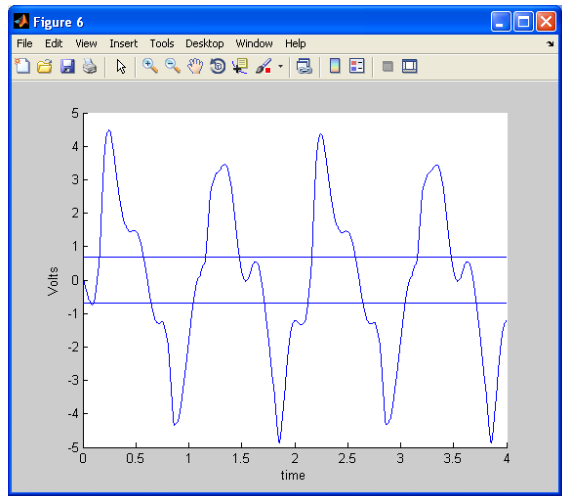
Application Note 51429
(Revision NEW)
Original Instructions



Speed Sensing for Gas & Steam Turbines

⚠ **General Precautions**	**Read this entire manual and all other publications pertaining to the work to be performed before installing, operating, or servicing this equipment.** **Practice all plant and safety instructions and precautions.** **Failure to follow instructions can cause personal injury and/or property damage.**

⚠ **Revisions**	**This publication may have been revised or updated since this copy was produced. To verify that you have the latest revision, check manual *26311* , *Revision Status & Distribution Restrictions of Woodward Technical Publications*, on the *publications page* of the Woodward website:** **www.woodward.com/publications** **The latest version of most publications is available on the *publications page*. If your publication is not there, please contact your customer service representative to get the latest copy.**

⚠ **Proper Use**	**Any unauthorized modifications to or use of this equipment outside its specified mechanical, electrical, or other operating limits may cause personal injury and/or property damage, including damage to the equipment. Any such unauthorized modifications: (i) constitute "misuse" and/or "negligence" within the meaning of the product warranty thereby excluding warranty coverage for any resulting damage, and (ii) invalidate product certifications or listings.**

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Revisions—Changes in this publication since the last revision are indicated by a black line alongside the text.

Warnings and Notices

Important Definitions

This is the safety alert symbol. It is used to alert you to potential personal injury hazards. Obey all safety messages that follow this symbol to avoid possible injury or death.

- **DANGER**—Indicates a hazardous situation which, if not avoided, will result in death or serious injury.
- **WARNING**—Indicates a hazardous situation which, if not avoided, could result in death or serious injury.
- **CAUTION**—Indicates a hazardous situation which, if not avoided, could result in minor or moderate injury.
- **NOTICE**—Indicates a hazard that could result in property damage only (including damage to the control).
- **IMPORTANT**—Designates an operating tip or maintenance suggestion.

WARNING

Overspeed / Overtemperature / Overpressure

The engine, turbine, or other type of prime mover should be equipped with an overspeed shutdown device to protect against runaway or damage to the prime mover with possible personal injury, loss of life, or property damage.

The overspeed shutdown device must be totally independent of the prime mover control system. An overtemperature or overpressure shutdown device may also be needed for safety, as appropriate.

WARNING

Personal Protective Equipment

The products described in this publication may present risks that could lead to personal injury, loss of life, or property damage. Always wear the appropriate personal protective equipment (PPE) for the job at hand. Equipment that should be considered includes but is not limited to:

- **Eye Protection**
- **Hearing Protection**
- **Hard Hat**
- **Gloves**
- **Safety Boots**
- **Respirator**

Always read the proper Material Safety Data Sheet (MSDS) for any working fluid(s) and comply with recommended safety equipment.

WARNING

Start-up

Be prepared to make an emergency shutdown when starting the engine, turbine, or other type of prime mover, to protect against runaway or overspeed with possible personal injury, loss of life, or property damage.

WARNING

Automotive Applications

On- and off-highway Mobile Applications: Unless Woodward's control functions as the supervisory control, customer should install a system totally independent of the prime mover control system that monitors for supervisory control of engine (and takes appropriate action if supervisory control is lost) to protect against loss of engine control with possible personal injury, loss of life, or property damage.

