Chapter 8

DSP-BASED CONTROL OF STEPPER MOTORS

8.1 Introduction

A stepper motor is an electric machine that rotates in discrete angular increments or steps. Stepper motors are operated by applying current pulses of a specific frequency to the inputs of the motor. Each pulse applied to the motor causes its shaft to move a certain angle of rotation, called a stepping angle. Since the input signal is converted directly into a requested shaft position without any rotor position sensors or feedback, the stepper motor has the following advantages:

- Rotational speed proportional to the frequency of input pulses
- Digital control of speed and position
- No need of feedback sensor for open loop control
- Excellent acceleration and deceleration responses to step commands

The stepper motor also possesses drawbacks such as the possibility of losing synchronism, harmonic resonance, and small oscillations at the end of each step. With the above parameters in mind, the stepper motor is used in applications such as printers, plotters, X-Y tables, facsimile machines, barcode scanners, image scanners, copiers, medical apparatus, and other devices.

The stepper motor has salient poles on both the stator and the rotor, and normally only the stator poles hold the poly-phase windings called the control windings. Usually stepper motors are classified as

- Active rotor (permanent magnet rotor)
- Reactive rotor (reluctance type)
- Hybrid motors (combining the operating principles of the permanent magnet (PM) and reluctance stepper motor)

While each of these types of stepper motors has merit, hybrid stepper motors are becoming more popular in industrial applications. In this chapter, we focus on the principles and implementation of a hybrid stepper motor control system using the LF2407 DSP controller.

8.2 The Principle of Hybrid Stepper Motor

8.2.1 The Structure of Hybrid Stepper Motor

Figure 8.1 shows a simplified construction of a unipolar hybrid stepper motor. The rotor of this machine consists of two star-shaped milled steel pieces with three teeth on each. A cylindrical, axially magnetized PM is placed between the milled pieces making the end of each rotor either a north or a south pole. The teeth are offset at the north and south ends as shown in Fig. 8.1. The stator has four poles, each of which has a center-tapped winding. Since all the windings have the common connection V+, only five wires, A, B, C, D, and V+, leave the motor. A winding is excited by sending current into the V+ wire and out one of the other wires. The windings are wound in the stator teeth in such a way so that the motor behaves in the following way:

- If winding A or C is excited, pole 1 or pole 3 is energized as south.
- If winding B or D is excited, pole 2 or pole 4 is energized as north.

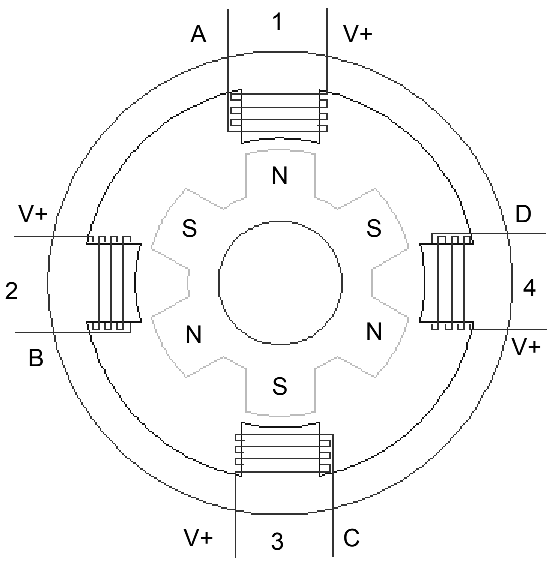

Figure 8.1 The four-phase, six-pole stepper motor.

Stepper motors are also classified with respect to the stator windings as being either bipolar or unipolar. Bipolar stepper motors have two windings with an opposing magnetizing effect in each pole, while unipolar stepper motors use only one winding per pole.

8.3 The Basic Operation

The operation of the stepper motor relies on the simple principle of magnetic attraction. This principle states that opposite magnetic poles attract while like poles repel each other. If the windings are excited in the correct sequence, the rotor will rotate following a certain direction. The basic operation of a stepper motor can be classified generally as either full step mode or half step mode. These modes are discussed in detail in the following section using the simplified stepper motor construction shown in Fig. 8.1.

