# Digital Measurement Dynamics - Industry Guidelines

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**Keywords:** sensor, transmitter, sampling, sampling rate, aliasing, filtering, anti-aliasing, delay.

**Note**: In this document the words sensor and transmitter are used interchangeably to mean a measurement device which makes a calibrated signal available.

## 1.0 Competitive Marketplace Background

The global market for manufactured products continues to focus on product quality and uniformity and more attention is being paid to process control equipment and its condition. EnTech Control Engineering Inc. has specialized in the analysis and optimization of pulp and paper manufacturing where product uniformity specifications are now approaching 1%. Paper product can be rejected when it deviates outside specified limits, or when the variability characteristics of the products adversely affect the operation of the customer's secondary manufacturing - such as a printing press. Mill audits have shown [1] that product variability is caused mainly by the combined behaviour of the many upstream process variables. Audits have identified that the cyclic behaviour of automatic control loops is a major cause for destabilizing production in the pulp and paper industry and that sometimes this is caused by the measurement equipment.

Digitally implemented sensors and transmitters together with digital signal transmission, in which inappropriately designed signal sampling and signal conditioning especially have resulted in signal aliasing and a loss of signal integrity. If measurement data is to be useful for feedback control and trouble shooting [2] there are fundamental principles of dynamics to which the measurement process must conform.

As the process industries, including pulp and paper, prepare for the advent of Fieldbus [3] technology, where all field devices transmitters and valves will be digital, it is even more important to ensure a high level of basic measurement and signal integrity.

**Summary of Digital Measurement Problems Encountered in Mill Audits**

- slow digital sampling rates,
- inability to change sampling rates,
- signal aliasing,
- no anti-aliasing filters,
- inability to change anti-aliasing filter settings,
- low bit resolution,
- nonlinear filtering & signal conditioning,
- excessively slow digital signal transmission,
- digital transmitter time delays,
- inability to access data via proprietary digital protocol,
- inability to access the measured signal ahead of signal filtering,
- inadequate signal conditioning documentation.

### Digital Measurement Dynamics - Recommendations - Purpose

Control in the pulp and paper industry is accomplished via a wide range of digital equipment including distributed control systems (DCS's), single loop controllers, programmable logic controllers (PLC's), variable speed drives, computer control systems and mill-wide historical data archiving systems. All of these systems communicate digitally. In the near future, most transmitters and control valves will also communicate digitally with all of the above equipment via the Fieldbus protocol [3] . Thus there is an even greater need to ensure that any problems related to digital signal processing are avoided.

These guidelines define the minimum requirements needed to provide the pulp and paper industry with measurements which are indeed useful as mills strive towards more efficient manufacture of higher uniformity product. This document is aimed at providing a design guide for sensor, transmitter and digital signal transmission equipment in order to ensure that the designs are capable of meeting the needs of process control, trouble-shooting and data acquisition, especially at a time where there are increasingly urgent needs in the pulp and paper industry for greater product uniformity and operating efficiency. This document has two intended purposes: as a guideline for pulp and paper companies when specifying or buying process measurement and data transmission equipment, and as a design guide for equipment suppliers to the pulp and paper industry.

## 2.0 Pulp and Paper Control and Digital Measurements - Problem Definition

### The Analog Signal

Until recently most sensors and transmitters were of analog design. Analog sensors obey Newtonian laws governing physical dynamic systems, and can be modeled as a linear system with low-pass filter dynamics and additive noise. Most transmitters and sensors produce an analog output signal, typically 4 to 2O mA. This signal is essentially linear. Its bandwidth is limited by the low pass filtering of the measurement device, plus any internal filtering which in most cases is adjustable. This signal is suitable for both control and trouble shooting.

### Digital Signals

There is no doubt that digital systems are flexible, powerful and here to stay. However, there are a number of important properties of digital signals, which are sometimes overlooked, yet which are important for both process control and process trouble shooting. These relate to signal quantization, sampling rates and data transmission delays. If any of these are badly chosen, the resulting signal may be useless for troubleshooting and even potentially hazardous for control. In addition, there are possibilities for altering the properties and character of the signal by aliasing, nonlinear filtering, or report-by-exception. These may also render the signal useless for both control and trouble-shooting.

### Signal Requirements for Control

Control algorithms such as PID are essentially linear. Control in the presence of nonlinear elements becomes very difficult and imposes very real limitations on control performance. The best approach is to eliminate all possible nonlinearities. Measurement nonlinearities should be avoided if possible.