NOTICE	
Battery Charging Device	**To prevent damage to a control system that uses an alternator or battery-charging device, make sure the charging device is turned off before disconnecting the battery from the system.**

Electrostatic Discharge Awareness

NOTICE

Electrostatic Precautions

Electronic controls contain static-sensitive parts. Observe the following precautions to prevent damage to these parts:

- **Discharge body static before handling the control (with power to the control turned off, contact a grounded surface and maintain contact while handling the control).**
- **Avoid all plastic, vinyl, and Styrofoam (except antistatic versions) around printed circuit boards.**
- **Do not touch the components or conductors on a printed circuit board with your hands or with conductive devices.**

To prevent damage to electronic components caused by improper handling, read and observe the precautions in Woodward manual *82715*, *Guide for Handling and Protection of Electronic Controls, Printed Circuit Boards, and Modules*.

Follow these precautions when working with or near the control.

1. Avoid the build-up of static electricity on your body by not wearing clothing made of synthetic materials. Wear cotton or cotton-blend materials as much as possible because these do not store static electric charges as much as synthetics.
2. Do not remove the printed circuit board (PCB) from the control cabinet unless absolutely necessary. If you must remove the PCB from the control cabinet, follow these precautions:
   - Do not touch any part of the PCB except the edges.
   - Do not touch the electrical conductors, the connectors, or the components with conductive devices or with your hands.
   - When replacing a PCB, keep the new PCB in the plastic antistatic protective bag it comes in until you are ready to install it. Immediately after removing the old PCB from the control cabinet, place it in the antistatic protective bag.

Speed Sensing for Gas & Steam Turbines

Speed Sensing Probe Selection, Application, and Installation Variables for Industrial Gas and Steam Turbines

by David Ried, Senior Staff Engineer
Woodward Industrial Turbine Systems
August 2011

Summary

Reliable speed sensing is one of the most important functions in gas and steam turbine control and safety monitoring. With all of the probe types available, passive probes are often the best selection because of simplicity and their attractiveness for safety applications. Either passive or active probes can work with any type of speed gear, but incorrect matching of probe type and tooth profile will lead to reduced operating range and signal robustness. This paper introduces the physics and the basic application differences between the combinations of probe type and tooth profile. Many performance factors interact with each other in the application of passive probes, but the user only has control over probe selection, speed-wheel tooth profiles, and wiring. With the information presented in this paper, system designers and integrators can more reliably choose and apply probes, match the speed tooth to the probe, and design the wiring system to achieve the best possible speed sensing performance.

Introduction

Rotating machinery requires speed sensing for functional systems such as control, monitoring, and safety. Speed sensing is accomplished using primarily passive magnetic pickups (MPUs) or active proximity probes.

Magnetic pickups are commonly selected because of simplicity, reliability, and low cost. MPUs are passive probes in the sense that there are no active signal conditioning electronics in the probe. Passive probes have variable signal outputs that depend on many factors and can be difficult to apply.

Active probes such as proximity sensors and other passive sensors with active signal conditioning integrated into the sensor are classified as active probes. Active probes usually have more consistent signal output because of the integrated electronics, but with the associated increase in complexity.

For industrial applications, API670 has guidelines on the application of speed sensors. Specifically, Annex J contains well proven information on relative dimensions of the MPU and speed sensing tooth parameters. Functional safety to IEC61508 and IEC61511 is increasingly required in new and retrofit systems. Passive probes are a good choice in these systems because they are Type A (passive) devices per IEC61508 and take up less of the safety allocation than active probes.

This paper focuses on the passive probe type and will cover the factors involved in the selection and application of probes that result in the best performance for a given system.

Background

Passive probes function by sensing the passing speed tooth near the pole face of the probe, which causes a magnetic flux to be generated in the probe that is converted to an electrical signal by a coil inside the probe. The amplitude of this signal is proportional to:

1. The amount of magnetic flux generated by the passing tooth. In other words, the distance from the probe to tooth (gap) and the speed of the tooth passing the probe.
2. The number of turns in the coil.
3. The loading on the coil due to the sensing circuit.

