Application Report

SLAA222B–November 2004–Revised July 2017

Rotation Detection With the MSP430™ Scan Interface

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ABSTRACT

This application report details the measurement principles for using an LC sensor to detect rotational movement. Based on this measurement principle, an example project is presented demonstrating contactless rotational measurement using the Scan Interface (Scan IF) of the MSP430FW42x family of devices. Software as well as hardware for the implementation is explained.

The source code and associated files described in this application report are available for download from www.ti.com/lit/zip/slaa222.

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1 Introduction to the Measurement Principle

In this application report a non-contacting rotational measurement principle is explained. It can be used for rotation measurement or fluid-flow measurement in applications such as water meters, heat meters, and general flow sensors.

A fluid-flow measurement is realized by transforming the fluid flow into rotation. A mechanical construction in the form of a screw wheel or worm wheel transforms the flow into a rotation. The rotation can be detected and the fluid volume flow can be calculated.

The rotation detection can be realized by placing the inductor of a resonant circuit (LC circuit) near a rotating plate (for example, the plate on the front of a screw wheel). Half of the plate is covered with a metallic coating such as copper. The damping factor of the stimulated resonant circuitry depends on the position of the inductor relative to the metal. If the inductor is above the metallic half of the plate the damping factor is higher than if located above the non-metallic half of the plate. By detecting the different damping factors the rotation measurement is realized.

Use of one LC circuit sensor allows measurement of rotation without detecting the direction. A second LC sensor makes it possible to also detect the direction of the rotation. Such a system is shown in Figure 1. The inductors are placed in a 90° off-axis angle above the plate and a 180° metallic coating is used. This assures that the damping factor of only one sensor at a time will change when the metallic/non-metallic boundary of the plate rotates across a sensor.

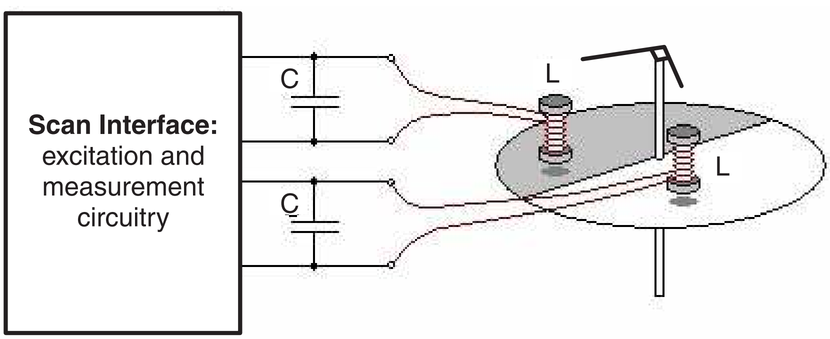

Figure 1. Rotation Detection Using Two LC Sensors

The sampling rate depends on the maximum rotational frequency that should be detected, and also on the system (number of sensors, angle between sensors, and angle of metallic plate coating). The following formula can be used for calculation of the minimum sampling rate of a system with two sensors and a 180° covered plate:

$$\text{sampling rate}_{min} = 2 \times \frac{360°}{\alpha} \times \text{rotation}_{max} \quad (1)$$

Where,

sampling rate_{min} = minimum sampling rate

α = angle between the two sensors (for example, 90°)

rotation_{max} = maximum rotational frequency to be detected

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The measurements of both sensors in a two-sensor system are triggered at the sampling rate. Ideally, both measurements would happen at the same time. However in a real application using the MSP430FW42x microcontroller, the measurements of the two sensors are done one after another. The time between the two measurements should be as short as possible. The measurement starts with the stimulation of the resonant circuitry (LC sensor). After releasing the sensor a damped oscillation with a frequency near $\frac{1}{2\pi} \times \sqrt{\frac{1}{L \times C}}$ is generated. The damped oscillation is created by the location of the damping plate relative to the sensor. Figure 2 shows this behavior.

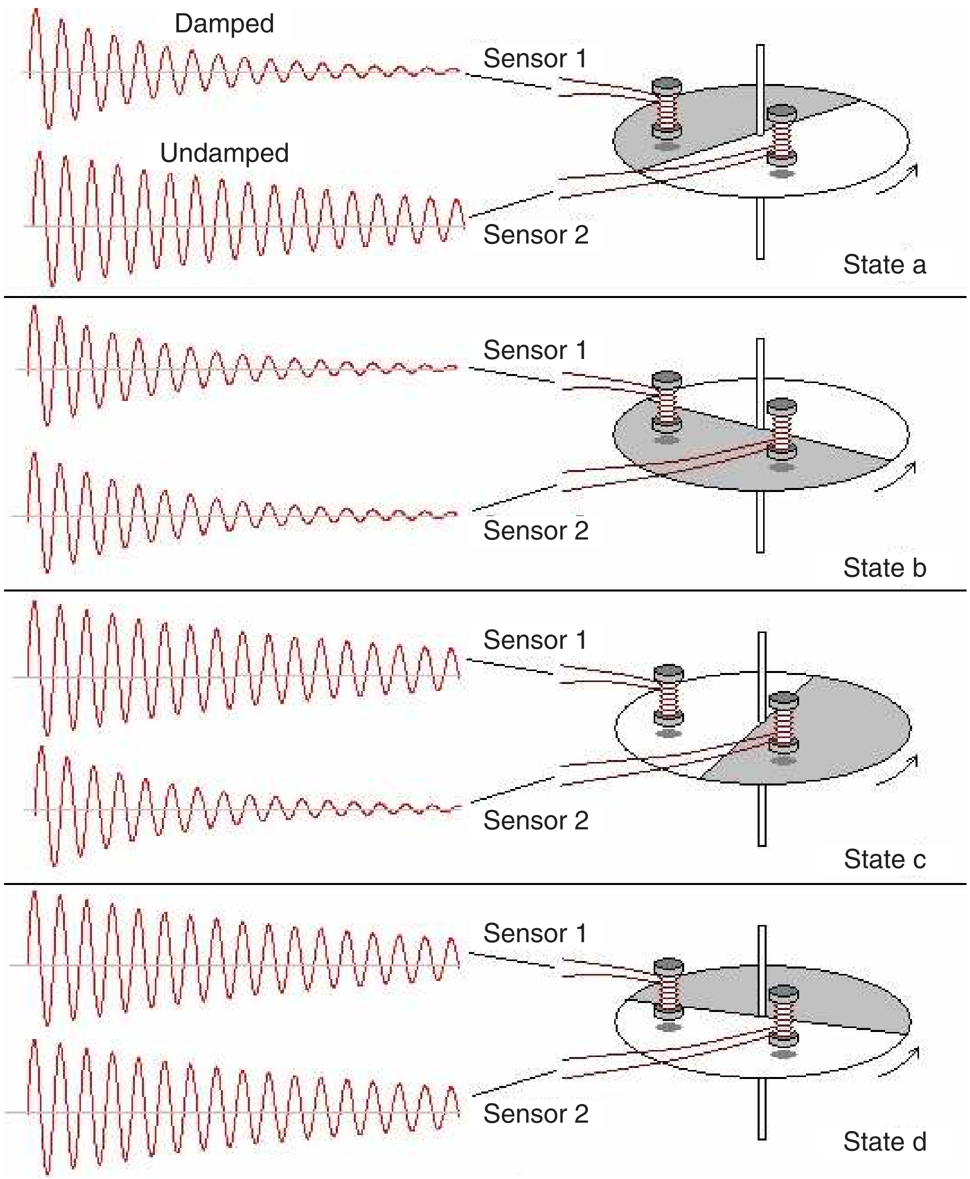

Figure 2. Example LC Sensor Output During Rotation

Before the microcontroller can process the sensor signals (damped oscillations) they must be converted into digital signals. The MSP430FW42x Scan IF module provides two ways to perform this conversion.

- Envelop Test

  The positive or negative alternation of the damped oscillation is used to charge a capacitor. The capacitor voltage builds the envelope curve of the damped oscillation. By measuring the discharge time of the capacitor voltage the damping factor of the oscillation can be measured. The application report *An Electronic Water Meter Design Using MSP430F41x* (SLAA138) describes such a solution.

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- Oscillation Test

  The amplitude of the damped oscillation is directly observed. After the excitation a defined delay time, t_{delay}, allows the LC oscillation to decay. After the delay time a comparator is used to test whether the remaining amplitude is above or below a user-define reference voltage. If the amplitude reaches the defined level during the time t_{gate} a latch is set (see the output stage description in the Scan Interface chapter of the *MSP430x4xx Family User's Guide*). If the amplitude does not reach the defined reference V_{REF} during the time t_{gate} the latch stays in the reset state. This operation is shown in Figure 3. The hardware (reference voltage, comparator) for this test is detailed in the Scan Interface module description as well. The reference voltage generation is realized by a built-in digital-to-analog converter, DAC.

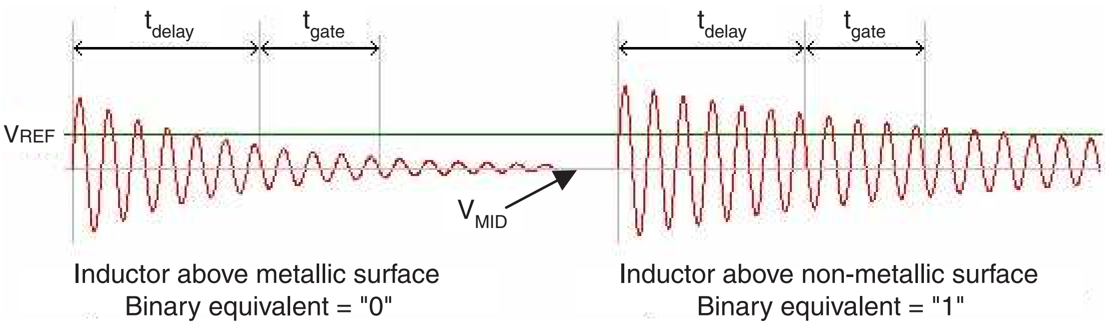

Figure 3. LC Sensor Signal Damping and Scan IF Detection

The oscillation test method is used in the implementation presented in this application report.

Finally the digitized damping factor is processed. Figure 4 shows the digitized signal for a rotating plate using two LC sensors. Depending on the direction of the rotation either the digital level of sensor 1 or the digital level of sensor 2 changes. If the old state and the new state are known it is possible to also detect the direction of rotation.

