GMR CRANKSHAFT TARGET DESIGN GUIDELINES

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INTRODUCTION

This application note offers guidelines for designing an optimal target for crankshaft applications. This document will explain the important characteristics for consideration when designing a target and the impact they have on deliverables, as these are important topics during the design phase—in particular, maximum air gap, jitter, and absolute accuracy target performance in the context of the ATS16951 back-biased device.

The ATS16951PSM is a giant magnetoresistance (GMR) integrated circuit (IC) and permanent magnet pellet combined with EMC protection components to provide a user-friendly and comprehensive solution for digital gear tooth sensing. The small package can be easily assembled and used in conjunction with a wide variety of gear tooth targets and is intended for automotive crankshaft applications. The device incorporates multiple GMR elements into a single IC that switch in response to differential magnetic signals created by a ferromagnetic target, offering robustness and sensitivity unparalleled by Hall-based solutions.

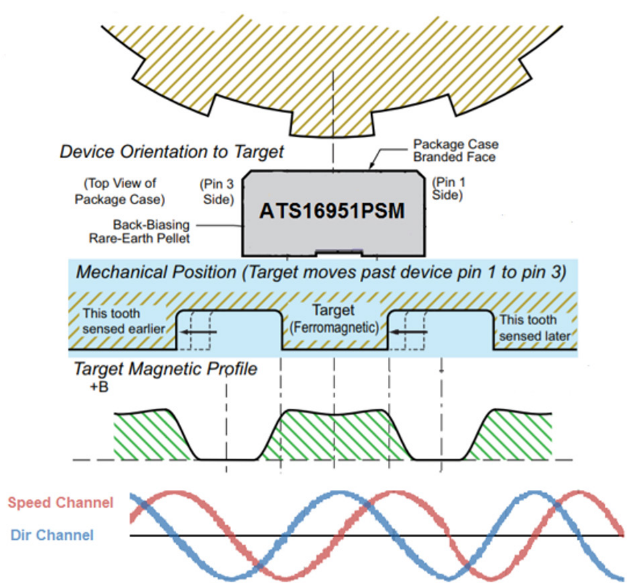

Figure 1: Magnetic profile

Figure 1 shows a classic example of signals generated by a ferromagnetic target as sensed by the ATS16951. The waveform diagram at the bottom of Figure 1 shows the induced magnetic signal by the mechanical profile of the target. It consists of two differential signals named Speed and Direction (Dir) Channel for easier reference. The two internal signals are used to determine the location of the output pulses as well as the direction of rotation, respectively. Nevertheless, this assignment is not strict, and it can be reconfigured to accommodate customer needs as explained in the following sections.

Depending on the application, the device will need to send an output pulse in the middle of a feature (valley or tooth) or on the mechanical edge of a feature (rising or falling mechanical edge). The ATS16951 offers the user great application flexibility because it can be configured to work in all four scenarios.

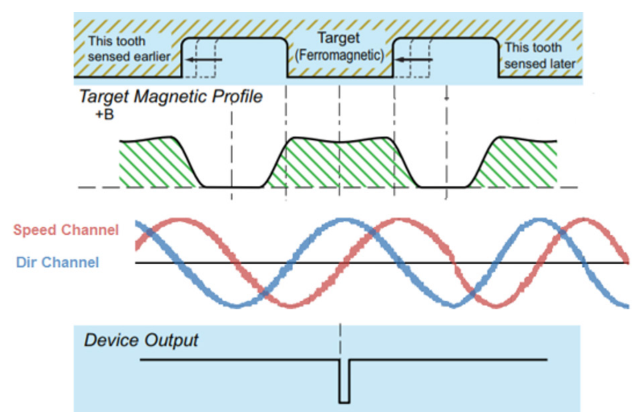

Figure 2: Output in the middle of the tooth

Figure 2 shows an example where the pulse is sent in the middle of the tooth. To make this possible, a threshold has been set at 50% of the Speed Channel signal and a pulse is sent every time the signal crosses this threshold from a lower level to a higher level, i.e., from the negative side. If the output pulse is desired to be in the middle of the valley, the transition from higher level to lower level can be used with the same threshold level on the Speed Channel. If instead of having the output pulse in the middle of a feature, the pulses should appear at the mechanical edge, i.e., transition from tooth to valley or vice versa, the exact same principle can be used but based on the Dir Channel. Again, changing the transition side determines which feature transition the pulses are on. The complementary channel that is not responsible for producing the output pulse is used to determine the direction of the rotation by evaluating its temporal offset with regard to the switching channel. In other words, one channel is first in forward rotation and the other in reverse.