Digital sampling rates for control should be a function of the process dynamics. For the pulp and paper industry, sampling rates should typically be 0.3 seconds per sample or faster for most common variables [4]. Digital sampling and control loop execution must be coincident (control must use the latest sample) and must also be evenly spaced in time.

**Signal Requirements for Process Trouble-Shooting**

Process trouble-shooting requirements are more demanding than those for control, as the nature of the problem cannot be pre-defined in advance. Trouble-shooting involves being able to find the cause of some process or control related behaviour - say a cycle - an intermittent spike, or a particular type of noise. It may be necessary to examine a particular sensor output at sampling rates much faster than those used for control (typically 10 to 100 times faster). Also it may be necessary to examine a sensor output without any filtering at all in order to see if there is any evidence of a particular type of disturbance characteristic present. Both of these requirements are very different from those of normal control, yet it may be necessary to make these special measurements without disturbing the normal operation of the control system.

# 3.0 Digital Signal Properties

Digital signals have two important properties: quantization and periodic sampling. If either of these are badly chosen, they can make the signal of little use.

**Quantization**

All digital signals are digitized by some form of analog-to-digital conversion (A/D). In all cases the resolution of these devices is limited. An A/D with 10 bits can resolve the signal to 1:1024. A 12 bit converter to 1:4096. This quantization limits the resolution of the signal, and hence also limits the usefulness of the signal for both control and diagnostics. In the pulp and paper industry 12 bit resolution is usually adequate.

**Sampling Rate**

The act of sampling at some rate $T_S$ limits the bandwidth of the signal to an upper frequency known as the Nyquist frequency $f_N$, where:

$$f_N = \frac{1}{2T_S}$$

The Nyquist frequency is based on Shannon's Sampling Theorem and requires at least two samples per sine wave period in order to be able to reconstruct the sine wave frequency from the digital samples (the ability to reconstruct the amplitude accurately, requires many more samples).

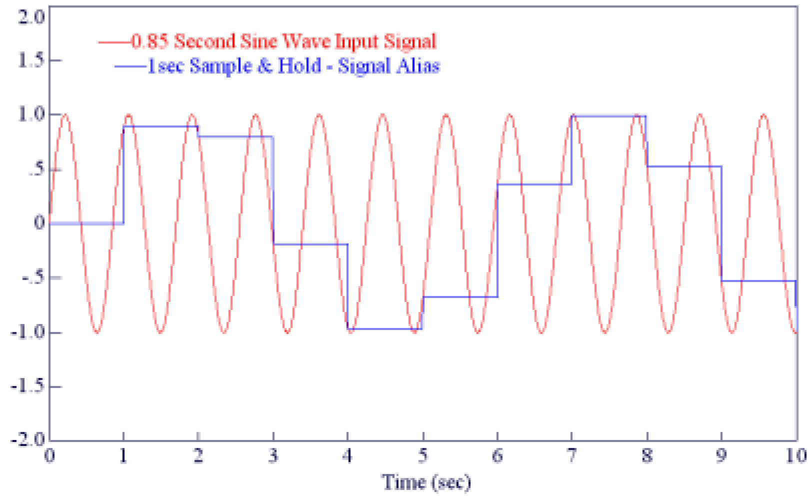


FIGURE 1- EXAMPLE OF SIGNAL ALIASING

**Signal Aliasing**

If the original analog signal contains frequency content beyond the bandwidth of the sampler (beyond $f_N$) then signal aliasing will occur. Aliasing is the creation of a fictitious signal, at slower frequency -- **a signal alias does not actually exist in the original data. An aliased signal is absolutely accurate at each sample, but the mistake made is that the samples are not joined by straight lines.** Figure 1 shows an example of signal aliasing, in which a 1.176 Hz sine wave is sampled via a sample-and-hold device at 1 .0 seconds per sample. Shown are 12.5 cycles of the 1.176 Hz signal. The sampled signal alias is seen as another sine wave with a period of about 6 seconds. In this example, $T_S$ is 1.0 seconds. Thus, the Nyquist frequency for this sampler is 0.5 Hz. As the input signal frequency is 1.176 Hz, which is faster than the Nyquist frequency, aliasing results.

Whereas the Nyquist frequency defines the limit at which aliasing occurs (Shannon's Sampling Theorem), some signal distortion and loss of integrity starts to occur at sampling rates which are much faster. Distortion starts to be visibly evident when the sampling rate is ten times faster than the signal content.

