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Autonomous Motor Condition Analysis with Vibration Feature Extraction

[1]Subharthi Banerjee, [2]Abhishek Chatterjee, [3]Nilanjana Chaudhary

Centre for Development of Advance Computing (ACTS), Kolkata, India

Abstract: **In Industry motor assemblies are expensive and for their precise operation we need constant monitoring throughout manufacturing, installation and operational periods. Downtime of this machine should be of minimum. The methods involved in monitoring can prolong the life of Motor. Industry prefers Vibration analysis for this, which rigorously aids engineers in the machine fault diagnosis. Vibration analysis requires trained professionals to detect faults, but in our research we made the entire process autonomous. Having ARM cortex as brain we could monitor mechanical & electrical faults with extensive signal processing from accelerometer data. It compares the processed data with the motor specifications following rules and generates the result. That's how the solution can not only detect the root cause for abnormalities but also the severity of the problems. Moreover it saves time, money and human resource in the industry which was our sole aim before undertaking the project.**

Keywords: **Vibration Analysis, ARM cortex, Motor faults, signal processing, FFT, remote monitoring, conditioning of motor, stellaris**

I. INTRODUCTION

Each machine if it has to work reliably it has to be well maintained. For all large and expensive equipments, to which vibration diagnostics mainly applies, operational life is an essential but often neglected part of the life of the machine. The life-cycle of machine involves period of creation (Design, Production, and Assembly) and operation. The operation life of machine is more than 20 to 25 years in the large industries with 100 000 to 200 000 operating hours. So the production and manufacturing of the industry depends on the machine relentlessly but without proper attention. This can lead to fatal break down in the production line.

The vibration analysis gets deployed in the operation life of machines for the aforesaid reasons like,

1. Determining the Initial Condition – A thorough measurement of the machine is performed and written down as machine specifications when the machine is in good state. This provides the basic reference values for subsequent comparisons.
2. Monitoring – Vibrations are measured continuously with regular time intervals.
3. Detection – Data obtained from the sensors are quantitatively evaluated. For each measured quantity limits are set. Above the limits alarms are displayed.
4. Zone Selection – Four zones gets selected (Zone A, B, C, D) according to the machine conditional severity.
5. Analysis – After detecting the problem if there is, signal processing are carried out to determine underlying cause for a clearer view.
6. Recommendation – Possible solutions with zone display can be displayed from the continuously evolving database.

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II. OVERVIEW

We carried out this research with two ARM cortex variance CORTEX M4 & M3. The architecture mainly varies with the presence of Floating point unit which is quite essential part for the signal processing and graphical implementation. The used processors are lm4f120h5qr and lm3s1968 with their respective stellaris boards and peripherals. The main blocks for the signal processing parts are same; just the speed varies with the ADC triggered DMA for processing samples in the case of cortex M4.

