Project: E-Mobility
Approved by: N/A

Created on: 06 January 2016
Last modified: 21 March 2017

MPC5744 resolver interfacing

Analysis document

Abstract:

This document describes possible options on how to interface a resolver directly to the MPC5744 without the use of an external resolver interface IC.

Revision History

Version	Date	Modifier	Description of modifications
0.1	2017-03-17	Gergely DZSUDZSÁK	Initial version

Distribution

Company	Name	Date of last distribution

List of Symbols and Abbreviations

Abbreviation	Description
AC	Alternating Current
ADC	Analogue to Digital Converter
DC	Direct Current
LSB	Least Significant Bit

References

No.	Authors	Title	Version
1.	Analog devices	AD2S1210 datasheet http://www.analog.com/media/en/technical-documentation/data-sheets/AD2S1210.pdf	Rev. A
2.			
3.			

Contents

List of Figures

List of Tables

1 Introduction

This document deals on how to process resolver signals directly with the MPC5744 without the use of external resolver interface ICs.

This document does **NOT DEAL** with:

- circuits necessary to interface the resolver signals to the ADC inputs,
- circuits necessary to generate and amplify the resolver excitation signal.

The following are assumed in this document:

- properly scaled (=using as much as possible of the converter input range) analogue signals are connected to the ADC inputs,
- the analogue signals are differential,
- the excitation signal, and the two sense signals are measured,
- the excitation signal generation and the sampling are done synchronously (if asynchronous sampling is simulated, then this is explicitly noted).

2 Resolver signal processing

This chapter generally deals with topics related to resolver signal processing which are not directly related to the used interface type.

2.1 Resolver input/output signals

Resolvers usually have 6 connections, 2 are used to input the excitation signal, 2 are used to output a sense signal and the remaining 2 are used to output another sense signal.

Resolvers (regardless of their type) need an excitation signal, since they are essentially rotating transformers, coupling the excitation signal onto the sense signals in function of the rotor angle.

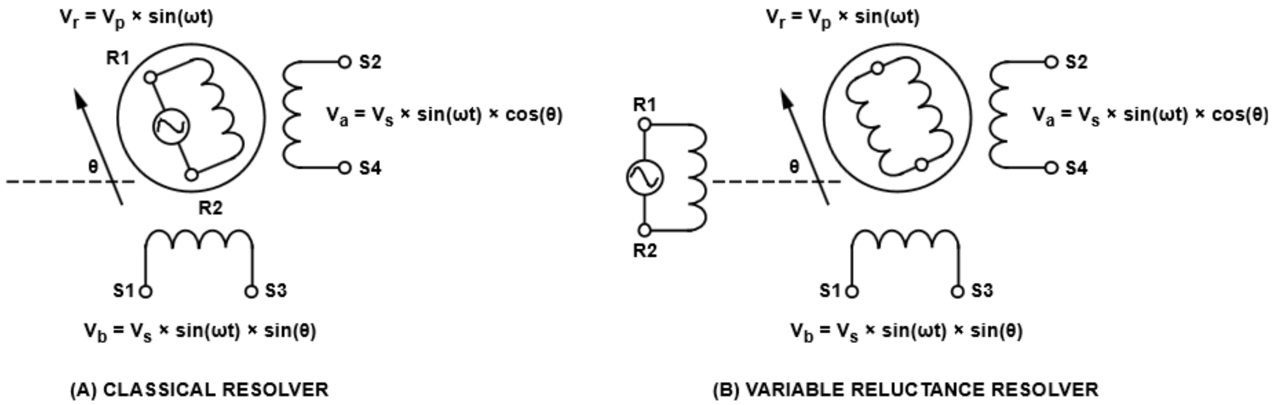


Figure 1 Resolver types [1]

The figure above shows two resolver types. The actual type is not really important, only that the input and output signals have a specific relation to each other. (Inputs R1 and R2 connect to the excitation signal, while outputs S1 and S3 connect to one of the sense windings, while outputs S2 and S4 connect to the other sense winding.) The angle θ represents the rotor angle. There are resolvers where the rotor (mechanical) angle is multiplied by design with an integer factor to increase the output signal resolution. (For example if this multiplication factor is the same as the pole pair count of the electric motor used, then the resolver angle signal can be used directly in the motor control.)

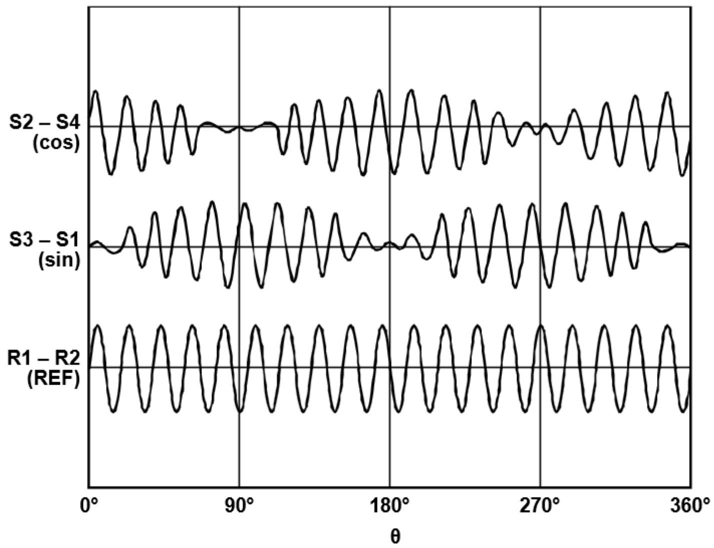


Figure 2 Resolver signals [1]

The figure above shows the resolver signals. It can be seen, that the excitation signal (REF) is a continuous sine wave with fixed amplitude. The two output signals (sin and cos) are both amplitude modulated versions of the excitation signal (with some additional phase shift).

$$S2 - S4 = K * REF * \cos(\theta)$$

$$S3 - S1 = K * REF * \sin(\theta)$$

$$REF = A * \sin(\omega t)$$

The equations above show the **ideal** behavior of each signal. The excitation signal is just a free running sine signal with a given amplitude (A) and frequency (ω). The sense signals have a static coupling factor (K) from the excitation signal and a dependency on the rotor angle θ. This corresponds to double-sideband suppressed-carrier modulation, which can not be demodulated just by envelope detection, the phase difference between the excitation and the sense signals has to be taken into account.

2.2 Auxiliary signal processing

Before the resolver signals can be processed some errors in the signals need to be corrected. These are:

- DC offset on the single ended signals (these may not cancel each other completely during the subtraction step),
- amplitude mismatch between the channels and also to the expected value (the following processing stages may expect properly scaled signals),
- offset error on the modulating signals (meaning that the average of the sin(θ) or cos(θ) modulating signal is not zero over a complete rotation, this is a resolver error),
- angular mismatch between the two demodulated sense signals (sine and cosine are not spaced 90° apart, this will not be discussed here),
- harmonics in the two demodulated sense signals (this will not be discussed here).

2.2.1 DC offset correction/tracking

There are multiple options to deal with DC offset (coming from the ADC and sense circuit inaccuracies):

- no DC offset correction, causes errors during demodulation, but as long as the errors are small this is fine (effect will be shown later)
- end-of-line calibration (may be used to remove static errors, but temperature and lifetime effects will be not removed),
- digital highpass filtering the signals, which would add additional delay to the processing loop, increasing the angle error at high speeds,

- digital lowpass filtering the signals (over significant amount of excitation periods) and then subtracting the lowpass filtered signal from the input signal (this way there is no additional delay in the processing loop),
- filtering the DC offset in the demodulation filter (which would mean stricter requirements for that filter, and probably cause additional delay as well.

In the later chapters the effects of not removing the DC offset are examined, but the correction methods listed here are not compared in effectiveness.

2.2.2 Modulating signal amplitude and offset correction/tracking

The modulating signals may have offsets and amplitude errors, which should be corrected before processing the signals any further. There are multiple options to deal with these errors as well:

- no amplitude and offset correction of the modulating signals (as long as the errors are small the angular error will be also small, the effects of these errors will be shown later),
- end-of-line calibration (calibrate end-of-line and then use those coefficients throughout the lifetime of the product),
- peak search on the raw signals to determine the positive and negative amplitude and from those the necessary correction factors (if the signals have DC offset, then that will influence the results and with the peak search the true amplitude may not be found correctly for a motor rotating at high speeds),
- peak search on lowpass filtered demodulated signal outside of the processing loop (no additional delays due to filtering inside processing loop)
- peak search on lowpass filtered demodulated signal inside the processing loop (same as above, but the next stages also using the lowpass filtered signal, this has drawbacks due to the filtering inside the processing loop, but not for the amplitude and offset tracking)

2.3 Signal processing options

The majority of applications using resolvers is using one of these techniques to extract the demodulated sense signals of the resolver:

- timed (or “critical”) sampling of all signals at the peaks of the excitation signal (which means basically two samples per excitation period, which is demodulation by sampling),
- oversampling of the resolver signals and using these samples to create the demodulated sense signal, these would be some options on how to deal with the sampled signals:
  - peak search on the oversampled excitation signal to determine which sense signal samples to use (which is basically equivalent to the critical sampling and therefore probably wasteful because it throws away samples and it only provides two values each excitation period),
  - peak search and then function fitting to determine the true peak location (which may be numerically intensive and it still provides only two samples per excitation period),
  - demodulating the sense signals by multiplying them with the excitation signal and using all values in the later stages (this could use much of the available samples, except of course where the signals have a zero crossing and the demodulated signal has a significant amount of harmonics which the later stages have to deal with)
  - demodulation by multiplication followed by lowpass filtering (eliminates the harmonics in the demodulated signal at the expense of introducing a time delay and therefore angle error at high speeds)

Only three methods are investigated in this document:

- peak search oversampling (without function fitting) which, with properly selected parameters is equivalent to critical sampling
- demodulation without filtering
- demodulation with filtering

All three implemented methods use a type II tracking loop to extract the actual angle and the actual speed.

2.3.1 Peak search with oversampling

This method determines the maximum and minimum locations on the excitations signal and then extracts the sine and cosine signal values from the sense signals at the same time instants. (At the minimum location the sine and cosine signals are inverted.)

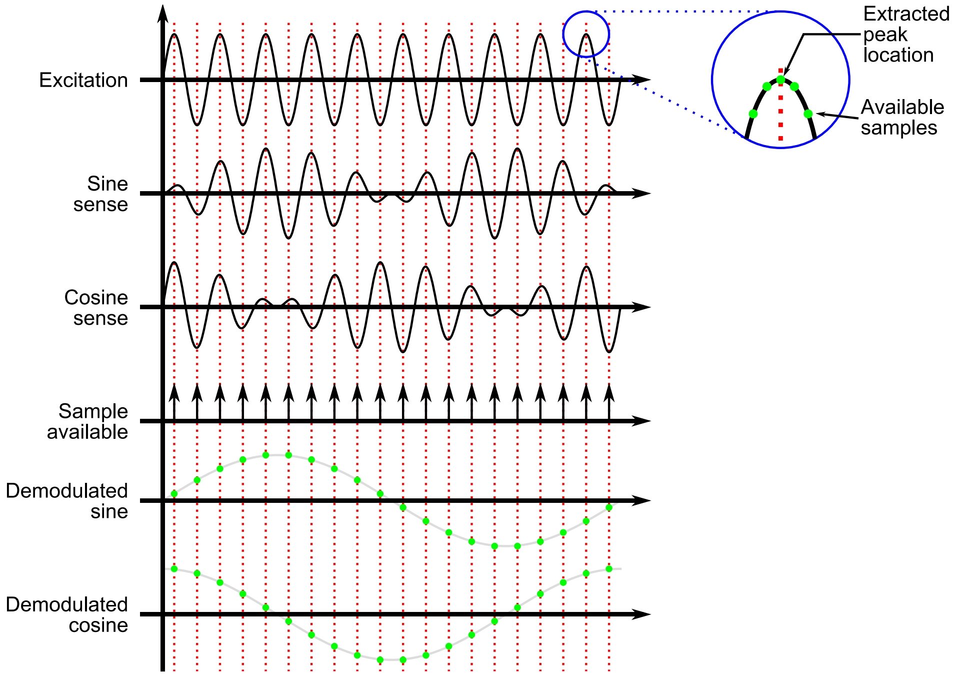


Figure 3 Peak search demodulation

The figure above shows the input and output signals of the peak search algorithm. As it can be seen demodulated **samples are available twice in each period** and the exact peak location is determined based on the excitation signal. The sense signal values at the same moment are then forwarded to further processing, all the other samples are thrown away.

2.3.2 Demodulation without filtering

This method basically multiplies the excitation and the sense signals together to get a demodulated signal (with significant harmonic content) to be fed into the tracking loop.

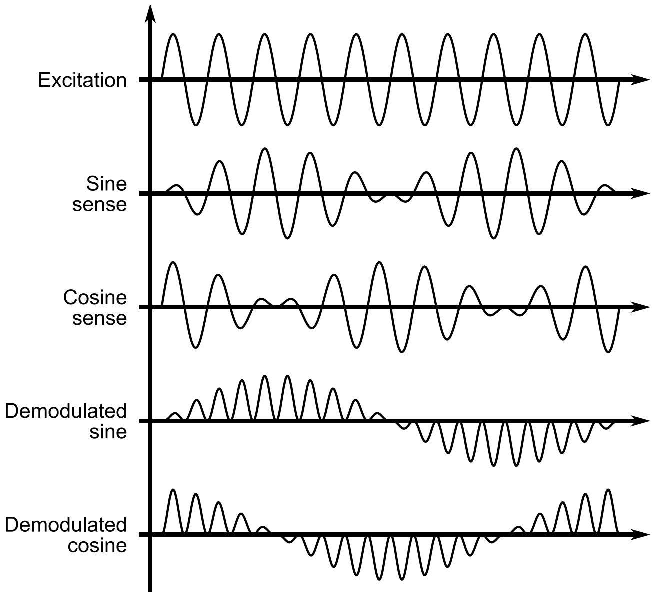


Figure 4 Demodulation without filtering

The figure above shows the inputs and outputs of the demodulation algorithm. (As already mentioned the output signals have significant harmonic content). The advantage of this demodulation is, that all input samples are processed and can be fed into the tracking loop. (The tracking loop has then to deal with the harmonics.)

2.3.3 Demodulation with filtering

In this method the excitation and sense signals are multiplied together and the lowpass filtered to get a demodulated signal with some phase shift.

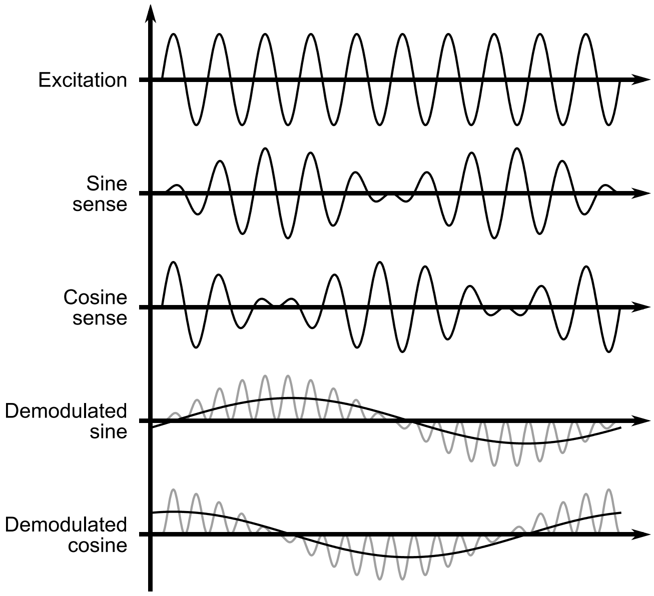


Figure 5 Demodulation with filtering

The figure above shows the inputs and outputs of this demodulation algorithm. In light grey the input signals to the filters are shown and the filter output is shown in black. Due to the filtering there is some phase shift between the true sine and cosine signals and the filtered sine and cosine signals. Since the harmonics are already filtered out the tracking loop gets a more stable input signal, but with additional phase shift, which will then show up on its output as angle error.

