Motor Torque Control Tests

Computational Robotics Lab, ETH Zürich
Marco Ruggia

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Contents

1 Overview

The goal of this report is to determine the torque control performance of various actuators designed for applications like legged robots. Specifically, to determine the discrepancy between desired / provided torque and to analyze if this discrepancy can be compensated for.

Two types of torque tests are presented:

- Static Steady-State Test: Where the motor is fixed to an unmoving torquemeter and a constant torque is requested from the motor.
- Static Transient Tests: Where the motor is also not moving, but the requested torque consists of a fast chirp signal to measure the transient behaviour.

2 Motor Connection

All tested motors use the CAN protocol for communication. A *Raspberry Pi 4B* is used as a host computer, sending and receiving the CAN packets. Since the Pi can't do this natively, it is equipped with a *MJBots Pi3Hat*, which translates the CAN interface of the motors to the SPI interface of the Pi.

Communication sent to the motors consists of a feed-forward torque (q_{ff}), a setpoint angular position/velocity (p_{des}, v_{des}) and P/D gains (K_p, K_d) that can be used for closed loop control (Eq. 1). In the majority of test presented here, only the feed-forward torque is used. Communication received from the motors consists of self reported position (p_{rep}), velocity (v_{rep}), torque (q_{rep}) and temperature (t_{rep}).

$$q_{out} = q_{ff} + K_p * (p_{des} - p_{rep}) + K_d * (v_{des} - v_{rep}) \tag{1}$$

The *MJBots Pi3Hat* only supports *MJBots* motors natively. Support for all other motors, like the *T-Motor*, is added by writing a custom driver for the *Pi3Hat*. The sending/receiving of motor setpoints/states is done directly on the Pi, to minimize latency, with a frequency of 800Hz. Very low jitter in the sending timestamps is observed at $0.7\mu s$ standard deviation. Further information about this setup and the source-code can be found on gitlab under `https://gitlab.inf.ethz.ch/mruggia/mjbots_driver` and `https://gitlab.inf.ethz.ch/mruggia/mjbots_driver_tests`

3 Static Torque Stand

For the static steady-state/transient torque tests a torque-meter is needed. The one used is a *PCE-DFG N 10TW*. It has a measuring range of $\pm 10Nm$ with an accuracy of $0.05Nm$, resolution of $0.005Nm$ and a sampling rate of $800Hz$. It connects via USB to the same *Raspberry Pi 4B* that communicates with the motors.

Since the measuring delay is not stated in the data-sheet, but is relevant for the transient tests, it is determined experimentally. For that, a program is ran on the Pi that turns on a LED as soon as any torque is detected from striking the torque-meter with a small hammer. A high speed camera from a *Google Pixel 4a 5G* smartphone, running at 240fps, is set up to capture both the LED and the hammer strike, such that the delay can be determined to the nearest frame (Fig. 1). Regrettably the torque-meter does not provide sample timestamps, so it is necessary to fully rely on the sample arrival time.

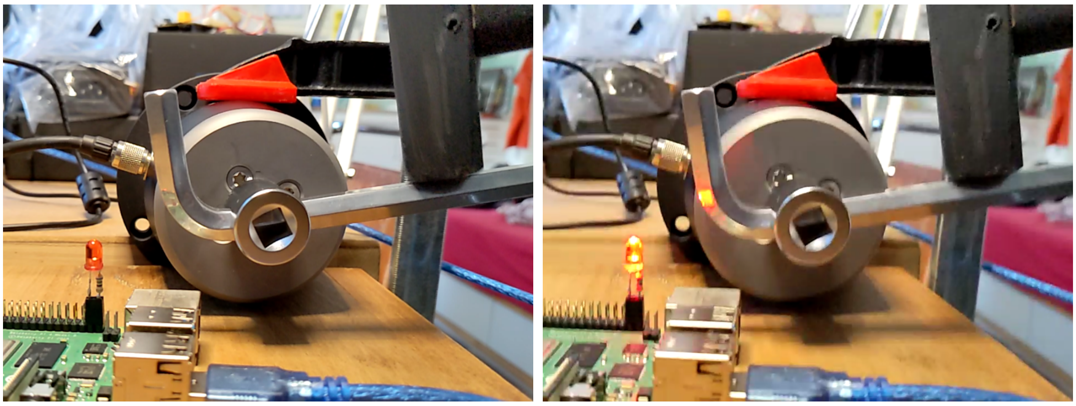


Figure 1: Torque-meter delay test: Impact frame (left), detection frame (right)

200 hits are recorded. The average measured delay is 5.37 frames (22.4ms) with a st. dev. of 2.99 frames (12.5ms). Looking at the delay distribution (Fig. 2), one can notice a flat section between 1 and 10 frames. This suggests that there is possibly an issue with a low re-sampling rate.