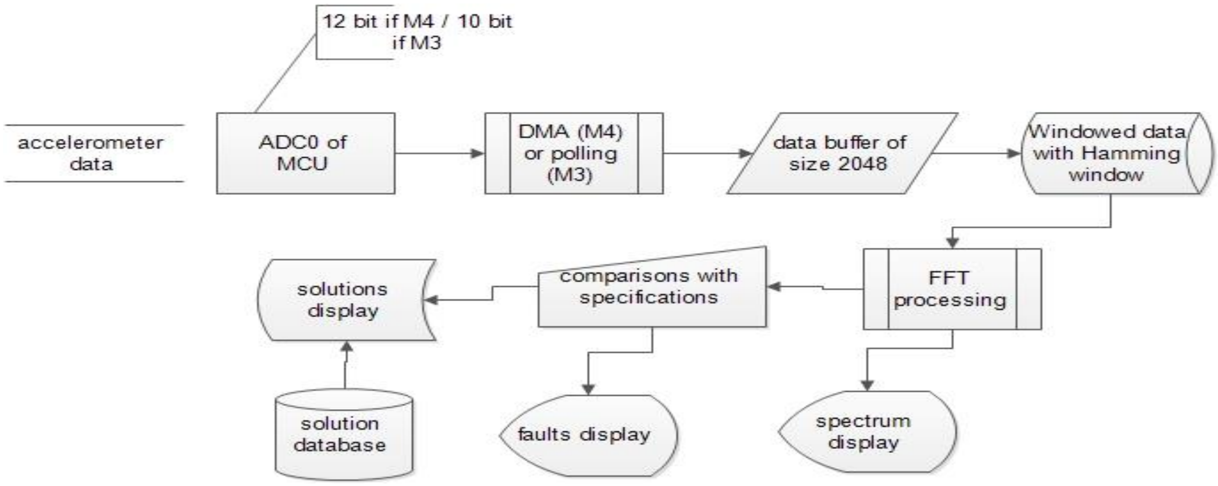

Fig. 1: Vibration Analysis Module

As most of the machines have considerable vibration with rotational parts, we considered vibration analysis with three modules i.e. a. Vibration analysis module (3D accelerometer module), b. Temperature sensing modules, c. Rotation per second (RPS) module. These three modules are interconnected with each other contributing dynamic specifications with the existing static specifications to be compared. In Fig. 1 the vibration analysis module MCU creates a pool of data for the FFT processing. The transformed data can be used with the specifications and the modules acting simultaneously to be compared with. Like the RPS data and internal temperature data together with the signal-processed data can be measured quantitatively to detect faults. These other two modules continuously monitor the temperature and the revolution per second of the main rotating part as the sensor involved is a shaft encoder. The limits here are the primary static limit which lead to the secondary dynamic limits as resonance is also involved here. The database which is included externally for the solutions to be embedded is made to be evolving in nature that it can generate the solution for the faults linked with the machine specifications. Fig. 2 comprises of the additional sensor modules of temperature and encoder.

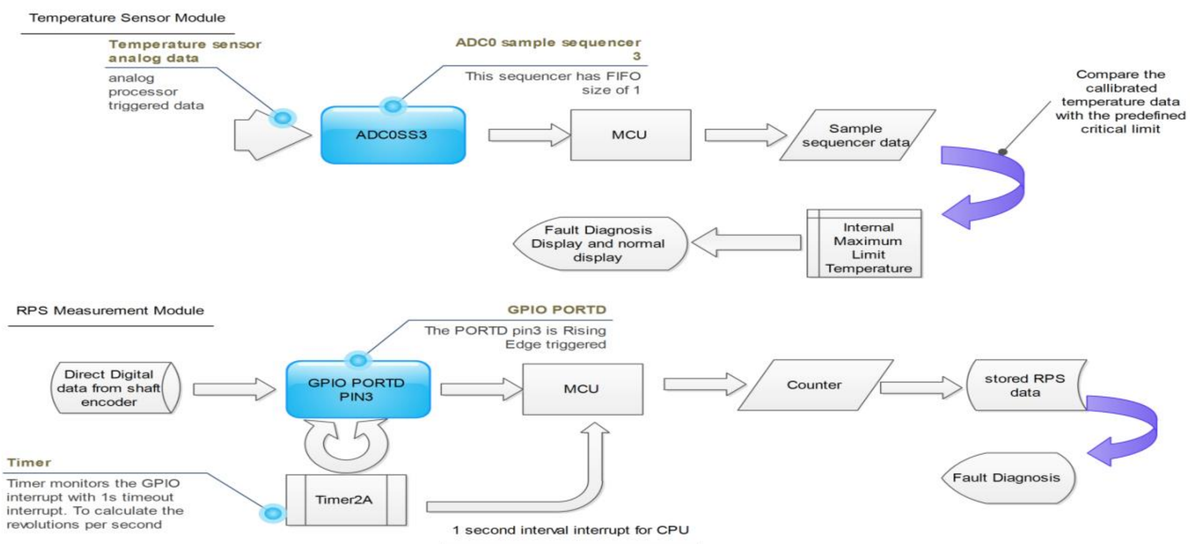

Fig. 2: Temperature and RPS modules

III. CONDITIONING OF MOTOR

Vibration Analysis: Vibration analysis is a non-destructive testing method which effectively determines machine problems early. This is really a useful predictive tool when used with rotating components. In order to maximize finite life of the machine the excessive wear due to misalignment, unbalance & resonance should be taken care of with vibration analysis.

Causes of Vibration: a). Change in direction with time, such as force generated by unbalance, b). change in amplitude with time, such as unbalanced magnetic forces in the induction motors, c). resulting friction between rotating and stationary components, d). impacts such as gear tooth contact, e). randomly generated forces like fluid turbulence etc.