3 Interfacing to the MPC5744

This chapter deals with the ADC connections and sampling configuration of the resolver signals. The following possible sampling configurations were investigated:

- ideal sampling, where all resolver signals are sampled at the same time (this is not possible on the MPC5744 when all 6 resolver signals have to be sampled and is only investigated to see the behaviour under ideal conditions),
- differential sampling, where each signal pair is sampled at the same time and there is a sampling time delay between the pairs (so at first the two sine signals are sampled, next the cosine signals and at last the excitation signals), this way only two ADCs have to be triggered simultaneously,
- polarity sampling, where from each pair the same polarity signals are sampled at the same time (so the noninverted (positive signal out of the differential pair) sine, cosine and excitation signals are sampled first and then the inverted (negative signal out of the differential pair) sine, cosine and excitation signals are sampled),
- two ADC sampling, which is similar to polarity sampling with the exception that first the positive sine and cosine signals are sampled, then the excitation signal pair and finally the negative sine and cosine signals.

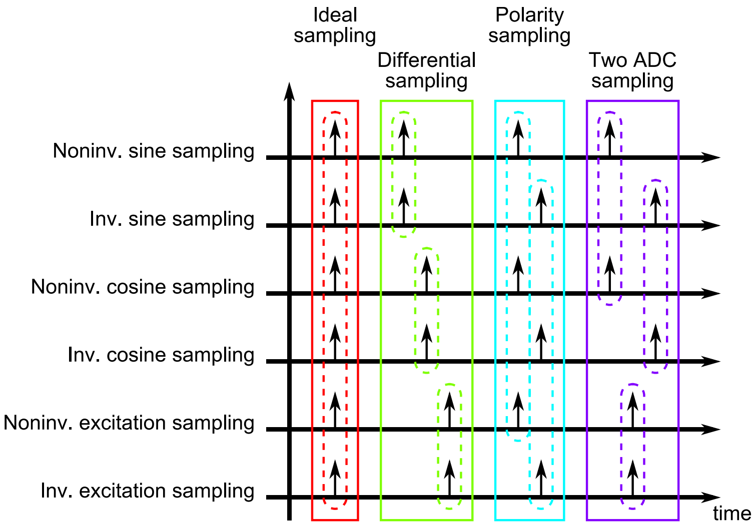


Figure 6 Comparison of the different sampling methods

The figure above shows the different sampling method sample groups. Each method has a different colored rectangle and in each rectangle the groups of signals sampled at the same time are in the same colored, smaller rectangles with dashed outlines.

4 Simulation results

This chapter shows the simulation results for the different sampling methods.

In general the simulations were performed with the following settings if not noted otherwise:

- 10 kHz resolver excitation frequency,
- 80 kHz sampling frequency,
- tracking loop bandwidth of 1500 rad/sec and a damping factor of 1.0,
- 0 μs initial sampling delay,
- 0° phase shift between excitation signal and sense output excitation component,
- 0 V uniform distribution noise amplitude (noise off),
- 1 μV ADC LSB size (almost ideal sampling)
- 0.5 V excitation signal amplitude (giving a differential amplitude of 1 V),
- 0.5 V excitation signal offset,
- 0.5 V sense signal offset (on all 4 sense signals),
- sense signal coupling factor of 1.0 (sense signals have the same maximal amplitude as the excitation signals),
- for the raw and filtered demodulation the tracking loop input signals were multiplied by 2 to correct for the gain loss due to the demodulation,
- sense signal modulating signal offset of 0.0,
- simulation starting angle of 0°,
- simulated angular acceleration of 120000 RPM/sec for 0.5 seconds (top speed of 60000 RPM, due to the expected maximal motor speed of 30000 RPM and a multiplication factor of 2 between the mechanical speed and the resolver signal output speed).

In some cases the values are not the expected ones (sense signal coupling factor or ADC LSB size or excitation amplitude). The reason for this was to keep the simulation simple, so some common factors or not required scaling factors were eliminated.

4.1 Ideal resolver signals with different sampling methods

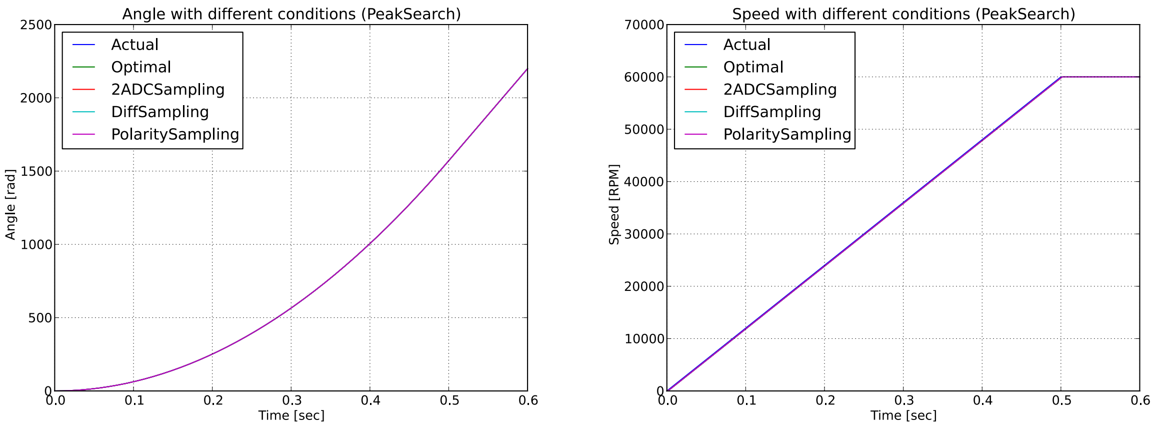


Figure 7 Rotor angle and speed in function of time

The figures above show the rotor angle and speed in function of time. Since for most of the results the actual (real) value and the estimated value overlap closely these figures will only be shown once, as information, and afterwards only the errors (in angle and speed) will be shown. (As already discussed the rotor peak speed is 60000 RPM, due to the multiplication factor of the resolver.)

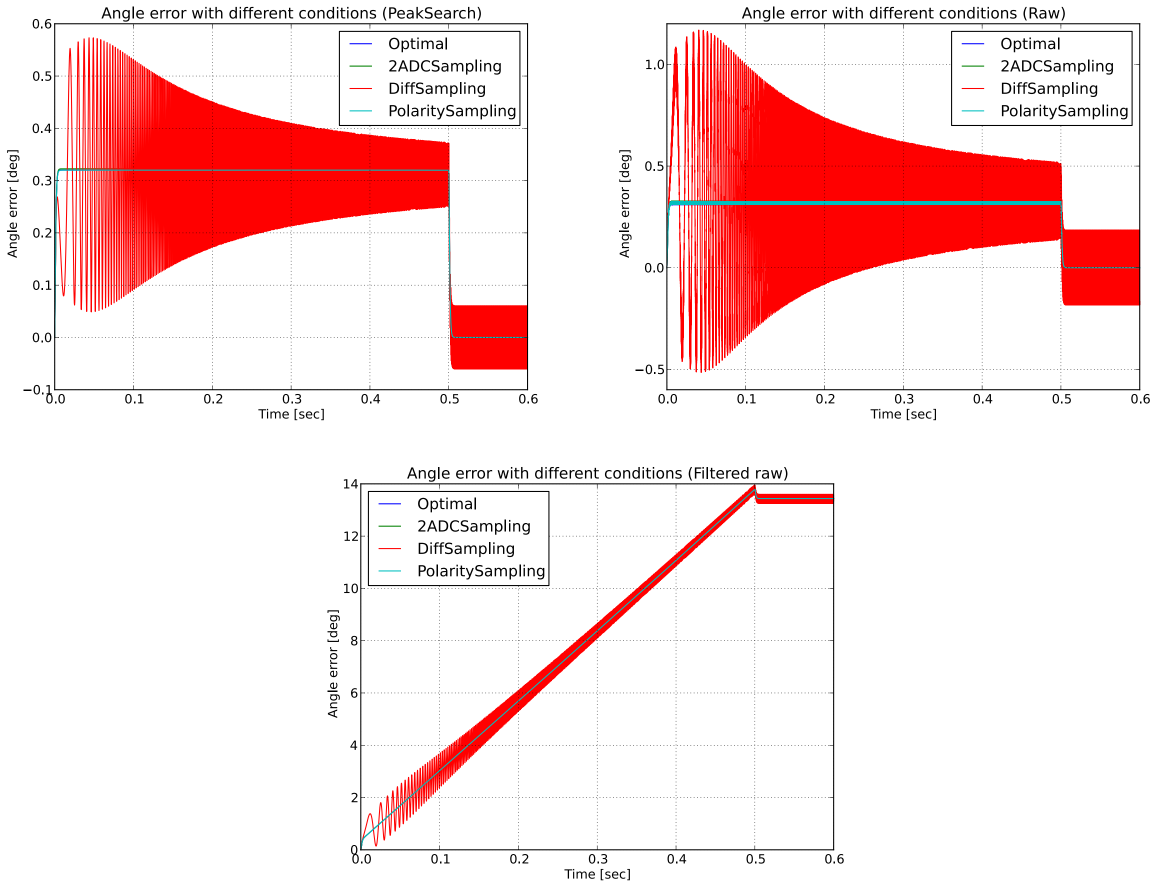


Figure 8 Rotor angle errors with various sampling methods under ideal circumstances

The figures above show the rotor angle error with the various sampling methods already discussed. As already discussed the filtered demodulation (denoted as “filtered raw”) has significant error at higher speeds due to the intrinsic delay of the demodulation filter. The next significant discovery is, that the pairwise differential sampling ("DiffSampling") shows significant errors compared with the other methods. The error in the unfiltered demodulation method is somewhat larger, than the error of the peak search method (only for the pairwise differential sampling). All the other sampling methods overlap the optimal sampling closely.

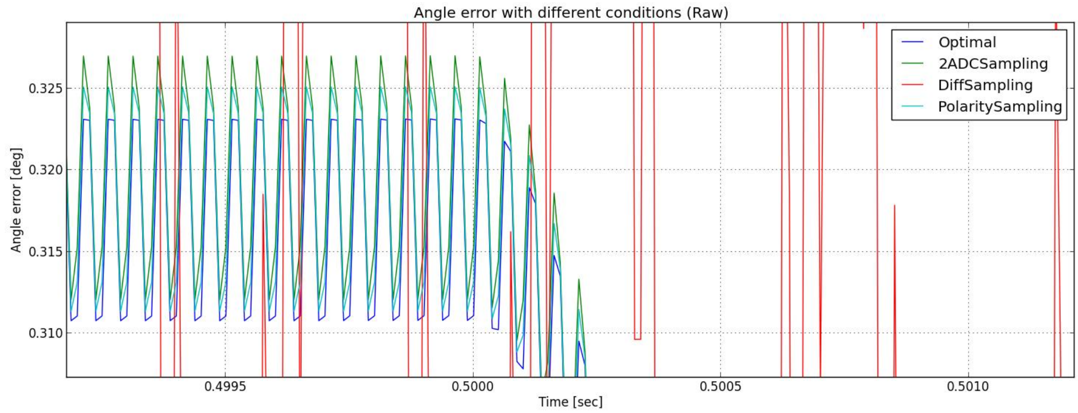


Figure 9 Rotor angle errors with unfiltered demodulation (zoom on good sampling methods)

The figure above shows a closer view on the error of the better sampling methods. As it can be seen even the optimal sampling has some noise on the error signal if the motor accelerates. The polarity based sampling and the 2 ADC sampling have a little bit higher average error. (In general since the signal sampling is synchronized to the excitation the real amplitude of the noise on the error signal would be somewhat larger, but of course the average value would stay the same.)

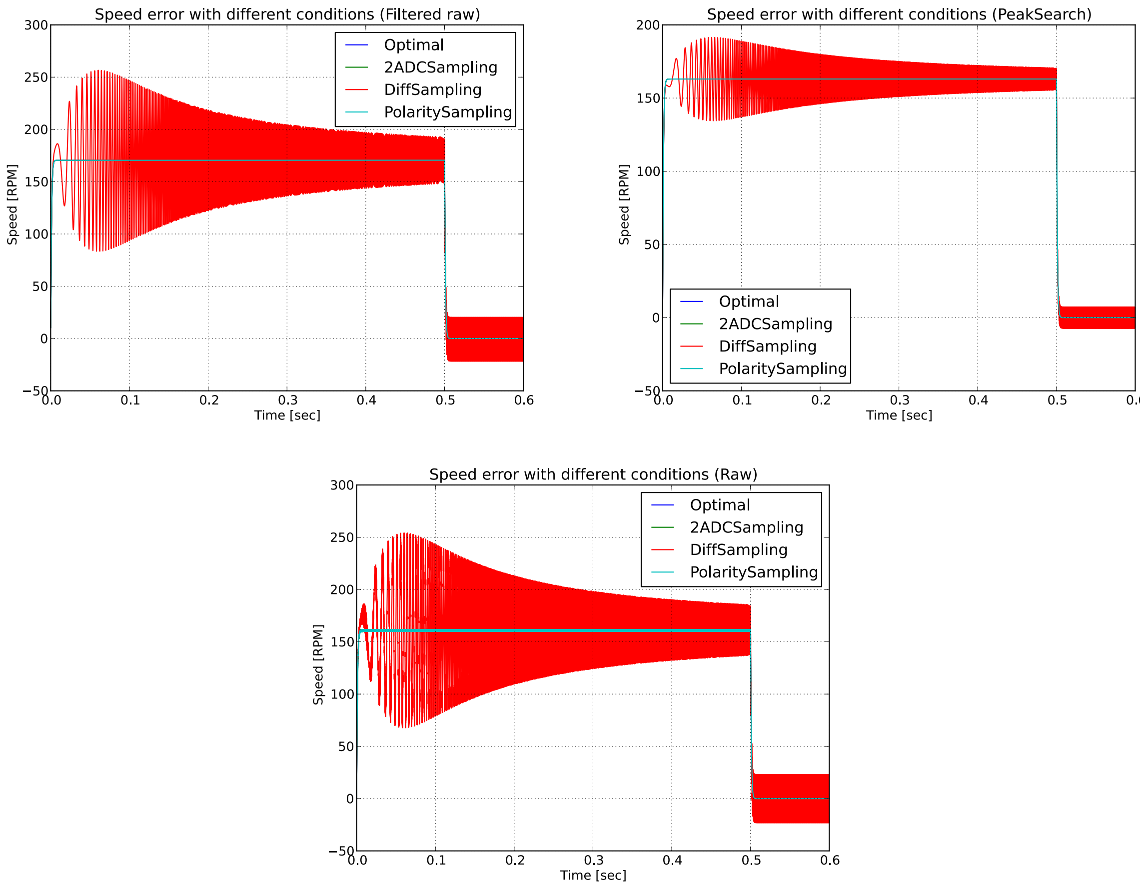


Figure 10 Rotor speed errors with various sampling methods under ideal circumstances

The figures above show the rotor speed errors for the various sampling methods. The most important point is, that as seen on the rotor angle error the pairwise differential sampling produces the largest error, with all the other sampling method results basically producing the same stable error.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,320°	0,000°	162,98 RPM	0,00 RPM	0,000°	0,000°	2,25 RPM	0,00 RPM
	2ADCSampling	0,323°	0,000°	162,98 RPM	0,00 RPM	0,003°	0,000°	2,25 RPM	0,00 RPM
	DiffSampling	0,311°	0,000°	162,92 RPM	-0,01 RPM	0,103°	0,043°	12,40 RPM	5,33 RPM
	PolaritySampling	0,320°	0,000°	162,98 RPM	0,00 RPM	0,000°	0,000°	2,25 RPM	0,00 RPM
Unfiltered demodulation	Optimal	0,317°	0,000°	160,75 RPM	0,00 RPM	0,007°	0,000°	0,76 RPM	0,00 RPM
	2ADCSampling	0,320°	0,000°	160,75 RPM	0,00 RPM	0,006°	0,000°	0,76 RPM	0,00 RPM
	DiffSampling	0,326°	0,001°	160,90 RPM	0,00 RPM	0,280°	0,120°	33,59 RPM	14,87 RPM
	PolaritySampling	0,318°	0,000°	160,75 RPM	0,00 RPM	0,006°	0,000°	0,76 RPM	0,00 RPM
Filtered demodulation	Optimal	7,037°	13,421°	170,43 RPM	0,00 RPM	7,397°	13,431°	9,72 RPM	0,00 RPM
	2ADCSampling	7,036°	13,415°	170,43 RPM	0,00 RPM	7,396°	13,424°	9,72 RPM	0,00 RPM
	DiffSampling	7,044°	13,414°	170,60 RPM	0,02 RPM	7,407°	13,425°	37,00 RPM	15,67 RPM
	PolaritySampling	7,037°	13,418°	170,43 RPM	0,00 RPM	7,397°	13,428°	9,72 RPM	0,00 RPM

Table 1 Signal statistics for different sampling methods with ideal circumstances

The table above shows some statistics about the different sampling methods and demodulation methods. As it was visible on the figures above the pairwise differential sampling ("DiffSampling") and the filtered demodulation method both have significant disadvantages.

