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Signal Processing and Data Acquisition using Low Cost Eddy Current Sensor for Position Control in Active Magnetic Bearing Systems

Ragunathan. P.[a] and Logashanmugam. E[b]

[a] *Research Scholar, Sathyabama University, Jeppiar Nagar, Rajiv Gandhi Salai, Chennai -600 119*

[b] *Professor, Faculty of Electrical and Electronics, Sathyabama University, Jeppiar Nagar, Rajiv Gandhi Salai, Chennai -600 119*

Abstract: Position control in active magnetic bearing systems require high speed rotor position detection and data acquisition for the control of the magnetic coil current. The present generation of advanced microcontrollers for motor control and digital power supply control applications which require peripherals like high speed ADCs, enhanced capture compare modules, multi-channel PWMs, has made it convenient to design real time controllers for active magnetic bearings with reduced system complexity and improved reliability. This paper presents a scheme to acquire signals from a very low cost eddy current sensor and use it as a position feed-back to a PID control algorithm on Texas Instruments C2000 real time microcontroller to control the position of amagnetically levitated rotor shaft by controlling the magnetic actuator's coil current. The magnetic actuators are electromagnetic coils that generate the magnetic force in the bearing.

Keywords: *Eddy current sensor, Microcontroller, Active magnetic bearing, PID control, Magnetic actuator, Magnetic bearing.*

1. INTRODUCTION

Eddy current sensors are widely used for noncontact position and displacement measurement. It operates on the principle of electro-magnetic induction and they are used for accurate measurement of position of metallic targets even in the presence of non-metallic materials such as plastics, non-conducting fluids and dirt in the measuring region [1,2]. Most commercial eddy current sensor, outputs analog voltages of 0-2volts or 0-5volts for zero to full-scale displacement value. Such sensors also have an inductor coil as probe head which forms a part of a sinusoidal oscillator circuit [9]. This sinusoidal signal output is passed on to a linear frequency to voltage converter. The output voltage is linear and proportional to target distance from the probe head.The controller connected to such sensor has to perform analog to digital conversion using high speed built-in ADCs [10,11,14]. Most eddy current sensors are used to measure displacement of a few millimeters to a maximum range roughly equal to the radius of the sensor coil used for sensing. They have a frequency bandwidth of around 20-40 kHz.

In this paper we present a novel method of converting the time period of the square wave output from our eddy current sensor into digital counts using the enhanced capture module (*e*CAP) of the Texas instruments C2000 real time controller. The captured digital count varies linear with the target position. This digital count is directly used as the position feed-back of a PID control loop to adjust the magnetic bearing's coil current.

2. LOW COST EDDY OF CURRENT SENSOR

The eddy current position sensor is similar to the inductive position sensor. A copper coil is used as the probe as shown in Figure 1. This coil may have a ferromagnetic core or an air core as the inductive sensor. The operating frequencies of eddy current sensor are much higher than for the inductive sensors and operate in the region of 150 KHz to a few MHz. Targets used with inductive andeddy current sensors must be a conductive material. The resolution of the eddy current sensor depends on the conductivity of the target material. The higher the conductivity of the target material the better is its displacement resolution [2]. The higher excitation frequency means eddy current sensors are less susceptible to noise causedby power amplifier switching [1].

A fabricated air core eddy current sensor designed for active magnetic bearing system is shown in Figure 2. The front end electronics connected to the sensor probe or copper winding is an oscillator circuit which generates a square wave is shown in Figure3[7].

In an active magnetic bearing system the rotor shaft is held suspended in air by controlling the magnetic force of the electromagnetic coil as shown in Figure 4[15,16]. The eddy current sensor is a critical feed-back control element which provides instant position data to the controller [3,4,12].