Methods to Detect Causes of Vibrations: There are thousands of specific mechanical and operational causes of vibrations. But each vibration has its own characteristics. The results from vibration analysis lead to the root causes. If we consider a motor assembly comprising of three rotating components with different speeds and after vibration analysis we get a significant vibration equals to a specific speed from the motors, we can straightforwardly detect the source of fault.

Sources of Vibration: a). Misalignment of couplings, gears, bearings etc, b). unbalance of rotating components, c). Looseness, d). Deterioration of rolling element bearings, e). Gear wear, f). Eccentricity of gear elements etc.

Detection by Vibration Analysis: a). Unbalance (static, couple, quasi-static), b). Misalignment (angular, parallel, combination), c). Mechanical looseness, structural weakness, soft foot, e). Resonance, beat vibration, f). Mechanical rubbing, g). Problems of belt driven machines, h). Bearing defect & antifriction bearing defect (inner race, outer race, rolling elements), j). Problems with hydrodynamic and aerodynamic machines (flow turbulence, cavitations), k). Gear problems (tooth wear, gear misalignment) etc.

TABLE 1: Fault Diagnosis

Frequency (RPS)	Causes	Other possible causes
1x RPS	Unbalance	1) Eccentric journals, gears, pulleys 2) Misalignment or bent shaft if high axial vibration (z axis)
2x RPS	Mechanical looseness	1) Reciprocating force
3x RPS	Misalignment	Combination of misalignment & axial clearance
< 1x RPS	Oil whirl (< ½ RPS)	1) Bad drive belts 2) Background vibration 3) Sub-harmonics resonance 4) ‘seat’ vibration
Synchronous	Electrical problems	Broken rotor bars, eccentric rotor, unbalanced phases in poly-phase systems, unequal air gap.
2x synch frequency	Torque pulses	Resonance check
Harmonically related frequency	Bad gears, aerodynamic forces, hydraulic forces, mechanical looseness, reciprocating forces	1) Gear teeth (n) times RPS of bad gear 2) Number of fan blades times RPS 3) Number of impeller vane times RPM
High frequency (not harmonics)	Bad antifriction bearing	1) Capitation, flow turbulence & recirculation 2) Random high frequency vibration 3) Improper lubrication 4) Rubbing

TABLE 1 guided us to print the causes of vibration in the display. This table was very useful when considering 3D accelerometer data as the three axis vibration analysis was altogether have given us greater grasp over the vibrations and their root causes. Not only we can display the sources but also the severity of faults marking them in groups with the order of severity. This solution is for determining in which zone the motor is in and how much attention the motor needs.

The highest value of measurements at different locations is called the vibration severity. The standard defines evaluation zone limits (EZL) of the vibration severity. EZLs are defined as macros throughout our design. Based on these limits, a machine can be classified into 4 zones-

Zone A – Vibration of newly commissioned machines fall within this zone (these falls in ideal macro range)

Zone B – Machines in these zones are considered acceptable for long time operation.

Zone C – Machine within this zone are susceptible to damage and normally considered unsatisfactory for long run. This is a zone of warning where concerned action is essential part.

Zone D – In this zone the machine undergoes severe damages which can lead to production halt and permanent end to the machine.

IV. SYSTEM DESIGN

The system we built is cost effective, user-variant, almost real-time, and ready to evolve with user specifications. As we can introduce 1D, 2D or 3D accelerometer according to user choice or can implement any kind of temperature sensor. The system design makes it easy to make it ready for market and for various machines as we can change the specifications according to our choice. The design contains four modules

i) Remote data acquisition
ii) Signal Processing of acquired data
iii) Specifications design
iv) Warning generation & fault diagnosis

