FUNDAMENTAL PROPERTIES OF SPEED SENSORS

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INTRODUCTION

The aim of this application note is to provide a solid foundation for understanding and comparing the fundamental properties of speed sensors that are valid not only for Allegro products but for speed sensors in general. First, these fundamental properties will be defined, followed by the factors that influence these properties and the effect of both on the observable properties in applications, such as angular position and velocity.

Throughout this document, several technical terms are used that unfortunately tend to be used interchangeably or with alternative definitions depending on the specific technical field or context. Therefore, these terms are formally defined first in the scope of this document, starting with the most general concepts and continuing to the most fundamental ones.

TERM DEFINITIONS

Figure 1 represents data from a physical measurement, depicting the observed period of the magnetic input signal and directly shows how the sensor properties affect the measurement result.

Target

A target can be a ferrous gear wheel, a ferrous stamped disk or cylinder, or an axially or radially magnetized ring magnet mounted on a rotation axis, for which angular velocity will be determined by the speed sensor. For general recommendations of target design, refer to the application note Target Design for Hall Transmission Sensors [1] or Magnetic Encoder Design for Electrical Motor Driving Using ATS605LSG [2]. As far as the magnetic properties of the target material are concerned, Impact of Magnetic Relative Permeability of Ferromagnetic Target on Back-Biased Sensor Output [3] offers a useful guide.

The sensor device outputs pulses at specific angular locations based on the time-varying magnetic input signal, and the speed can be calculated as the inverse pulse distance. Figure 1 is an example of such a period measurement. In addition, Allegro's speed sensors have advanced integrated algorithms that also provide rotation direction robustly even under adverse conditions such as temperature and signal variation, signal drift, various vibration signatures, etc.

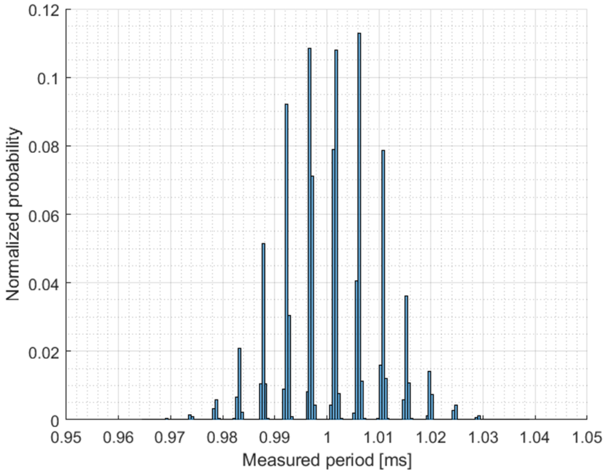

Figure 1: Histogram of observed period of a rotating magnetic encoder

Accuracy

Accuracy denotes the difference between the true value and average of all observations. It is important to differentiate between absolute and relative accuracy, which, besides being expressed in different units, also denotes different properties in the context of speed sensors.

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[1] https://www.allegromicro.com/-/media/allegro/allegromicro/files/application-notes/an296178-hall-transmission-sensor-target-design.ashx

[2] https://www.allegromicro.com/en/insights-and-innovations/technical-documents/hall-effect-sensor-ic-publications/magnetic-encoder-design-electrical-motor-driving-ats605lsg

[3] https://www.allegromicro.com/en/insights-and-innovations/technical-documents/hall-effect-sensor-ic-publications/magnetic-relative-permeability-ferromagnetic-target-back-biased-sensor-output

Relative Accuracy

Relative accuracy quantifies the difference of the average measured period or speed and actual input frequency. In the example of Figure 1, there is an input signal with 1 kHz and a mean observed period of 1 ms, therefore having no deviation.

It is generally more convenient to express the relative accuracy in angular degrees normalized by the signal period or simply in percent of the signal period. First, this makes accuracy a relative measure. Second and more importantly, accuracy then becomes independent of both the input speed and target period (consequently the number of teeth or pole pairs).

Absolute Accuracy

Absolute accuracy is the difference between the angular position of the output pulses and the true mechanical position of the target. Absolute accuracy is important in applications where the absolute angular position is required in addition to angular speed, for example, in absolute encoders or cam and crank applications.

In summary, relative accuracy is for velocity and absolute accuracy is for angles. It is important to keep in mind that both the relative and absolute accuracy are averaged values and represent a systematic bias from the correct measure. For an instantaneous (or random) deviation, jitter must be used.

Precision

Precision represents the spread of multiple measurements and quantifies the repeatability of the results. It describes only the random fluctuations from the true value per definition. In the context of speed sensors, the temporal fluctuations of the output pulses are called jitter.

Jitter[4]

Jitter is the width of the measurement distribution around the average. In the case of Figure 1, jitter is around 10 µs. Conventionally, it is reported at one standard deviation level and can be calculated as shown in Equation 1.