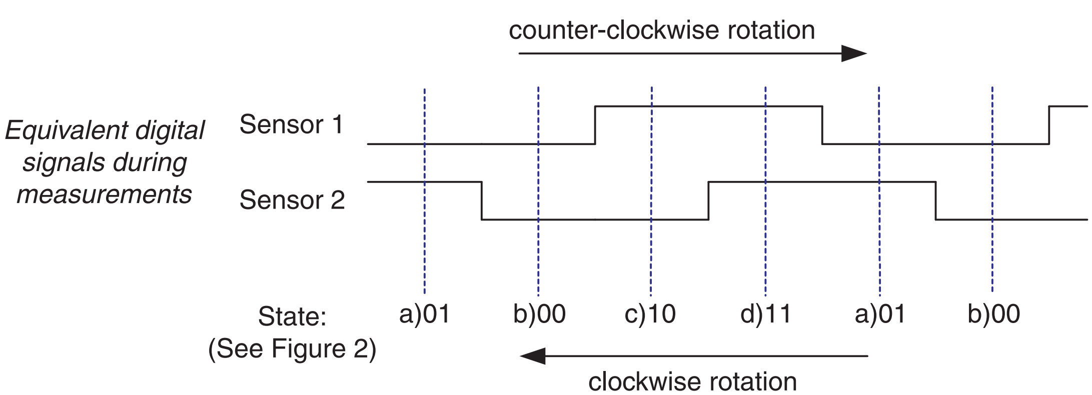

Figure 4. Example Scan IF Signal Digital Representation During Rotation

The timing shown in Figure 4 can also be realized as a state machine. This state machine is shown in Figure 5.

Counting of each rotation is done in the following way:

- Increment rotation counter

  If the previous state was "State d" and changed to "State a".
- Decrement rotation counter

  If the previous state was "State b" and changed to "State a".

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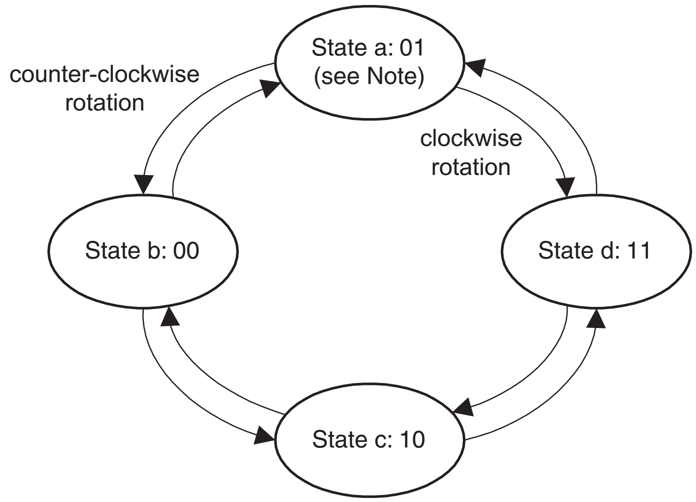

Figure 5. Example State Transitions During Rotation

2 Rotation Detection with MSP430FW42x – Hardware Description

The MSP430FW42x's Scan Interface module can handle the complete measurement sequence which is described in Section 1. Only the LC sensor(s), a bypass capacitor for the VMID voltage generation and a 32.768 kHz reference clock (crystal) needs to be connected to the MSP430™ MCU to establish proper Scan IF module operation.

Figure 6 shows the schematic of an example rotation detection implementation. Two LC sensors are connected to the Scan IF interface. On the LCD display the number of rotations or the calculated fluid volume flow can be shown.

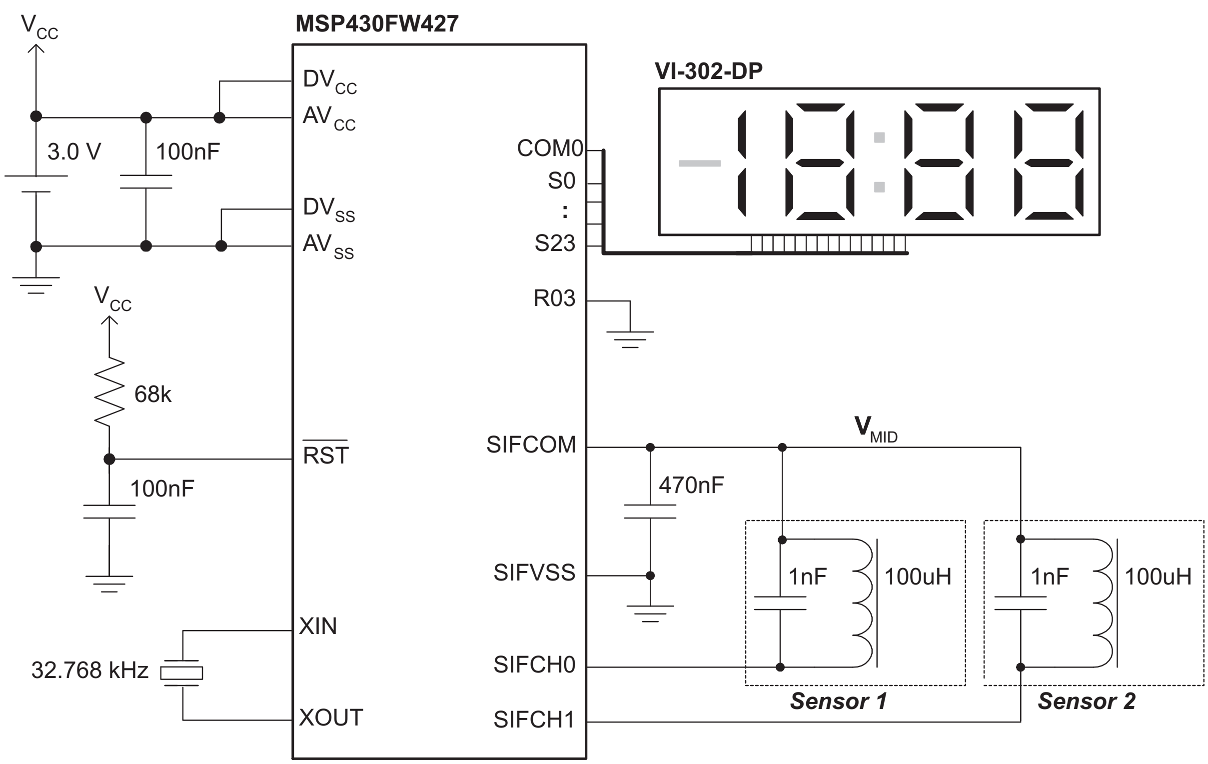

Figure 6. Example Application Schematic

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The MSP430FW42x implementation shown in Figure 6 was used to test the software explained in the following chapters. This design along with a rotating 180° copper-coated plate makes up the entire test setup.

2.1 LC Excitation Generation

The LC excitation pulse generating the required oscillation is output on the given SIFCHx pin. The oscillation occurs around V_{MID} and is generated on the SIFCOM output. For the SIFCOM voltage generation an external capacitor connected between SIFCOM and SIFVSS is required. The VMID generator built into the Scan IF analog front-end generates a $V_{CC}/2$ or V_{MID} voltage. The V_{MID} generator provides that the voltage swing of the LC sensor is not clipped by the two integrated protection diodes (ESD protection) at the pins SIFCH0 and SIFCH1 to AV_{SS} or AV_{CC}. The damped oscillation swings around $V_{CC}/2$ and the maximum amplitude is limited to $AV_{CC} + V_{DIODE}$. The V_{MID} generator dissipates low current and the dynamic impedance is ensured due to the external 470-nF capacitor. The refresh period is derived from ACLK and $V_{CC}/2$ can only be generated if the ACLK signal – typically 32.768 kHz – is switched on.

2.2 LC Sensor

After excitation, the decaying oscillation of the LC circuitry causes an alternating electromagnetic field around the coil. If conductive material is placed into this alternating field an eddy current is generated within the conductive material and the energy of the LC circuitry is dissipated more quickly. Therefore the damping ratio of the decaying oscillation is influenced.

For the inductor coil it is important to concentrate the electromagnetic field in front of the plate's rotation. This can be realized by using the appropriate ferrite core inductor as shown in Figure 7.

The magnitude of the decaying oscillation depends on:

- Distance and position of the damping material
- Dimension and form of the damping material
- Conductivity and permeability of the damping material

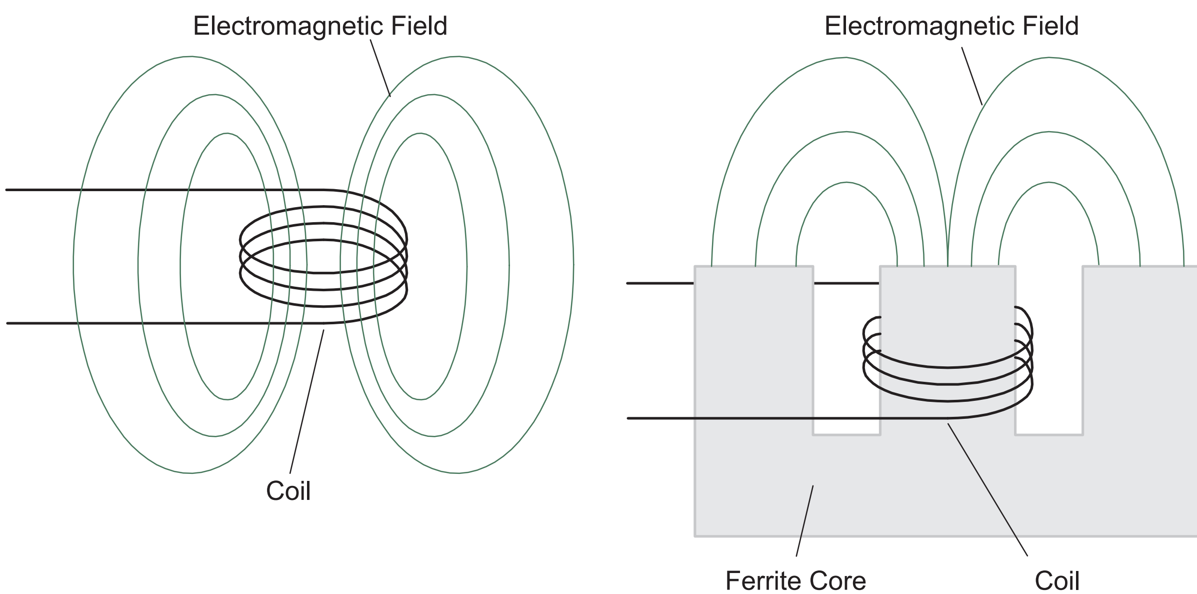

Figure 7. EM Field Representations for Air and Ferrite Core Coils

The decaying oscillation can be calculated with the following formula:

$$V(t) = V_0 \times \exp(-\delta \times t) \times \cos(\omega \times t) \quad (2)$$

Where,

δ = Damping constant

ω = Angular frequency

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The angular frequency ω of a damped oscillation depends on the damping constant.

$$\omega = 2 \times \pi \times T_D = \sqrt{\omega_0^2 - \delta^2} < \omega_0 \tag{3}$$

In this formula, $\omega_0 = \frac{1}{\sqrt{L \times C}}$ is the angular frequency of a harmonic oscillation. These formulas also show that the frequency of a damped oscillation will change if conductive material is placed within the electromagnetic field of the coil. Note that the conductive material influences the damping constant δ.