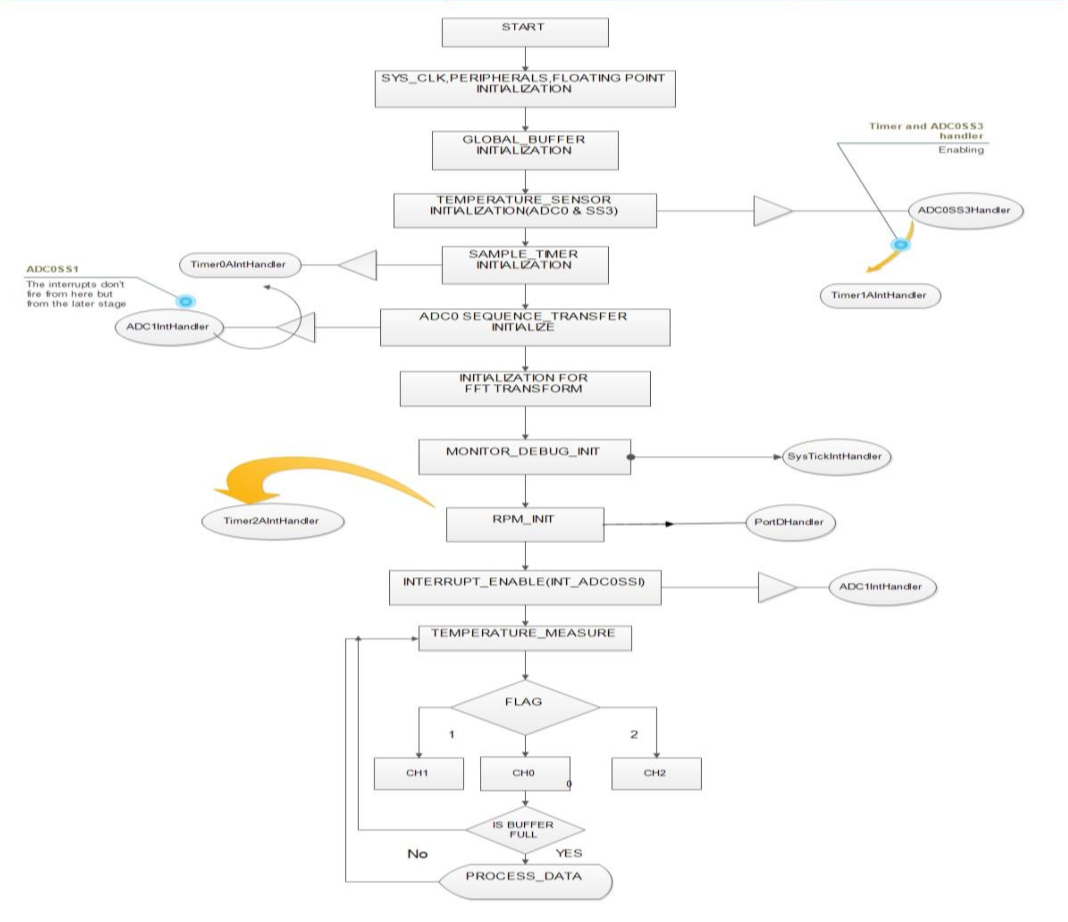

Fig. 3: Program Flow

Fig. 3 is the program flow diagram for the data acquiring to data processing module. The flow is entirely event driven. So there is no polling or unwanted waiting occurs for data redundancy.

Remote Data Acquisition – Data acquisition remotely but wired when the sensors are tightly attached with the machines so that the data the MCU acquire is not disrupted or corrupted. Considering each one of them as sensor modules, these modules are controlled by timers. For accelerometer data we have taken 10Hz-10 kHz range to sample. So a timer triggered Analog to digital conversion happens dedicatedly with its own interrupt service routine. For temperature sensor the ADC is processor triggered but the processor triggers from a time service routine. And RPS module depends on a shaft encoder which provides digital data as PWM. So for the encoder we programmed a down-timer for providing interrupt at one second. Till this duration a counter gets increased by one with every encounter of high edge trigger pulse in a GPIO pin. Now as we know the accelerometer could be of three types we programmed three pins of ADC for each axis data so that for signal processing we can recognize from which axis the signal is processed.

The process follows ISO 10816 where the measuring frequency is between 10 Hz to 1 kHz for velocity measurement and for typical use of accelerometer the range is between 0.1Hz to 30 KHz. So the Nyquist frequency could be of > 2fm which is > 20K.