The columns of the table are as follows:

- Method: demodulation method name,
- Test case: test case name, which is the sampling method in this case,
- Average angle error (accelerating): shows the average angle error to the real (true) angle while the rotor is accelerating (average from 0.05 s to 0.45 s),
- Average angle error (stable speed): shows the average angle error to the real (true) angle while the rotor speed is stable (average from 0.52 s to 0.59 s),
- Average speed error (accelerating): shows the average speed error to the real (true) speed while the rotor is accelerating,
- Average speed error (stable speed): shows the average speed error to the real (true) speed while the rotor speed is stable,
- RMS angle error to ideal (accelerating): shows the RMS angle error compared to an ideally sampled and processed output angle signal (with the tracking loop parameters shown before) while the rotor is accelerating,
- RMS angle error to ideal (stable speed): shows the RMS angle error compared to an ideally sampled and processed output angle signal while the rotor speed is stable,
- RMS speed error to ideal (accelerating): shows the RMS speed error compared to an ideally sampled and processed output angle signal while the rotor is accelerating,
- RMS speed error to ideal (stable speed): shows the RMS speed error compared to an ideally sampled and processed output angle signal while the rotor speed is stable.

4.2 Noisy resolver signals with different sampling methods

In this chapter the same sampling methods with the same rotor speed profile are investigated with additional uniformly distributed noise on the signals with an amplitude of 2.5mV, which corresponds to 5‰ of the single ended signal amplitudes, which corresponds to approximately ±20 LSB noise on a 12 bit ADC.

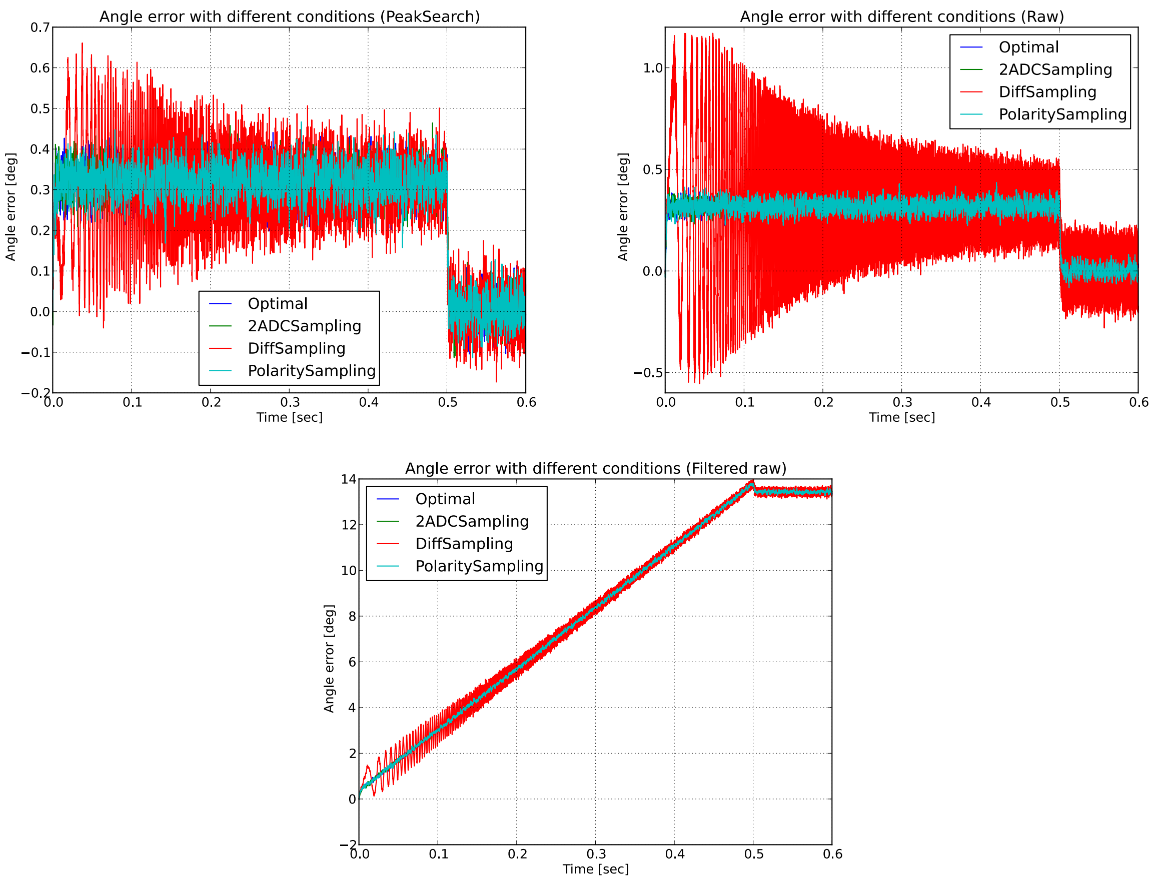


Figure 11 Rotor angle errors with various sampling methods with noisy input signals

The figures above show the angle error in case there is noise on the input signals. As expected the pairwise differential sampling is still the worst of all sampling methods. It should be noted, that in case of the peak search algorithm the relative error amplitudes are not that much different between the four sampling methods! This is of course due to the fact, that the peak search algorithm only uses two samples out of the 8 available per excitation period. Using more samples provides an advantage in terms of output noise as it can be seen in the simulation results of the unfiltered demodulation algorithm. The noise level reduction is significant, but it is not halved, because the relative noise level on the samples not at the signal peaks is worse, so they do not provide that much noise reduction which would be the case if the relative noise level for all samples would be the same.

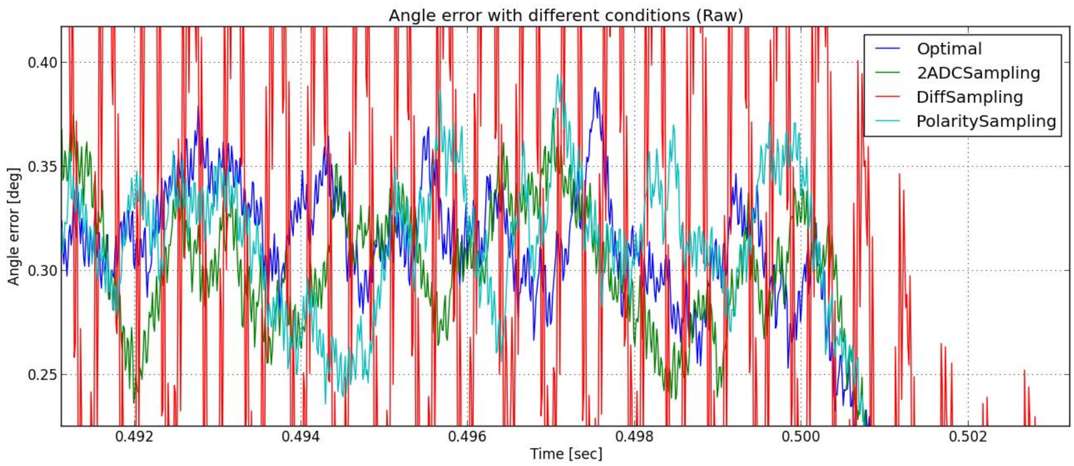


Figure 12 Rotor angle errors with various sampling methods with noisy input signals (zoom on acceleration end)

The figure above shows the angle error of the unfiltered demodulation algorithm at the end of the acceleration phase. The error amplitudes on the signals produced by the usable sampling methods is similar.

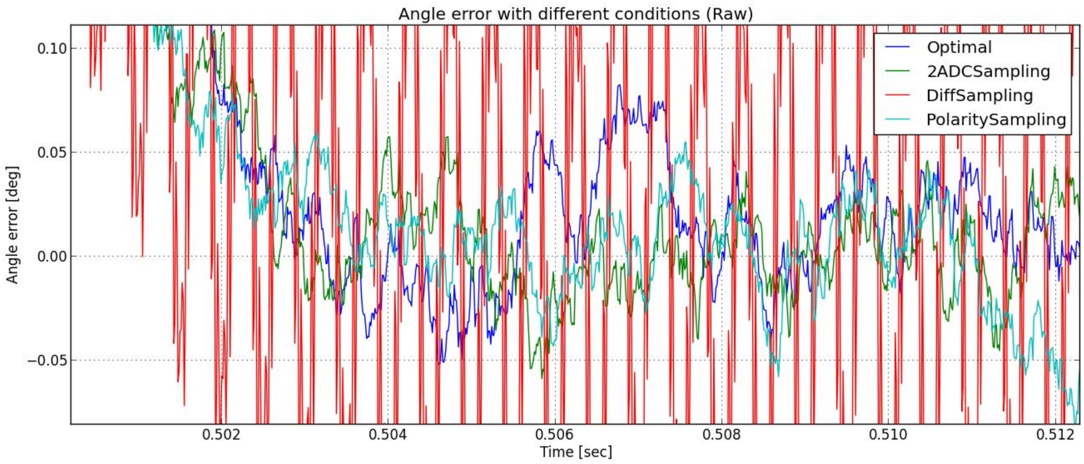
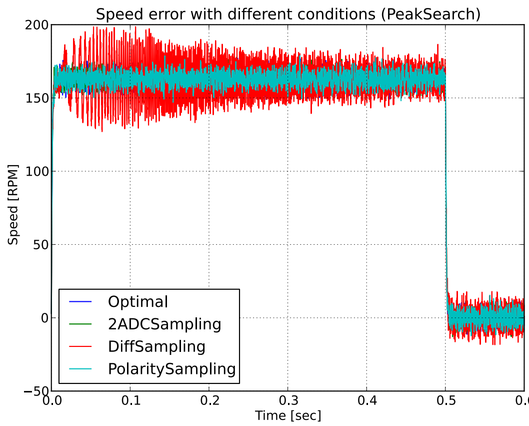
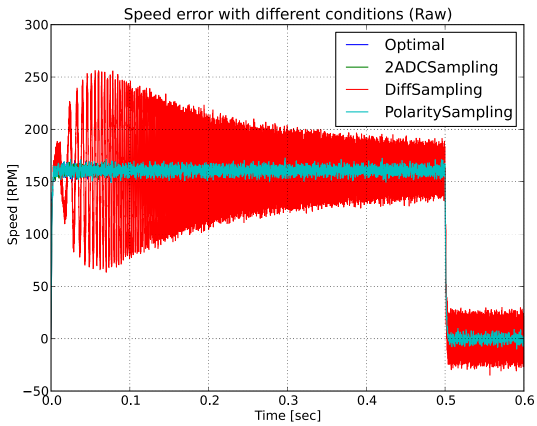


Figure 13 Rotor angle errors with various sampling methods with noisy input signals (zoom on stable speed)

This figure shows the rotor angle error at the beginning of the stable speed period. The peak-to-peak error amplitude of the good sampling methods is very similar. (So at stable speed the used sampling method does not seem to matter much as long as the average sampling delay of the differential sine and cosine signals is similar.)





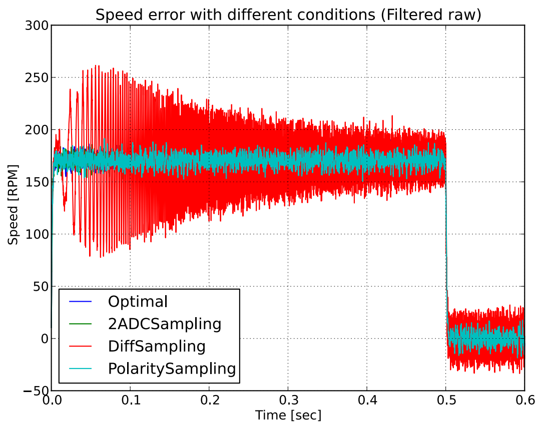


Figure 14 Rotor speed errors with various sampling methods with noisy input signals

The rotor angle speed figures also show basically the same result as the angle error figures. The ADC sampling does not seem to matter much if there is noise in the system. (Except of course the pairwise differential sampling, which still produces larger errors than the other methods.)

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,320°	0,000°	163,00 RPM	0,07 RPM	0,039°	0,039°	4,86 RPM	4,36 RPM
	2ADCSampli	0,320°	0,000°	162,97 RPM	-0,02 RPM	0,037°	0,036°	4,71 RPM	4,10 RPM
	DiffSampling	0,311°	0,003°	162,92 RPM	-0,02 RPM	0,112°	0,058°	13,28 RPM	6,75 RPM
	PolaritySamp	0,321°	0,004°	162,98 RPM	0,06 RPM	0,038°	0,039°	4,69 RPM	4,33 RPM
Unfiltered demodulation	Optimal	0,318°	0,000°	160,75 RPM	0,01 RPM	0,026°	0,026°	2,98 RPM	2,87 RPM
	2ADCSampli	0,320°	0,003°	160,75 RPM	0,01 RPM	0,027°	0,027°	3,04 RPM	2,97 RPM
	DiffSampling	0,328°	0,002°	160,91 RPM	0,00 RPM	0,281°	0,122°	33,64 RPM	15,09 RPM
	PolaritySamp	0,318°	0,004°	160,74 RPM	0,01 RPM	0,027°	0,025°	3,01 RPM	2,80 RPM
Filtered demodulation	Optimal	7,040°	13,426°	170,43 RPM	0,07 RPM	7,401°	13,436°	11,12 RPM	5,46 RPM
	2ADCSampli	7,037°	13,414°	170,41 RPM	-0,08 RPM	7,396°	13,424°	10,96 RPM	5,74 RPM
	DiffSampling	7,045°	13,417°	170,61 RPM	0,02 RPM	7,408°	13,427°	37,25 RPM	16,24 RPM
	PolaritySamp	7,040°	13,412°	170,44 RPM	-0,01 RPM	7,400°	13,422°	11,20 RPM	5,57 RPM

Table 2 Signal statistics for different sampling methods with noisy input signals

As already discussed the unfiltered demodulation algorithm has a little bit smaller speed noise, but otherwise the output angle error is very similar to the peak search method values.

4.3 Noisy resolver signals with different sampling methods and ADC LSB size

In this chapter the simulation results with 2.5mV noise amplitude and 0.25mV LSB size (which corresponds to an ADC resolution of approximately 12 bits.)