8.3.1 Full-step Mode

If none of the stator windings are excited, an attraction between the stator poles and rotor teeth still exists because the PM rotor is trying to minimize the reluctance of the magnetic flux path from one end to the other. As a result, the rotor will tend to rest at one of the rest equilibrium positions. From Fig. 8.1, a rest position exists when a pair of rotor teeth are aligned with two of the stator poles. In the case of Fig. 8.1, the rotor is aligned with pole 1 and pole 3 on the stator. There are a total of 12 possible equilibrium positions for a 4-phase, 6-pole stepper motor. The force or torque that holds the rotor in one of these positions is called the detent torque. The value of the detent torque is usually small because no current flows through the stator windings.

Consider the case of the stator windings being excited according to Table 8.1. Assume at the beginning we are in mode 1 and the rotor aligns with poles 1 and 3 as shown in Fig. 8.2(a). When the excited sequences switch from mode 1 to mode 2, the north and south stator poles become pole 2 and pole 4. When this happens, the teeth of opposite polarity on the rotor will experience an attractive force, creating a torque on the rotor. Since this torque is much greater than the detent torque, the rotor will turn 30^0 counterclockwise, corresponding to one full step. Following the sequence of modes 1, 2, 3, and 4, the stator field rotates 90^0, attracting the corresponding rotor poles when the mode switches from one to the next. After switching four times, the rotor has moved four steps (120^0) and the rotor and stator fields return back to the initial condition or mode 1. A complete revolution requires 12 steps. The clockwise direction will be obtained if the reverse excited sequence of the stator winding is applied.

Table 8.1 Full step, single-phase excited sequence

	Winding A	**Winding B**	**Winding C**	**Winding D**	**Rotor Position**
Mode 1	On	Off	Off	Off	0
Mode 2	Off	On	Off	Off	θ
Mode 3	Off	Off	On	Off	2θ
Mode 4	Off	Off	Off	On	3θ