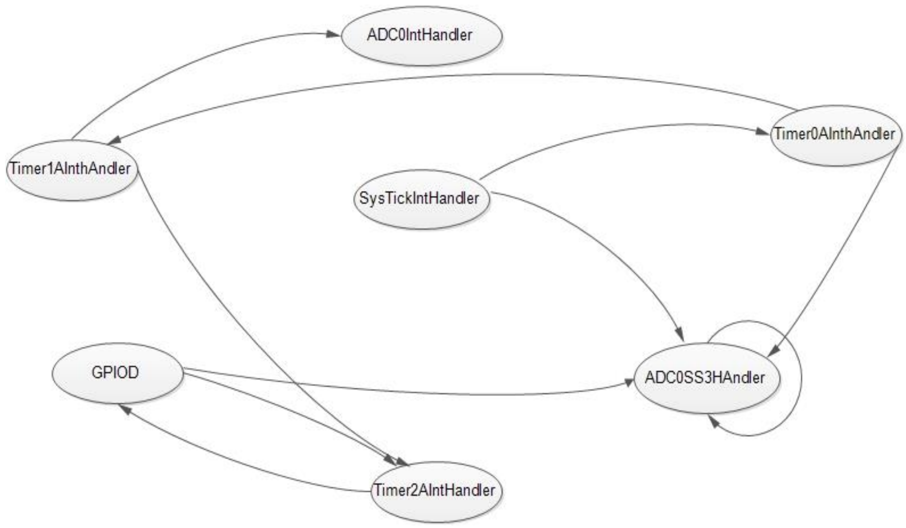

Fig. 4: Interrupt state diagram

In the Fig. 4 ADC0IntHandler is for the 3D accelerometer sampled data poll or DMA trigger where the sampler timer is Timer0. ADC0SS3Handler is for temperature sensing with timer1A service routine handling the processor trigger. Timer2AIntHandler handles the down timer of 1s to measure the RPS with counter making GPIOD high edge trigger sensitive.

Signal Processing of Acquired Data - After data acquisition of accelerometer data we need to convert it to frequency domain to analyze it. Vibration Analysis tells us about the characteristics of frequency components. So we have used a optimized library for cortex M CMSIS DSP library. From that library Fast Fourier Transform FFT API are used. The library follows a Radix 2^n type FFT with 2^n samples. As we know even the 2048 point FFT gives us result of less than of that half of the maximum size, we have to take maximum for real time sampling and processing experience. CMSIS FFT API takes 2048 samples as maximum input.

The steps are:

1. This sets up the break points for FFT analysis .As the bins (sample number) we can get in a corresponding frequency region (or window of region) . So setting up the break point is important. It gives us the flexibility of operation and monitoring the harmonics.

2. The corresponding frequency with the i^{th} sample number depends with the following formula,

$$\text{freq}(i) = \frac{\text{sampling}_{\text{frequency}}}{\text{max samples}} i$$

So the Hz per bin calculation is done here to get the frequency for i^{th} sample. It is done with some array initialization and FFT initialization with the number of samples.

3. FFT processing starts if and only if the global array buffer for accelerometer for each axis is complete. It gives the fundamental frequency of the sampling signal first then maintaining the break point, it analyzes total signal.

Specifications Design – Specifications design is most important part of our system design what we can do studying the machine documentation or manually taking notes of machine specifications like critical speed, limiting temperature, fundamental frequency for first run, gear harmonics limiting value etc. These values solely depend on the user choices and design needs. The specifications can be filed in the ROM as a macro file with conditional execution. As the conditions are set with the zones or the conditional ranges are set with the zone. Basically these specifications are static to make the system ready for the run.

Warning Generation & Fault Diagnosis – TABLE 1 showed vibration causes. This module just follows the tables comparing processed data value with the specified value. As we could see the fundamental frequency for each axis is important equally. So the values are stored as global. Solution database just complements the fault diagnosis table.

As thumb rule the calculation involved with the specification for the bad gear and misalignment faults are-

i. Checking the harmonics amplitude with n x (1x RPS) for bad gear fault where n is number of gear teeth.

ii. Checking if horizontal and vertical 1x frequency amplitude ratio is greater than 3

iii. Checking for axial misalignment, if angular misalignment

1x amplitude > 2x amplitude > 3x amplitude

If parallel misalignment

2x amplitude > 1x amplitude > 3x amplitude

V. CONCLUSION

As we come to conclusion we can just say the whole process of vibration analysis is not time critical or hard real time system but it needs stability in continuous monitoring. The system needs to run continuously providing it consumes too less power and doesn't add into the budget of the organisation.

For implementing a high end display or HMI the core has to be DSP sensible, other wise to make it cost effective and just managing the task effectively Cortex M3 is enough to handle the whole process. The predictive event handling gives us the flexibility to handle lots of events simultaneously and attentive design pattern doesn't let us miss any event.

After the design implementation we can be sure of here that this can cope up in the market with the high priced simulators to monitor the motors. The testing, calibration and real time monitoring without affecting work life will be employed later to test its feasibility in the production line.

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