For this reason, it is important to consider the exact signal shape the target is generating at the 50% switching threshold level. A clean and steep slope at this point will ensure great absolute accuracy, better jitter performance, and proper output behavior. Not all targets are created equal, and in differential sensing, sensitivity is relative to changes in the target profile, so large flat regions typically produce only offset signal. This is shown in Figure 3, where well-designed and poorly designed targets and their impact on the magnetic signals are compared.

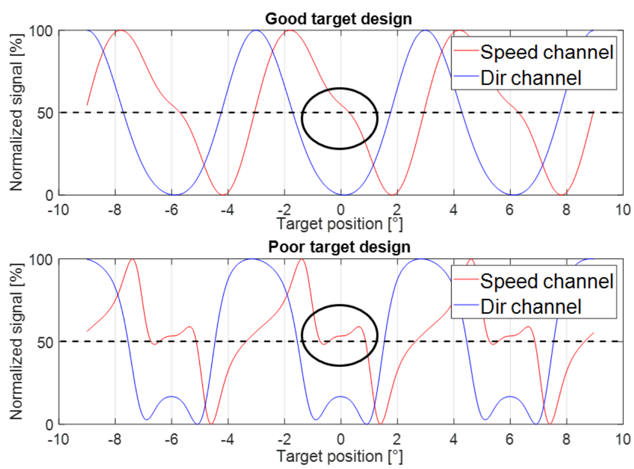

Figure 3: Good vs. poor target design

In the upper plot, the encircled zone around 50% is steep without any flat regions. This makes it easier for an observer to determine the x position of the transition, thus yielding lower uncertainty, which manifests in better absolute accuracy and lower jitter. On the other hand, the lower plot has a lot of "squiggles", technically known as rebound, in the critical region and even crosses the threshold several times. It is easy to see why such a target would have poor performance.

Fortunately, the ATS16951 features advanced proprietary algorithms that offer robust performance and reliable switching despite rebound target signatures. If an external observer only looks at the bottom circled region in Figure 3 without having the information on the x axis, it can be tricky to accurately say in which direction the target is rotating, especially due to the reverse slope of the rebound. This ultimately puts limits on discerning rebound region from genuine direction reversal. In order to achieve the best performance from a target in terms of accuracy, jitter, reliable edge, and direction detection, it is recommended to strive for rebound with peak-to-peak less than 5% of the total signal peak-to-peak on the speed and 20% on the direction channel when designing a target.

DESIGN PROCESS

The points from the previous section make target design a challenging and daunting task given how many degrees of freedom there are. However, this need not be the case—the focus will be on several key parameters to see what their impact is on the significant application output parameters. This would allow for the creation of a straight-forward design guide that makes the process hassle-free.

Target Diameter

This is simply the diameter of a circle which is tangential to the outermost point of each tooth. It is the largest target size in the sensing plane.

Tooth Dimension L

This is the width of the tooth top surface, as shown in Figure 4. Together with the diameter and target period T, it uniquely defines the valley width.