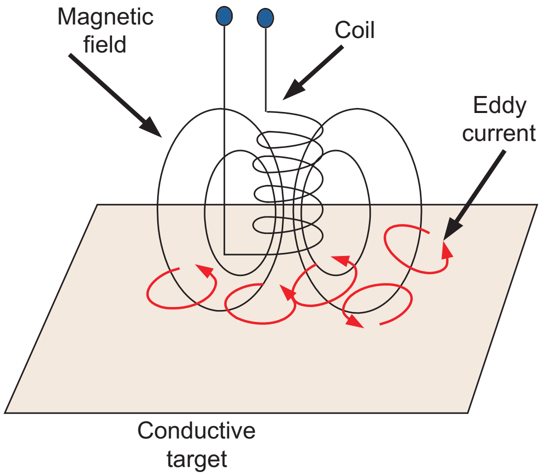

Figure 1: Eddy current displacement sensor working principle

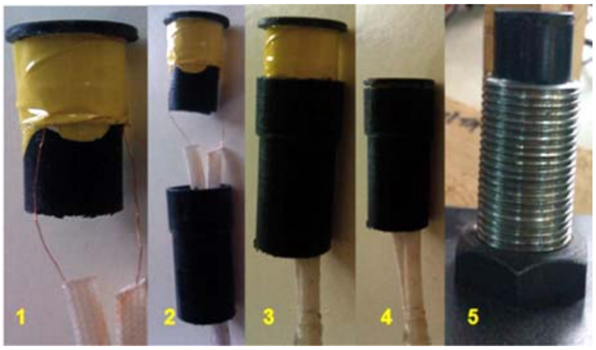

Figure 2: Air core copper coil wound on a plastic former works as the probe head of the sensor

The frequency of the square wave generated by the sensor oscillator is directly proportional to the target distance from the sensor probe [4].

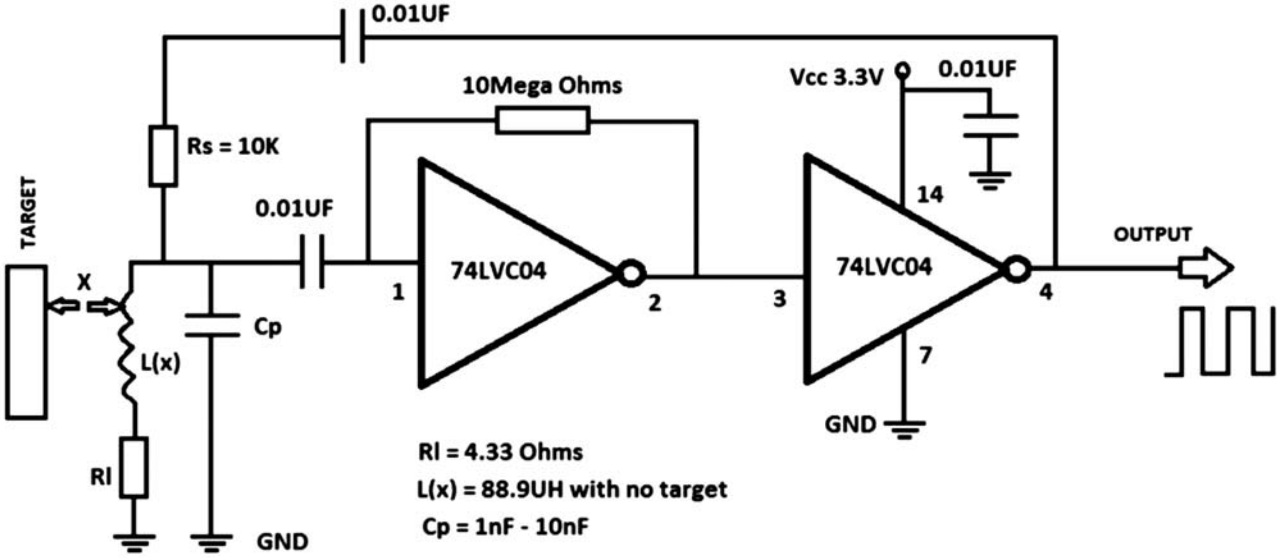

Figure 3: Electrical schematic of eddy current sensor electronics

L(*x*) in figure 3 is the sensor coil's inductance which varies with the distance of the target material. R1 is the equivalent DC resistance of the sensor coil.

The basic elements of an active magnetic bearing systems are the electromagnetic coil, the suspended rotor, position sensor and the controller that controls the actuators coil current and hence the position of the rotor shaft [5].

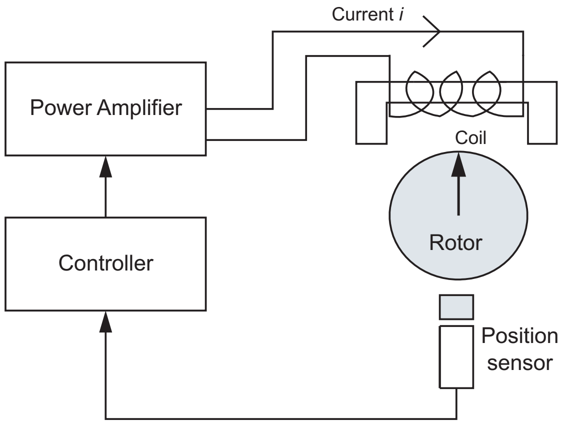

Figure 4: Block diagram of active magnetic bearing system

3. PROPOSED METHOD FOR SENSOR SIGNAL PROCESSING AND CONTROL

We have employed a novel method of using time to digital conversion which converts the time period of the eddy current sensor's square wave signal into digital counts using the 32bit timer counter of the enhanced capture module available in Texas Instruments C2000 controller. The digital counts give us the direct displacement value that can be used as feedback to generate the required error signal in the PID control loop.Both the signal data acquisition and PID control algorithm is employed on a single C2000 microcontroller chip thereby reducing number of discreet components, increasing speed of control loop and thereby increasing system reliability.