The amount of flux generated in #1 above is a complex function of the probe pole face dimensions, the speed tooth dimensions, tooth speed, MPU and speed tooth magnetic properties, and the gap between the probe and the gear tooth. API670 covers the dimensional aspects of probe and speed wheel selection, so those items will not be repeated in this paper. Instead, this paper will cover physical explanations of why the API670 guidelines work. The physics behind the flux generation comes from one of Maxwell's equations that govern electromagnetic behavior. In it simplified form, it states that:

$$V = N * d\varphi/dt$$

Where:

N = number of turns on the coil
dφ/dt = the amount of magnetic flux generated by the passing tooth

This equation has several important pieces of information:

1. It is time (frequency) related.
2. Voltage is proportional to N, the number of turns in the coil.
3. Voltage is proportional to the rate of change in flux, or the change of flux divided by the time the flux is changing. The flux change results from a change in the magnetic coupling as the tooth edge passes the pole face. The amount of flux in the magnetic circuit is also dependent on the material properties of the MPU core and the tooth. The tooth must be a ferromagnetic material like annealed iron and not a paramagnetic like aluminum or stainless steel.

To help interpret this equation, three cases for tooth profile are considered.

1. On one extreme, a flat speed wheel with no teeth has a constant magnetic coupling and will not create any change in flux (*dφ/dt=0*), and therefore will not generate a signal.

2. On the other extreme, a square tooth profile will generate very rapid change in flux, and therefore generate very high voltage for a very short time (*large dφ/dt*). This voltage will look more like a spike instead of a continuous sinusoidal waveform. Since signals that look like spikes have very wide frequency content, they can create signal distortion, drive cable and circuit resonances, and can be difficult to sense. The duration of the spike is related to energy storage in the probe coil inductance, cable parameters, and sensing circuit capacitance. Although this type of probe signal can be filtered, the signal quality is highly sensitive to uncontrolled factors such as cable parameters and variable circuit characteristics. The square profile type of speed tooth design makes consistent application of passive speed probes difficult over a wide range of operating speeds. However, square tooth profiles are good for proximity probes because the sharp transition of the signal as the tooth edge passes the probe sensing element results in less timing variability over the speed range.

3. In the middle of this spectrum, where most MPU gear tooth designs reside, is a shaped tooth that will generate a continuously changing flux and will present a more sinusoidal waveform to the sensing circuit. The more sine-wave-like signals have lower frequency harmonics and are much easier to filter and detect. In comparison to the square-tooth profile, signals from the shaped speed tooth are less sensitive to uncontrolled factors. These designs offer the widest range of frequency operation and result in the most stable signals. The above equation also explains why passive probes generate more voltage at high tooth frequencies. As the frequency increases, the tooth edge passes the probe pole face more rapidly, resulting in a larger $d\varphi/dt$.

Matching Probe Type to Gear Tooth Profile

In general, passive (MPU) probes work best with shaped gear-tooth profiles, and active (proximity) probes work best with square-tooth profiles. The previous section provides the physics-based explanation. The following figures explain the general guideline in more detail.

Figure 1 shows a square tooth passing the probe pole face. Figure 2 shows a simulated example of the resulting waveform at the output of the probe. This signal has high peaks, and is near zero for a long time, making it vulnerable to zero-crossing noise. Fast signals such as these are wide-bandwidth signals and can excite resonances in the probe, cabling, and detection circuit.

Conversely, for active probes, the fast rising edge is easy to detect by a proximity probe and usually results in clean signals with minimal jitter.