The diagram shown in Figure 8 is based on these formulas. In this example a simplification is used. Only the capacitor C is charged. In a real application the capacitor would be charged and the electromagnetic field of the coil would be generated during the excitation. The stored energy in the resonant circuitry causes the damped oscillation after the switch is closed as shown in the figure.

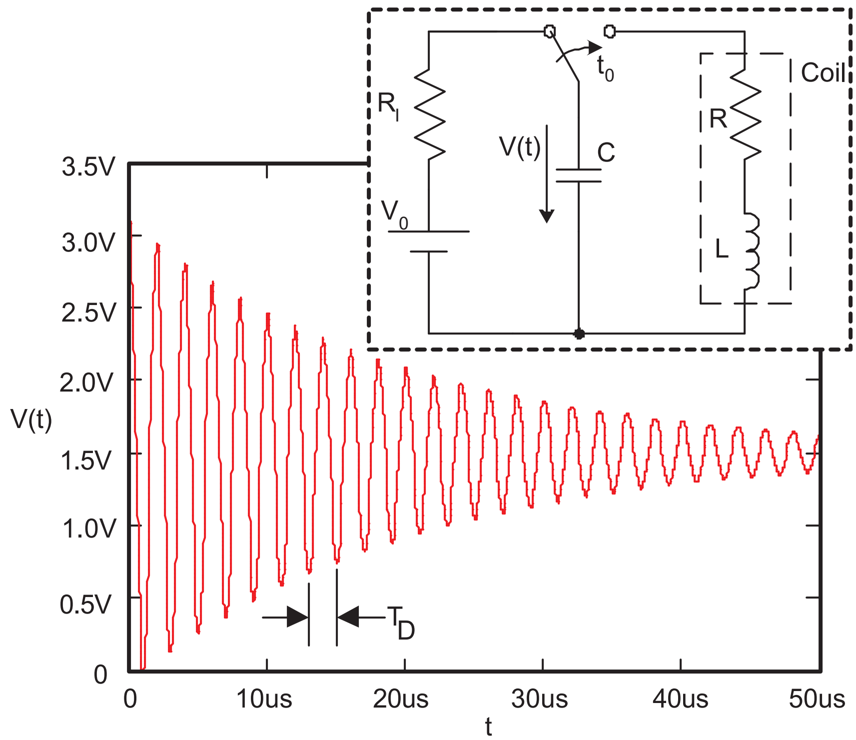

Figure 8. Oscillation Damping of LC Sensor

An oscillation can be seen when $\delta < \omega_0$. Therefore:

$$\delta = \frac{R}{2 \times L} \quad , \quad \omega_0 = \frac{1}{\sqrt{L \times C}} \quad \Rightarrow \quad R < 2 \times \sqrt{\frac{L}{C}} \tag{4}$$

For the calculation of the resonance circuit, the frequency variation caused by the damping constant can be neglected. So for the dimensioning of the LC sensor the capacitance is calculated as follows:

$$f_r = \frac{1}{2 \times \pi} \times \sqrt{\frac{1}{L \times C}} \quad \Rightarrow \quad C \approx \frac{1}{L \times 4 \times \pi^2 \times f^2} \tag{5}$$

Where,

f = Frequency of the decaying oscillation

L = Inductance of the used coil

In Table 1, measurements using different capacitances and inductances are listed. Note that here only the resonant frequency was measured. For dimensioning of the LC sensor, the decay time and the current consumption due to the excitation pulse must be taken into consideration.

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Table 1. LC Combination Resonant Frequencies

		Capacitance, C			
		100 pF	**270 pF**	**470 pF**	**1 nF**
Inductance, L	**47 µH**	2.08 MHz	1.37 MHz	1.06 MHz	725 kHz
	100 µH	1.45 MHz	933 kHz	725 kHz	500 kHz
	220 µH	980 kHz	641 kHz	490 kHz	338 kHz
	470 µH	658 kHz	435 kHz	333 kHz	233 kHz

For the selection of the frequency it is important to know that a delay time is necessary before the measurement is made. The ACLK signal is used for the delay time generation. The programming of the timing state machine of the Scan IF should correspond to the selected LC sensor dimensioning. In the example described in the following sections a delay time of around 30 µs (~ 1 ACLK cycle) is used.

The dimensioning of the LC sensor will also affect the current consumption. The excitation pulse length required for proper excitation depends on the selected LC circuitry. The longer the excitation pulse required, the higher the current consumption.

Figure 9 shows two differently dimensioned LC sensors. On the left side a 4.7-nF and 100-µH LC sensor was used, and on the right side a 1.0-nF and 100-µH sensor was used. The resulting different frequencies can be seen and, more importantly, the different initial amplitudes are shown. For proper functionality and a defined start condition, the initial amplitude should reach $V_{CC} + V_{DIODE}$. The behavior as shown on the left side in Figure 9 should be avoided, otherwise the start condition of the oscillation may be different for each measurement.

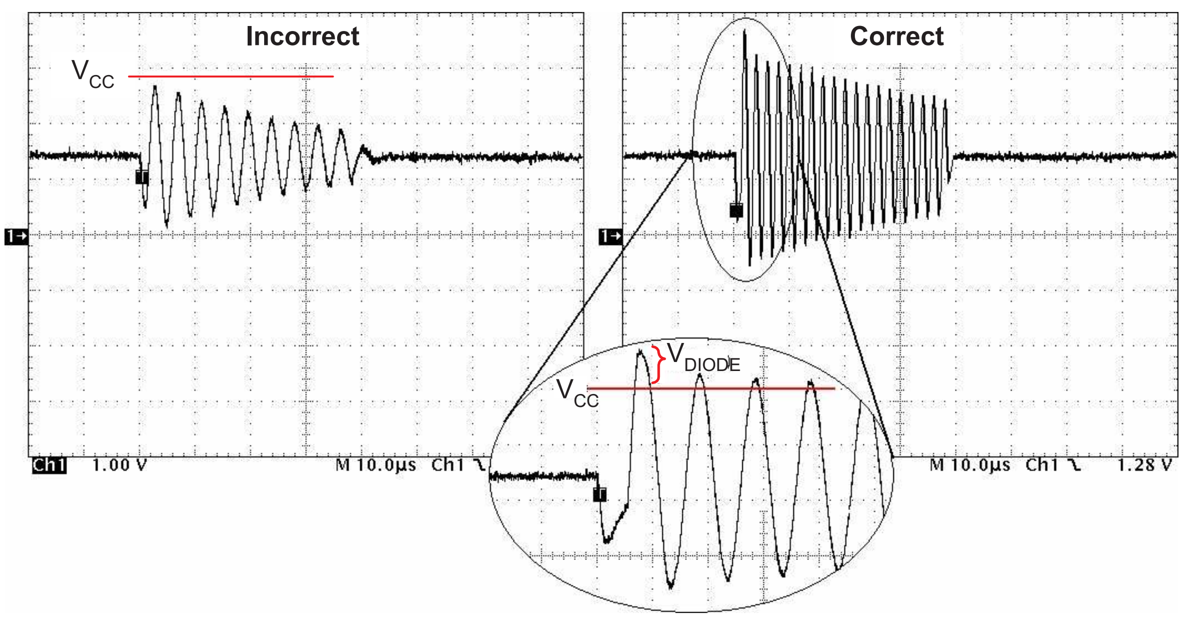

Figure 9. LC Sensor Dimensioning Comparison

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3 Programming the Scan Interface – One-Sensor Solution

The Scan Interface was designed to process information from up to four sensors using the Processing State Machine, PSM. It is also possible to perform rotation detection with as few as one sensor. In the following example one sensor is assumed and only the rotation, not the direction of the rotation, is detected.

During the software development of the Scan Interface the software developer should consider the following:

- Basic Scan Interface Settings
- Programming of the Timing State Machine, TSM
- Definition of DAC Levels (for example, V_{REF})
- Programming the Processing State Machine, PSM

For a real-world application, it is also important to think about temperature drift, voltage drift, and aging of components.

3.1 Basic Scan Interface Settings

Basic settings are configured with the control registers SIFCTL1 through SIFCTL5. An overview of these registers and the functionality is listed in Table 2.

Table 2. Scan Interface Control Register Settings

Control Register	Functionality Description
SIFCTL1	• Interrupt enable bits and interrupt flags • Test cycle request bit • Scan interface enable bit
SIFCTL2	• DAC enable bit • Comparator enable bit and comparator settings • Input selection • Sample-and-Hold enable bit (not needed for LC sensors) • VMID generator • Excitation enable bit • Test channel settings
SIFCTL3	• Processing State Machine Input selection • Interrupt source settings • Timer_A comparator signal selection
SIFCTL4	• Processing State Machine settings • Sample rate definition
SIFCTL5	• Timing State Machine settings

3.1.1 SIFCHx Pin Setup

During the initialization of the Scan Interface module it is necessary to configure the required pins for module functionality (for example, P6SEL=0x01). Otherwise the digital input influences the measurement. In addition, the damping of other Scan IF inputs when multiple LC sensors are used will not function correctly if the module function is not selected. For additional information, see Section 4.1.

3.1.2 Switch On SIFCOM

The SIFCOM voltage is switched on in the control register SIFCTL2 with the bit SIFVCC2. Note that the ACLK signal is needed to refresh the SIFCOM voltage. If the ACLK signal is switched off the SIFCOM $V_{CC}/2$ output breaks down.

The V_{MID} generator takes some time to switch on the SIFCOM voltage. The maximum time is given in the MSP430FW42x data sheet. The measurement sequence should only be started if the SIFCOM voltage has settled.

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In the example software a simple FOR-loop is used to create the delay:

```
                                      CLR.w    R15              ; 1 cycle
                               Loop:
                                      CMP.w    #0x035A,R15      ; 2 cycles
for (i=0;i<=857;i++);                 JGE      Next             ; 2 cycles
                                      INC.w    R15              ; 1 cycle
                                      JMP      Loop             ; 2 cycles
                               Next:
```

Next to each assembler instruction the CPU cycle time is also noted. The loop takes 7 CPU cycles each time through and the total time for the delay is:

$$t_{delay} = 7 \times \frac{1}{f_{CPU}} \times 858 \quad (6)$$

Keep in mind that the compiled output may be compiler dependent and may differ slightly from the assembly output as shown above.

