix to the report and refer to it so that you don't have to copy the information in it.

b. A careful description of the work that you did in Sections 3 through 8 above.

    i. Give clear derivations of mathematical expressions. Include consistency checks.

    ii. Explain how you chose the value of the components and include a table listing component values.

    iii. Explain all measurements carefully and include data appropriately in clearly labeled tables (some of them might be placed in appendices).

    iv. Include a listing and explanation (may be in the form of comment statements) of your computer programs in an appendix.

    v. Give a clear comparison of measured and calculated values by plotting calculated and measured values on the same set of axes (see Section 7). Explain why calculated and measured values are not the same.

c. Conclusions, including:

    i. A discussion of the validity of the models used for the operational amplifier.

    ii. A discussion of the success of your design procedure and the usefulness of your device for producing a rotating force field. State its limitations.

I. YOUR GRADE

Your report will be graded according to the following:

Category	Points
Communications	20
3. Oscillator design	15
4. Integrator design	10
5. Voltage and force field graphs	7
6. Circuit measurements	14
7. Comparison	8
8. Construct motor	11
Conclusions	15
Total	100