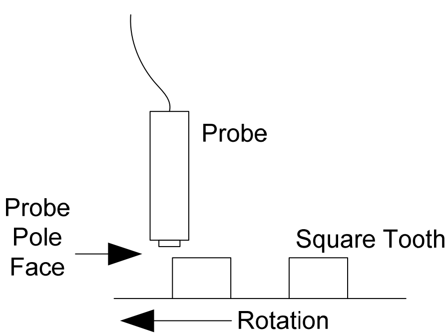

Figure 1

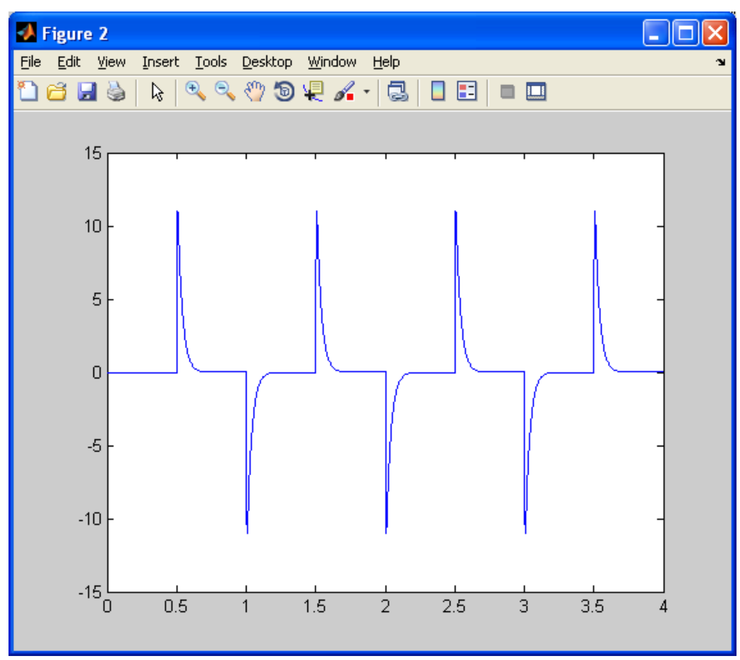

Figure 2

Figure 3 shows a shaped tooth passing the probe pole face. Figure 4 shows a simulated example of the resulting waveform at the output of the probe. This signal is relatively smooth with lower harmonic content, and does not spend much time near zero. Thus it is easier for the detection circuit to reliably sense the signal. However, for active probes such as proximity probes, this is not as good as the square tooth case because the slow-rising edge can cause jitter when sensing the on/off threshold.

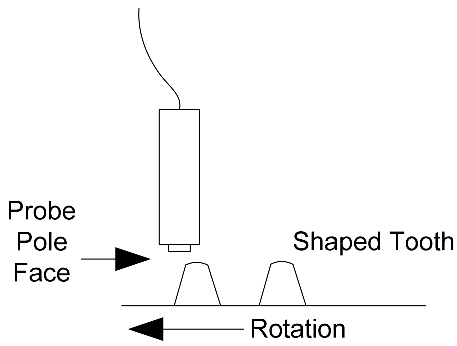

Figure 3

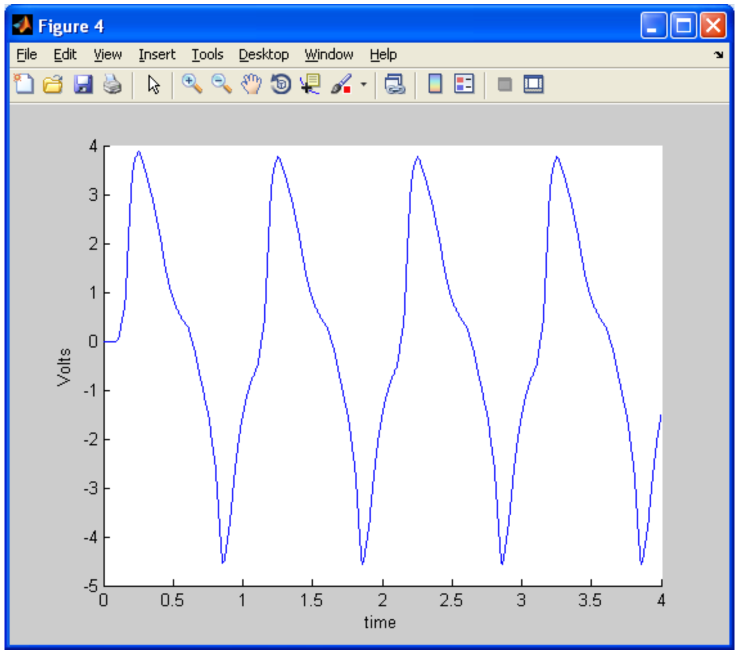

Figure 4

Performance Factors

With the probe physics explained, it is easy to see why there are so many factors involved in good speed sensing. What makes passive probes so difficult to understand is that all the performance factors interact with each other. Adjusting any of the factors will likely have an effect on the others. Important performance factors include:

- Range of voltage amplitude
- Range of frequency sensing
- Wiring length
- Speed tooth dimensions
- Probe pole face dimensions
- Sensing circuit parameters and filtering

Since voltage amplitude varies with frequency, the probe must provide adequate signals over the speed range of interest. Probe-to-tooth gap distance variation creates a design problem for the detection circuit because signal amplitude may vary as much as 150:1. Gear imperfections such as run-out, tooth spacing, and dimensional variance cause signals that can look amplitude modulated as the speed wheel rotates a full revolution. At low speeds, the signal must be strong enough for the detection circuit to work reliably. At high frequencies, the probe can develop significant power that the detection circuit must handle.

