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TRIGGERING METHODS IN BLADE TIP-TIMING SYSTEMS

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Abstract. *The uncertainty of non-contact blade vibration measurements depends on the precision of time-of-arrival (TOA) or phase measurement. Various TOA estimation methods are used in the existing tip-timing measurement systems, which contribute to differences in vibration amplitude results. The known hardware triggering circuits have structure related to the sensor type and limitations specific to analogue circuits. The paper reviews the current hardware and software methods for conditioning of tip sensors and estimation of time of arrival, including customizable triggering circuits and processing of the sampled sensor output. It presents some measurement solutions developed at ITWL and example results. Selected algorithms of phase estimation, their possible implementation and performance issues are discussed. An exemplary software phase detector, implemented as a state machine, able to adapt to the mean pulse amplitude and ignore noise peaks is demonstrated. Numerical techniques, such as linear and polynomial interpolation and curve fitting, are proposed to process sampled sensor signal in order to increase resolution in time and measure characteristics of the blade-related pulse, including zero-crossing, maximum amplitude, rise time and pulse width. The selection of optimum clock or sampling rate in relation to the blade passing frequency and pulse rise time is discussed.*

1 INTRODUCTION

Tip-timing is now a significant technique for ensuring structural integrity of jet engines and stationary turbines. ITWL uses this method to monitor blade health in aero-engines and stationary turbines. Tip deflection is measured with sensors installed in the casing. The type of the used sensor depends on required resolution, available space, gas temperature and required life expectancy.

Eddy-current, microwave and capacitive sensors, considered as alternative technologies to optical fibers, are usually used in health monitoring applications. They generate pulses of different shapes at the output and require dedicated conditioning units and triggering methods. Upgrading or reconfiguring the triggering hardware is costly and time consuming. A modification of the triggering circuit may also be necessary when the system is adopted to another machine due to differences in terms of the stand-off distance, speed range, tip geometry or blade material. Common issues with signals include:

- Both edges are not stuck to blade tip and cannot be used for phase detection
- Lack of the common trigger level, proper for all blades.
- The peak cannot be measured precisely due to noise.
- DC level of the analog waveform is floating.
- Twin pulses – the peak includes a valley (Figure 1).
- Blades produce pulses of varying amplitudes due to differences in magnetization, cross section, cleanness of blade tips etc.

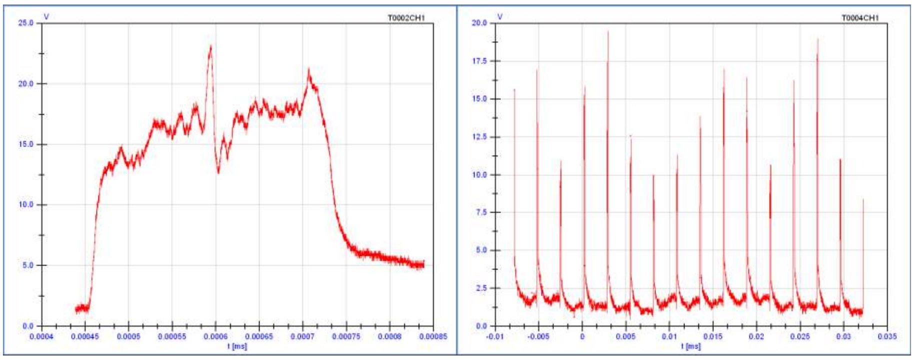

Figure 1: Examples of a twin pulse and varying peak amplitudes in optical sensor signal

Selected solutions aimed to provide more flexibility in triggering are presented below. Instead of hard-wired analog circuits, high rate sampling and numerical processing of the signal is commonly used in test cell. However, some applications, such as onboard blade health monitoring, may prefer hardware triggering, as the available computing power is limited or the certification procedure is too complicated. Examples of advanced reconfigurable circuits are presented here as well.