The output frequency of the eddy current sensor is in the range of 700 kHz. The graph showing the variation in output frequency with the target distance is shown in Figure 4. The captured square wave signal from the eddy current sensor is shown in Figure 5. This signal frequency is scaled down to 10 kHz by using the built-in divide by counter in the C2000 controller before feeding it to the capture module to capture the time period in a 32bit timer counter. All this can be conveniently done by software programming of the controller.

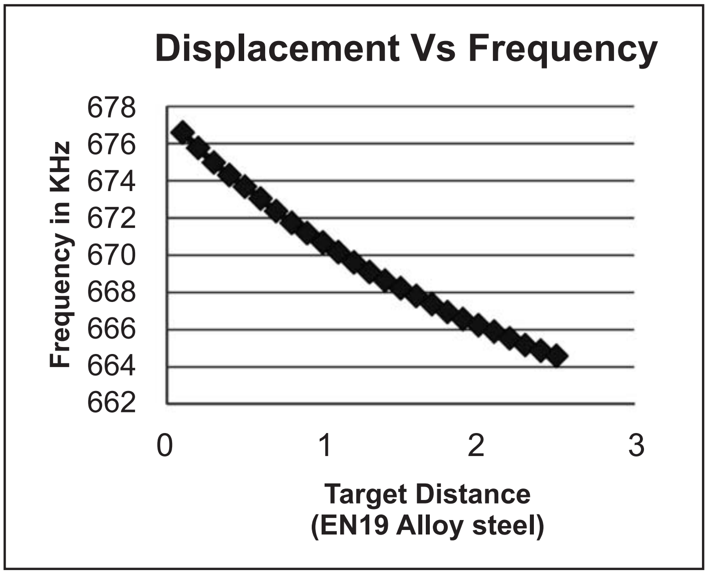

Figure 4: Plot of target distance Vs sensor output frequency of the designed air core eddy current sensor with 80 turns of 39-SWG copper wire (for EN19 Alloy steel)

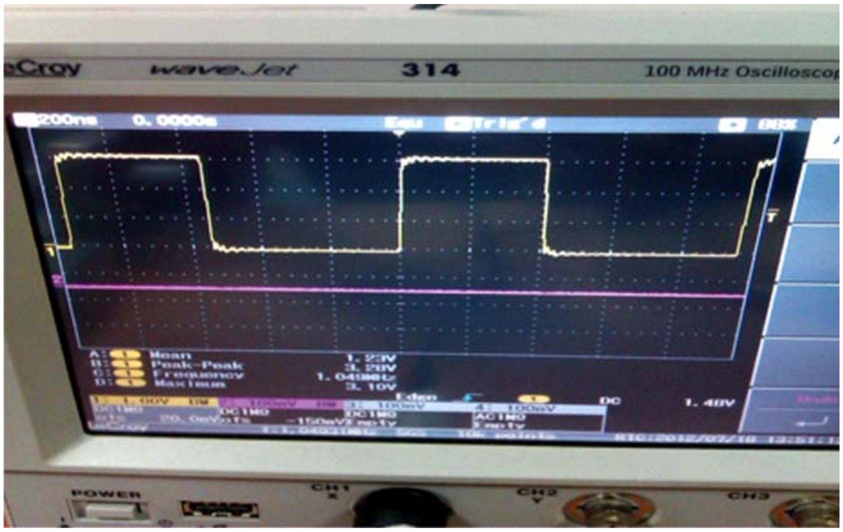

Figure 5: Output wave form of an eddy current sensor used in our application

3.1. Hardware Description of Digital Signal Controller

The hardware for the digital signal processing and PID control was designed and implemented on Texas Instrument's C2000 real time controller [6]. **TMS320F28035** is the microcontroller part that is used for this design. The complete block diagram of the enhanced capture module (**eCAP**module) used to capture the time period of the signal from the eddy current sensor is shown in Figure 6.

ECAPxin Figure 6 is a configurable general purpose I/O pin in the controller to which we have to interface the eddy current sensor's square wave output signal. Make sure the signal voltage is within 0-3.3volts which is the operating voltage of the C2000 controller [18]. Any voltage greater than 3.3 or less than -0.3 volts will permanently damage the controller [18]. Use voltage level shifter in case there is a difference in operating voltage between the sensor and controller. It is also a good practice to connect the I/O pins of the controller to high speed optical isolators for the interface of sensors to eliminate emi-rfi noise that may at times cause controller to malfunction [13].