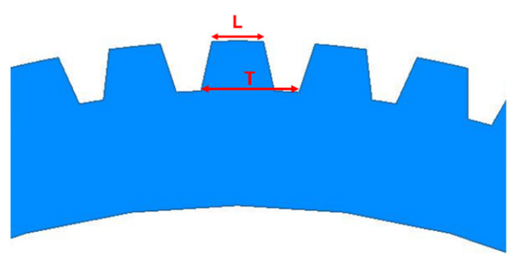

Figure 4: Tooth over period ratio

Tooth Shape

Various levels of sharpness or obtuseness of the teeth have been tested. This is given by ratio R between the tooth top width D and base width L:

$$R = D / L$$

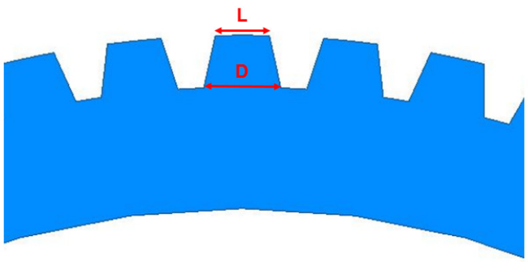

Figure 5: Tooth shape definition

The effect of the three parameters (Diameter, tooth size L, shape of tooth R) is evaluated on both the Speed Channel and Dir Channel.

Air Gap

Throughout this document, the word *air gap* will be used in different cases. The air gap consists of the distance between the top of the tooth of the target to the IC package. Figure 6 represents this definition:

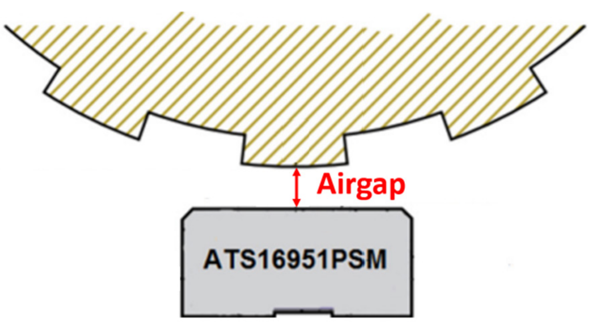

Figure 6: Air gap definition

The effect of air gap on the following quantities will be discussed.

Peak-to-Peak of the Signal

This is a measure of the strength of the target magnetic signal and ultimately determines the achievable application air gap range and jitter through the signal-to-noise ratio. The peak-to-peak of the signal will be based on the Allegro reference 60× target specified in the ATS16951 datasheet, and is expressed in arbitrary units (a.u.). The following limits should be observed.

- The peak to peak of the Speed Channel should be higher than 0.7 a.u., which corresponds to 3 mm air gap on Allegro 60× reference target
- The peak to peak of the Dir Channel should be higher than 1.5 a.u., which corresponds to 3 mm air gap on Allegro 60× reference target

Signal Rebound

As discussed in the introduction, this can affect absolute accuracy and switching capability.

Absolute Accuracy

This defines how precisely the output pulse position corresponds to the true feature position. Ideally, the pulse should be located exactly in the middle of the feature or on the mechanical edge of the target.

TOOTH SHAPE

The tooth shape effect was studied first. Different ratios R from 1 to 4 were considered and parameters such as peak-to-peak, rebounds, etc., were verified. The conclusion of this study was that the best configuration is ratio 1 as shown in Figure 7.

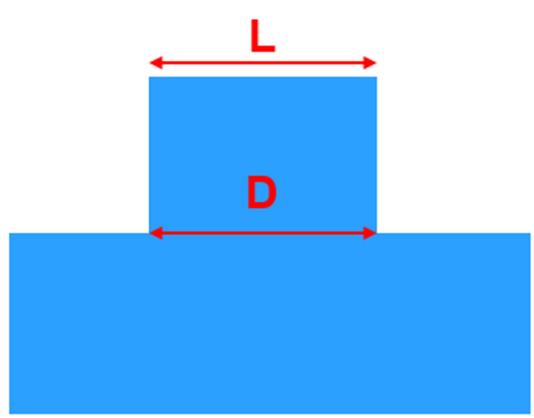

Figure 7: Ratio 1 tooth shape

For the rest of this study, only tooth shape will be considered in order to reduce unnecessary complexity.

REBOUND LEVEL

The rebound level is worse on smaller air gaps. This is why throughout this study, the minimum air gap of 1 mm is considered for the rebound level.

Figure 8 shows the 50% rebound level versus tooth size on the Speed Channel.