2 HARDWARE TRIGGERING

Time of arrival is measured by triggering circuits also known as phase detectors. Edge triggering at a certain level is the primary method used in industrial electronics to capture the phase of pulses. The task is performed by the analog circuit producing digital pulses when the threshold is crossed. Counters implemented in ASIC or FPGA chips are used then to measure the phase or period of those pulses [13].

In most cases, a simple comparator is not suitable for triggering as it would generate spikes on noise. Therefore Schmitt triggers are used instead, which feature hysteresis i.e. switch on when a higher threshold is passed and switch off below a lower threshold [1]. This approach works well in blade tip-timing especially with inductive and optical sensors. The trigger level in an optical system is selected arbitrarily to avoid extra or missing blades [2]. In case of inductive sensor the trigger level is simply zero. However, if amplitude of pulses is not constant, an adaptive phase detector may be required. It is available as a sophisticated integrated circuit e.g. [3], which arm on positive edge and trigger on zero crossing.

The arm level is usually set as a fraction of medium peak amplitude (Figure 2) in such a way that noise and spurious low-amplitude pulses are ignored. On the other hand, if the arm level is set too high, some blades can be lost.

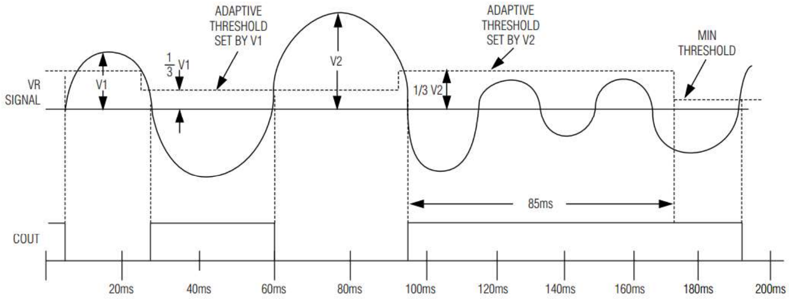

Figure 2: Adaptive Peak Threshold Operation [3]

The eddy-current sensor developed by QinetiQ features an adaptive trigger implemented in analog electronics [10]. The leading edge is used to arm the circuit and load the capacitor to be able to trigger at leading edge at a fraction between the trough and peak voltage, e.g. 50%.

In the system developed by Hood Tech, the conditioning unit called BSVI is connected to the computer and conFigure d via GUI [4], enabling triggering on most of existing signal types. User selects gain, polarization, arm level, trigger level and also can define hold-off period to mask twin pulses, which happen in case of thick tips with rough surface. BSVI's microprocessor receives these commands and recon figures amplifiers and trigger hardware respectively.

2.1 Smart conditioning

Passive magnetic sensors such as inductive or eddy-current generate signals, which amplitude is proportional to the rotational speed and also decreases exponentially with the distance. Therefore, a conditioning system was developed in ITWL able to adapt to a wide range of speeds and clearances. Physically, the device consists of two 4-channel amplifiers and the main board (Figure 3), which manages their operation, expanding their measuring range. Changing the configuration of the amplifiers is implemented in the microcontroller code and does not require user intervention.

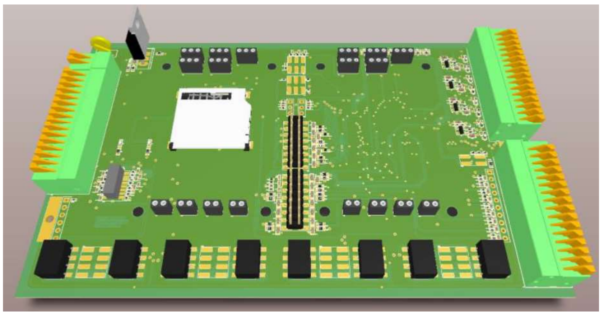

Figure 3: Overview of the main board

Each of the two amplifiers picks up signals from the coils of inductive sensors. The input impedance is almost zero and the coil nearly short-circuits the amplifier. The circuit is conFigure d as the current-to-voltage converter to improve performance and reduce the influence of external electromagnetic interference.