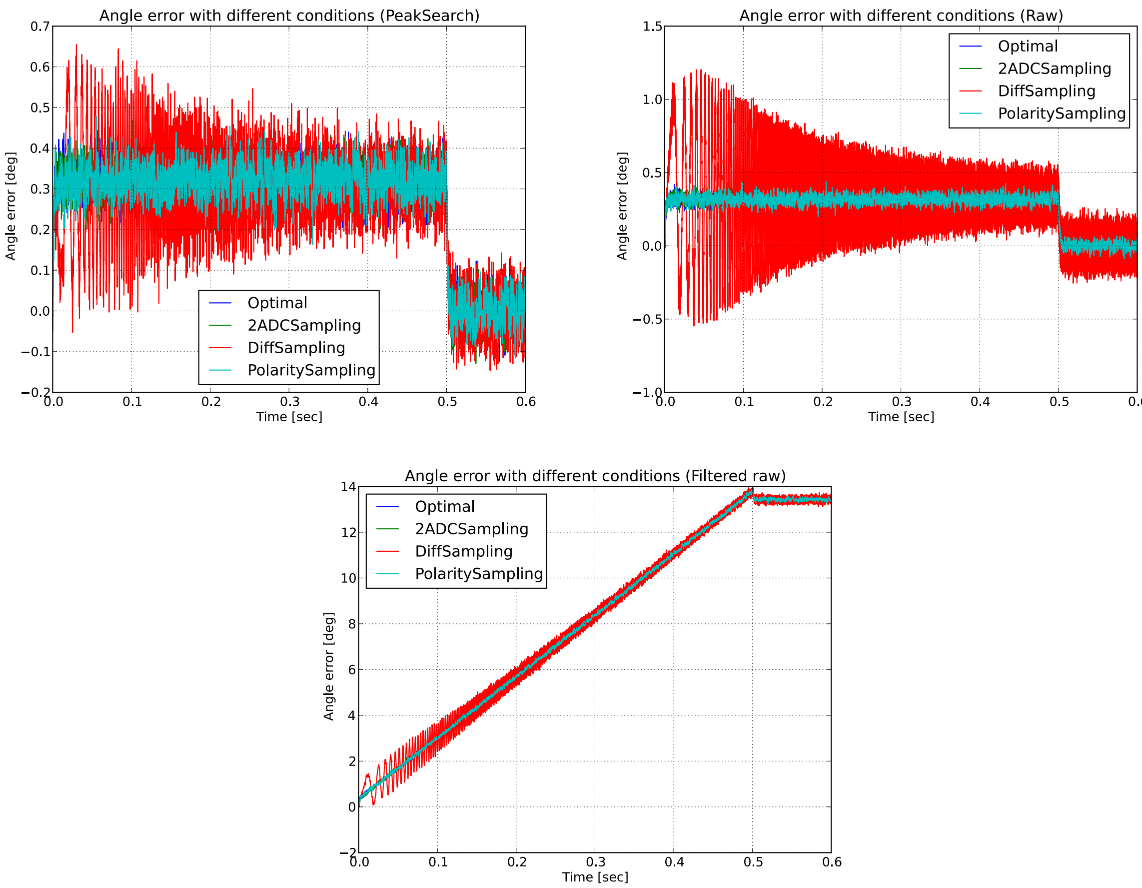


Figure 15 Rotor angle errors with various sampling methods with noisy input signals and limited ADC resolution

There is no significant increase in noise level when the ADC resolution is limited, because it is essentially additional noise which is swamped by the significantly larger amplitude of the external noise.

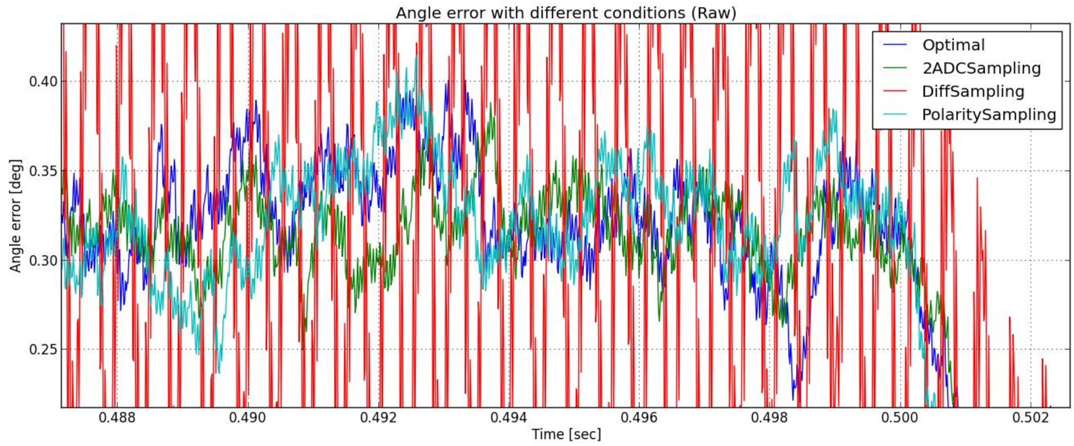


Figure 16 Rotor angle errors with various sampling methods with noisy input signals and limited ADC resolution (zoom on acceleration end)

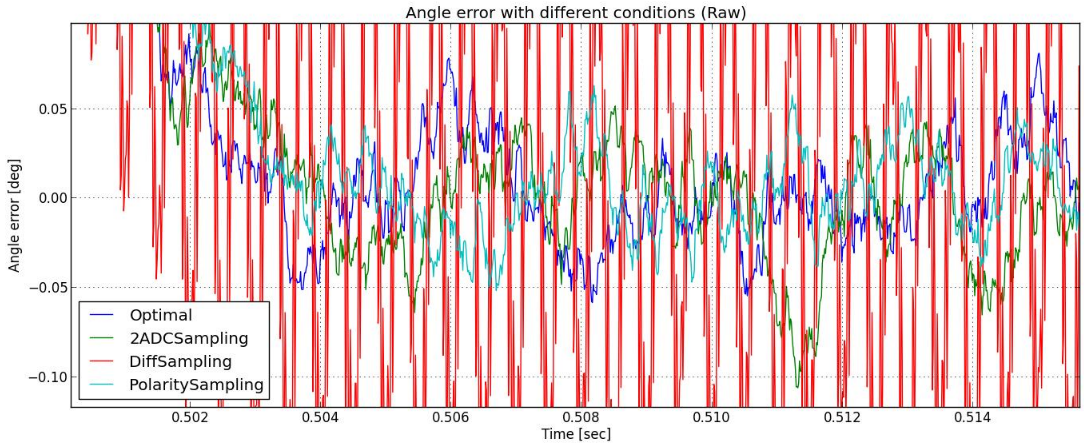


Figure 17 Rotor angle errors with various sampling methods with noisy input signals and limited ADC resolution (zoom on stable speed)

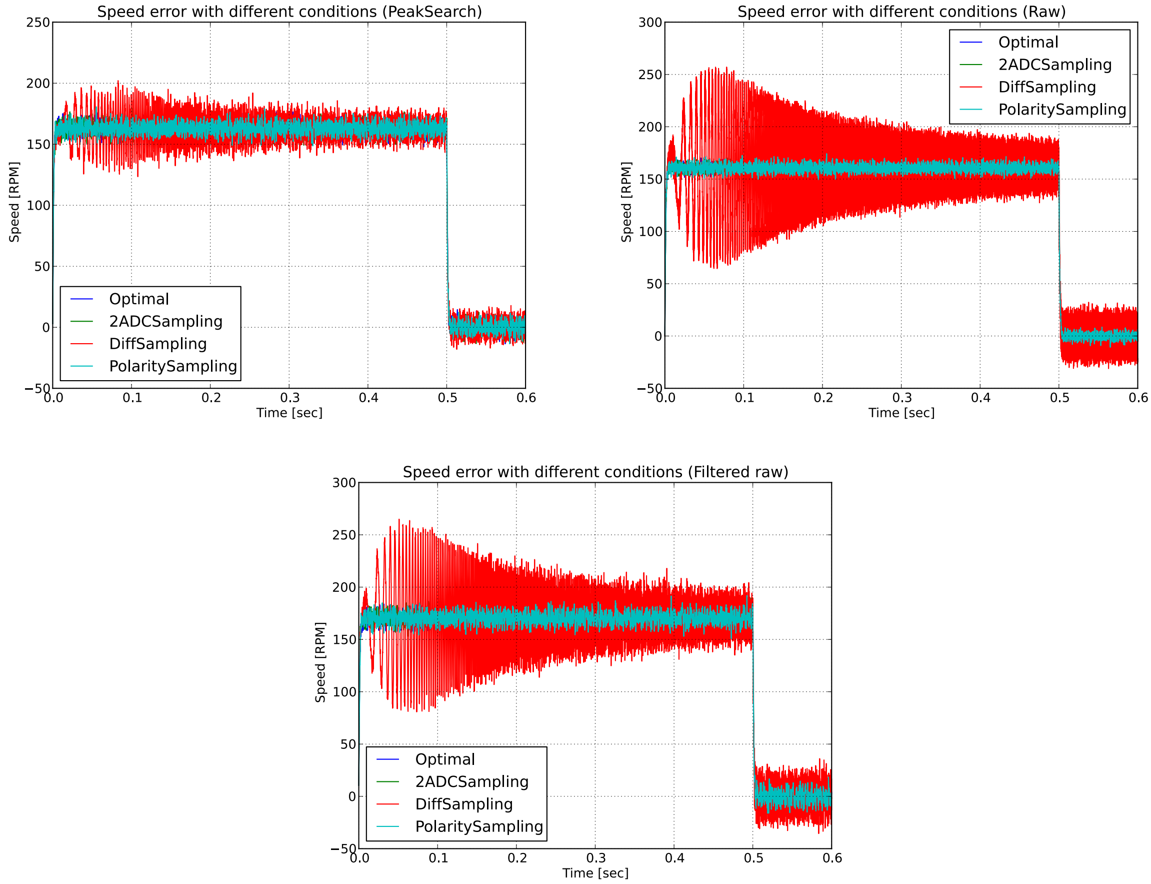


Figure 18 Rotor speed errors with various sampling methods with noisy input signals and limited ADC resolution

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,319°	0,002°	162,97 RPM	0,05 RPM	0,037°	0,038°	4,67 RPM	4,11 RPM
	2ADCSampling	0,321°	0,000°	163,00 RPM	0,06 RPM	0,038°	0,037°	4,82 RPM	4,23 RPM
	DiffSampling	0,310°	-0,006°	162,92 RPM	-0,01 RPM	0,111°	0,057°	13,19 RPM	6,64 RPM
	PolaritySampling	0,323°	-0,001°	162,96 RPM	-0,03 RPM	0,038°	0,037°	4,69 RPM	4,05 RPM
Unfiltered demodulation	Optimal	0,315°	-0,001°	160,76 RPM	-0,02 RPM	0,026°	0,025°	2,83 RPM	2,72 RPM
	2ADCSampling	0,317°	-0,003°	160,74 RPM	-0,01 RPM	0,026°	0,025°	2,94 RPM	2,74 RPM
	DiffSampling	0,327°	-0,001°	160,90 RPM	0,06 RPM	0,281°	0,123°	33,62 RPM	15,23 RPM
	PolaritySampling	0,318°	0,001°	160,75 RPM	-0,05 RPM	0,027°	0,025°	3,06 RPM	2,79 RPM
Filtered demodulation	Optimal	7,039°	13,429°	170,47 RPM	0,08 RPM	7,399°	13,439°	11,16 RPM	5,32 RPM
	2ADCSampling	7,037°	13,411°	170,42 RPM	0,01 RPM	7,397°	13,421°	11,04 RPM	5,23 RPM
	DiffSampling	7,042°	13,408°	170,58 RPM	-0,03 RPM	7,405°	13,419°	37,43 RPM	16,41 RPM
	PolaritySampling	7,036°	13,413°	170,46 RPM	0,07 RPM	7,396°	13,423°	11,09 RPM	6,09 RPM

Table 3 Signal statistics for different sampling methods with noisy input signals and limited ADC resolution

As expected there is no significant difference compared to the previous analysis.

4.4 Resolver signals with asynchronous sampling

In this chapter the effects of asynchronous sampling are examined. First with no noise and ideal sampling, then with noise and 2 ADC sampling.

Five test cases were investigated:

- “Optimal”: in this case the sampling is synchronous at 80 kHz (10 kHz excitation frequency),
- “Sampl78049”: asynchronous sampling at 78.049 kHz,
- “Sampl79999”: asynchronous sampling at 79.999 kHz,
- “Sampl80039”: asynchronous sampling at 80.039 kHz,
- “Sampl82883”: asynchronous sampling at 82.883 kHz.

The asynchronous sampling rates are all prime numbers to exclude the possibility of synchronous sampling at some subharmonic of the excitation frequency.

4.4.1 No noise and ideal sampling

In the simulation in this chapter ideal sampling (all resolver signals sampled at the same time, with no ADC resolution limit) was used with no noise on the sampled signals.

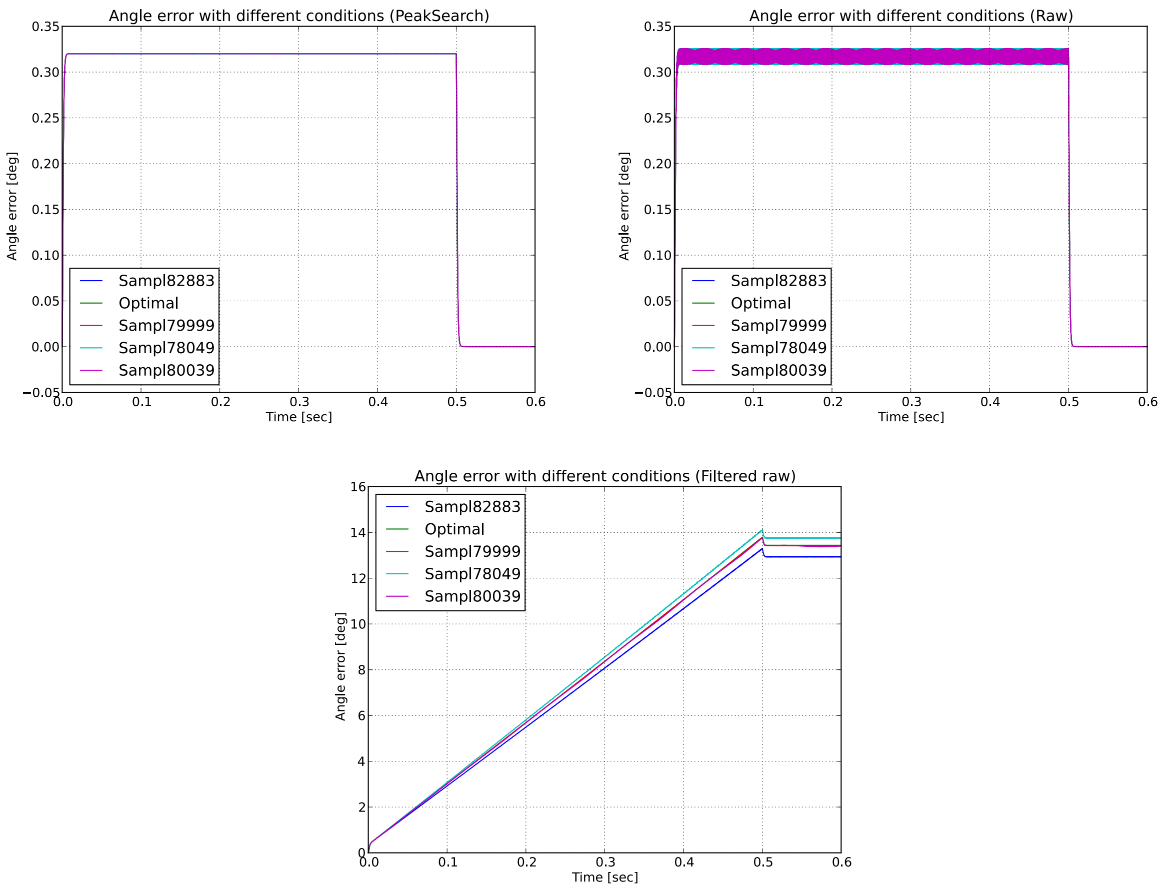


Figure 19 Rotor angle errors with various sampling rates under ideal conditions

As it can be seen there is no significant deviation from the angle error value of the “Optimal” case when the sampling is not synchronous to the excitation signal. (In the peak search algorithm the used sine and cosine samples have to be divided by the actual excitation signal value, otherwise a modulation appears on the angle error with the same frequency as the amount of asynchronicity between the synchronous sampling and the actual sampling frequency.)