In the example code the default clock settings are used. The CPU frequency is generated by the DCO providing ~1.048-MHz MCLK frequency when a 32.768-kHz crystal is present on LFXT1. The delay realized with the for-loop is ~6 ms.

Figure 10 shows the time delay between switching on the SIFCOM voltage and the first measurement on SIFCH0 with the settling time of ~6ms. The additional delay shown is due to the synchronization of the TSM start trigger to ACLK.

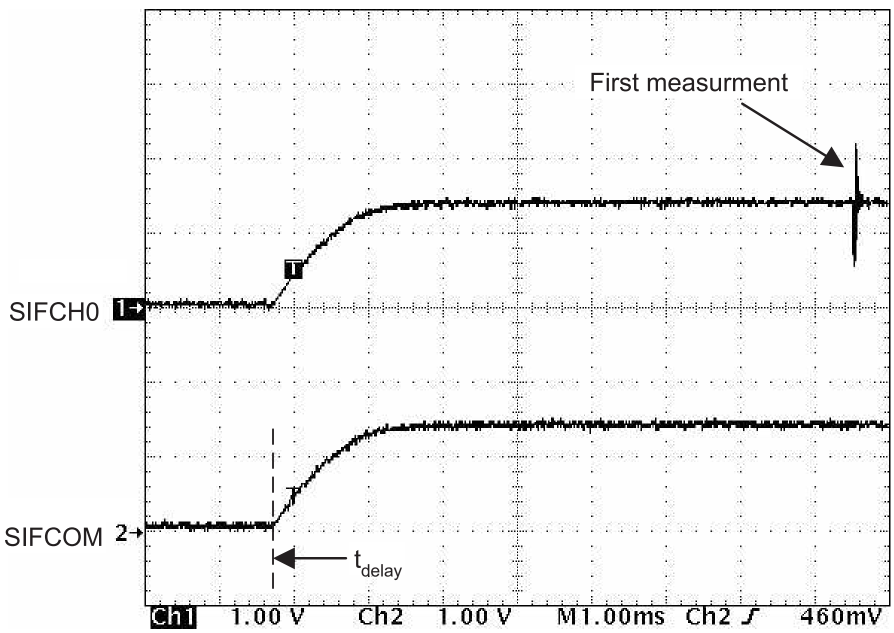

Figure 10. SIFCOM Settling Time

3.1.3 Clock Source

There are usually two clock sources needed to operate the Scan I/F – a low-frequency clock and a high-frequency clock. For the low-frequency clock, the ACLK signal is used; for the high-frequency clock, two different clock sources can be choosen, either the Scan IF internal SIFOSC or the SMCLK.

For proper SIF operation, a low-frequency clock (ACLK) of 32.768 kHz is needed. Typically, the ACLK is generated using a watch crystal. The ACLK signal is used for the definition of the sampling rate as well as the time delay generation as explained in the following chapters.

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For the high-frequency clock source, either the SMCLK or SIFOSC can be selected. The SIFOSC is a dedicated RC-oscillator integrated into the Scan Interface module. This oscillator generates either an 1-MHz or 4-MHz clock signal. The output frequency can be calibrated if voltage or temperature drift causes a deviation. To simplify the calibration measurement process, a counter is integrated into the SIFOSC.

It is not allowed to change the high-frequency clock while the Scan Interface is running, as the complete TSM timing will change, which will lead to unpredictable behaviors of the Scan IF. To change the high-frequency clock source, the TSM needs to be disabled before.

3.1.4 Use of Processing State Machine Counters

There are two 8-bit counters available in the Processing State Machine and are triggered by the PSM on system state transitions. One counter is used as an up/down-counter and the other as a down-counter. During processing the up/down-counter can be used to filter the effects of bouncing as shown in Section 4.

3.2 Programming of Timing State Machine

The Scan IF's Timing State Machine, TSM, controls the timing of specific tasks of the module which defines the sequence of measurements of the external channels. Using the TSM it is possible to accurately adjust the time that is needed for each process step independently. In general, the sequence follows the transitions detailed below.

1. Define Idle State (using control register SIFTSM0)
2. Generate LC sensor excitation
3. Delay for ideal sensor measurement window
4. Enable DAC and Comparator, wait for t_{settle}
5. Initiate sensor measurement
6. Stop Scan IF

These single steps are described in detail in Section 3.2.1 through Section 3.2.6.

Each TSM state for the actions listed above is shown in the following program code lines which are also used in the example software, which define the TSM operation.

```
...

SIFTSM0 = 0x0000;   // DAC=off, Comparator=off,  1xSIFCLK, Idle state
SIFTSM1 = 0x002C;   // DAC=off, Comparator=off,  1xSIFCLK, Excitation of sensor
SIFTSM2 = 0x0404;   // DAC=off, Comparator=off,  1xACLK  , Measurement delay
SIFTSM3 = 0x0934;   // DAC=on,  Comparator=on,   2xSIFCLK, Analog enable
SIFTSM4 = 0x3174;   // DAC=on,  Comparator=on,   7xSIFCLK, Measurement
SIFTSM5 = 0x0220;   // stop sequence                     , Stop state
...
```

3.2.1 Defining the Idle State

The Idle state is the initial condition of the TSM. In addition, as soon as the measurement sequence is finished by executing the SIFTSM5 state in the above example, the Scan Interface will be switched into the idle state. For the idle state the TSM bit settings in the SIFTSM0 control register are used.

```
...
SIFTSM0 = 0x0000;   // DAC=off, Comparator=off,  1xSIFCLK, Idle state
...
```


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If bit 2 (SIFLCEN bit) within the SIFTSM0 control register is reset, all SIFCHx channels are shorted to ground and no oscillation will occur. As soon as the stop state (SIFTSM5) is executed, the idle state will be entered and the SIFTSM0 settings will be applied causing the SIFCHx channels to be tied to ground through SIFCOM. Any present oscillation on the channel will immediately stop.

3.2.2 LC Sensor Excitation

After the system is powered up and initialized the first measurement sequence can be started. This is done by exciting the LC circuitry with a VSS pulse and is given by the TSM state below.

```
...
SIFTSM1 = 0x002C;   // DAC=off, Comparator=off,  1xSIFCLK, Excitation of sensor
...
```

Setting the SIFEX bit in the SIFTSMx control register generates this pulse on the SIFCHx pin. After releasing the SIFCHx pin, the LC sensor oscillates with decreasing amplitude about the $V_{CC}/2$ level provided on SIFCOM. The initial amplitude of the oscillation can be higher than the V_{CC} voltage of the MSP430 but will be limited to VCC + VDIODE. The amplitude of the first oscillation should be tuned such that it is clipped, assuring maximum excitation has occurred. By driving the first amplitude above the V_{CC} + V_{DIODE} voltage, a defined and repeatable start condition of the decaying oscillation is realized. The excitation pulse should be long enough to provide this initial clipping. This behavior is shown in Figure 11.

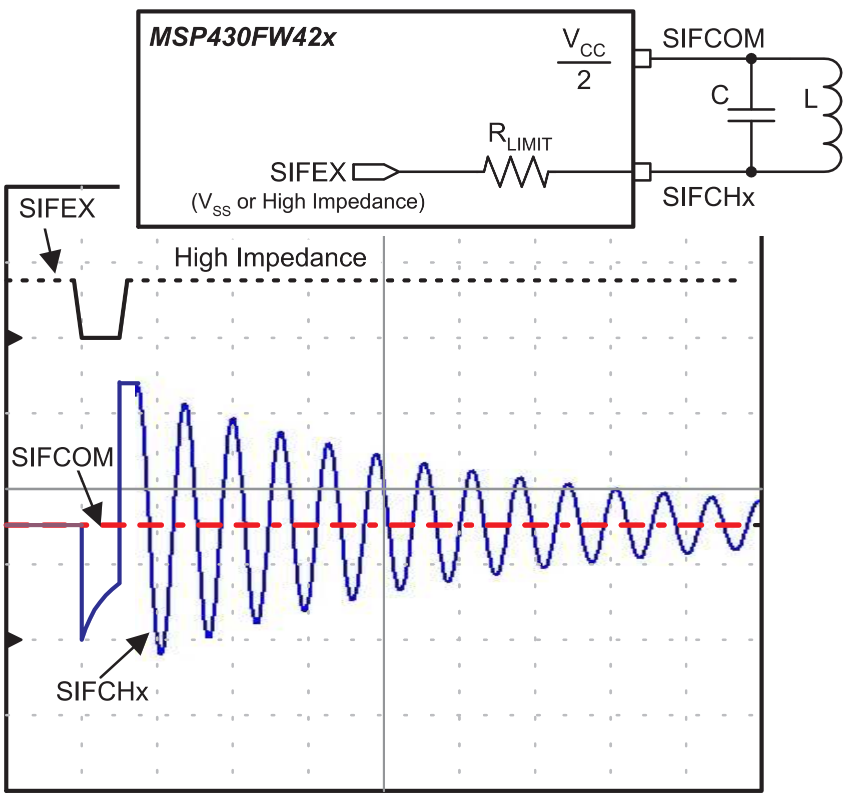

Figure 11. LC Sensor Excitation and Decay Around SIFCOM

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3.2.3 Measurement Time Delay

The measurement of the comparator output signal is taken after a defined time during which the oscillation of the sensor has had time to decay. Figure 12 shows a measurement of an un-damped oscillation as well as a damped oscillation. A certain time after excitation the difference between a damped and un-damped oscillation is large enough to adequately measure in comparison to the first few oscillations of the sensor. Therefore a delay is programmed before the measurement is started and is defined in the TSM state shown below.

```
...
SIFTSM2 = 0x0404;   // DAC=off, Comparator=off,  1xACLK  , Measurement delay
...
```

For this delay, typically ACLK is used which has the advantage of keeping MSP430 current consumption to a minimum. The low current consumption is reached by switching off the high-frequency clock source (SIFCLKG) as well as the comparator and DAC of the Scan IF module during this delay time. Note that the delay time generation using ACLK always synchronizes to the rising edge of ACLK. It is also shown in Figure 12 that the frequency of the damped oscillation has changed slightly in comparison to the undamped signal. The damping material located in the electromagnetic field causes the damping as well as this frequency shift.