Listed below are some of the capabilities of the capture eCAP module [18].

1. Dedicated input capture pin
2. 32-bit time base (counter) incremented by system clock
3. 4 x 32-bit time-stamp capture registers (**CAP1-CAP4**)
4. 4-stage sequencer (Mod4 counter) that is synchronized to external events, **eCAP** pin rising / falling edges.
5. Independent edge polarity (rising / falling edge) selection for all 4 events.
6. Input capture signal pre-scaling (from divide by 2 to 62). See Figure 7.
7. One-shot compare register (2bits) to freeze captures after 1 to 4 time stamp events.
8. Control for continuous time-stamp captures using a 4-deep circular buffer (**CAP1-CAP4**) scheme.
9. Interrupt capabilities on any of the 4 capture events.

The system clock frequency used in our design is 60MHz. The maximum frequency of the signal pulse that can be given to the capture pin is half the system clock frequency [18]. In our case the eddy current sensors output is around 1MHz maximum and is within the specification for measurement.

We use the programmable pre-scaler unit shown in Figure 7 to bring down the frequency to around 10 kHz.

Assuming eddy current signal frequency = **700 kHz**

Using Divide by 62 in pre-scaler we have

$$\mathbf{F} = \frac{\mathbf{700}}{\mathbf{62}}$$

$$= \mathbf{11.29\ kHz}$$

ECAP Control Register1(**ECCTL1**) is the register in the controller that has to be configured to accomplish this. This register also allows in selecting counter capture events on rising edge or falling edge on the scaled down signal [12, 13]. We have used capture event on the rising edge in our program.

Four time stamp Capture registers **CAP1, CAP2, CAP3 and CAP4**shown in Figure 8 are available to load the 32bit time stamp counter value upon event triggers that are set in **ECCTL1** registers. There are two modes of time stamp operation, the absolute time stamp mode and the difference mode of operation [18]. We choose the difference mode of operation in order to get the digital counts of the time period of our scaled down signal. The register values used for our project are…

ECap1Regs.ECCTL1.all = 0xFFAA; // set the div pre-scaler and capture trigger event

ECap1Regs.ECCTL2.all = 0x96; //set continuous capture mode and enable eCAP module

The above naming conventions of the registers are defined in Texas instruments device header files.