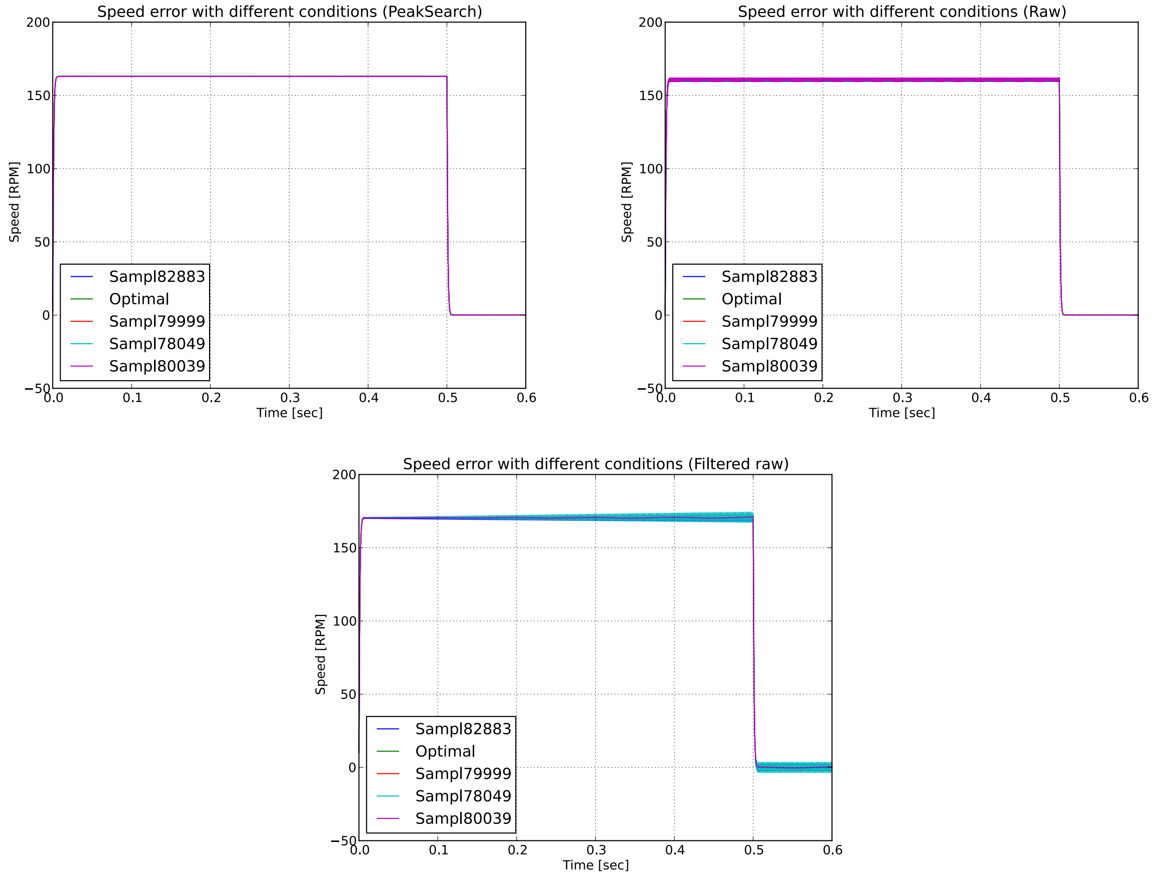


Figure 20 Rotor speed errors with various sampling rates under ideal conditions

In case of asynchronous sampling there is no significant deviation in the speed error from the “Optimal” test case.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,320°	0,000°	162,98 RPM	0,00 RPM	0,000°	0,000°	2,25 RPM	0,00 RPM
	Sampl78049	0,320°	0,000°	163,00 RPM	0,00 RPM	0,000°	0,000°	2,27 RPM	0,00 RPM
	Sampl79999	0,320°	0,000°	162,98 RPM	0,00 RPM	0,000°	0,000°	2,25 RPM	0,00 RPM
	Sampl80039	0,320°	0,000°	162,98 RPM	0,00 RPM	0,000°	0,000°	2,25 RPM	0,00 RPM
	Sampl82883	0,320°	0,000°	163,00 RPM	0,00 RPM	0,000°	0,000°	2,27 RPM	0,00 RPM
Unfiltered demodulation	Optimal	0,317°	0,000°	160,75 RPM	0,00 RPM	0,007°	0,000°	0,76 RPM	0,00 RPM
	Sampl78049	0,317°	0,000°	160,76 RPM	0,00 RPM	0,007°	0,000°	0,76 RPM	0,00 RPM
	Sampl79999	0,317°	0,000°	160,75 RPM	0,00 RPM	0,007°	0,000°	0,84 RPM	0,00 RPM
	Sampl80039	0,317°	0,000°	160,75 RPM	0,00 RPM	0,007°	0,000°	0,75 RPM	0,00 RPM
	Sampl82883	0,317°	0,000°	160,72 RPM	0,00 RPM	0,007°	0,000°	0,75 RPM	0,00 RPM
Filtered demodulation	Optimal	7,037°	13,421°	170,43 RPM	0,00 RPM	7,397°	13,431°	9,72 RPM	0,00 RPM
	Sampl78049	7,189°	13,735°	170,69 RPM	0,00 RPM	7,565°	13,745°	10,08 RPM	2,49 RPM
	Sampl79999	7,030°	13,394°	170,42 RPM	-0,01 RPM	7,389°	13,404°	9,72 RPM	0,01 RPM
	Sampl80039	7,020°	13,382°	170,42 RPM	-0,14 RPM	7,379°	13,392°	9,71 RPM	0,23 RPM
	Sampl82883	6,788°	12,919°	170,06 RPM	0,00 RPM	7,123°	12,928°	9,40 RPM	1,56 RPM

Table 4 Signal statistics for different asynchronous sampling cases with ideal circumstances

As it can be seen the RMS errors are also very similar to the case with optimal, synchronous sampling.

4.4.2 With noise and 2 ADC sampling

In the simulation in this chapter 2 ADC sampling was used with 2.5 mV noise on the sampled signals.

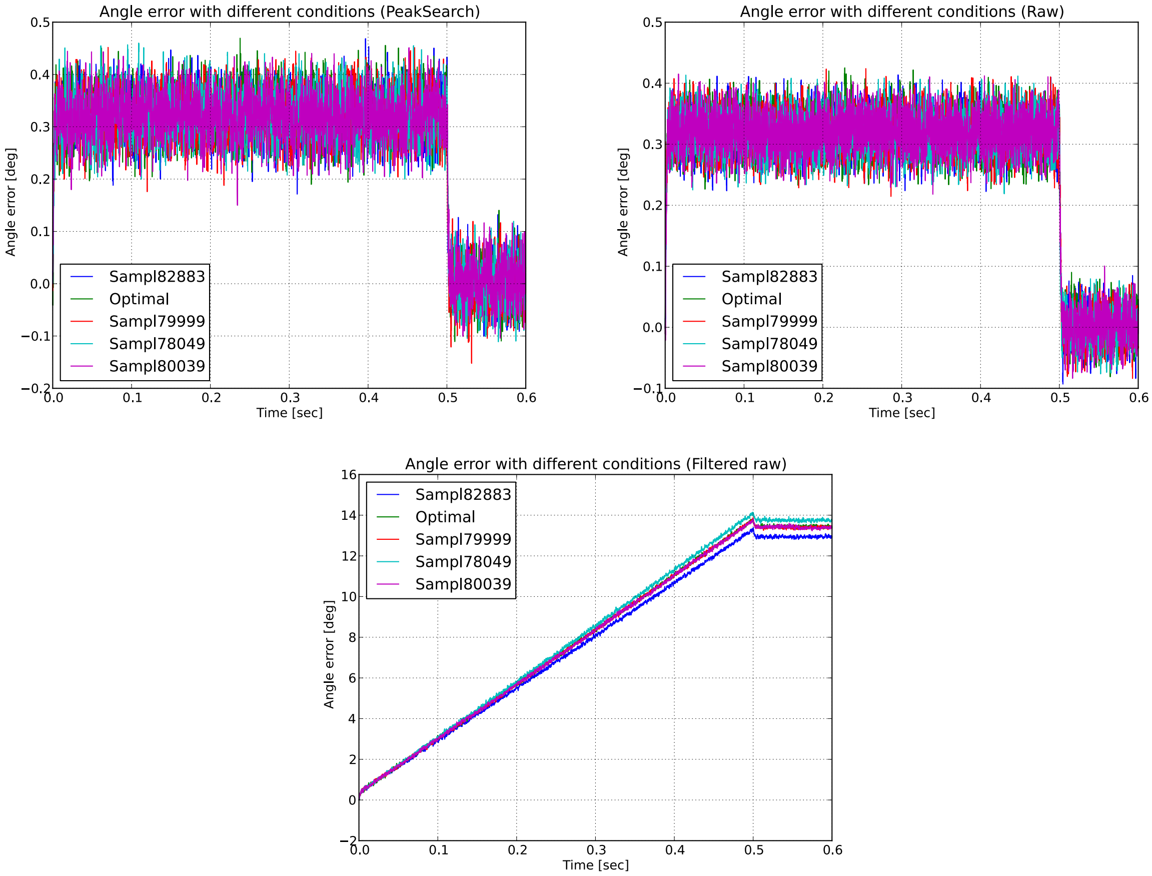


Figure 21 Angle speed errors with various sampling rates under more realistic conditions

As expected there will be some additional noise on the angle error if there is noise on the input signals, but there is no significant difference between the test cases with synchronous or asynchronous sampling.

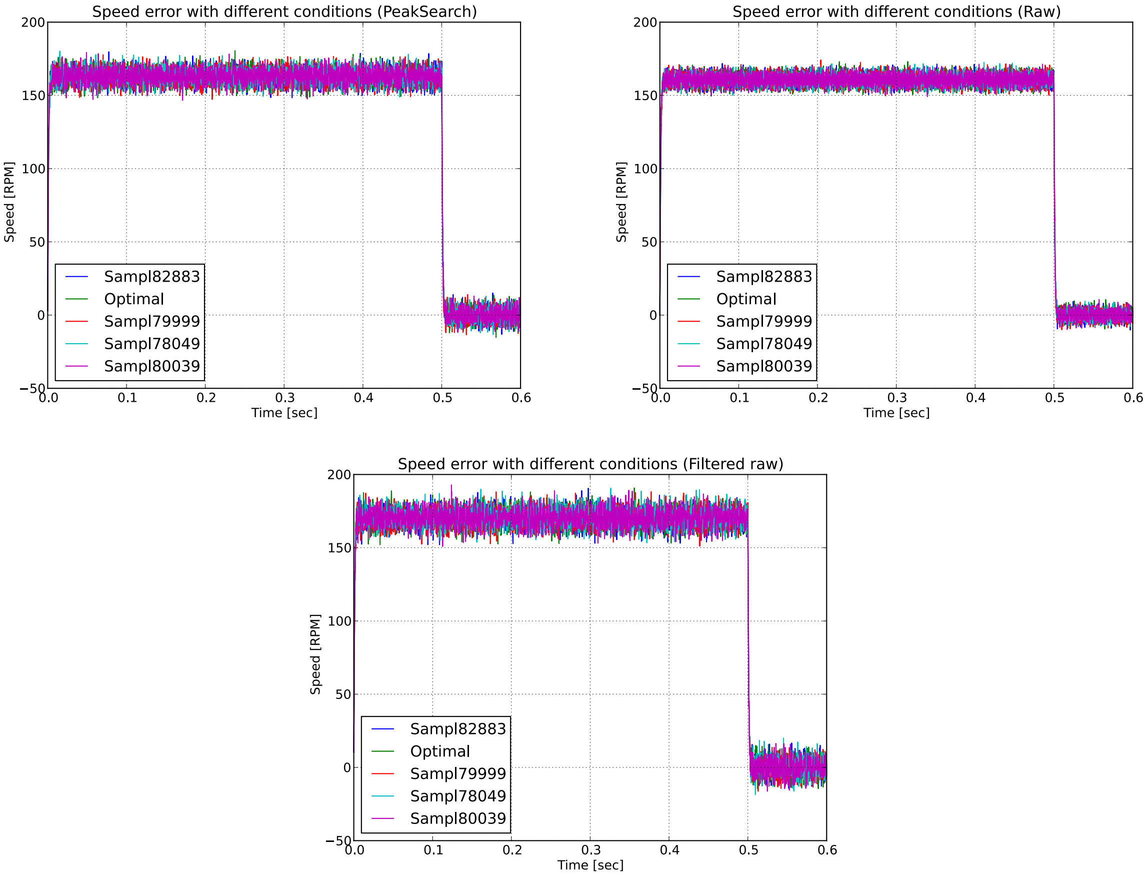


Figure 22 Rotor speed errors with various sampling rates under more realistic conditions

There is also some noise on the speed signals, but there is no significant impact on the performance if the sampling is not synchronous.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,324°	-0,005°	162,99 RPM	-0,07 RPM	0,039°	0,035°	4,88 RPM	3,93 RPM
	Sampl78049	0,323°	-0,001°	163,01 RPM	-0,03 RPM	0,040°	0,039°	4,93 RPM	4,26 RPM
	Sampl79999	0,321°	-0,002°	162,98 RPM	-0,01 RPM	0,038°	0,039°	4,82 RPM	4,32 RPM
	Sampl80039	0,321°	0,005°	162,97 RPM	-0,03 RPM	0,039°	0,036°	4,82 RPM	3,90 RPM
	Sampl82883	0,320°	0,003°	163,00 RPM	0,11 RPM	0,037°	0,036°	4,73 RPM	3,99 RPM
Unfiltered demodulation	Optimal	0,320°	0,002°	160,75 RPM	0,01 RPM	0,027°	0,025°	3,00 RPM	2,83 RPM
	Sampl78049	0,318°	-0,002°	160,77 RPM	0,00 RPM	0,027°	0,025°	3,02 RPM	2,81 RPM
	Sampl79999	0,319°	0,001°	160,75 RPM	-0,04 RPM	0,027°	0,025°	3,07 RPM	2,82 RPM
	Sampl80039	0,319°	0,002°	160,74 RPM	0,02 RPM	0,026°	0,026°	2,93 RPM	2,88 RPM
	Sampl82883	0,319°	0,003°	160,71 RPM	0,01 RPM	0,026°	0,026°	2,90 RPM	2,96 RPM
Filtered demodulation	Optimal	7,037°	13,421°	170,42 RPM	-0,01 RPM	7,397°	13,431°	11,10 RPM	5,57 RPM
	Sampl78049	7,193°	13,728°	170,69 RPM	0,12 RPM	7,570°	13,738°	11,39 RPM	5,60 RPM
	Sampl79999	7,028°	13,386°	170,43 RPM	0,01 RPM	7,386°	13,396°	11,03 RPM	4,85 RPM
	Sampl80039	7,017°	13,382°	170,43 RPM	-0,11 RPM	7,376°	13,391°	11,15 RPM	5,83 RPM
	Sampl82883	6,790°	12,917°	170,06 RPM	0,03 RPM	7,124°	12,926°	10,73 RPM	5,29 RPM

Table 5 Signal statistics for different asynchronous sampling cases with more realistic circumstances

As already visible in the figures the RMS and average errors are all very similar, which is also shown in the table above.