**The ultimate danger of allowing aliasing to occur is that the control system will attempt to control out the alias signal components. If it does so, it will de-stabilize process and product uniformity as a result. Equally important is the fact that no one will be aware that this is happening.**

Figure 2 illustrates the importance of providing proper anti-aliasing for control purposes. This is a dynamic simulation example which illustrates a unit step change in a process variable which has a first order time constant of 3 seconds. The step change is initiated after 4 seconds. The full change can be observed after four time constants, or another 12 seconds, at second 16 of the illustration. The raw signal however is corrupted by a sine wave of 4.04 Hz and an amplitude of 1.0. There are four signals shown 1) the raw signal, 2) the actual process change, 3) the raw signal sampled at 0.25 seconds with no anti-aliasing, and 4) the raw signal sampled at 0.25 seconds after a first order anti-aliasing filter of time constant 0.325 seconds ($t_F$ = 1.3 Ts). The signals have been displaced vertically for clarity. It is evident that if signal 3) the raw signal sampled without an anti-aliasing filter were used for control, that the resulting control action would destabilize the process severely for a completely fictitious reason.

**Once a signal has been aliased, there is no way to retrieve the true signal,** no matter how many times the aliased signal is filtered or sampled. **The only solution is to prevent signal aliasing from occurring.**

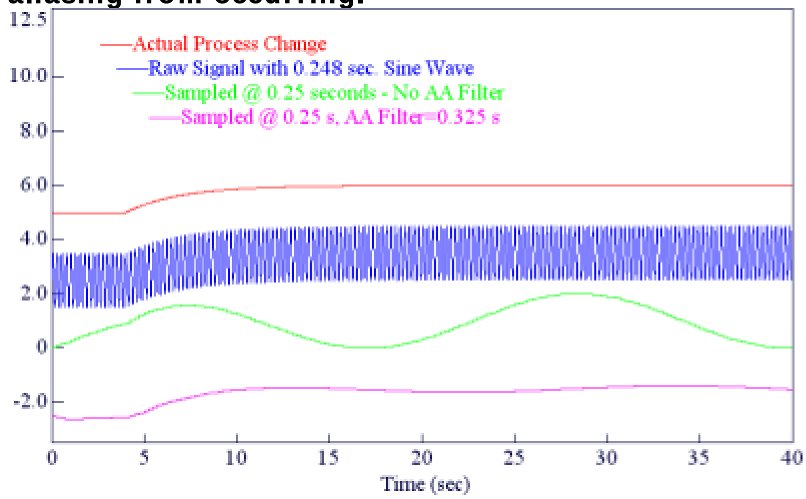


**FIGURE 2 – THE IMPACT OF SIGNAL ALIASING ON CONTROL**

## Random Variability

The previous examples of signal aliasing used single sine waves to illustrate the point. In practice, process signals are usually corrupted by noise which tends to be random in nature (white noise). Mill troubleshooting and auditing experience makes heavy use of time series analysis [1] in which Fourier analysis and power spectra are common tools. These techniques are key to measuring and understanding variability and its impact. The underlying principle of these techniques is that any random signal can be decomposed into its harmonic content, hence many sine waves existing concurrently and each at a different frequency. The impact of aliasing can be readily understood. Each harmonic which is faster than the Nyquist frequency will produce its own unique signal alias. This phenomenon is known as "fold-over" and involves the corruption of the power spectrum as a result of aliasing.

## Anti-Aliasing

There are two ways to prevent aliasing. One is to sample faster than the fastest frequency components of the input signal if these are known--usually they are not. The other is to install an anti-aliasing filter before the sampling device, thereby filtering out all of the signal content which is faster than the Nyquist frequency of the sampler at the chosen sampling rate, hence preventing aliasing from occurring. The anti-aliasing filter should provide a minimum of -12 dB of attenuation at the Nyquist frequency. This can be provided by a first order low pass filter of time constant $T_F = 1.3T_S$. It can also be provided by an arithmetic averager with $T_A = 4T_S$($T_A$- averaging time). The -12 dB recommendation represents a bare minimum requirement. Where possible, more effective anti-aliasing should be considered by employing a filter with a sharper cut-off and more attenuation at the Nyquist frequency.