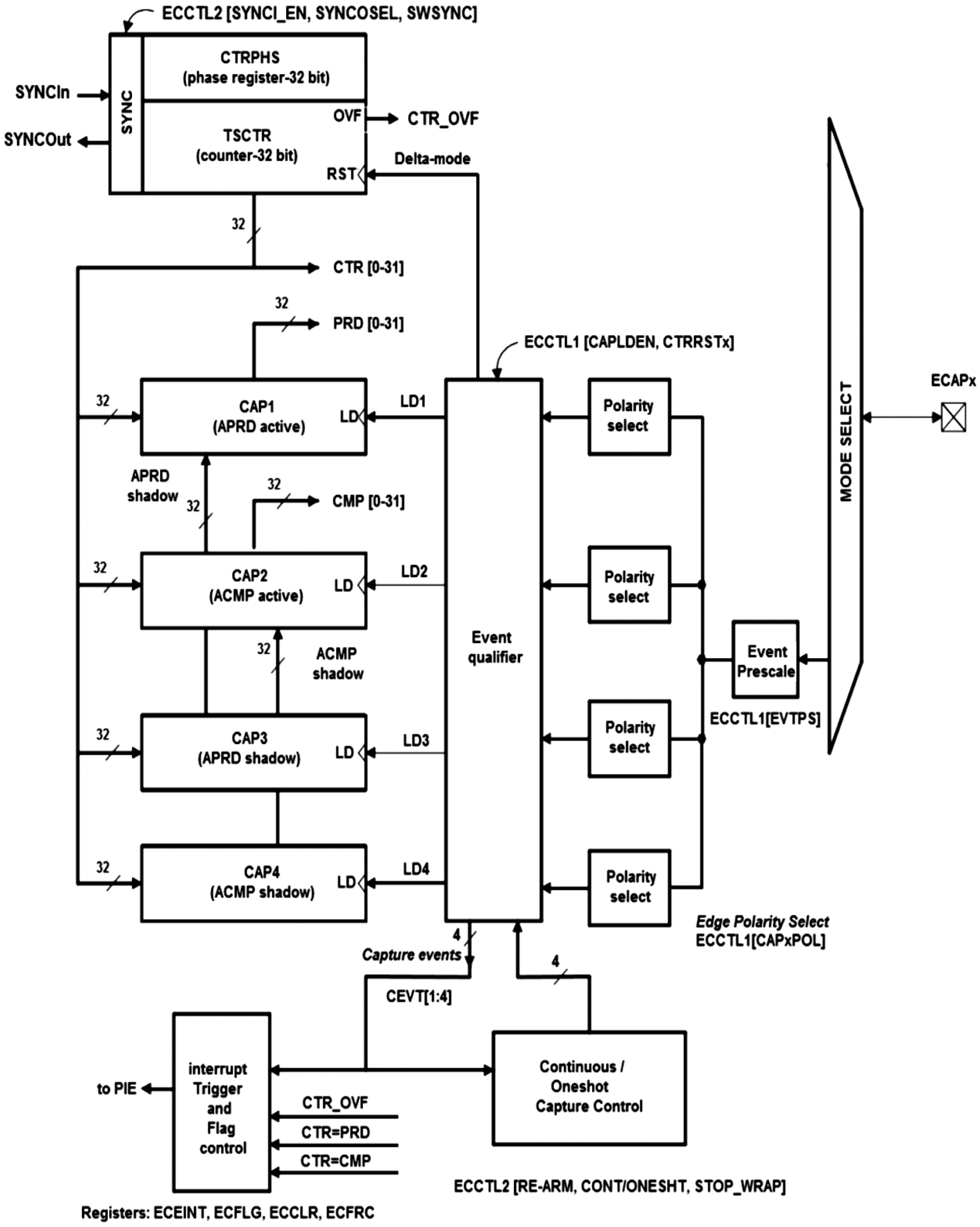

Figure 6: TMS320F280xx Capture function block diagram [18]