4.5 Noisy + DC offset resolver signals

In this chapter the 2 ADC sampling method will be used with noisy (2.5 mV) input signals and limited ADC resolution (0.25 mV) with various DC offset values. The used DC offset values are:

- 0 mV in the "Optimal" test case,

- 10 mV alternating on the excitation signal (so the positive differential pair will have +10 mV offset, while the negative differential pair will have -10 mV offset) in the “Exc10m” test case
- 10 mV alternating on the sine signal in the “Sine10m” test case,
- 10 mV alternating on the excitation signal and on the sine signal in the “Same10m” test case,
- 10 mV alternating on the excitation signal and on the sine signal, but with opposite sign, in the “Opposite10m” test case,
- 10 mV alternating on the sine and cosine signals in the “Sense10m” test case,
- 10 mV alternating on all excitation signals in the “All10m” test case.

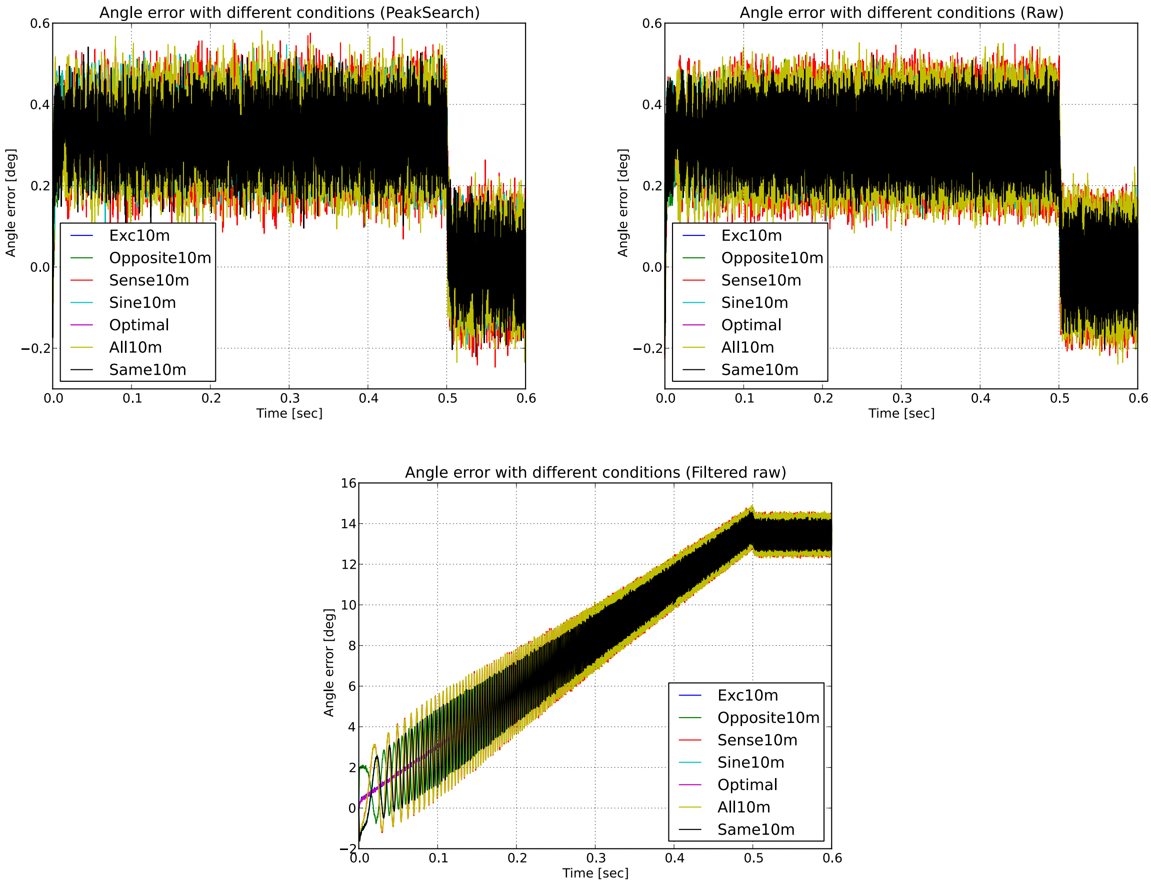


Figure 23 Angle position errors with DC offset on the signals

As it can be seen DC offset has a significant effect on the angular accuracy. In the next close-up figures it can be seen, that a DC offset on the excitation signal has no significant effect compared to the case with no DC offset, but of course the added noise may mask effects if they are small. For the case filtered demodulation there is also significant fluctuation which is possibly due to the filter of the demodulated waveforms not filtering out all components due to the DC offset. (In the demodulation the measured excitation signal is multiplied by the measured sense signal, so a DC offset on the sense signal will be shifted to the excitation frequency after demodulation.)

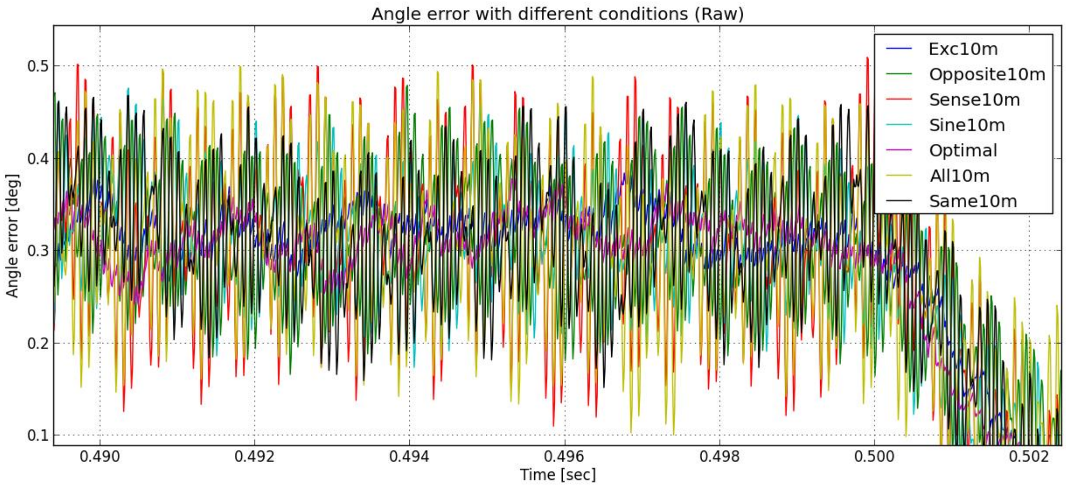


Figure 24 Angle position errors with DC offset on the signals (zoom on end of acceleration)

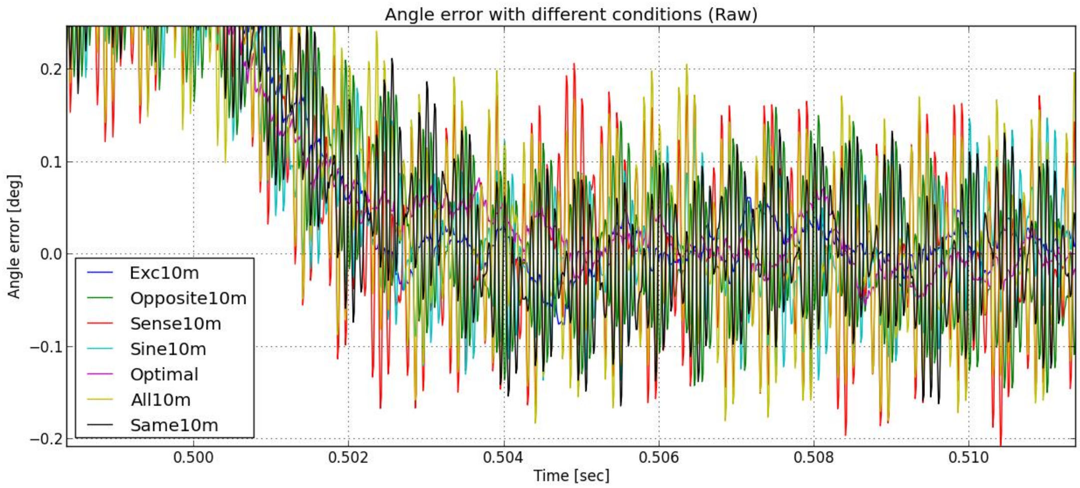
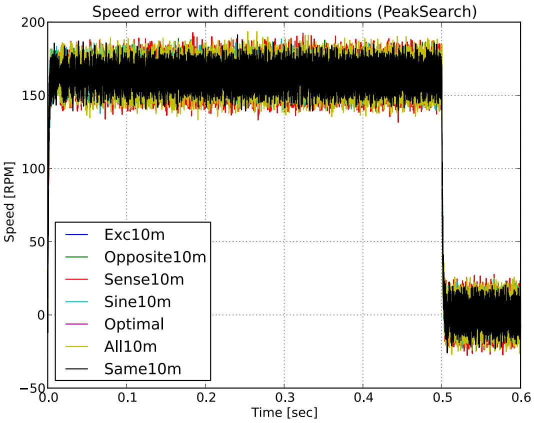
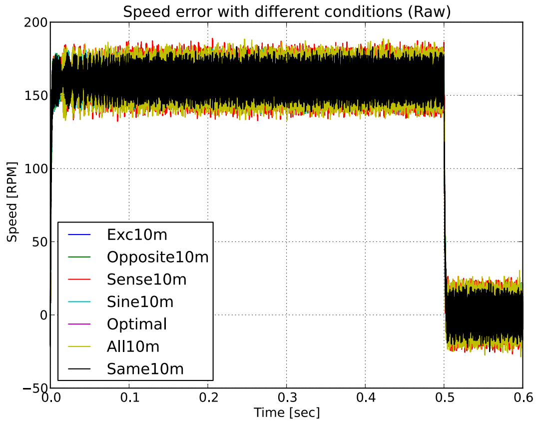


Figure 25 Angle position errors with DC offset on the signals (zoom on start of stable speed)

The two figures above show a close-up on the angle error at the end of the acceleration stage and at the beginning of the stable speed phase. (As already discussed, the DC offset of the excitation does not really have a significant effect, while all other offsets do.)





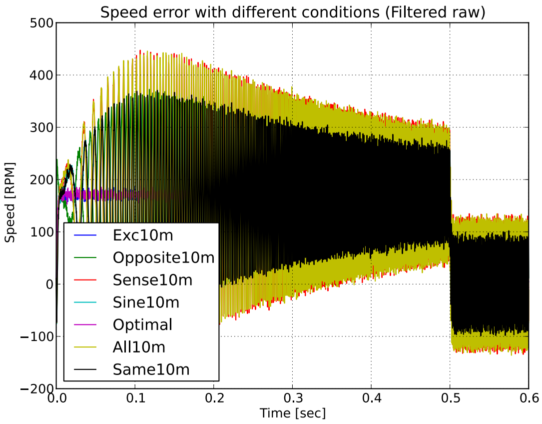


Figure 26 Angle speed errors with DC offset on the signals

These figures show the angle speed errors. As it can be expected the large angle error of the filtered demodulation algorithm also shows up as speed error on the speed output.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,323°	-0,001°	162,97 RPM	0,12 RPM	0,039°	0,038°	4,88 RPM	4,26 RPM
	Exc10m	0,323°	0,001°	162,95 RPM	0,01 RPM	0,038°	0,039°	4,73 RPM	4,32 RPM
	Sine10m	0,325°	0,005°	162,97 RPM	0,03 RPM	0,078°	0,078°	9,56 RPM	9,32 RPM
	Sense10m	0,323°	0,002°	162,97 RPM	0,02 RPM	0,104°	0,105°	12,71 RPM	12,66 RPM
	Same10m	0,322°	0,005°	162,98 RPM	-0,04 RPM	0,077°	0,081°	9,47 RPM	9,49 RPM
	Opposite10m	0,324°	-0,005°	162,96 RPM	-0,09 RPM	0,078°	0,078°	9,58 RPM	9,39 RPM
	All10m	0,325°	0,003°	162,99 RPM	-0,06 RPM	0,103°	0,103°	12,72 RPM	12,54 RPM
Unfiltered demodulation	Optimal	0,320°	0,002°	160,75 RPM	0,02 RPM	0,027°	0,025°	3,02 RPM	2,80 RPM
	Exc10m	0,319°	-0,004°	160,75 RPM	-0,11 RPM	0,027°	0,028°	3,00 RPM	3,19 RPM
	Sine10m	0,319°	-0,004°	160,74 RPM	-0,05 RPM	0,064°	0,064°	7,82 RPM	7,80 RPM
	Sense10m	0,319°	-0,005°	160,75 RPM	-0,04 RPM	0,086°	0,087°	10,66 RPM	10,70 RPM
	Same10m	0,320°	-0,005°	160,74 RPM	0,00 RPM	0,064°	0,065°	7,83 RPM	7,93 RPM
	Opposite10m	0,320°	0,000°	160,76 RPM	0,04 RPM	0,064°	0,065°	7,82 RPM	8,00 RPM
	All10m	0,321°	-0,005°	160,75 RPM	-0,04 RPM	0,087°	0,088°	10,67 RPM	10,84 RPM
Filtered demodulation	Optimal	7,035°	13,413°	170,43 RPM	-0,07 RPM	7,394°	13,422°	11,09 RPM	5,81 RPM
	Exc10m	7,034°	13,415°	170,49 RPM	0,12 RPM	7,394°	13,425°	11,18 RPM	5,84 RPM
	Sine10m	7,048°	13,423°	170,02 RPM	-0,13 RPM	7,471°	13,443°	107,90 RPM	63,82 RPM
	Sense10m	7,055°	13,431°	169,61 RPM	0,32 RPM	7,541°	13,462°	152,19 RPM	90,61 RPM
	Same10m	7,050°	13,422°	170,03 RPM	-0,10 RPM	7,471°	13,442°	108,23 RPM	63,54 RPM
	Opposite10m	7,048°	13,426°	170,85 RPM	0,04 RPM	7,470°	13,446°	108,09 RPM	64,32 RPM
	All10m	7,060°	13,436°	169,62 RPM	0,31 RPM	7,547°	13,467°	152,34 RPM	90,41 RPM

Table 6 Signal statistics for different cases with DC offset on the signals

This table also shows, that in case there is a DC offset on the excitation signal the errors do not significantly increase compared to the optimal case with noise. If there is DC offset on one of the sine or cosine signals, then the errors increase significantly and if there is an offset on both, then the error is even higher.

Just for reference the following table shows the results if there is no noise on the signals, just DC offset and limited ADC resolution.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,322°	0,000°	162,98 RPM	0,00 RPM	0,003°	0,000°	2,26 RPM	0,05 RPM
	Exc10m	0,322°	0,000°	162,98 RPM	0,00 RPM	0,003°	0,000°	2,26 RPM	0,05 RPM
	Sine10m	0,322°	0,000°	162,98 RPM	0,01 RPM	0,068°	0,068°	8,62 RPM	8,38 RPM
	Sense10m	0,322°	0,000°	162,97 RPM	0,01 RPM	0,096°	0,097°	11,96 RPM	11,85 RPM
	Same10m	0,322°	0,000°	162,98 RPM	0,01 RPM	0,068°	0,068°	8,62 RPM	8,38 RPM
	Opposite10m	0,322°	0,000°	162,98 RPM	-0,01 RPM	0,068°	0,068°	8,62 RPM	8,38 RPM
	All10m	0,322°	0,000°	162,97 RPM	0,01 RPM	0,096°	0,097°	11,96 RPM	11,85 RPM
Unfiltered demodulation	Optimal	0,320°	-0,001°	160,75 RPM	0,00 RPM	0,006°	0,001°	0,77 RPM	0,04 RPM
	Exc10m	0,320°	-0,001°	160,75 RPM	0,00 RPM	0,006°	0,001°	0,77 RPM	0,04 RPM
	Sine10m	0,319°	-0,001°	160,75 RPM	0,00 RPM	0,059°	0,059°	7,29 RPM	7,32 RPM
	Sense10m	0,319°	-0,001°	160,75 RPM	0,00 RPM	0,083°	0,083°	10,27 RPM	10,35 RPM
	Same10m	0,319°	-0,001°	160,75 RPM	0,00 RPM	0,059°	0,059°	7,29 RPM	7,32 RPM
	Opposite10m	0,319°	-0,001°	160,75 RPM	0,00 RPM	0,059°	0,059°	7,29 RPM	7,32 RPM
	All10m	0,319°	-0,001°	160,75 RPM	0,00 RPM	0,083°	0,083°	10,27 RPM	10,35 RPM
Filtered demodulation	Optimal	7,036°	13,414°	170,43 RPM	0,00 RPM	7,396°	13,423°	9,73 RPM	0,13 RPM
	Exc10m	7,036°	13,414°	170,43 RPM	0,00 RPM	7,396°	13,423°	9,73 RPM	0,13 RPM
	Sine10m	7,049°	13,423°	170,02 RPM	-0,04 RPM	7,470°	13,443°	107,73 RPM	63,78 RPM
	Sense10m	7,055°	13,435°	169,60 RPM	0,20 RPM	7,542°	13,466°	152,14 RPM	90,14 RPM
	Same10m	7,049°	13,423°	170,02 RPM	-0,04 RPM	7,470°	13,443°	107,73 RPM	63,78 RPM
	Opposite10m	7,048°	13,424°	170,86 RPM	0,04 RPM	7,471°	13,444°	107,80 RPM	63,80 RPM
	All10m	7,055°	13,435°	169,60 RPM	0,20 RPM	7,542°	13,466°	152,14 RPM	90,14 RPM

Table 7 Signal statistics for different cases with DC offset on the signals (but no noise)

As already observed the RMS error does not increase if there is a DC offset on the excitation signal only. There is a significant increase in the RMS error if one of the sense signals have a DC offset and another significant increase if both have it.