Equation 1:

$$\sigma = \sqrt{\sum_i (x_i - \mu)\frac{1}{N-1}}$$

where N is the number of measurements, and μ is the average of all measurement values. It defines that, on average, 68%[5] of all measurement would fall (either left or right) less than the jitter value away from the average.

Another convention is to report the jitter at either the three or six sigma level, which is achieved by multiplying the 1-sigma value by 3 or 6 respectively. The general formula for the proportion of observations laying within the double-sided interval from $-n \times \mathrm{sigma}$ up to $+n \times \mathrm{sigma}$ is calculated with the error function, shown in Equation 2.

Equation 2:

$$prop = \mathrm{erf}\,(\frac{n}{\sqrt{2}})$$

Jitter is most conveniently expressed in percent of the target period, as this value is independent of rotational speed and number of teeth/pole pairs. It is important to note that the signal period is not necessarily equal to the target period, as some sensors output multiple pulses per period. Not taking this into account would lead to substantial overestimation of jitter (precisely by a factor equal to the number of pulses per period). Moreover, some Allegro sensors offer configurable number of pulses per period, so disregarding the above note would result in fictitious variation of the jitter value without any physical foundation for it. More on the topic can be found in the section about the source of jitter.

Single- and Double-Edge Jitter

With a signal from a magnetic encoder with a period of six degrees (e.g., 60-tooth target with one pulse per period), then single-edge jitter is the variation of each individual pulse position around the mean tooth position (0°, 6°, 12°, etc.) over all revolutions. Double-edge jitter refers to the variation of the periodicity of the signal. It can be calculated either for each teeth pair individually over all revolutions or as a running difference of consecutive teeth.

Theoretically, this is shown in Equation 3:

Equation 3:

$$\sigma_{DE} = \sqrt{2}\,\sigma_{SE}$$

as it can be derived from the statistical principles; however, in practice, this is rarely the case. The reason is the period-to-period variation of the input signal, which will be discussed further in the following sections. Figure 1 shows the double-edge jitter.

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[4] For further information, see application note "Guidelines For Measuring Output Repeatability On Speed Sensors" (available on request; contact Allegro).

[5] Assuming normal distribution, which generally is fulfilled.

Resolution

Generally, resolution is the minimum possible step/difference of the output of a measurement device, or how finely the output is quantized. This term only makes sense for digital devices, as the resolution for analog devices is zero, i.e., they can output any arbitrary value. The resolution of the sensor data shown in Figure 1 is the distance between the individual groups, which in this case is 4 µs. Theoretically, it can be calculated as the difference between two neighboring clusters, but this requires classification of the data. A more practical approach is to take the median of all pairwise distances between consequent measurements. As it can be seen from the histogram, the individual groups do not have discrete values but rather a slight spread, which is caused by jitter of the pulse-capturing equipment. Using the median instead of the minimum provides robustness against that. Resolution is typically expressed in nanoseconds (ns) or microseconds (µs).

Propagation Delay

Propagation delay is the time it takes from a magnetic edge until a pulse is output and roughly describes how quickly the sensors react to changes of the input. Due to physical laws, the magnetic signal does not have any defined edges, but is rather a smooth (continuously differentiable) curve. Therefore, under a magnetic edge, it is generally meant to be the point when the signal crosses an adaptive threshold. The propagation delay is typically measured in nanoseconds (ns) or microseconds (µs), similar to the resolution.

IMPORTANT INFLUENCING FACTORS

This section details what factors plays an important role for determining each of the sensor characteristics previously defined. Contrary to the previously given order, this section is organized from the fundamental properties up, as they are simpler and often have impact themselves to the more abstract ones.

Propagation delay is the time necessary for the sensor to process the input signal. It is determined by the algorithmic complexity, IC processing throughput, and fundamentally the system clock, as each digital operation step takes one clock cycle. Some applications specifically define a requirement for propagation delay, such the AK protocol for wheel speed sensors, and it could be an essential part of proper device functionality.

Sensor resolution depends on the input sampling rate and output update rate, and again, ultimately, on the system clock. If everything else was instantaneous, the propagation delay would be at minimum zero and at maximum equal to the resolution. Allegro's sensors have sub-microsecond propagation delay and resolution, and these properties are optimized so that there are no adverse effects on the remaining characteristics.

Jitter is not determined by propagation delay or resolution. However, it must be pointed out that the resolution must be sufficiently small for a given jitter; otherwise, it would become the system's limiting factor and increase the jitter. Figure 1 is an example of when this condition is still satisfied despite the small margin. Conversely, the output of the speed sensor must be sampled with sufficient resolution as to not adversely affect jitter. A good rule of thumb is to use the same or better resolution than the sensor itself.