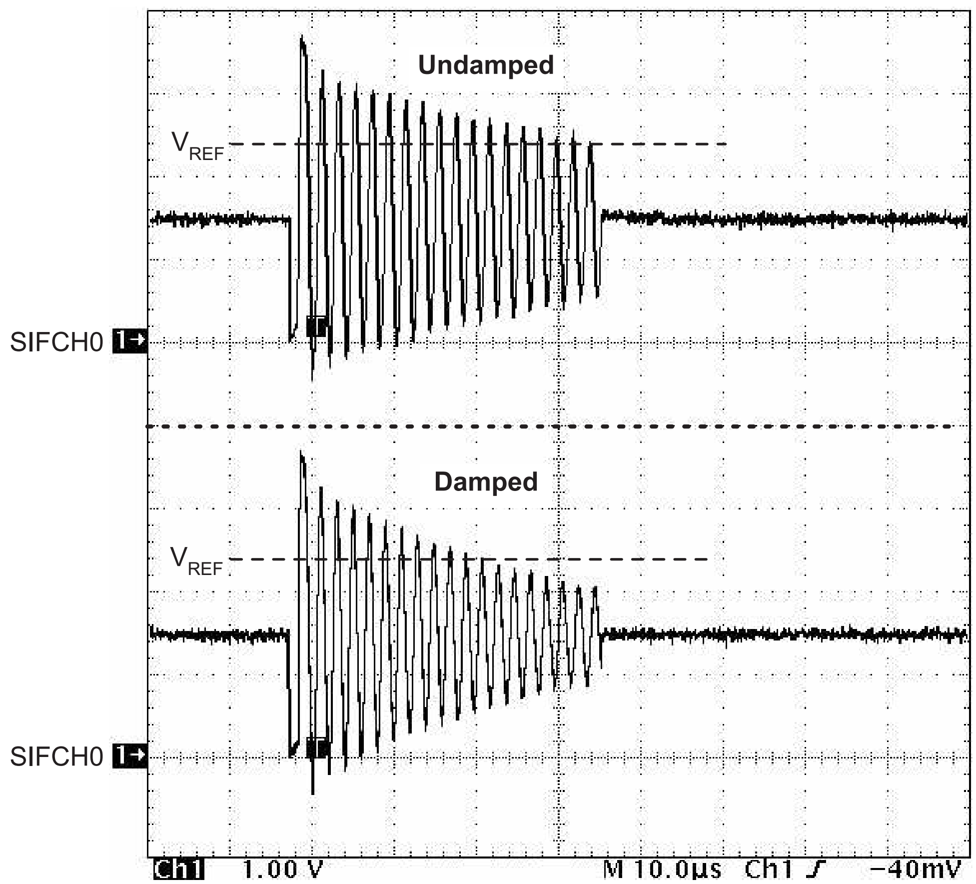

Figure 12. Undamped vs Damped Sensor Output Signals

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3.2.4 Enable DAC and Comparator

Before the measurement can be made the DAC and comparator must be switched on. This can be achieved in two different ways. One method is to permanently enable the DAC and comparator for all TSM states. The bits in the control register SIFCTL2 are used to enable these elements. In this case the SIFTSMx DAC enable and comparator enable bits are inactive.

However, if the respective bits SIFCTL2 are reset, the DAC and comparator can be activated only when a measurement is made. This is done with the bits located in the SIFTSMx control register and given in the state entry below.

```
...
SIFTSM3 = 0x0934;   // DAC=on,  Comparator=on,   2xSIFCLK, Analog enable
...
```

The activation of the DAC and comparator only for the short time during each measurement will reduce the current consumption of the system. In addition, it is important to wait until the DAC and comparator have settled after being enabled since these are precision analog components. The settling time for each is defined in the device-specific data sheet.

3.2.5 Sensor Measurement

Actual measurement of the LC sensor is made during TSM state 4.

```
...
SIFTSM4 = 0x3174;   // DAC=on,  Comparator=on,   7xSIFCLK, Measurement
...
```

The TSM states discussed in the prior sections are also shown in Figure 13. It is important to note that between 3 and 4 sensor oscillation periods are sampled during the measurement. It is critical that multiple oscillations are used for the measurement since the damping of the coil will also influence the resonant frequency potentially causing a single oscillation to shift outside of the measurement window.

Figure 13 also shows the rising edge synchronization of ACLK. The measurement sequence starts at SIFTSM0 with the rising edge of ACLK. Initially, SIFCLK has been switched on and then the excitation pulse is generated which takes a few SIFCLK cycles. After excitation, the delay of one ACLK (to the next rising edge of ACLK) is generated.

The single clock cycles of the sequence for SIFTSM2, SIFTSM3, SIFTSM4, and SIFTSM5 are shown in detail as well.

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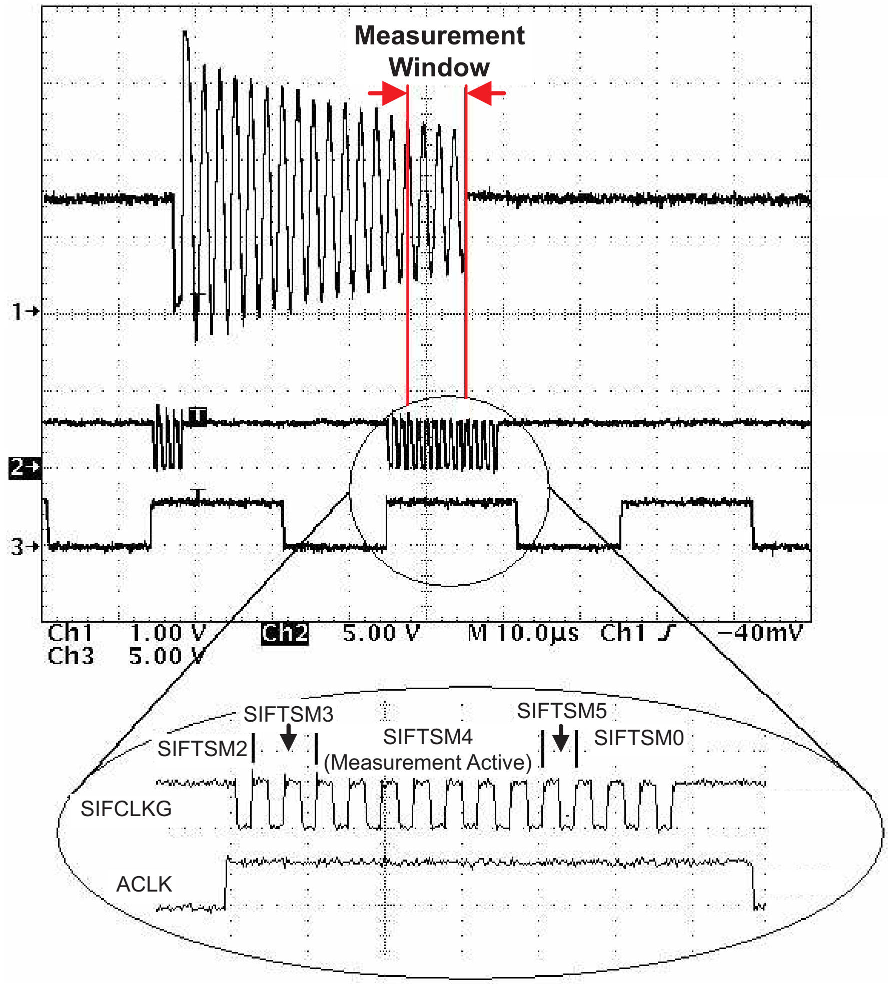

Figure 13. Scan IF TSM Details During Single Sensor Measurement

3.2.6 Stop Sequence

Setting the SIFSTOP bit in the last SIFTSMx control register stops the Scan IF sequence and is shown with the program code below.

```
...
SIFTSM5 = 0x0220;   // stop sequence                          , Stop state
...
```

It is important to note that after the processing of the SIFSTOP state the TSM is reset. This returns the TSM to the initial state when the SIFSTOP bit is set and the SIFTSM0 settings are loaded.

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3.3 Definition of DAC Levels

For the single sensor solution, constants are used for the DAC levels. These levels are determined by activating the DAC signal on the pin of the MSP430FW42x. Note that during normal operation the DAC voltage should not be switched out on a pin. This may influence the accuracy of the sensor measurement.

By monitoring the damped oscillation of the sensors and the DAC level, the DAC threshold level can be adjusted. The two cases – damped and undamped oscillation – should be used to determine the DAC level thresholds.

An algorithm that automatically finds the DAC levels is described in Section 4.3.

3.4 Single-Sensor Processing State Machine

The processing state machine, or PSM, processes the measurement results of two definable input channels. In this example only one sensor has been used. In this case, the measurement result of the input channel SIFCH0, which generates the SIFOUT0 signal, is configured to drive both inputs S1 and S2 of the PSM.

Figure 14 shows the processing state machine used for the single sensor example implementation.

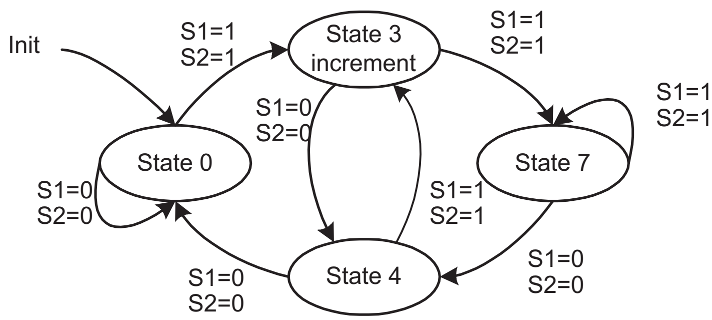

Figure 14. Processing State Machine Example: One Sensor

Note that every update of the processing state machine will increment the counter if the corresponding PSM bit is set. This means if the state is not changed and the counter increment bit is set within this state the counter would be incremented each time a measurement is triggered. To generate only one trigger pulse for the counter, the count state, State 3, is exited with the next measurement.

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4 Programming the Scan Interface – Two-Sensor Solution

In addition to the single sensor implementation described earlier, this section presents a two sensor implementation that detects rotation and direction. The two sensor system is based on the Scan IF fundamentals of operation as given in the one sensor solution.

4.1 SIFCHx Pin Setup

To properly measure each LC sensor, it is important that each SIFCHx port pin is initialized properly. There is the possibility to short those SIFCHx channels that are not used for the current sensor measurement. This feature was implemented to prevent multiple coils, which are usually located close together, from influencing each other.