The system allows to condition signals in the range suitable for the build-in triggering circuit and external data acquisition modules. The use of a low-noise operational amplifier in the input circuit provides an enhanced signal-to-noise ratio, while maintaining high slew rate and bandwidth. Additional noise reduction is achieved by detaching mass power from the ground signal.

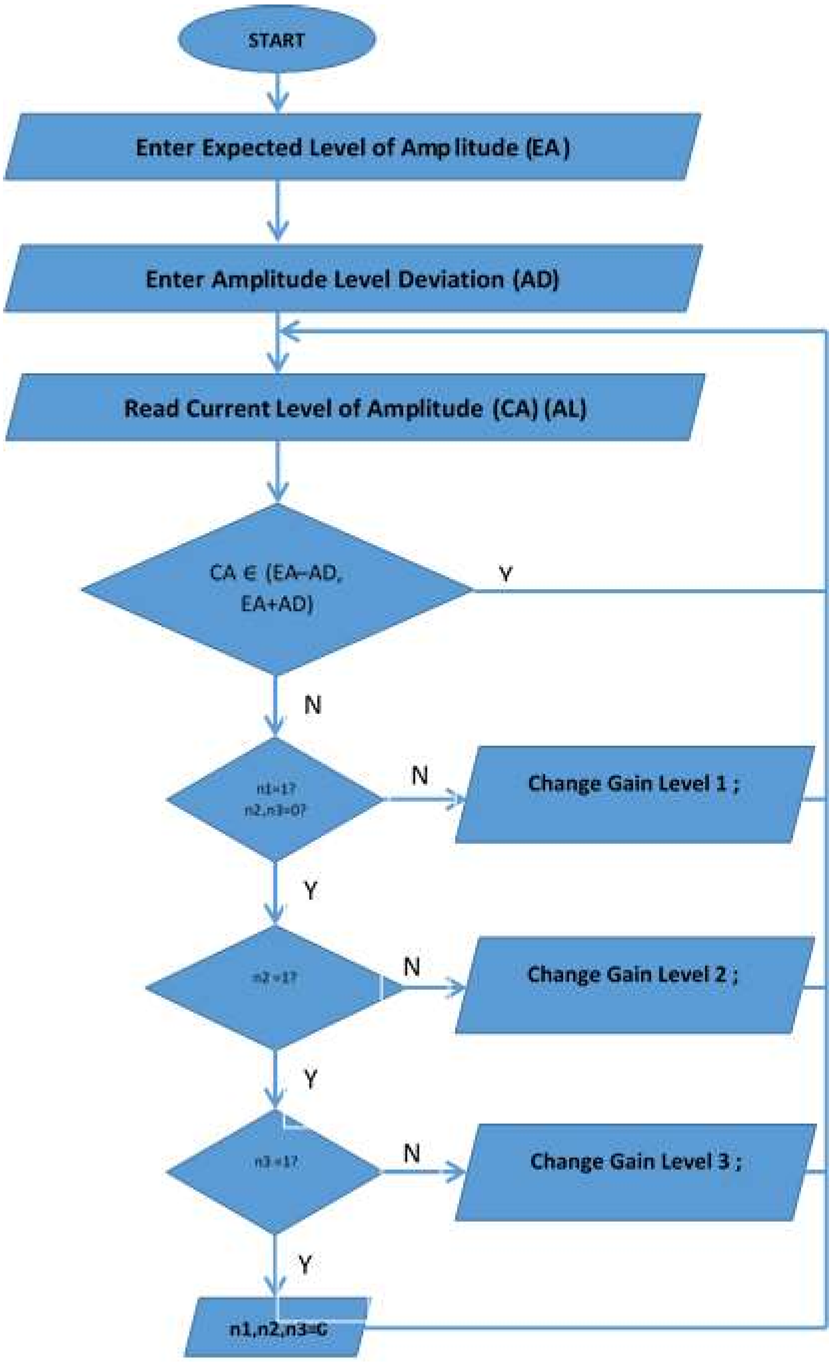

Figure 4: Gain selection algorithm

Four analog outputs of the amplifier provide analog signals in a real time. The use of Adaptive Sense Amplifier integrated circuits provides extra four outputs of rectangular TTL pulses with a constant amplitude for the purpose of counter time measurement. Adding extra amplifiers increase the number of input channels, which directly translates into the number of supported sensors. The system enables the measurement of the 8 sensors using the 8 individual input chains.

The main board is equipped with a Pic32 microcontroller, which continuously monitors amplitudes of input signals in order to modify gains of amplifiers when required. Changing the signal level is performed automatically, when the amp setup options is enabled, in accordance with the implemented algorithm. Finally, at the output of the main board, the signal is generated whose amplitude is within the expected range. The selected configuration can then be saved to the memory of the microcontroller, which enables reproducibility of the signal levels after restarting the device.

The microcontroller is programmed in such a way that it finds the optimal gain of the signal by switching the relay assigned to particular amplifier channels. One of the three possible positions of the flip-flop sets 3 different gain values. The primary task of the operator is to define the expected amplitude value and the allowed deviation. Microcontroller knowing this value, analyzes the current level of gain and changes the value to get closer to the expected level (Figure 4).

The system allows to use different sources of power supply (6 or 24 [V]), and can also record TOA data to a microSD card. The user interface consisting of a membrane keypad and LED display allows to conigure and control the system as well as inform about the current operating mode.

3 TRIGGERING IN SOFTWARE

More and more often triggering circuits and counters are replaced with direct sampling and digital signal processing, particularly for non-optical sensors. Standard computers and of-the-shelf data acquisition modules can be employed to this task. They offer sufficient throughput to process ten or more channels simultaneously to calculate TOA in real time and can be upgraded to more powerful versions at low cost. Alternatively FPGA chips equipped with AD converters can accomplish the task to reduce the load of the main processor.