Fundamentally, jitter is caused by the temporal uncertainty of when exactly the magnetic signal crosses the switching threshold. This in turn depends on the ratio of the signal to noise and the signal slope at the crossing point. For single-edge jitter, the noise of the sensor is the major contributor. It is inversely proportional to the temperature (which is inevitable for all electronic devices), input bandwidth, IC components, noise spectrum, and sensitivity of the magnetic sensing technology. Of course, higher sensitivity gives better signal-to-noise ratio for a given signal strength, which is the case for magnetoresistive technologies. Signal slope is governed by the amplitude and the specific signal shape at the switching thresholds. Unless there is a flat region, which is commonly the case for targets with a signature region, the slope is generally rather similar across different targets. So, signal amplitude has a larger impact on jitter performance, and in order to improve it, it is advised to use optimized target design, smaller air gap, stronger magnets, and lower temperature.

Variation of the input signal periodicity has a negative impact on double-edge jitter performance because it directly impacts the relative pulse position even if the sensor had perfect precision. Hence, speed variation, tooth-to-tooth variation, pole-to-pole variation, run-out, AG variation, and angular vibration all cause the signal amplitude to fluctuate and consequently lead to increased double-edge jitter.

In summary, single-edge jitter provides the sensor's contribution to system precision, whereas double-edge jitter is a combination of sensor and target variation; therefore, it is worth distinguishing both in evaluations. Henceforth, single-edge jitter will simply be referred to as jitter, as it is more representative of sensor performance. As mentioned before, some sensors output multiple pulses per period, but fundamentally that changes neither the noise level nor the signal amplitude, so it does not have any real effect on jitter. Consequently, it is vital that jitter is always normalized to the target angular period and not the pulse period.

Allegro's portfolio consists of sensors with top competitive jitter performance. Contact Allegro's representatives to find the best solution for your application.

Relative accuracy is solely determined by the ratio of detected edges to the actual number. If a sensor outputs only half of pulses it should, then this would lead to an observer underestimating the velocity by a factor of two and vice versa. Allegro's sensors incorporate a guarantee for no missing or extra pulses as part the ASIL-related hardware safety requirements, and as such have the maximum possible relative accuracy of 100%.

The absolute accuracy is determined by both the propagation delay and the update rate because it is defined as the absolute shift with respect to the true timing.

Finally, the specific signal shape of targets is a decisive factor because it determines the switching position accuracy.

EFFECTS ON OBSERVABLE QUANTITIES

The most important aspect for customers is the effect all of the above sensor characteristics have on observable and application-relevant quantities such as angular position and velocity. Although Allegro's speed sensors are used to measure speed, as the name suggests, that is only a derived quantity, and the actual device output are pulses in the time domain. Consider how that translates to the properties of the aforementioned quantities. For the following analysis, it is assumed that no additional processing is performed in the ECU besides registering the pulse timings and performing simple arithmetic steps to calculate the angle and speed as described below. Advanced software processing like filtering, averaging, etc., add another layer of complexity and are outside the scope of this document.

Position is simply the number of observed pulses times the target period. Its resolution is only governed by the number of periods, pulses per period, and typical values ranging from 2° to 30°. Its absolute accuracy and precision correspond directly to the absolute accuracy and jitter of the sensor. The sensor's relative accuracy is only defined for speed measurements. The resolution could be improved computationally by integrating speed over a period, but that must be performed on a system level.

Velocity is the difference of two pulse positions divided by the elapsed time.

Equation 4:

$$v = \frac{A_2 - A_1}{T_2 - T_1} = \frac{360}{N(T_2 - T_1)}$$

with $A_{1,2}$ the angle, $T_{1,2}$ the timing, N the number of pole pairs/teeth. Since the sensor absolute accuracy is a constant time offset, by definition, it cancels out in the difference, so the absolute accuracy of the speed signal is perfect. Only in the case of braking will there be an error to the true velocity equal to:

Equation 5:

$$v_{error} = |accel| \times t_{offset}$$

Take for example propagation delay of 100 µs and acceleration of 10 m/s^2: the error is only 0.0036 km/h. The sensor relative accuracy is 100% (due to no missing or extra pulses), so the velocity relative accuracy is also 100%. The relationship between the velocity precision and sensor jitter is the following:

Equation 6:

$$v_{prec} = \sqrt{2}\, v\, \sigma_{SE} /100$$

The velocity resolution is determined by sensor resolution through:

Equation 7:

$$v_{res} = N v^2 t_{res}/60$$

where the speed is measured in rpm, t_{res} in seconds.

Revision History

Number	Date	Description	Responsibility
–	June 11, 2021	Initial release	E. Pavlov
1	June 28, 2021	Updated footnote 4 (page 2), equations 1, 5, and 6 (pages 2 and 4), and Single- and Double-Edged Jitter section (page 2).	E. Pavlov