Wiring length is normally not a big concern, but can cause secondary problems. Excessive cable capacitance can cause signal distortion from the L-C network formed by the coil inductance, cable inductance, and capacitance and sensing circuit capacitance. The signal distortion caused by the L-C network is one of the biggest reasons why the square tooth profile discussed above can cause unpredictable results. It is best to use low-capacitance, twisted/shielded wire.

Speed tooth dimensions are important as described above. API670 contains the industry's best knowledge of the sizing factors, including the recommended dimensions of the tooth size and depth relative to the probe pole face. These will not be covered in this paper since they are covered in depth in API670. One parameter that is not discussed in great length is the shape of the tooth profile. There are no specific guidelines for the shape of the tooth, but throughout the API documentation the diagrams indicate the shaped tooth for passive applications. The shaping consists of a chamfer of the tooth profile.

The last performance factor is not one that is under control by the user, but it is useful to understand the sensing circuit effects on the probe signal. There are many trade-offs in detection circuit design. If the probe is overloaded, the circuit may not detect the low-speed signals effectively. If it is under-loaded, the circuit will have to handle high voltages at high speeds. Too much input filtering can cause excessive signal attenuation, making low-speed detection difficult, and introduce resonance in long cable length as discussed above. Too little filtering can leave the detection circuit vulnerable to noisy or edgy signals from poor probe/speed wheel compatibility.

Another choice is the detection method. Two common methods are threshold detection and zero-crossing detection. Figure 5 shows an example of the threshold detection method. In this figure, noise has been added to the signal caused from some of the factors discussed above. The two lines at 1.5 V and 1.3 V show the detection levels with some hysteresis to reduce noise sensitivity. The main drawback of the threshold method is that the threshold must be low enough to sense the minimum desired signal. For a 0.25 V (rms) minimum signal, this means the threshold must be less than 0.7 V.

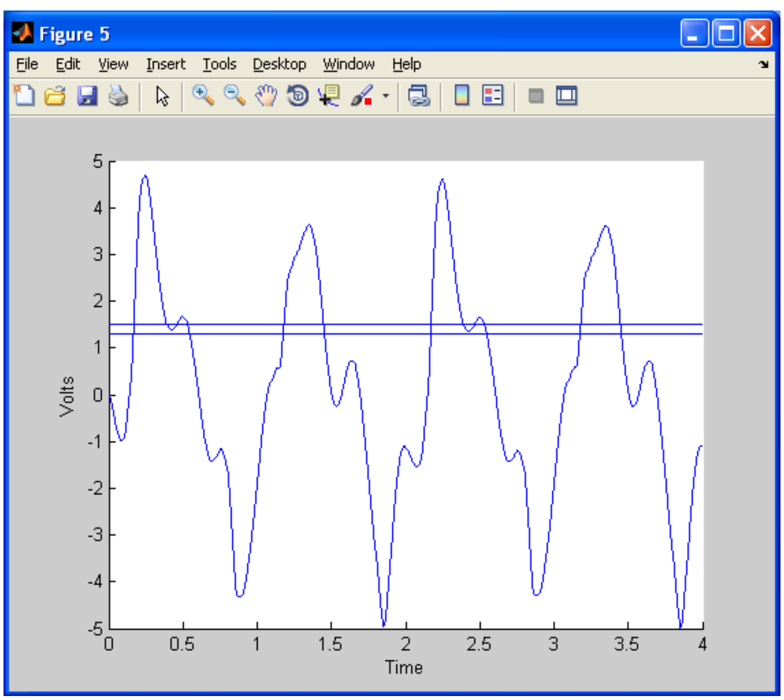

Figure 5

Figure 6 illustrates the zero-crossing method. The hysteresis band is also shown. In this method, the size of the hysteresis is determined by the minimum desired signal. If the minimum signal is 0.25 V (rms) (approximately 0.7 V pk), the hysteresis band must be less than (2 * 0.7) V. Since a larger hysteresis band makes the circuit less sensitive to noise, it is difficult to make circuits that can detect small signals and are insensitive to noise at the same time.