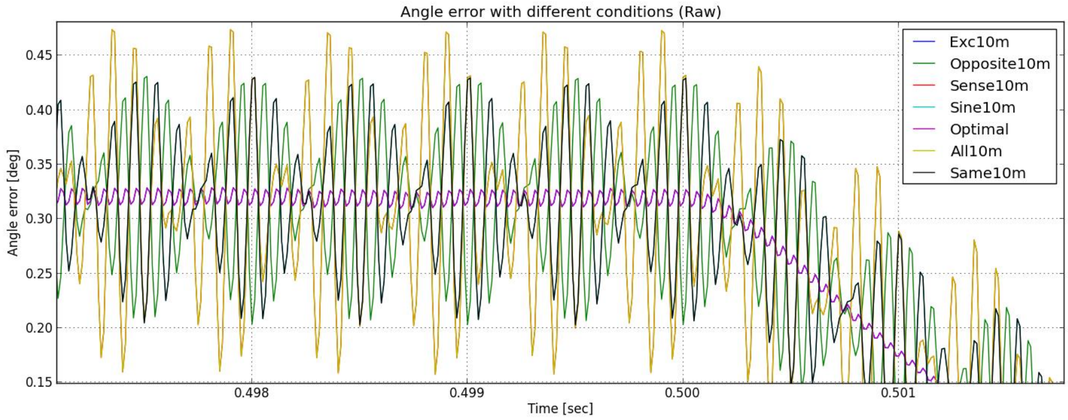


Figure 27 Angle position errors with DC offset on the signals (zoom on end of acceleration) without input noise

The figure above shows a close-up on the angle error at the end of the acceleration phase if there is no input noise.

4.6 Noisy, amplitude mismatched resolver signals

In this chapter the 2 ADC sampling method will be used with noisy (2.5 mV) input signals and limited ADC resolution (0.25 mV) with various amplitude mismatch values on the sense. The amplitude mismatch is realized by changing the modulation signal amplitude. The following test cases were defined:

- "Optimal" has no amplitude mismatch,
- "Sine1p" has 1% higher amplitude on the sine signal, so the modulation signal has a maximum value of 1.01 and a minimum value of -1.01, compared to the ±1.00 of the ideal case,
- "All1p" has 1% amplitude mismatch on both the sine and cosine signals in the same direction,
- "Opposite1p" has 1% amplitude mismatch on the sine signal and -1% mismatch on the cosine signal.

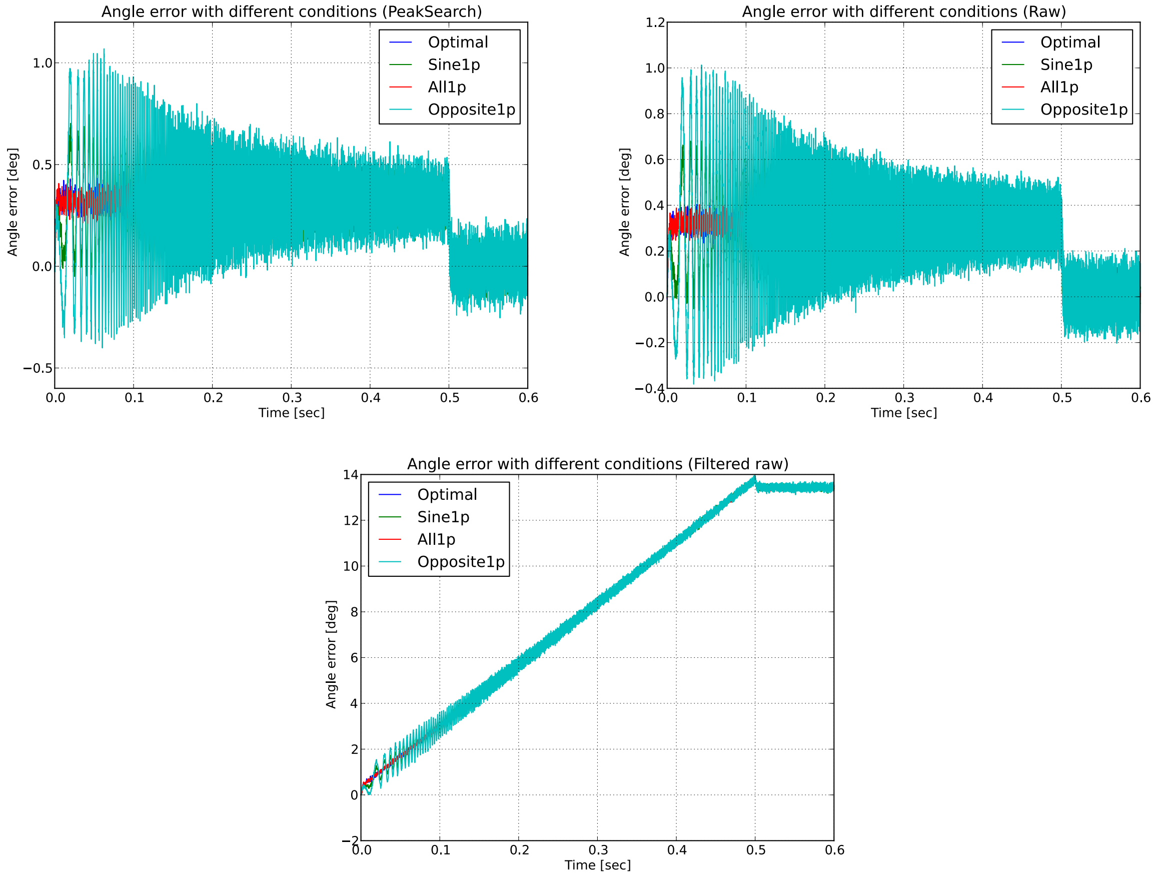


Figure 28 Angle position errors with amplitude mismatch on the signals

The figures above show the simulation results with amplitude mismatch on the resolver signals. The errors seen here correspond to the errors seen in DC excited (for example magnetic) sensors in case there is uncompensated amplitude mismatch on the input signals.

At higher speeds the tracking loop suppresses some of the error, but it does not eliminate all of it. **Additionally the tracking loop will not suppress this error in case the rotor is not turning, so it is absolutely crucial to either prevent such additional error terms or to filter them out before the tracking loop!**

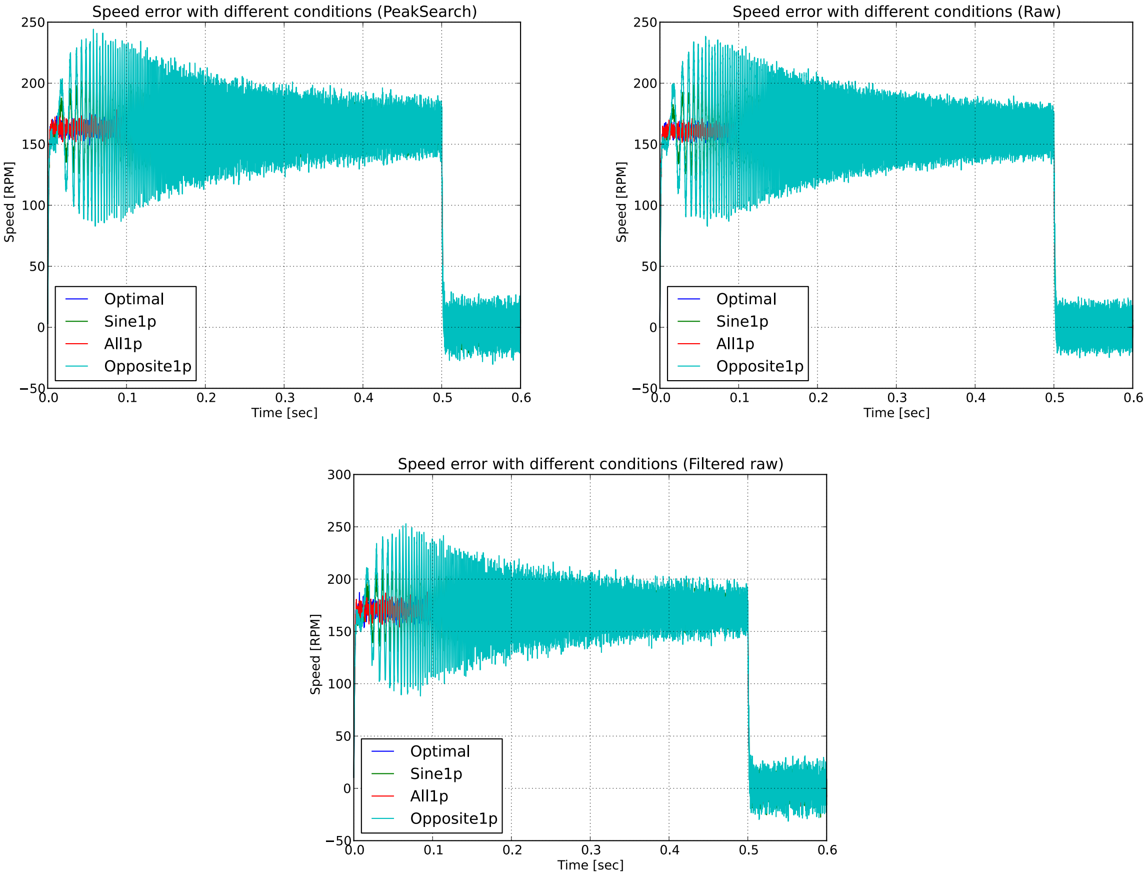


Figure 29 Angle speed errors with amplitude mismatch on the signals

As expected the angle position error also shows up in the angle speed error figures.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,321°	0,003°	162,98 RPM	0,00 RPM	0,037°	0,036°	4,71 RPM	3,93 RPM
	Sine1p	0,320°	0,001°	162,90 RPM	-0,01 RPM	0,133°	0,062°	15,85 RPM	7,42 RPM
	All1p	0,319°	-0,007°	162,99 RPM	-0,02 RPM	0,035°	0,037°	4,53 RPM	4,05 RPM
	Opposite1p	0,325°	0,000°	162,84 RPM	-0,03 RPM	0,260°	0,112°	30,79 RPM	13,54 RPM
Unfiltered demodulation	Optimal	0,320°	-0,002°	160,75 RPM	0,03 RPM	0,027°	0,026°	2,99 RPM	2,97 RPM
	Sine1p	0,318°	0,004°	160,67 RPM	-0,03 RPM	0,124°	0,055°	14,86 RPM	6,71 RPM
	All1p	0,317°	-0,004°	160,74 RPM	0,01 RPM	0,026°	0,025°	2,92 RPM	2,83 RPM
	Opposite1p	0,319°	0,001°	160,62 RPM	0,00 RPM	0,246°	0,102°	29,43 RPM	12,56 RPM
Filtered demodulation	Optimal	7,038°	13,416°	170,43 RPM	0,06 RPM	7,398°	13,426°	11,04 RPM	5,70 RPM
	Sine1p	7,035°	13,410°	170,35 RPM	0,04 RPM	7,396°	13,420°	18,41 RPM	8,33 RPM
	All1p	7,029°	13,406°	170,42 RPM	0,16 RPM	7,390°	13,416°	11,06 RPM	5,37 RPM
	Opposite1p	7,037°	13,414°	170,32 RPM	0,06 RPM	7,401°	13,424°	31,89 RPM	14,36 RPM

Table 8 Signal statistics for different cases with amplitude mismatch on the signals

From the statistics it is visible, that if both sine and cosine signals have the same amplitude mismatch in the same direction (test case "All1p"), then the error is low, same as in the optimal case, since the signals are otherwise ideal.

4.7 Noisy, AC offset resolver signals

In this chapter the 2 ADC sampling method will be used with noisy (2.5 mV) input signals and limited ADC resolution (0.25 mV) with various AC offset values on the sense signals. (The "AC offset" is only a DC offset in the signal modulating the excitation signal (carrier)). The following test cases were defined:

- "Optimal" has no AC offset,

- “Sine1p” has 1% AC offset on the sine modulation signal (so the maximal value of the modulating signal is 1.01 while the minimal value is -0.99),
- “All1p” has 1% AC offset on both the sine and cosine signals,
- “Opposite1p” has 1% AC offset on the sine and -1% AC offset on the cosine signal.

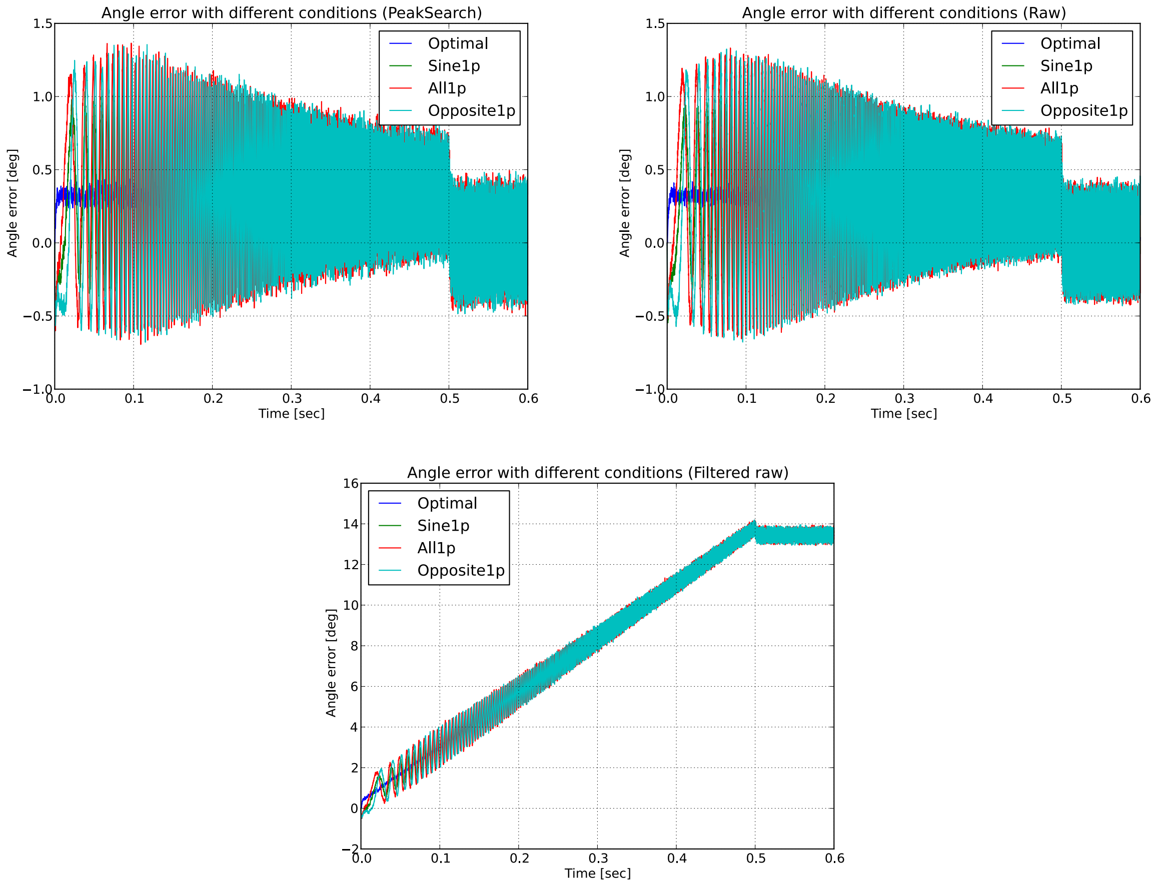


Figure 30 Angle position errors with AC offset on the signals

The figures above show the effect of the AC (modulation signal) offset on the angular error. The situation is very similar to the case with amplitude mismatch, at higher speeds the tracking loop is able to reduce the error signal amplitude, but at lower speeds the errors are very large, so AC (modulation signal) offset has to be prevented from occurring or it has to be filtered out before entering the tracking loop!