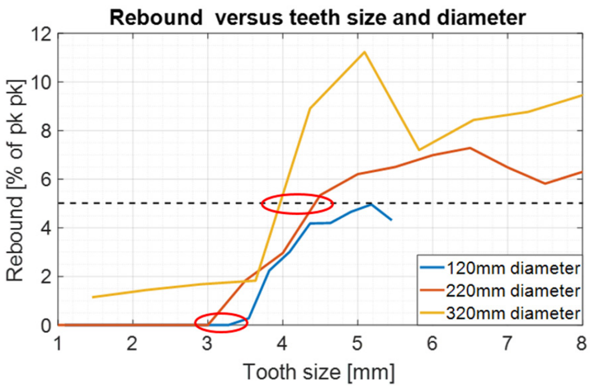

Figure 8: Speed channel 50% rebound level versus tooth size

For applications where the output pulses are sent based on Speed Channel (middle of the tooth), a rebound is undesireable. According to Figure 8, this is satisfied for targets with a maximum tooth size of 3 mm at a target diameter of 220 mm and 3.2 mm at 120 mm diameter. For optimal performance on targets larger than 320 mm diameter, the Dir Channel for switching would offer better performance.

On the other hand, for applications where the output pulses are not sent based on Speed Channel but based on Dir Channel (i.e., at mechanical edge), a rebound of up to 5% for the Speed Channel signal is optimal. According to Figure 8, any tooth size can be used with a small diameter target (120 mm). For targets with a diameter of 220 mm, optimal tooth width is lower than 4.4 mm, and for targets with a diameter of 320 mm, optimal tooth width is lower than 4 mm.

Tooth rebound on the Dir Channel over tooth size is shown in Figure 9.

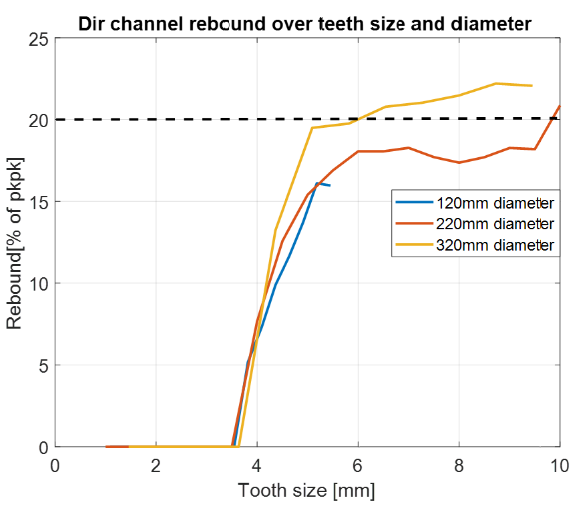

Figure 9: Dir channel tooth rebound over tooth size

As can be seen, except for large targets of 320 mm of diameter with a tooth higher than 5 mm, all other combinations are already within the recommendations.

PEAK-TO-PEAK

Peak-to-peak of Speed Channel and Dir Channel is observed over tooth size and diameter of the maximum air gap of 3 mm.

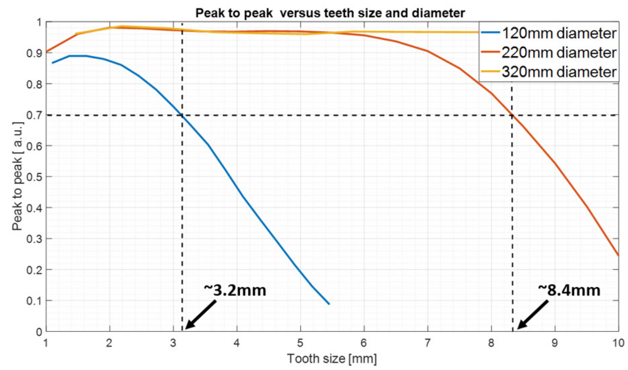

Figure 10: Speed channel peak-to-peak versus teeth size and diameter

Figure 10 shows that the 120 mm target would require a maximum tooth size of 3.2 mm, and the 220 mm target would require a maximum tooth size of 8.4 mm in order to provide more than 3 mm of maximum air gap. On the other hand, the larger target with 320 mm diameter would comply to this condition on any tooth size. This would imply a satisfied jitter performance if the output pulses are sent based on the Speed Channel and if there is no rebound.