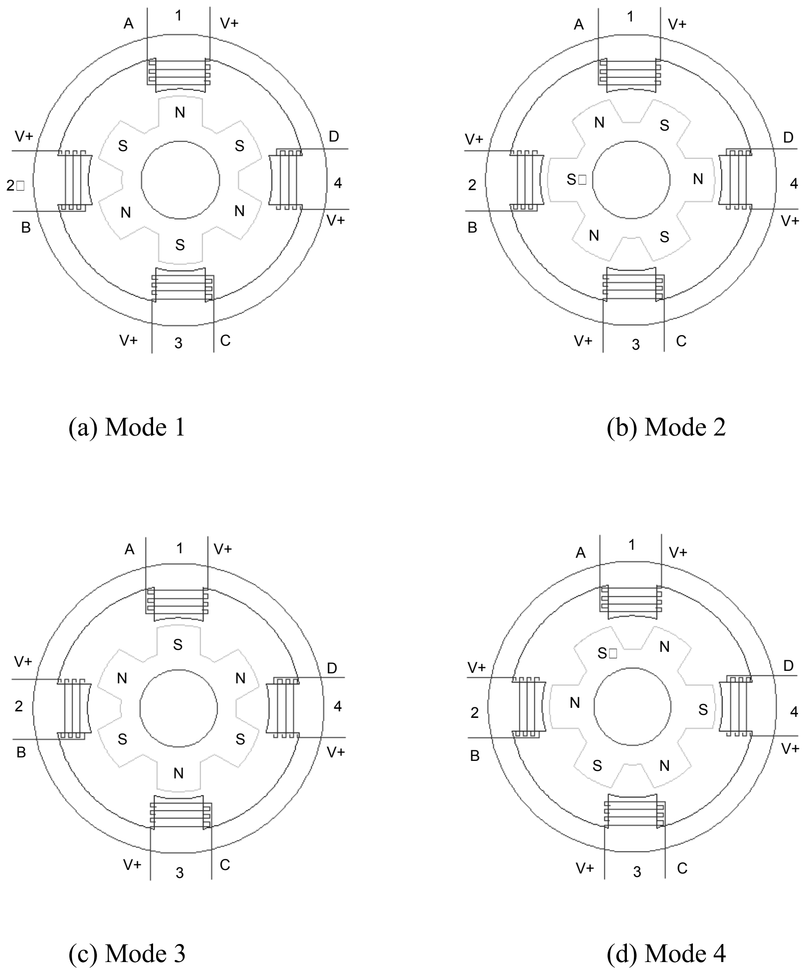

Figure 8.2 The principle of single-phase full-step mode.

For the full-step operation, greater torque can be produced if the two windings are excited simultaneously. The excited sequence of the stator winding is given in Table 8.2. During this operation, the rotor takes up an intermediate position because it experiences an equal attraction to the two stator poles as shown in Fig. 8.3. As in the single-phase full-step operation, a switch between two adjacent modes will cause a 90^0 shifting of the stator field. This results in a 30^0 rotation of the rotor. Twelve steps are required for a complete revolution in this mode as well. The sequence in Table 8.2 will rotate the motor counterclockwise, while reversing the sequence will run the motor clockwise.

Table 8.2 Full step, two-phase excited sequence

	Winding A	Winding B	Winding C	Winding D	Rotor Position
Mode 1	On	On	Off	Off	θ/2
Mode 2	Off	On	On	Off	3θ/2
Mode 3	Off	Off	On	On	5θ/2
Mode 4	On	Off	Off	On	7θ/2

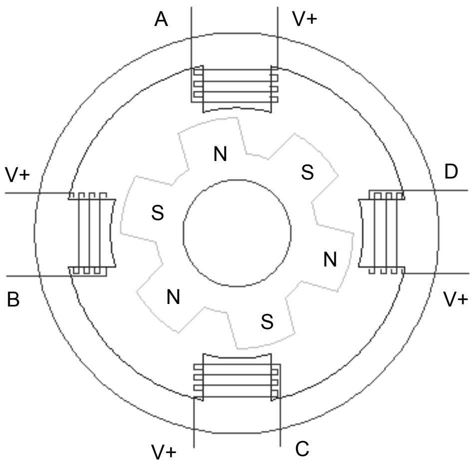

Figure 8.3 The rest equilibrium position of two-phase full-step mode.

8.3.2 Half-Step Mode

The stepper motor operation discussed rotates 30^0 per step. In the half step mode, alternately exciting one winding, then exciting two windings, will cause the rotor to move through only 15 degree per step. Though there is a slight loss of the torque while the single winding is being excited, half-step operation allows for smoother operation at lower speeds and less overshoot at the end of each step. The excitation sequence of the stator windings in half-step mode is given in Table 8.3.

During this operation, each switch between the two nearest modes will cause a 45^0 shift of stator field which results in a 15^0 rotation of the rotor. A total of 24 steps are required for a complete revolution, double of what is required for full step modes.

Table 8.3 Half-step, two-phase excited sequence.

	Winding A	Winding B	Winding C	Winding D	Rotor Position
Mode 1	On	Off	Off	Off	0
Mode 2	On	On	Off	Off	θ/2
Mode 3	Off	On	Off	Off	θ
Mode 4	Off	On	On	Off	3θ/2
Mode 5	Off	Off	On	Off	2θ
Mode 6	Off	Off	On	On	5θ/2
Mode7	Off	Off	Off	On	3θ
Mode8	On	Off	Off	On	7θ/2

8.3.3 Micro-Step Mode

For the operating modes discussed previously, the same amount of current flows through the energized stator windings. However, if the currents are not equal, the rotor will be shifted toward the stator pole with the higher current. The amount of deviation is proportionate to the values of the currents in each winding. This principle is utilized in the micorstep mode. During this mode, each basic full mode step can be divided into as many as 500 microsteps, providing the proper current profile is applied.