In the commercially available system, based on a standard PC [5], [6], a pre-trigger is used to restart sampling at every edge (with the rate 5 MHz). Only a number of samples (8 points) is acquired to avoid storing inter-blade spacing and reduce disk usage. TOA is calculated in real time using voltage level, area averaging or fractional trigger.

The phase detection algorithm depends on the signal type. The most basic one is two-point linear interpolation, which helps to overcome time quantization. The

British BHM system [12] takes several points of the falling edge to perform linear least-square fitting, which is the optimal method in terms of noise reduction. However, most gas-turbine blades generate symmetric pulses without the zero crossing and you have to measure the peak value with the polynomial interpolation [9] or alternatively trigger on both edges of pulse and take their mean value.

ITWL operates the tip-timing data acquisition system based on PXI platform, which performs on-line processing of samples or measure phase of TTL signals with gated counters [8]. Several modules can be used together and synchronized in PXI chassis to increase the number of channels or handle signals of different types. LabVIEW visual language provides flexible tools to implement acquisition and real time processing, such as DAQmx library to interface input modules, Data Analysis library, queues and Front Panel controls and indicators.

Producer/Consumer architecture was selected to implement required functionality including online data processing. Using the queuing mechanism ensured that numerical and other procedures receive as much data as they require without locking the application. Consequently, the structure of the program is not subjected to data acquisition only. A similar approach was adopted in the GE system [11].

The same code can process data in acquisition and replay mode. The risk of data loss is better managed when compared to Simple Design Pattern (without queuing). Data integrity is crucial in diagnostic applications and generation of false alarms or ignoring failure symptoms should be avoided.

Our LabVIEW code is composed of four major parts:

1. Data acquisition loop reading a signal from the sensor or from binary file in Replay mode,
2. Loop that selects samples including of a single pulse (the window),
3. Loop accumulating samples for linear fitting when armed,
4. Loop recording TOA values to TDMS files.