Figure 11 plots the dependence of the peak-to-peak of the Dir Channel based on the tooth size.

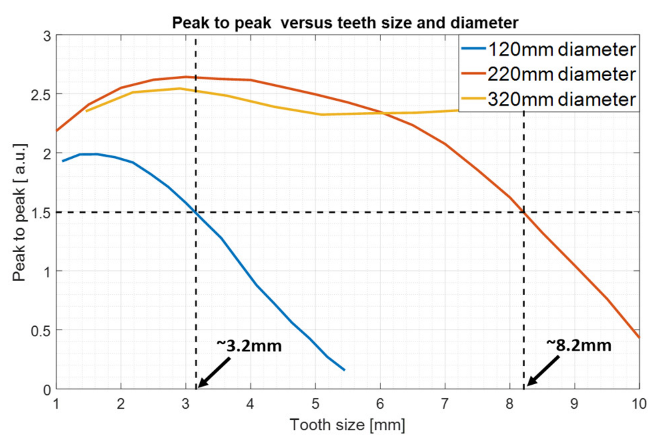

Figure 11: Dir channel peak-to-peak versus tooth size and diameter

Similar to the Speed Channel results, if the output pulses are sent based on the Dir Channel, the peak-to-peak is large enough to meet specifications if the teeth are equal or smaller than 3.2 mm for small diameter targets (<120 mm diameter) and equal to or smaller than 8.2 mm for targets with 220 mm diameter. For the largest target, any tooth size would be good for the desired peak-to-peak limit of the signal.

ABSOLUTE ACCURACY ON MECHANICAL EDGE

The absolute accuracy quantifies the distance in angle degrees between the desired mechanical edge and the actual output pulses based on 50% of the signal. This can also be called a "shift" in angle or a Hard-Edge Offset (HEO). The accuracy on the mechanical edge will be based on both the rising and falling edge of the Dir Channel. The absolute accuracy has a slight air gap dependence; therefore, the performance at 1 mm and 2 mm is plotted simultaneously for comparison.

Figure 12 and Figure 13 show the error between the rising/falling mechanical edge and the actual 50% switching based on the Dir Channel.

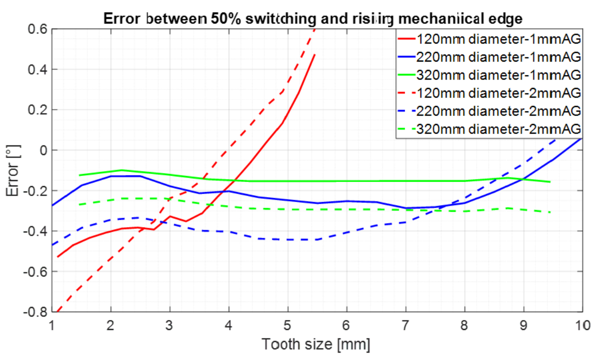

Figure 12: Dir channel rising edge error

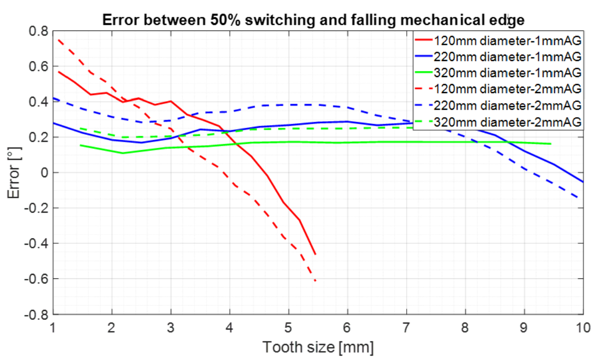

Figure 13: Dir channel falling edge error

As can be seen from these plots, the HEO toward the mechanical edge can change significantly on a 120 mm diameter target over different tooth sizes. For a tooth size around 3 mm, this accuracy is about 0.2°. On the other hand, for larger targets, the accuracy is much more consistent over tooth size. Different methods can be used to compensate for a constant HEO. This can be achieved as described in the application note *Method for Mechanical Mounting Tolerance Compensation on Allegro's Speed Sensors*. Another method relies on an ECU that can be programmed to compensate the fixed HEO for all different kinds of targets (different sized teeth) as long as their diameters are similar.