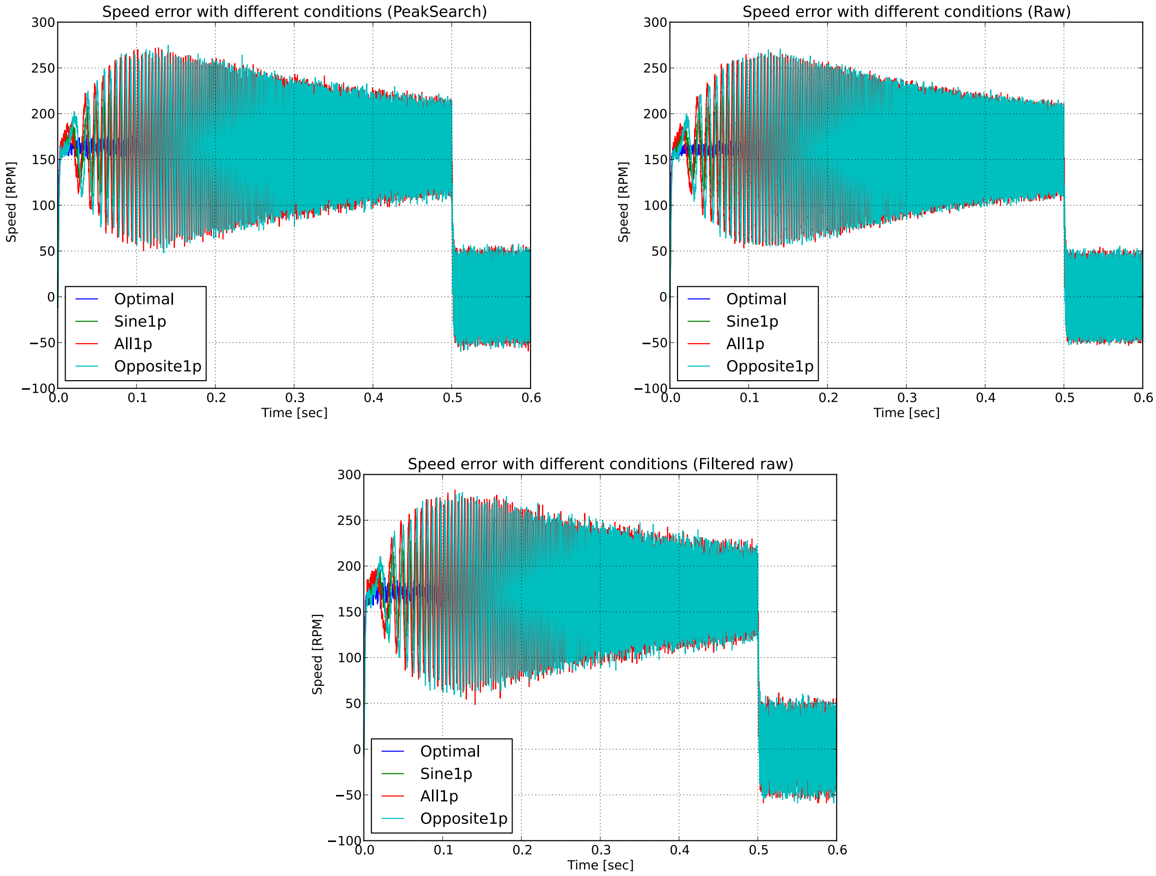


Figure 31 Angle speed errors with AC offset on the signals

There is also significant error on the angle speed signal as well.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,321°	0,001°	162,97 RPM	0,04 RPM	0,039°	0,035°	4,90 RPM	4,03 RPM
	Sine1p	0,323°	0,003°	162,79 RPM	-0,08 RPM	0,360°	0,202°	40,62 RPM	24,59 RPM
	All1p	0,325°	0,002°	162,67 RPM	0,00 RPM	0,509°	0,282°	57,52 RPM	34,34 RPM
	Opposite1p	0,329°	0,000°	162,96 RPM	-0,02 RPM	0,509°	0,287°	57,43 RPM	34,92 RPM
Unfiltered demodulation	Optimal	0,318°	-0,004°	160,74 RPM	0,02 RPM	0,027°	0,026°	3,06 RPM	2,77 RPM
	Sine1p	0,322°	0,005°	160,59 RPM	-0,03 RPM	0,351°	0,190°	39,96 RPM	23,44 RPM
	All1p	0,320°	0,002°	160,45 RPM	-0,02 RPM	0,494°	0,268°	56,41 RPM	33,10 RPM
	Opposite1p	0,325°	0,006°	160,72 RPM	0,00 RPM	0,498°	0,267°	56,61 RPM	33,00 RPM
Filtered demodulation	Optimal	7,037°	13,411°	170,41 RPM	0,13 RPM	7,397°	13,421°	11,07 RPM	5,48 RPM
	Sine1p	7,035°	13,423°	170,27 RPM	-0,05 RPM	7,403°	13,435°	41,32 RPM	24,36 RPM
	All1p	7,037°	13,416°	170,13 RPM	0,16 RPM	7,416°	13,429°	58,01 RPM	34,20 RPM
	Opposite1p	7,043°	13,416°	170,45 RPM	-0,07 RPM	7,416°	13,429°	57,67 RPM	34,41 RPM

Table 9 Signal statistics for different cases with AC offset on the signals

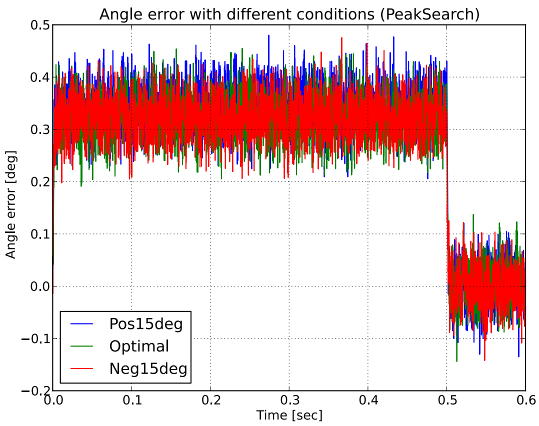
The statistics show, that any kind of AC offset has a significant influence on the output angle error.

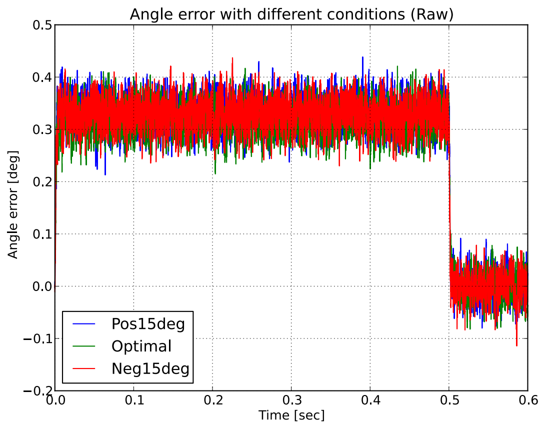
4.8 Noisy resolver signals with phase shift between excitation and sense signals

In this chapter the 2 ADC sampling method will be used with noisy (2.5 mV) input signals and limited ADC resolution (0.25 mV) with phase shift between the measured excitation signal and the excitation signal component in the sense signals. The following test cases were defined:

- “Optimal” has no phase shift,

- "Neg15deg" has negative phase shift between the excitation and sense signals (negative means, that the excitation signal value used to calculate the sense signals is delayed compared to the value on the resolver input),
- "Pos15deg" has positive phase shift between the excitation and sense signals.





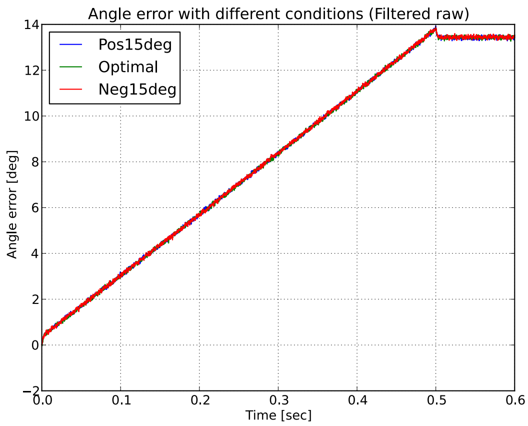


Figure 32 Angle position errors with excitation signal phase shift

There is no significant effect of the ±15° phase shift on the angle position error.

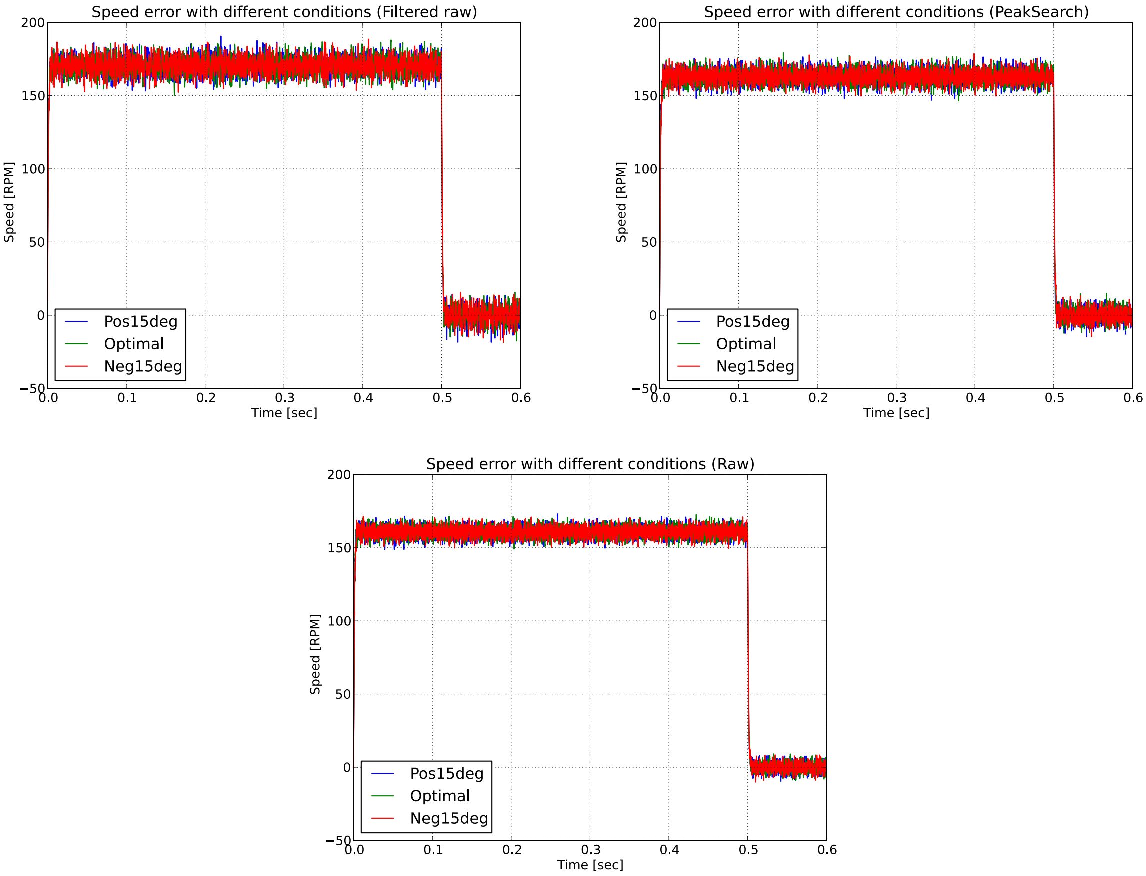


Figure 33 Angle speed errors with excitation signal phase shift

There is also no significant effect of the phase shift on the angle speed error.

Method	Test case	Average angle error (accerating)	Average angle error (stable speed)	Average speed error (accelerating)	Average speed error (stable speed)	RMS angle error to ideal (accelerating)	RMS angle error to ideal (stable speed)	RMS speed error to ideal (accelerating)	RMS speed error to ideal (stable speed)
Peak search	Optimal	0,323°	0,004°	162,97 RPM	0,16 RPM	0,039°	0,040°	4,80 RPM	4,38 RPM
	Pos15deg	0,345°	0,003°	163,01 RPM	-0,07 RPM	0,047°	0,039°	4,84 RPM	4,20 RPM
	Neg15deg	0,324°	0,001°	162,98 RPM	0,07 RPM	0,038°	0,037°	4,75 RPM	4,17 RPM
Unfiltered demodulation	Optimal	0,319°	-0,001°	160,75 RPM	0,02 RPM	0,027°	0,025°	2,97 RPM	2,85 RPM
	Pos15deg	0,332°	0,000°	160,74 RPM	0,02 RPM	0,030°	0,027°	3,08 RPM	2,95 RPM
	Neg15deg	0,329°	-0,001°	160,74 RPM	0,00 RPM	0,029°	0,027°	3,02 RPM	2,88 RPM
Filtered demodulation	Optimal	7,038°	13,415°	170,42 RPM	-0,02 RPM	7,396°	13,425°	11,08 RPM	5,19 RPM
	Pos15deg	7,047°	13,405°	170,42 RPM	-0,08 RPM	7,405°	13,415°	11,09 RPM	5,44 RPM
	Neg15deg	7,053°	13,429°	170,39 RPM	0,03 RPM	7,412°	13,438°	11,08 RPM	5,94 RPM

Table 10 Signal statistics for different cases with excitation signal phase shift

The statistics also show no significant effect on the angle position and speed error values if there is sense signal carrier is phase shifted to the excitation signal.

5 Summary

Various resolver signal sampling possibilities were investigated. Based on the result the following conclusions can be stated:

- during sampling of the resolver signals the average sampling delay between the sine ad cosine signals should be minimized, otherwise the angular position error will increase (this is why the consecutive sampling of the sine, cosine and excitation signal pairs did not work well),
- modulation signal amplitude mismatch and offset should be prevented or filtered out before signals enter the tracking loop, because they cause significant angle position and speed errors,

- DC offset on the resolver signals also increases the angular error somewhat, but compared to the modulation signal errors its effects are much smaller,
- asynchronous sampling of the resolver signals is also possible without significant impact on the angular error.

Therefore it is recommended to sample the signals with 2 ADCs as described in this document. (This kind of sampling will of not suppress common mode noise, but all simulations were performed with uncorrelated noise on the single ended signals.