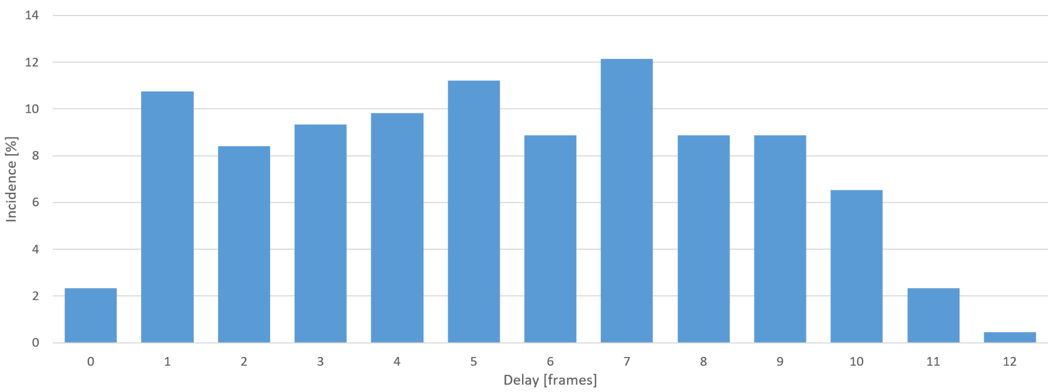


Figure 2: Histogram torque-meter delays (without any correction)

An explanation of this result can be found by looking the time at which sampling data is received (Fig. 3). There it can be confirmed that the torque-meter does indeed send samples at an average of 800Hz, but it does so by sending data in batches of always 496 bytes. With each sample measuring 14 bytes, this averages 35.42 samples/batch at 22.58 batches/second. In terms of camera frames, the later is equal to 10.63 frames/batch. Since the batch containing the sample with nonzero torque can arrive at any time during those 10.63 frames, this explains the torque-meter delay distribution (Fig. 2). All efforts to fix this behaviour have failed.

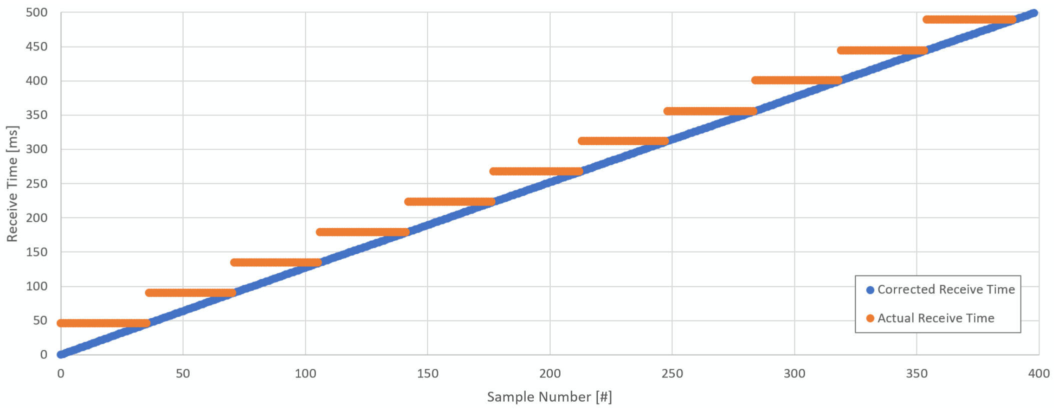


Figure 3: Actual timing at which samples arrive on the Raspberry Pi and corrected timings after batch correction

A natural assumption that can be made is, that the samples are uniformly distributed across the time before the last batch. The hammer-LED delay test is repeated with this batch correction in place, this time with 100 hits. The test (Fig. 4) shows consistent results, never exceeding 1 frame of delay. The mean delay is approximated by weighting the frame times by their incidence, resulting in 1.45ms mean delay. Ideally a faster method to detect delays would be beneficial at this point. As the batch arrival time can vary, even after this correction, a slight jitter of 9.6μs st. dev. remains in the timestamps. In the remainder of this report both the batch correction and delay offset are applied to all torque-meter data.