## Sub-Sampling

In digital control systems, not only are analog signals sampled to produce digital versions of the input signals, but the digital signals are usually sub-sampled many times later on. For instance, in modern DCS's, the input sub-system which does the A/D conversion may run at say 100 ms while the controller sub-system may have variable sampling rates depending on the individual needs of each controller. Typical controller execution rates may be 1 second. Aliasing can hence occur between the input sub-system and the controller, even if aliasing was prevented at the input sub-system. **It is the final sampling rate which governs aliasing.**

In DCS's there are many other uses for the data. For instance, the process values from the controller will be sampled again to update the operator's console. Typically this is done at a slower rate than the controller update frequency. The mill-wide archiving system will also sample the same data at a much slower rate, typically once per minute. Other control loops may sample the data at slower sampling rates for feedforward compensation. All of these operations are subject to data aliasing. **Anti-aliasing filters are required before each sampling operation** and must be matched to the sampling rate. **This is usually neglected in most systems today.**

## 4.0 Digital Signal Transmission

Signals can be transmitted digitally via data highways, data links, RS232, Fieldbus, Ethernet, LAN's, protocol converters, gateways and other communications links and devices. All of this communication processing should be completely transparent to the control and trouble-shooting applications by providing 100% reliable on-time data transfer. This means that each data sample is transferred at the agreed-upon sampling rate without the introduction of noticeable time delays (say less than 5% of sample period).

**Report-by-Exception**

To prevent data highway overload, many digital systems employ report-by-exception whereby a signal is only updated via the data highway if its value has changed by at least the value of a selectable deadband. Often such deadbands are set at 1%. **This seriously limits the signal quantization and should never be used for control or trouble-shooting.**

## 5.0 Digital Sensors and Transmitters

Digital sensors and transmitters are becoming increasingly prevalent and are flexible, useful and here to stay. These are primarily microprocessor based devices, often referred to as "smart transmitters" which provide many additional useful functions such as on-board diagnostics and remote re-spanning and re-calibration features.

Digital sensors and transmitters sample their primary measurement elements internally prior to processing this data into a calibrated and filtered signal. Many sensors and transmitters re-transmit this information as an analog signal.(typically 4 to 2O mA). It is important to recognize that this "analog" signal is a re-transmission of a digital signal, hence is capable of containing aliased information. Most transmitter in the future will transmits their output digitally on Fieldbus.

Some digital sensors and transmitters use primary measurement principles which are inherently analog in nature such as a force balance system. In such sensors, the analog measurement system itself can be considered as the anti-aliasing filter ahead of the A/D converter. The sampling rate of the A/D should be chosen in such a way that these measurement dynamics are considered as part of the anti-aliasing filter. Other sensors are inherently digital in nature. For instance, a pulsed-DC magnetic flow meter takes readings at 30 Hz typically. These readings are digital samples of the flow through the meter. There is no inherent anti-aliasing mechanism possible except for the fluid residence time in the flow meter volume which provides a natural averaging of the fluid velocity over the measurement volume. It is important to understand under what conditions this type of physical process might provide adequate anti-aliasing. Another example of a digital sensor is a paper machine infrared moisture sensor with a spinning optical filter wheel which measures light samples every rotation of the wheel. Clearly, such a sensor has no inherent mechanism by which aliasing can be prevented since each sample represents a separate “spot” on the paper, each one potentially at a different moisture value. Questions such as these need to be posed when such sensors are used for feedback control.

The micro-processor execution rate often determines the sampling rate of a digital sensor. Choice of sampling rate has serious implications for feedback control and even greater consequences for trouble-shooting. Some digital transmitters also introduce measurement “latency” or time delay. This introduces a measurement time delay or deadtime and may have very serious consequences for control. This should be limited to less than 5% of sample period.

## 6.0 Fieldbus Implications for Digital Sensor / Transmitter Design

Once Fieldbus has become a reality, process control system architecture will undergo a major change. All users will have access to the source of measurement information at the transmitter. However, each user has different needs with regards to sampling rate and data integrity. Control requires anti-aliased data every 0.3 seconds typically. The operator's console may require anti-aliased data every second, but only when this measurement is selected on the screen. The trend package may want anti-aliased data every 10 seconds. The mill-wide archiving package may want this data together with all data points in the mill every minute. Meanwhile, the trouble-shooter may want the anti-aliased signal every l0 milliseconds-but only for a short burst extending over a few minutes, during which time a multi-variable trial is being run. Alternatively, the trouble-shooter may also want access to the raw sensor data, should signal aliasing be suspected.