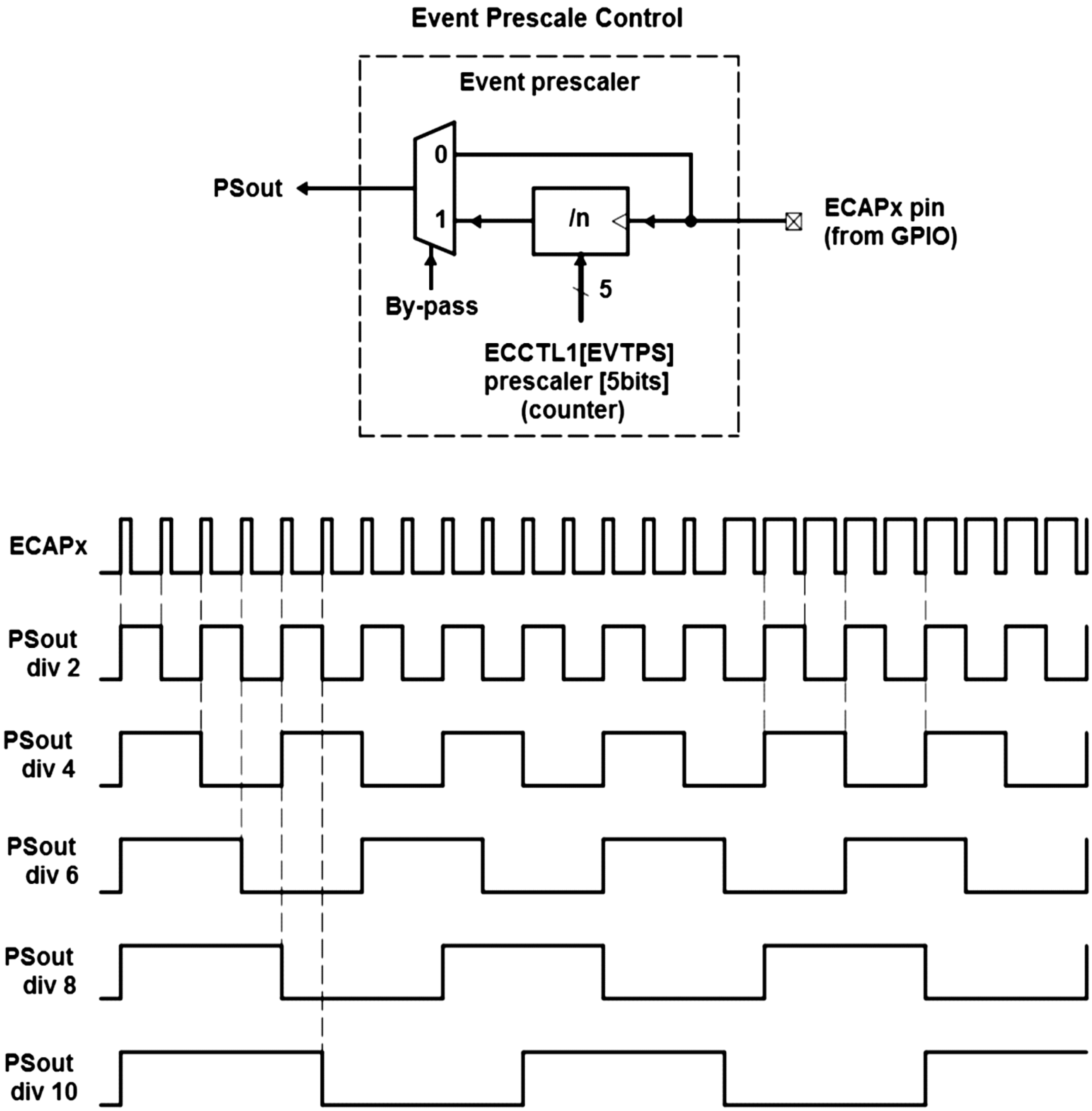

Figure 7: A representation of programmable divide by counter. The eddy current sensor's 700 kHz square wave form is scaled down by div 62 counter

Figure 8 shows the counter timer which is also called **TSCTR** or time stamp counter register which provides the time-base for the event capture and is clocked via the system clock**. CAP1, CAP2. CAP3** and **CAP4** are 32bit registers which are loaded from the **TSCTR** on capture events [18].

Figure 8 shows how the **TSCTR** counter is incremented via the system clock and upon event trigger the time stamp value gets loaded to **CAP1, CAP2, CAP3** or **CAP4** register and after that the **TSCTR register counter** is reset.

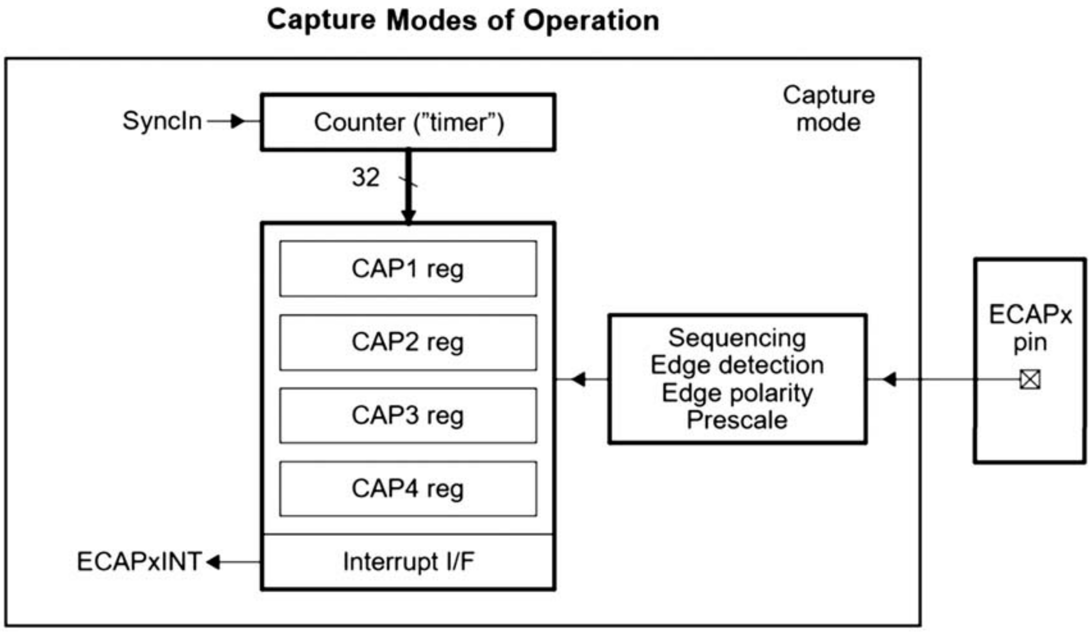

Figure 8: Event triggered Capture registers in C2000 Controller[18]