8.4 The Stepper Motor Drive System

An open loop stepper motor control system is shown in Fig. 8.4. The total control system consists of the power electronic drive circuit and controller. These components will be discussed in detail in following sections.

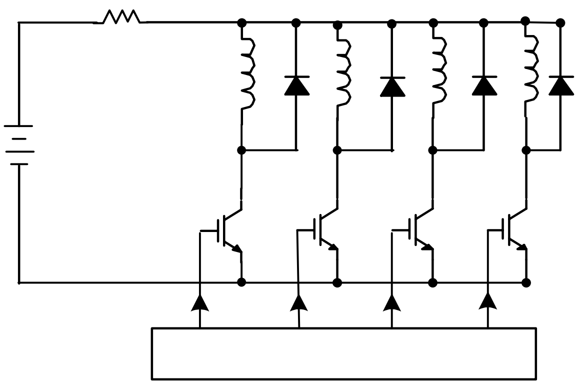

Figure 8.4 The stepper motor speed control system.

8.4.1 Power Electronic Drive Circuit

The drive circuit of a stepper motor is displayed in Fig. 8.4. Wires A, B, C, and D are connected to the power switch device T_1, T_2, T_3, and T_4. The V+ wire is connected to a +12V power supply through a series resistor. When one of the switches turns on, the corresponding winding is excited.

The windings in a stepper motor also have inductance. When the switch turns on, the winding inductance will increase the amount of time it takes for the current to reach its full value. Since the speed of the stepper motor is proportionate to the switching frequency, this effect limits the maximum motor speed. A series resistance (R_s), as shown in Fig. 8.4, is added to reduce this problem. Assuming the winding's inductance and resistance are L and R, when the switch turns on, the winding current can be calculated by:

$$i(t) = \frac{V_{dc}}{R + R_s}\left(1 - e^{-\frac{R+R_s}{L}t}\right) \tag{8.1}$$

From (8.1), it can be seen that the series resistance reduces the time constant so that the current can increase faster. However, the resistance causes a voltage drop, which requires a larger power supply to compensate for the resistor losses so that the same current can be applied to the motor windings.

The winding inductance also leads to another problem when the switch turns off. If no additional current path is provided to dissipate the energy stored in the inductance, a voltage spike will be generated across the switching devices and may damage them. To solve this problem, a freewheeling diode (D_1-D_2) parallel to the winding is employed. In addition, a series resistor may also be added to the circuit to limit the voltage spike.

8.4.2 Controller

The LF2407 DSP controller is used to implement the speed control of a stepper motor drive system. The interface of the LF2407 is illustrated in Fig. 8.5. Since this control scheme is an open-loop control system, no feedback information is required. The four I/O ports on the DSP provide the gating signals to the transistors, which provide current to the windings in the specified sequence. The speed rate at which the switching sequence is applied determines the speed of the motor.

Figure 8.5 DSP interface.

8.5 The Implementation of Stepper Motor Control System Using the LF2407 DSP

The assembly code associated with the LF2407 was developed to implement the open loop speed control system discussed previously. The flowchart for the DSP software is shown in Fig. 8.6.