The program structure and LabVIEW flexibility allowed to scale the single-channel version to multichannel one. Signals of different trigger level, amplitude and frequency can be processed simultaneously. The transition was performed by extending dimension of selected variables and registers, which happened almost automatically after adding a for-loop to selected code sections. Moreover, some queues have to store the channel number in addition to the data.

Producer/Consumer pattern helped to avoid interference between channels (or building artificial Select case structures) which existed in previous programs where Point-By-Point (re-entrant) VIs were used. Moreover, we were able to implement real-time calculation of some statistic parameters, which are required to verify data integrity and to assess blade health.

Our phase detector is implemented as a state machine, which is armed when the threshold (or arm level) is reached on the rising edge of the inductive sensor signal (Figure 5). At this moment it starts gathering samples in a circular buffer. When the signal falls below zero, it continues collecting samples until the number of points with positive and negative sign is the same. After that, the state of detector changes to unarmed and waits for a new sample crossing the threshold.

The detector is able to adapt to the mean pulse amplitude and ignore noise peaks. The proposed zero crossing detector is triggered only for the pulses of a certain amplitude, which prevents distortion of the results by noise in the input signal. In a basic approach, a constant arming threshold can be assumed, which is equal to e.g. half of the expected signal amplitude. In practice, the possibility to adapt the detector to the mean pulse amplitude is preferred, due to the dependence of the signal level of the rotor speed characteristic of the inductive sensor.

A major challenge is to identify pulses' phase with accuracy higher than the sampling frequency as 100 MHz digitizers are costly and generate large data streams difficult to handle in industrial or embedded systems. Therefore, the resolution of time measurement is improved by the linear regression of a number of samples adjacent to the zero-crossing, taken from the falling edge of the sensor signal (Figure 5).

The number of points used in the linear regression should be less than fall time. Typically 10-20 samples are collected to get better fitting results and reduce the impact of measurement noise. We also use polynomial regression to measure signal peaks for sensors of other types when zero-crossings are not available.

We experimentally determined that uncertainty of the complete measurement chain is below 20 µm with interpolation and 500 kHz sampling rate, which is satisfactory for steam turbines and axial compressors. For gas turbines and higher vibration modes the sampling frequency has to be increased beyond 2 MHz.

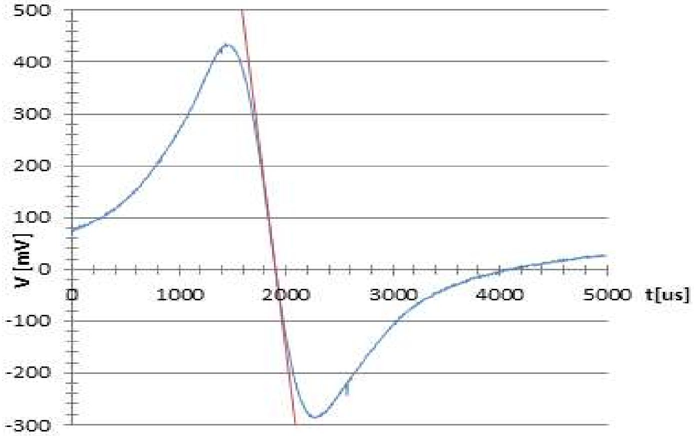

Figure 5: Zero-crossing measurement with the use of linear regression

4 CONCLUSIONS

Presented tip-timing data acquisition systems include flexible phase detectors, required to process signals of alternative (non-optical) sensors or sense untypical tip geometries e.g. shrouded disks. However, the results of tip deflection measurement performed by various teams can significantly differ as there are several equivalent triggering methods and the code of the phase detector can be easily modified. Therefore, system configuration should be carefully documented to facilitate traceability and reproducibility [15]. Besides that, the contribution of the sensor and the triggering process to the uncertainty the complete measurement chain has to be assessed [16].

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