Figure 15 shows on the left side the SIFCHx signals of a two-sensor system. In the port initialization the SIFCHx pins were not defined as "module function", i.e. the corresponding PSEL bits were not set. In this case, the integrated digital I/O logic is active and influences the LC sensor signal. Only if the digital I/O is defined as a module input the behavior on the right side of Figure 15 can be realized.

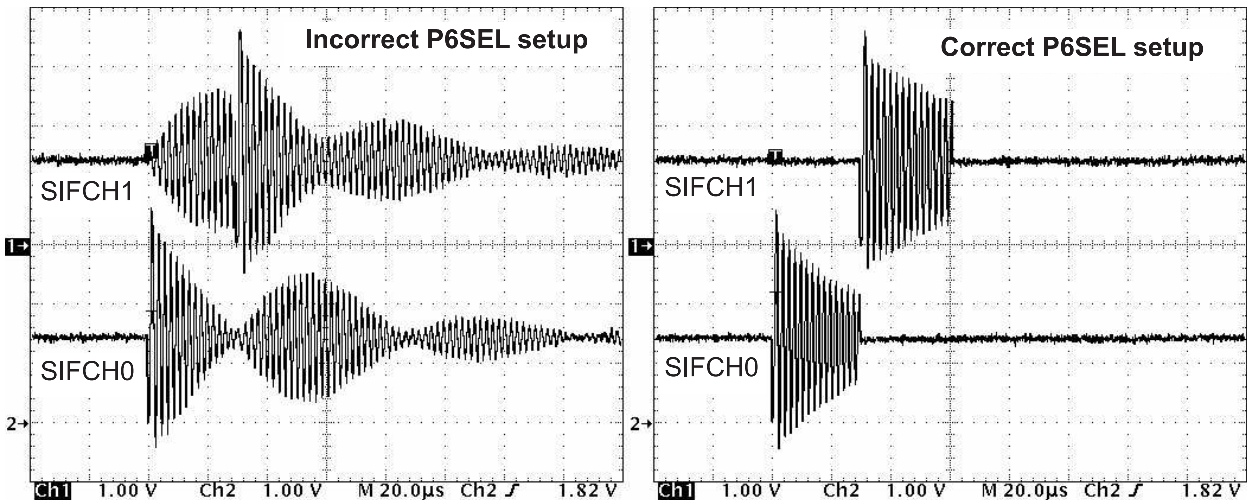

Figure 15. Scan IF Channel Setup and LC Sensor Behavior

If the digital I/O is defined as a module output, no oscillation will be generated on the SIFCHx pins. The correct initialization has to set the corresponding bits of the P6SEL control register. For example, if SIFCH0 and SIFCH1 are used the correct initialization is given by:

```
P6SEL |= 0x03;    // use P6.0 (=SIFCH.0) and P6.1 (=SIFCH.1) in module function
```


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4.2 Defining the Idle State

As described in the single sensor example, SIFTSM0 defines the settings for the Scan IF Analog Front-End after the measurements are finished and defines the time until the next measurement begins. An example TSM definition is shown below.

```
SIFTSM0 = 0x0000;   // DAC=off, CA=off,  1xSIFCLK

SIFTSM1 = 0x002C;   // DAC=off, CA=off,  1xSIFCLK, excitation  SIFCH.0
SIFTSM2 = 0x0424;   // DAC=off, CA=off,  1xACLK                SIFCH.0
SIFTSM3 = 0x1934;   // DAC=on,  CA=on,   4xSIFCLK              SIFCH.0
SIFTSM4 = 0x4134;   // DAC=on,  CA=on,   9xSIFCLK              SIFCH.0
SIFTSM5 = 0x2174;   // DAC=on,  CA=on,   5xSIFCLK              SIFCH.0

SIFTSM6 = 0x002D;   // DAC=off, CA=off,  1xSIFCLK, excitation  SIFCH.1
SIFTSM7 = 0x0425;   // DAC=off, CA=off,  1xACLK                SIFCH.1
SIFTSM8 = 0x1935;   // DAC=on,  CA=on,   4xSIFCLK              SIFCH.1
SIFTSM9 = 0x4135;   // DAC=on,  CA=on,   9xSIFCLK              SIFCH.1
SIFTSM10 = 0x2175;  // DAC=on,  CA=on,   5xSIFCLK              SIFCH.1

SIFTSM11 = 0x0220;  // stop
```

The TSM states defined above provide a two sensor measurement cycle as shown in Figure 16. It is obvious that although the TSM definitions for each sensor are identical, the excitation and oscillations are slightly different.

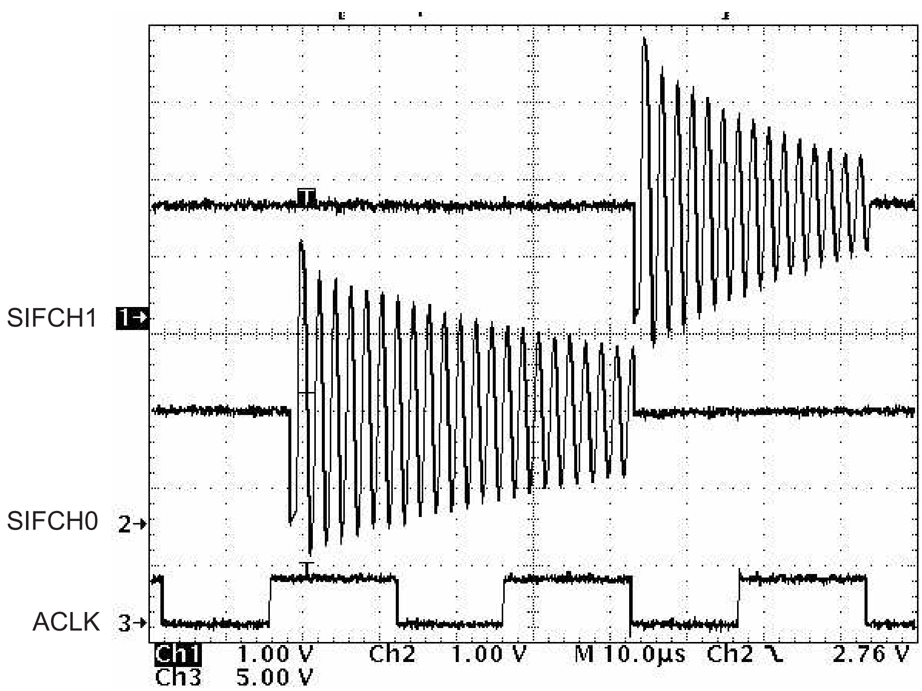

Figure 16. Two Test Channels: Asynchronous Scan IF Timing

The two SIFCHx signals in Figure 16 have different timing even though the TSM setup is identical. The reason for the different timing is the synchronization with the ACLK signal. Each measurement sequence is triggered by a rising edge on ACLK. The sequence for SIFCH0 starts with 1 SIFCLK cycle after one ACLK cycle delay is generated (a delay to the next rising edge of ACLK). In total 18 SIFCLK cycles are programmed for settling of the DAC and comparator and performing the measurement.

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The measurement sequence for SIFCH1 then follows. The SIFCH1 cycle starts with the excitation pulse (1 SIFCLK cycle) and a delay of 1 ACLK until the next rising edge of ACLK is available. Due to the previous measurement there is a delay of approximately 1/2 of an ACLK cycle. This causes the programmed 1 ACLK delay for the SIFCH1 sequence to be shorter than the delay generation for the first measurement on SIFCH0.

In contrast, by simply changing the definition of the idle state, both channel measurements can be properly controlled and synchronized.

```
SIFTSM0 = 0x8800;   // DAC=off, CA=off, 31xSIFCLK  (delay for proper timing for both
                    //                              LC sensors.)
...
```

By including a delay at the beginning of the complete measurement sequence (SIFTSM0) the synchronization with the ACLK signal can be corrected and the measurement for SIFCH0 and SIFCH1 is realized with the same timing. This is shown in Figure 17.

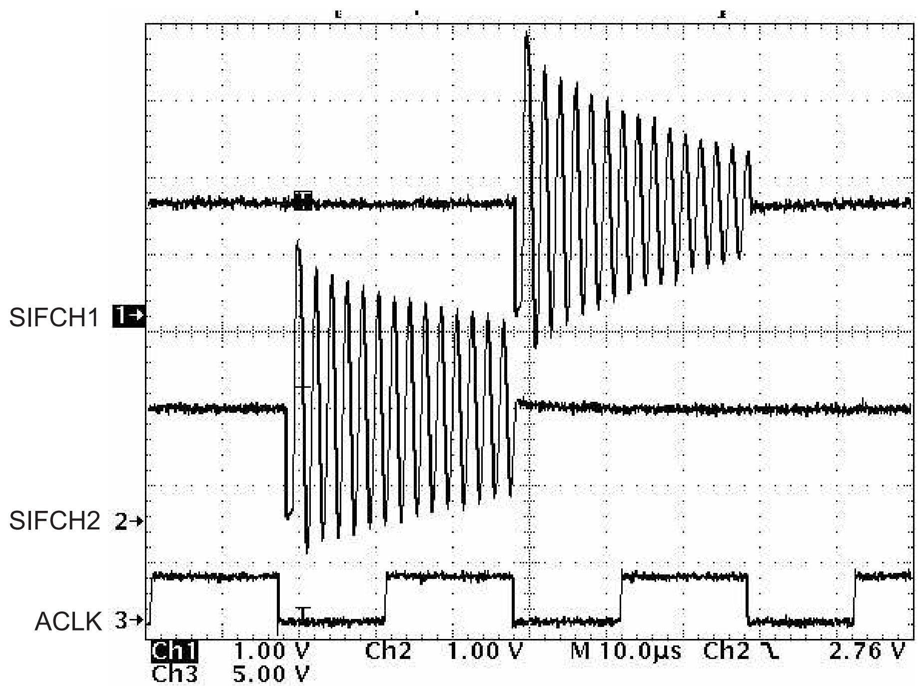

Figure 17. Two Test Channels: Synchronous Scan IF Timing

The same timing for different measurement channels may be interesting if adjustment algorithms for the DAC thresholds are included and the capture inputs of Timer_A are used for the proper time measurements.

4.3 Finding the DAC Levels

The two sensor example software uses a simple DAC threshold calibration to determine the V_{REF} levels for each sensor. During the threshold calibration the plated disc must be rotating.

The calibration for each sensor is done in two steps. First the DAC value is set to the maximum, 0x3FF. Then the SIFxOUT bit in the SIFCTL3 control register is checked. As long as SIFxOUT = 0, the DAC value is decremented and the SIFxOUT bit is tested again. When SIFxOUT = 1, the DAC value is stored in the address V0. For the second step, the DAC value is set to mid-scale, 0x0200. This value defines a reference level that should be approximately equal to the V_{MID} voltage and the SIFxOUT bit will be set. Now the DAC value is incremented until SIFxOUT =0. In this case the DAC value is stored in V1.