## 7.0 Sensor/Transmitter Requirements - Fieldbus Multi-Channel Design

Considering Fieldbus, sensor/transmitter design and all of the needs and requirements stated previously, the sensor/transmitter design for the future should include the following features.

**Field Measurement Verification Capability**

The ability to interrogate and verify the integrity of a measurement is of paramount importance. It often happens during process troubleshooting that the integrity of a measurement is brought into question and steps must be taken to verify the measurement by comparing the signal to signals gathered from other sensors. Such investigations rely on having analog signals available in order to have access to the full sensor bandwidth. Sensors which are inherently digital can only provide the signal at the fastest sampling rate available. To provide this capability, the sensor should have the following terminals available in the field with the following signals accessible:

1) An analog output signal (4 to 20 mA or 1-5 V) which has not been filtered or digitized and which represents the measurement in as near a calibrated form as possible. This signal can only be obtained from an inherently analog sensor.
2) Inherently digital sensors should provide an analog output (4 to 20 mA or 1-5 V) of the signal at the fastest sampling rate available (via a D/A).
3) There should be a Fieldbus connector available in the field so that any of the Fieldbus signals can be assessed as well.

**Fieldbus Data Access**
Data access on Fieldbus should take into account the multiplicity of users for each measurement at different sampling rates with anti-aliasing. This can be done by providing the unfiltered signal at the fastest sampling rate available, say 10 milliseconds, together with anti-aliased signals at a number of frequently used sampling rates, say 10 milliseconds, 30 milliseconds, 100 milliseconds, 300 milliseconds, 1 second, l0 seconds, and one minute. There may be other preferred sampling rates. Alternatively, it may be possible to design the system "hand-shake" software to accommodate and recognize the specific sampling and anti-aliasing needs of each user. At any rate, once the specific sampling rates have been established, the sensor software must run the appropriate samplers and filters to support and sustain the measurement at all of the sampling rates that have been established.

## 8.0 Recommendations Summary

The following recommendations apply to most of the digital measurements in the pulp and paper industry.

**Sampling Rates**

**Process Troubleshooting:**

10 to 100 milliseconds/sample

**Process Control:**

0.3 seconds/sample or faster; 1 second/sample can be tolerated for signals with time constants of 3 seconds and slower.

**Operator Console:**

Typically 1 second update.

**Trending:**

Typically 1 second down to 10 second update.

**Archiving:**

Typically 10 second down to one minute update

**Time delays (Measurement Processing or Data Transmission):**

Less than 5% of sample update period.

**Anti-Aliasing:**

A minimum of -12 dB of attenuation at the Nyquist frequency of each sampler device.

**Filtering:**

Sensor internal filtering should be adjustable beyond the needs of anti-aliasing. The minimum filter time should be small compared to the expected process time constant. The filtering employed should be linear.

**Quantization:**

The minimum acceptable signal quantization is 1:4096 or 12 bits equivalent.

**Measurement Data Access:**

**Field Access:**

Each sensor should provide field access via an analog output port to the earliest possible significant signal. Purely digital sensors should provide analog output of the raw signal. There should also be field access via a digital port allowing full access to all sensor outputs.

**Digital Output:**

Digital sensors should support all of the sampling rates potentially needed in a typical mill installation as a set of multiple channels. Each channel should provide the anti-aliasing filter needed at the sample rate in question.

**Documentation:**

The documentation for each sensor should clearly explain the following issues:

- measurement principle,

- calibration procedure,
- signal path dynamics from the raw measurement through to the sensor output should be specified as a linear transfer function,
- sampling rate, or range of sampling rates,
- anti-aliasing process and attenuation at the Nyquist frequency,
- signal quantization.

## Nomenclature and Symbols

A/D = analog-to digital converter
dB = decibel. Amplification/attenuation expressed as 20 Log (Amplitude Ratio)
D/A = digital-to-analog converter
DCS = Distributed Control System
$f_N$ = Nyquist frequency, the cyclic frequency at the sampling rate,
PID = Proportional-Integral-Derivative algorithm user for control,
$T_A$ = averaging time,
$T_S$ = controller sampling time,

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**For more information:**

For more information on Variability Management please visit our website www.EmersonProcess.com/solutions/VariabilityManagement , or

Contact us at:

email: AAT@emersonprocess.com
phone: +1 512-832-3575

Emerson Process Management
12301 Research Blvd.
Research Park Plaza, Building III
Austin, Texas 78759 USA

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Process Management