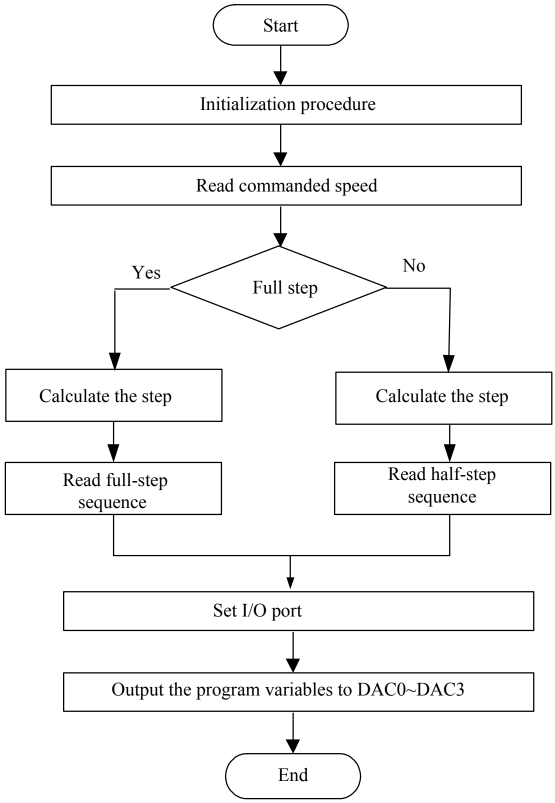

Figure 8.6 Flowchart of the stepper motor control algorithm.

It can be seen from Fig. 8.6 that the control algorithm of the stepper motor drive system consists of one main routine and includes four subroutine modules:

- Initialization procedure
- Speed control module
- Output signals via I/O port
- DAC module

Only the speed control module is specific to the stepper motor control system and will be dicussed in detail.

8.6 The Subroutine of Speed Control Module

The Timer 1 period interrupt is used for the speed control subroutine. This subroutine performs the task of reading the commanded speed and then converting it to a pulse output on the I/O ports. Hence, the motor speed is determined by the time interval of this interrupt. The block of assembly code below shows the Timer 1 Interrupt Service Routine (ISR), which executes all subroutines upon every interrupt.

```
T1_ISR:      NOP
;-------------------*
; Context Saving    *
;-------------------*
;Context save regs
        MAR     *,      AR1            ;AR1 is stack pointer
        MAR     *+                     ;skip one position
        SST     #1,     *+             ;save ST1
        SST     #0,     *+             ;save ST0
        SACH    *+                     ;save acc high
        SACL    *                      ;save acc low
        POINT_EV
SPLK    #0FFFFh ,       EVIFRA

POINT_B0

RUN_MODE POINT_B0
        CALL    SPEED_PROFILE
        CALL    VTIMER_SEC
        LACC    STEP_FLG
        BCND    HALF_MODE,GT
        CALL     FULL_STEP
        B       END_MODE

HALF_MODE
        CALL    HALF_STEP

END_MODE
        CALL   DAC_VIEW_Q15I
;-------------------------------*
;* Context restore and Return   *
;-------------------------------*
END_ISR:
        MAR     *,      AR1            ;make stack pointer active
        LACL    *-                     ;Restore Acc low
        ADDH    *-                     ;Restore Acc high
        LST     #0,     *-             ;load ST0
        LST     #1,     *-             ;load ST1
        POINT_PG0
        CLRC    INTM
        RET
```

8.6.1 Full-Step Mode

Two-phase full-step mode described in Section 8.3.1 is implemented in the full-step subroutine as shown in the code on the next page. The commanded speed is converted first to a pulse with a certain frequency in this routine. According to Table 8.2, the different sequence is read and then the corresponding I/O ports (IOPB0, 1, 2, 3 – A, B, C D) are set high/low to control the turn on/off of the switches.

```
FULL_STEP:      POINT_B0
        …
        …
        POINT_B0
        LACC    #MODE_FUL
        sub             #3
        BCND    SET_MODE_FUL,NEQ
        SPLK    #0,MODE_CNTL_FUL
        B       FUL_EXIT
        …
        …
        RET
```

8.6.2 Half-Step Mode

Following the same procedure as described above, two-phase half-step mode strategy described in Section 8.3.2 is implemented in the code block shown below.

```
HALF_STEP:    POINT_B0
        POINT_B0
        …
        …
        POINT_B0
        LACC    MODE_CNTL_HLF
        sub     #7
        BCND    SET_MODE_HLF,NEQ
        SPLK    #0,MODE_CNTL_HLF
        B       HLF_EXIT
        …
        …
        RET
```

Reference

1. Digital Signal Processing Control of Electric Machines and Drives Laboratory Manual, Department of Electrical Engineering, The Ohio State University, March 2002.