The average value of V1 and V2 is calculated and represents the threshold point for the damped vs. undamped measurement. A small hysteresis is added to and subtracted from the average value for the two DAC settings per sensor channel, respectively, to reject small variations from the measurement. This simple algorithm is used in the example code that is supplied with this report.

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4.4 Two-Sensor Processing State Machine

This section details two approaches for configuring the PSM in the two sensor example.

4.4.1 Simple Two-Sensor PSM

Table 3 lists the states for a simple two sensor system that detects rotation and direction.

Table 3. Quadrature Transitions for 2-Sensor Implementation

State Number	Previous Quad. Pair	Current Quad. Pair	Movement	State Table Entry					
				Q6 Error	Q2 - 1	Q1 + 1	Q3	Q0	Byte Code
							Current Quad. Pair		
0	0	0	No Rotation	0	0	0	0	0	0x00
1	0	1	Turns Right (+1)	0	0	1	0	1	0x03
2	0	10	Turns Left (-1)	0	1	0	1	0	0x0C
3	0	11	Error	1	0	0	1	1	0x49
4	1	0	Turns Left	0	0	0	0	0	0x00
5	1	1	No Rotation	0	0	0	0	1	0x01
6	1	10	Error	1	0	0	1	0	0x48
7	1	11	Turns Right	0	0	0	1	1	0x09
8	10	0	Turns Right	0	0	0	0	0	0x00
9	10	1	Error	1	0	0	0	1	0x41
10	10	10	No Rotation	0	0	0	1	0	0x08
11	10	11	Turns Left	0	0	0	1	1	0x09
12	11	0	Error	1	0	0	0	0	0x40
13	11	1	Turns Left	0	0	0	0	1	0x01
14	11	10	Turns Right	0	0	0	1	0	0x08
15	11	11	No Rotation	0	0	0	1	1	0x09

In the column "Movement" the expressions have the following meaning:

- **No Rotation:** Input signals S1 and S2 do not change and the PSM stays in the same state. (for example, State 5 and input signals S1=1, S2=0)
- **Turns Right or Turns Left:** The PSM is in a state that will be exited with the next measurement. Depending on the direction of the rotation the S1 and S2 input signals will be different allowing for sensing the direction of the rotation.
- **Error:** An erroneous state transition has occurred. A properly functioning system will not make such a transition.

Figure 18 shows the state diagram for the Simple PSM configuration in Table 3 (Error transitions are shown in the diagram).

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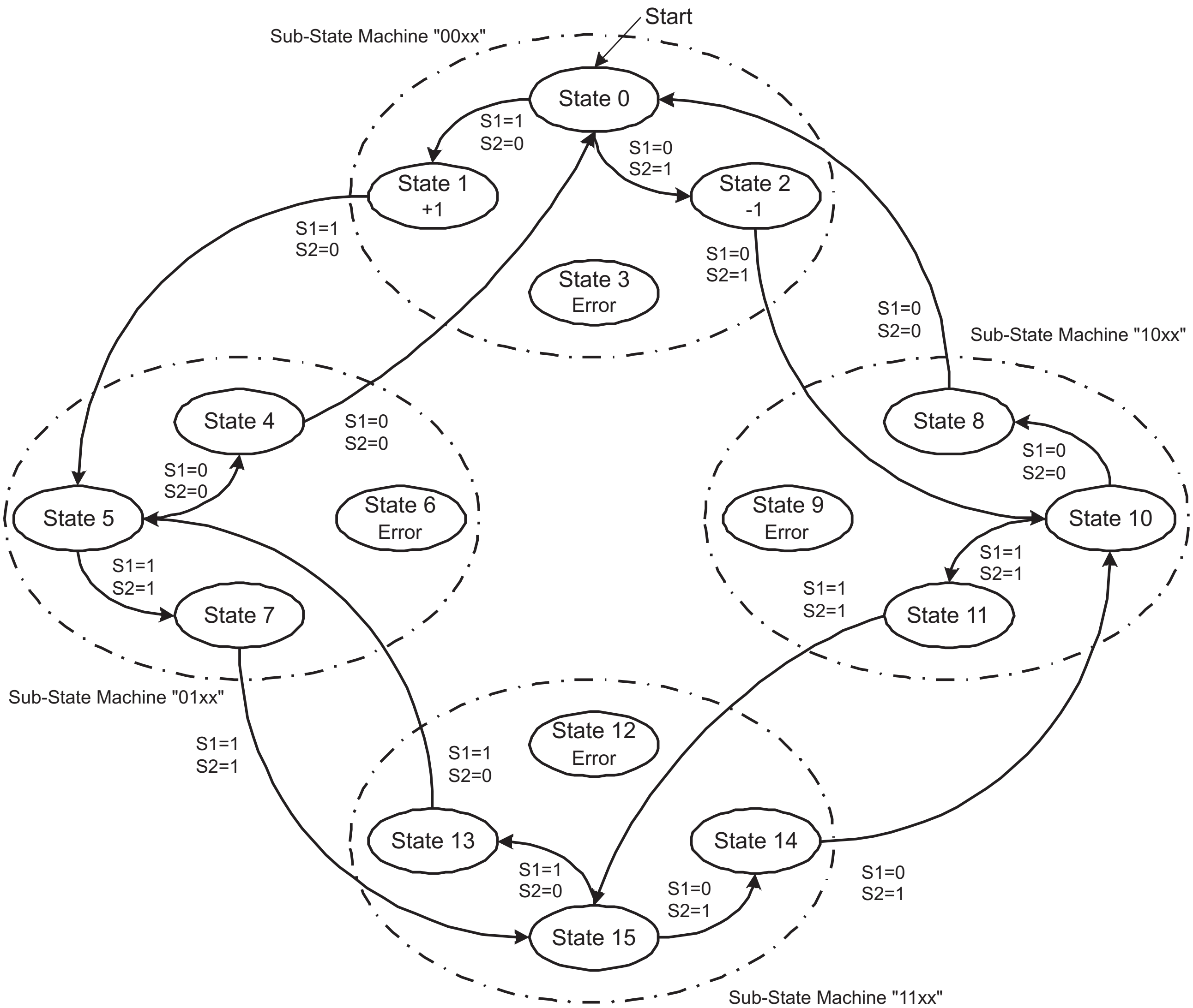

Figure 18. Two-Sensor Simple PSM Example

Four sub-state machines are used to realize the PSM in Figure 18. In contrast to the single sensor implementation, the two-sensor PSM includes the detection of the rotational direction in addition to simple rotation. This version only increments or decrements the PSM counter if a complete rotation is completed.

A shortfall of this PSM version is the ability to handle potential bouncing of the disc. If a coil is just between the non-metallic and metallic areas of the bouncing disc one of the PSM input signals may toggle. For example, this could be a problem if the PSM points to state 0 and disc bounce occurs. Assume the input signal S1 toggles. When S1 is set, the PSM will change to state 1 and increment the counter.

For the next measurement S1=1 is again measured. Now the PSM points to state 5. Assume now S1=0 due to the bounce of the disc. The PSM points to state 4 and with the next measurement to state 0. Note that no rotation has been completed. Only bouncing of the disc and sensor S1 has occurred. If this bouncing continues, the PSM counter will be incremented again without a complete rotation.

For completeness, Figure 19 shows all transitions that start at state 1 and state 2. All transitions from one state have to point to the same sub-state machine. In the figure the transitions from state 1 point to the sub-state machine 01xx and the transitions from state 2 points to the sub-state machine 10xx.

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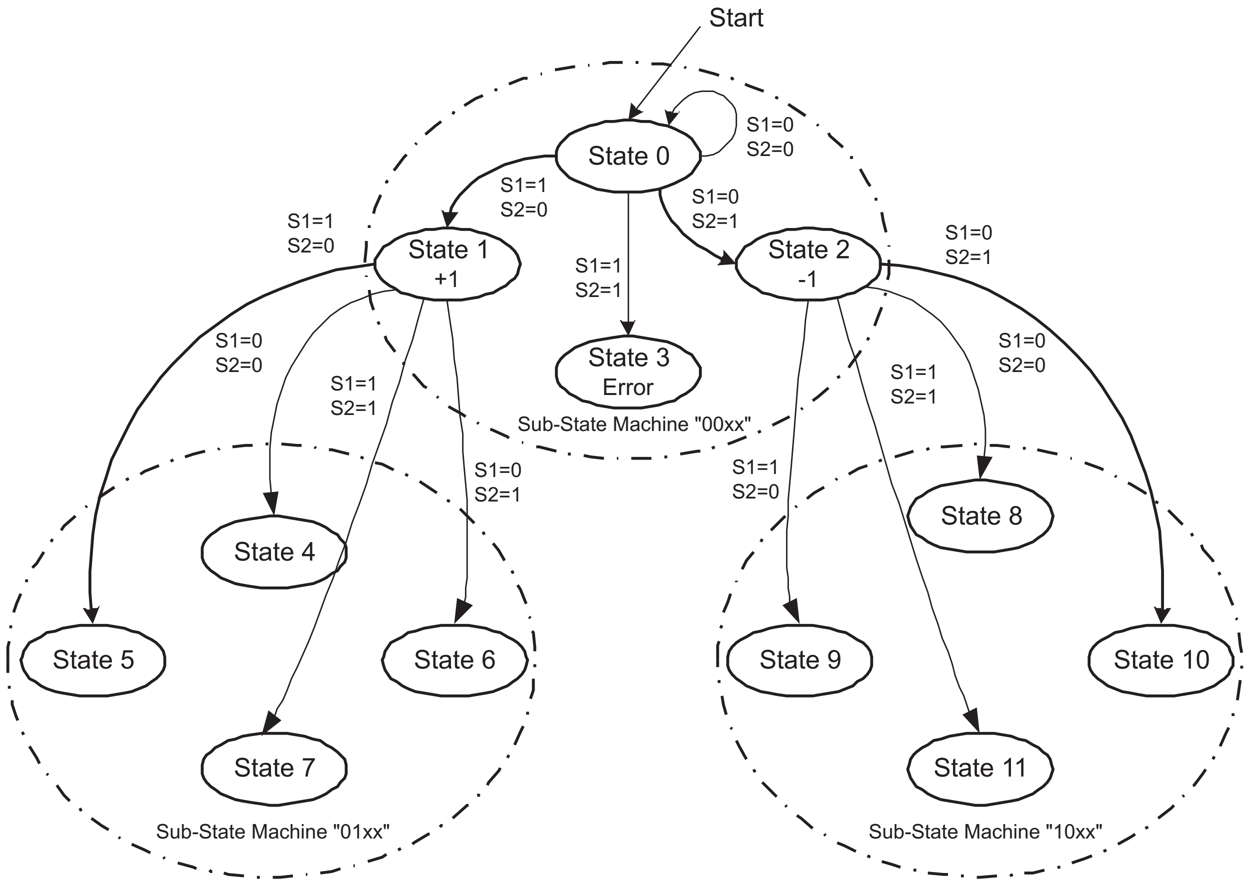

Figure 19. Two-Sensor Transition Detail

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4.4.2 Advanced Two-Sensor PSM

Table 4 shows the advanced two-sensor PSM that detects both rotation and direction, as well as rejects sensor bounce.