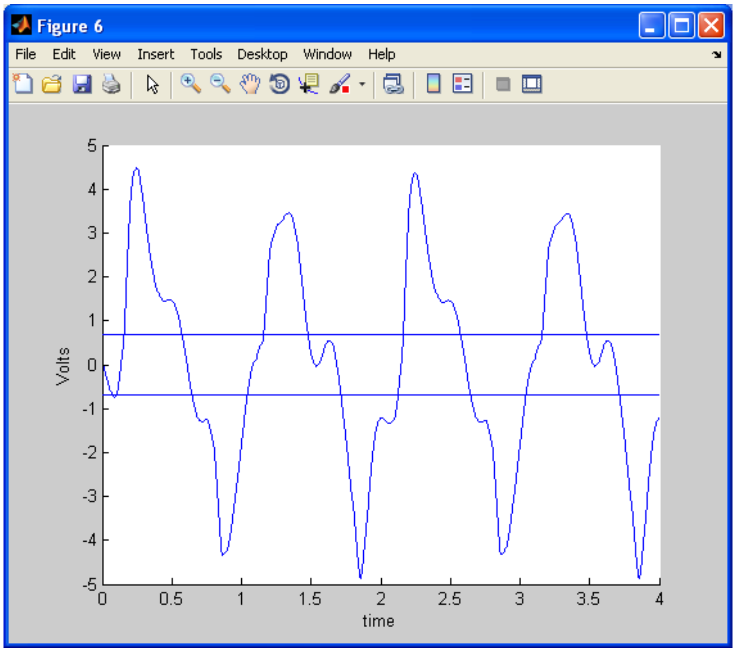

Figure 6

In Figure 7, the square-tooth waveform is shown with the same noise added as in Figure 5. This graph shows why signals of this type are more difficult to detect and are more vulnerable to double-pulse sensing. There is no good choice of threshold setting and hysteresis band that does not sacrifice both amplitude and frequency operating range and therefore allows smaller application possibilities.

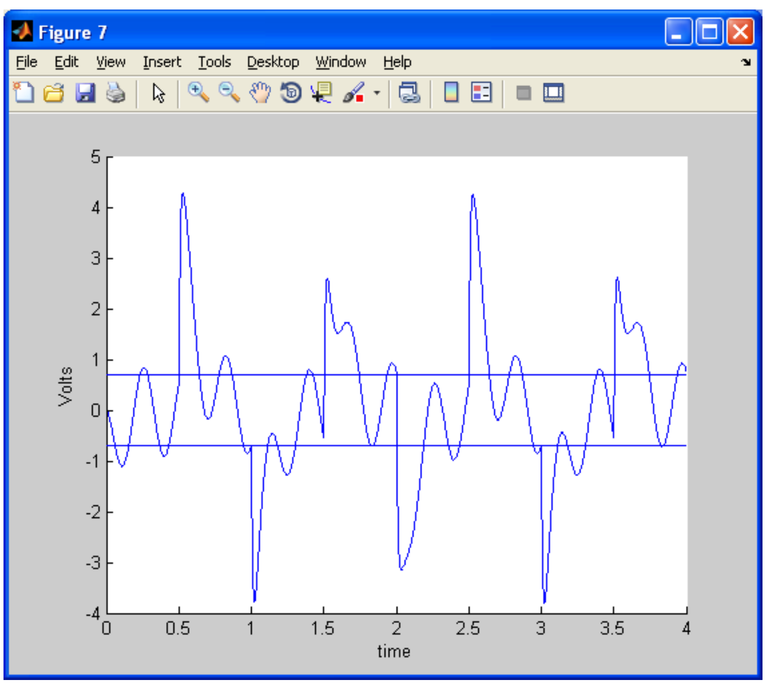

Figure 7

There are many variations of the two basic methods that attempt to improve the tradeoffs. A more advanced method now commonly in use is an adaptive threshold method where the threshold is dynamically adjusted to accommodate signal amplitude. With the proper detection and filtering algorithms, this method minimizes the risk of false speed detection, increases the signal edge detection quality, and increases overall speed detection dynamic range.

The choice of isolation is also important. Speed sensors can be several hundred meters away from the sensing electronics and therefore highly vulnerable to ground differentials caused by high-speed transients and lightning.

As dynamic range increases (wider voltage and speed ranges), more care is required on probe and speed-sensing wheel selection. Filtering can be implemented in hardware or a combination of hardware/software. With microprocessors, DSPs, and FPGAs becoming small and inexpensive, very sophisticated filtering algorithms are being developed. With all the different speed detection choices to be made, it is not surprising that there is so much variability in speed detection quality.

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