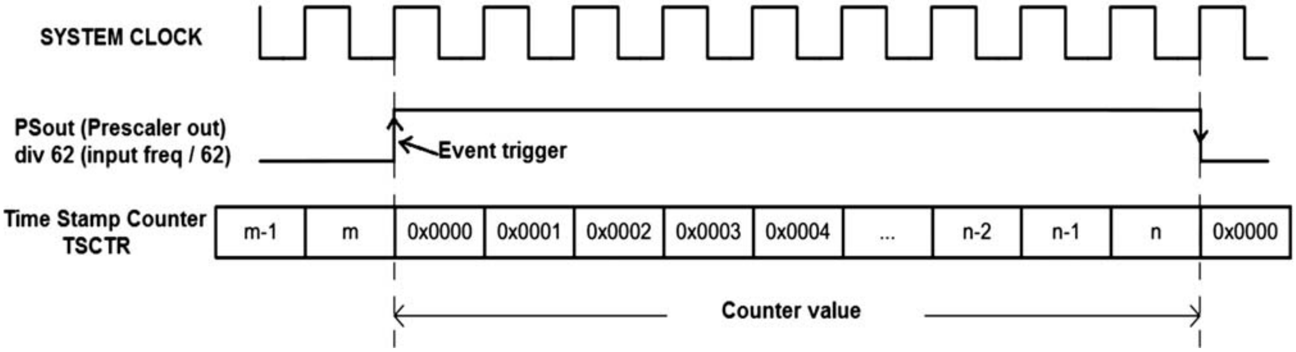

Figure 9: Time stamp counter (TSCTR) being incremented by system clock and reset by capture event triggers

3.2. Software Description of Digital Signal Controller

Texas instruments provides a software called Control Suite which has many application specific C-library for various peripheral modules. They are available as **C-Macro** functions. These are very easy to use C-code blocks with which one can create complex loops of data acquisition and control functions. We have used the **eCAPmacro** in our application. The pseudo code for initialization of the capture unit is shown below…

```
/*---------------------------------------------------------------------------------------------------
CAP_INIT & CAP Macro Definitions
---------------------------------------------------------------------------------------------------*/
#define CAP_INIT_MACRO(v)
/* Init ECAP Control Registers 1 and 2 for ECAP1*/
ECap1Regs.ECCTL1.all = 0xFFAA;
```

```
ECap1Regs.ECCTL2.all = 0x96;
EALLOW;  /* Enable EALLOW */
/* Set up the ECAP1 pin to primary function*/
GpioCtrlRegs.GPAMUX2.bit.GPIO24 = 1;  /* GPIO24 is ECAP1 */
EDIS;  /*  Disable EALLOW */
/*----------------------------------------------------------------------------------------------------------------------*/
#define CAP_MACRO(v)
if(ECap1Regs.ECFLG.bit.CEVT1 != 0)/* Check status of one entry of first event of ECAP1 pin */
{
v. EventPeriod = ECap1Regs.CAP1;   /* Stamp the timer counter difference between two edges detected*/
v.CapReturn = 0; /* Then, return zero*/
}
else
{
v.CapReturn = 1; /* Else, return one */
}
/*----------------------------------------------------------------------------------------------------------------------*/
```

Using the above Macro one can create multiple instances of reusable code. "(*v*)" in the Macro defines the name of the instance created.The displacement value of the target from the sensor is read in the interrupt service routine (ISR) of the PID control loop. The interrupt is set by the ePWM module which generates the pulses to drive the magnetic actuator coil of the bearing system. The time period of the PWM used in our application is 10 kHz and hence each control update takes place in the time interval of 0.1 milliseconds.

Below is the algorithm and pseudo code for measurement of displacement in the ISR….

```
//********* Read the time stamp value of the cap module ******//
//*******************************************************//
CAP_MACRO(cap1);// call the capture read macro
Status = (int16)(cap1.CapReturn);
if(Status==0)
{
EventPeriod=(int32)(cap1.EventPeriod);// Read out the new time stamp
Displacement=_IQ15toIQ((5760-EventPeriod)<<6);
}
// -------------------------------------------------------------------------------------------//
```

The above code snippet uses IQ Math library provided by Texas Instruments. IQ math is most suitable for fixed point processors and also at times used in floating point processors where good resolution or precision is required throughout the measurement range or dynamic range of a variable data [20]. As can be seen from the above code the value 5760 is used to zero the initial offset of our sensor which is a fixed offset value.

In our PID feed-back control system this displacement value is compared with the target value or set value entered in the PID controller C-Macro module, from which the error value is deduced.

Let's determine theoretically roughly the time stamp captured value for the time period of our eddy current sensor'spre-scaled signal which is 11.29 kHz as calculated earlier using div 62 pre-scaler.

$$\text{The counter value} = \frac{\text{System Clock Frequency}}{\text{Pre-scaled Clock Frequency}}$$

$$= \frac{60\text{ kHz}}{11.29\text{ kHz}}$$

$$= 5314\text{ Hz.}$$

The above count value tallies well with the actual counts received while testing the eddy current sensor in real-time emulator debugger mode.

The output frequency of the scaled down signal varied form 11.29 kHz when the target was touching the sensor tip to 10.48 kHz when there was no target placed in front of the sensor. The target material used was aluminum. It was found that target material with better conductivity produced larger variation in output sensor frequency resulting in better displacement resolution.

For a frequency of 10.48 kHz, the period time stamp counter generated digital counts around 5725. The eddy current sensor designed has a radius of 5mm and hence its sensing range is restricted to 3mm for linear operation.