Table 4. Advanced Two-Sensor PSM With Bounce Reject

State Number	Previous Quad. Pair	Current Quad. Pair	Movement	State Table Entry						
				Q6 Error	Q2 - 1	Q1 + 1	Q4 Direction	Q3 (Current Quad. Pair)	Q0 (Current Quad. Pair)	Byte Code
0	0	0	No Rotation	0	0	0	0	0	0	0x00
1	0	1	Change Direction	0	0	1	1	0	1	0x13
2	0	10	Turns Left (-1)	0	1	0	0	1	0	0x0C
3	0	11	Error	1	1	0	0	1	1	0x4D
4	1	0	Turns Left (-1)	0	1	0	0	0	0	0x04
5	1	1	No Rotation	0	0	0	0	0	1	0x01
6	1	10	Error	1	1	0	0	1	0	0x4C
7	1	11	Change Direction	0	0	1	1	1	1	0x1B
8	10	0	Change Direction	0	0	1	1	0	0	0x12
9	10	1	Error	1	1	0	0	0	1	0x45
10	10	10	No Rotation	0	0	0	0	1	0	0x08
11	10	11	Turns Left (-1)	0	1	0	0	1	1	0x0D
12	11	0	Error	1	1	0	0	0	0	0x44
13	11	1	Turns Left (-1)	0	1	0	0	0	1	0x05
14	11	10	Change Direction	0	0	1	1	1	0	0x1A
15	11	11	No Rotation	0	0	0	0	1	1	0x09
16	0	0	No Rotation	0	0	0	1	0	0	0x10
17	0	1	Turns Right (+1)	0	0	1	1	0	1	0x13
18	0	10	Change Direction	0	1	0	0	1	0	0x0C
19	0	11	Error	1	0	1	1	1	1	0x5B
20	1	0	Change Direction	0	1	0	0	0	0	0x04
21	1	1	No Rotation	0	0	0	1	0	1	0x11
22	1	10	Error	1	0	1	1	1	0	0x5A
23	1	11	Turns Right (+1)	0	0	1	1	1	1	0x1B
24	10	0	Turns Right (+1)	0	0	1	1	0	0	0x12
25	10	1	Error	1	0	1	1	0	1	0x53
26	10	10	No Rotation	0	0	0	1	1	0	0x18
27	10	11	Change Direction	0	1	0	0	1	1	0x0D
28	11	0	Error	1	0	1	1	0	0	0x52
29	11	1	Change Direction	0	1	0	0	0	1	0x05
30	11	10	Turns Right (+1)	0	0	1	1	1	0	0x1A
31	11	11	No Rotation	0	0	0	1	1	1	0x19

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This version uses different sub-state machines for right and left rotation. The "Change Direction" expression marks the states that cause a change of the state machine which handles the opposite rotation direction. Figure 20 show the state diagram for Table 4.

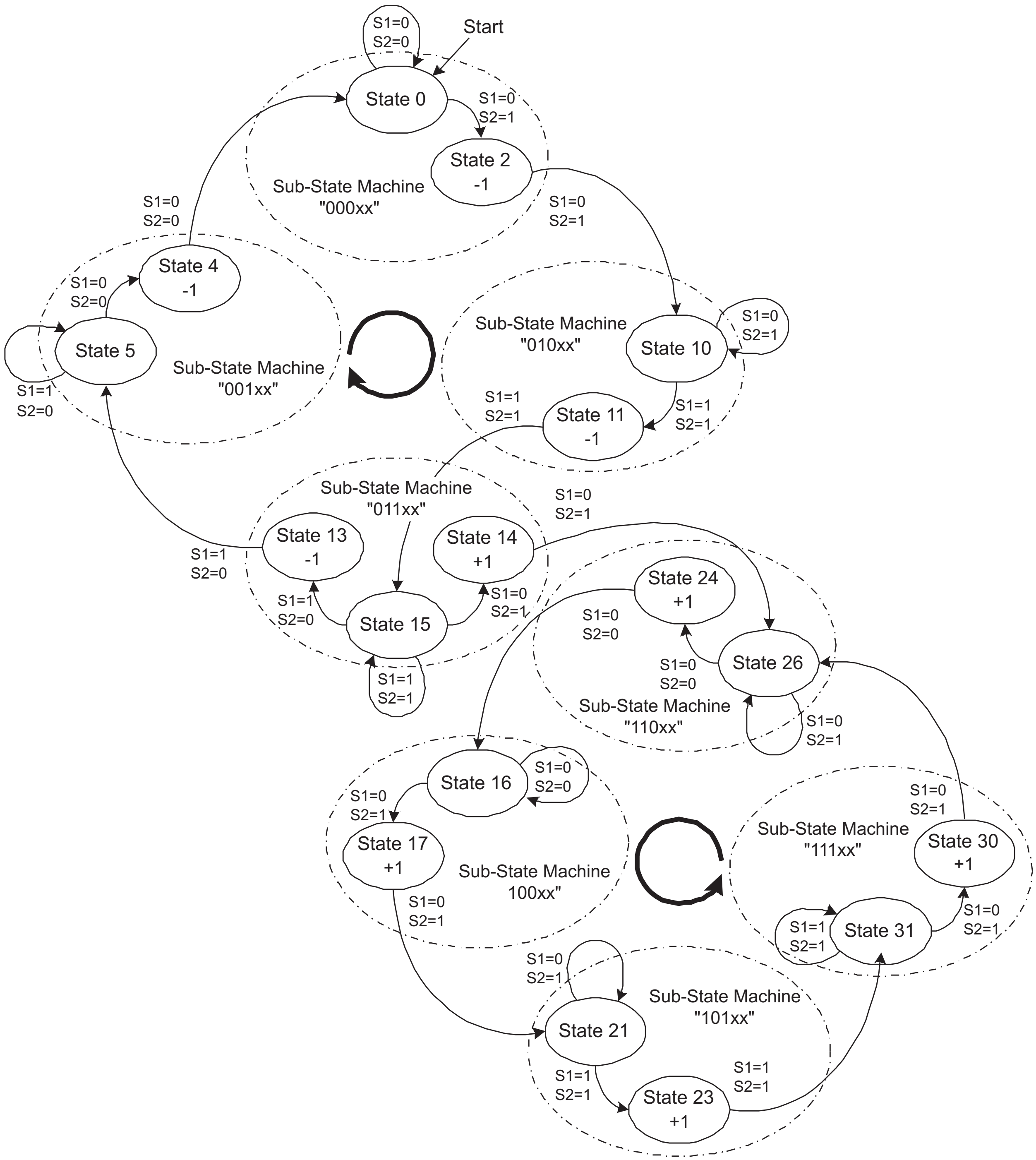

Figure 20. Advanced Two-Sensor PSM with Bounce Reject

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In the advanced example the PSM counter increment is done each time a sensor signal changes. The PSM counter should be defined in the up- and down-counting mode.

The usage of different sub-state machines for the different rotation direction provides states that handle bouncing. In Figure 21 an example for bouncing states is shown. When PSM input signals S1=1 and S2=1 and the signal S1 toggles, the following will happen:

S1=1	→	State 15		
S1=0	→	State 14	→	PSM counter + 1
S1=1	→	State 27	→	PSM counter - 1
S1=0	→	State 14	→	PSM counter +1
S1=0	→	State 26		
S1=1	→	State 27	→	PSM counter –1
S1=1	→	State 15		
S1=0	→	State 14	→	PSM counter +1

…

This example shows that in spite of input signal bouncing the counter is not corrupted and will correctly increment or decrement only on full rotations.

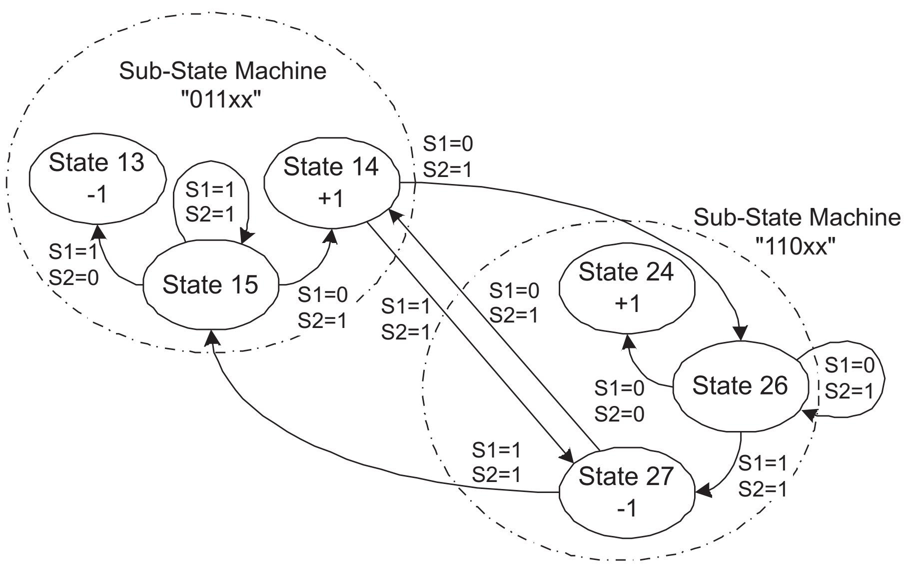

Figure 21. Sensor Bounce Rejection State Transitions

The implementations shown here are meant to serve as a starting point for development of other MSP430FW42x systems and as a guide for using the Scan IF module. While each system may vary as required by the given application, the fundamental operation of the Scan IF will still apply.

5 References

1. MSP430x4xx Family User's Guide
2. MSP430FW42x Mixed-Signal Microcontrollers data sheet
3. An Electronic Water Meter Design Using MSP430F41x

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from April 30, 2011 to July 26, 2017	Page
• Changed the Byte Code column for State Number 18 from 0x0D to 0x0C	23

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