ABSOLUTE ACCURACY IN MIDDLE OF FEATURE

This absolute accuracy is given by the distance in angle between the middle of the tooth and the actual output based on 50% of the signal. This can also be called a "shift" on angle or a hard offset. The accuracy versus the middle of the tooth will be based on the falling edge of the Speed Channel.

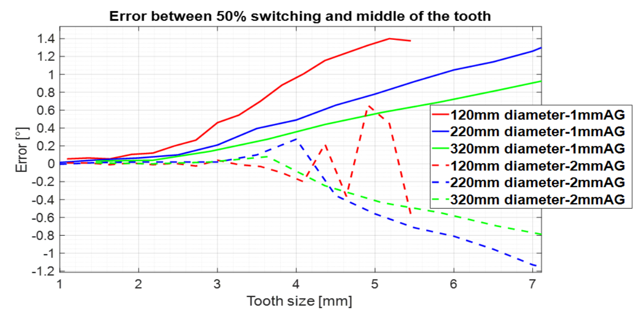

Figure 14: Error between middle of tooth and 50% switching

Figure 14 shows accuracy over tooth size for three types of targets. For a tooth size smaller than or equal to 3.5 mm, the error is non-discernable, and the output is centered in the middle of the tooth. If the tooth size becomes larger, the error starts to become much larger and thus out of usual specifications. Note the nonlinearity of the error in cases where the tooth is larger than 4 mm. This is due to the fact that the switching happens on the flat region and so it can change a lot from case to case. Thus, in cases where the pulse is desired to be located in the middle of the tooth, a small-sized teeth target is strongly suggested.

CONCLUSION

As a conclusion, applications can be separated into two types:

1. Applications that require an output on the mechanical edge (output switching on the Dir Channel)
2. Applications that require the output in the middle of the tooth (output switching on the Speed Channel)

For any of the two applications, for optimal target design, Allegro recommends the use of teeth with length L shorter than 3.5 mm. This would assure a correct function of the device without the risk of having any extra switching due to rebounds.

If a small target with a diameter of 120 mm is used in applications of type one, the ideal target teeth size would be maximum 3.2 mm. For larger targets, any tooth size would have both greater jitter and accuracy performance, and the limiting factor would be rebound.

For applications of type two, it would be preferrable to avoid rebounds on the Speed Channel. The reason is that, having a rebound near the output area would introduce more jitter effect. Unless the jitter performance is not crucial, for these kinds of applications, it is suggested to use target of 120 mm with teeth smaller than ~3.2 mm, or targets of 220 mm with teeth smaller than 3 mm. It is not recommended to use targets with a diameter of 320 mm for these applications.

As a general conclusion, application one would give a much better jitter and consistent accuracy (if HEO can be compensated) than application two. This happens because on the Dir Channel, there is no rebound and the peak-to-peak of the signal is much larger than that of the Speed Channel.

Classic ferromagnetic materials can be used for the targets (see application note *Impact of Magnetic Relative Permeability of Ferromagnetic Target on Back-Biased Sensor Output*). Generally, a thickness of equal or greater than 3 mm would be preferred in order to have good detection of the teeth.

If the diameter of the target is different from the ones represented in this document, two solutions can be considered:

1. Send this diameter to the Allegro technical support team to help design the optimized target
2. Use the value of the diameter of the target shown in this document that is smaller than the real diameter in order to determine the other parameters

Allegro technical support can assist in designing the best target for a specific application.

For recommendations about transmission applications, refer to application note *Target Design For Hall Transmission Sensors* or in case of e-motors to *Magnetic Encoder Design for Electrical Motor Driving Using ATS605LSG*.

Revision History

Number	Date	Description	Responsibility
–	March 4, 2022	Initial release	E. Pavlov, Y. Vuillermet