Resolution of displacement can be measured as follows…

$$\text{Step displacement resolution} = \frac{\text{Sensing range}}{\text{Total counts variation in sensing range}}$$

$$= \frac{3mm}{5725 - 5314}$$

$$= \frac{3mm}{411}$$

$$= 0.0072\text{ mm}$$

Hence the designed eddy current sensor can resolve displacement values of 7.2 microns at frequency bandwidth of around 10 kHz which is a fairly good resolution for servo-control in magnetic bearing application.

The digital motor control library for C2000 controllers provided by Texas instruments provides us the necessary C functions (or macros) to build our own unique controls for our application [19]. Since the library of macro blocks consists of both peripheral control modules (Controller specific macros) and math algorithm modules (target-independent macros) we can make our own control loops by interconnecting and tweaking the C code of these modules to suite our specific control application.

Figure 10 shows the implementation of closed loop control designed for our active magnetic bearing system using C macros. CAP MACRO, PID MACRO, PWM MACRO are the three main blocks used in our control loop.

Every C macro module has certain number of inputs and outputs. These inputs and outputs can be interfaced with other macro modules but one should make sure the inputs and outputs are compatible in data type (software variables) or signal voltage type (external signal voltages to hardware peripheral *i*/o pin) [18,19,20].

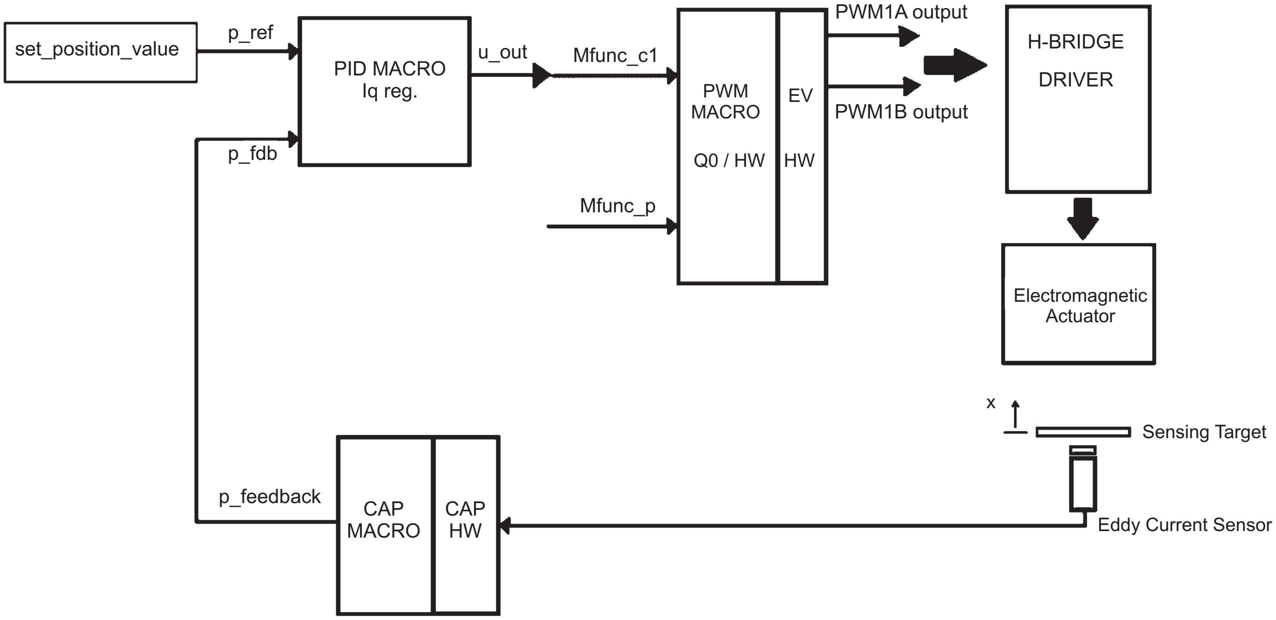

Figure 10: The control loop for Active magnetic bearing constructed using the C macro blocks provided by Texas Instruments digital motor control library

4. CONCLUSION

The C2000 Piccolo Texas instruments real time controller was used to efficiently capture and process the low cost eddy current sensor's signal and to produce a fast servo control feed-back for the active magnetic bearing system. Using the capture technique for displacement measurement we could achieve displacement resolutions of 7microns at a frequency 10kHz. The system clock frequency used for time stamping of the capture register is 60MHz. If a controller with higher system clock frequency like the Texas instruments C2000 Delfino working at 200Mhz is used than the displacement resolution of our sensor could be further increased by a factor of 3times because the time stamp counter will register more clock pulses for the same capture period.

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