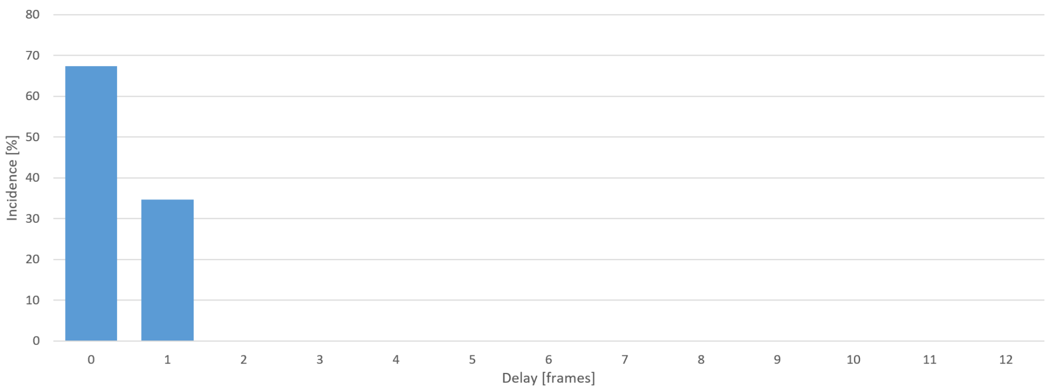


Figure 4: Histogram torque-meter delays (with batch correction)

The dynamic response characteristics of the torque-meter could not feasibly be determined. Still, a lower bound for the bandwidth can be found by analyzing the hammer strikes (Fig. 5). In time domain, the overall shape of the curve seems to be consistent with a stiff elastic impact, measuring a reasonable 20ms in duration. In frequency domain, a drop-off is observed around 24Hz, whereas a perfect unit impulse would be expected to have a flat distribution. It is thought that this drop-off is due to the elasticity of the impact and not to a bandwidth limit of the torque-meter, but it can still serve as a lower bound for the later.

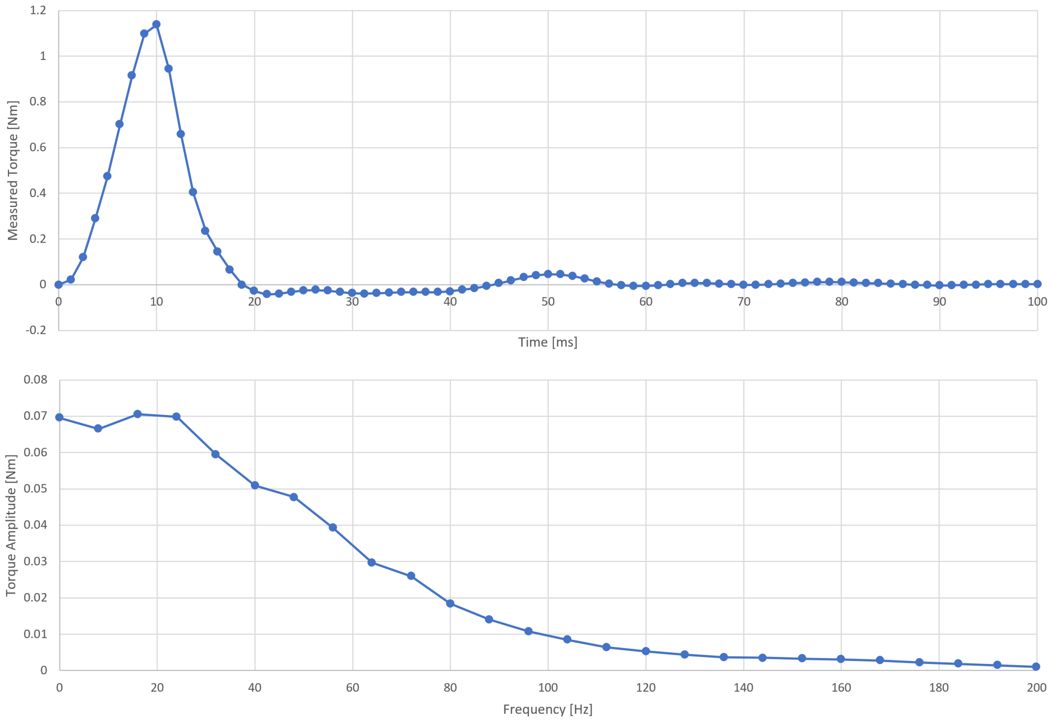


Figure 5: Averaged measured torque of hammer strikes in time domain (top) and frequency domain (bottom)

These results show that the torque-meter *PCE-DFG N 10TW* is suitable to perform the static torque tests. For motors that can produce more than ±10Nm torque, the *PCE-DFG N 50TW* torque-meter is used instead. It has a higher torque rating of ±50Nm and a reduced accuracy of 0.25Nm, but otherwise appears to be equivalent to the ±10Nm model.

To mechanically connect this torque-meter with the motors, a frame is built as rigidly as possible, such that the measured torque is not influenced by any elasticity of the connection. A reasonably stiff setup is constructed by using aluminium for the coupling piece and very thick wood for the outer frame. The actuator and torque-meter are place very close together to minimize the distance over which torsion can occur (Fig. 6, 7). It is thought that this frame is sufficiently stiff, but no validation has occurred.

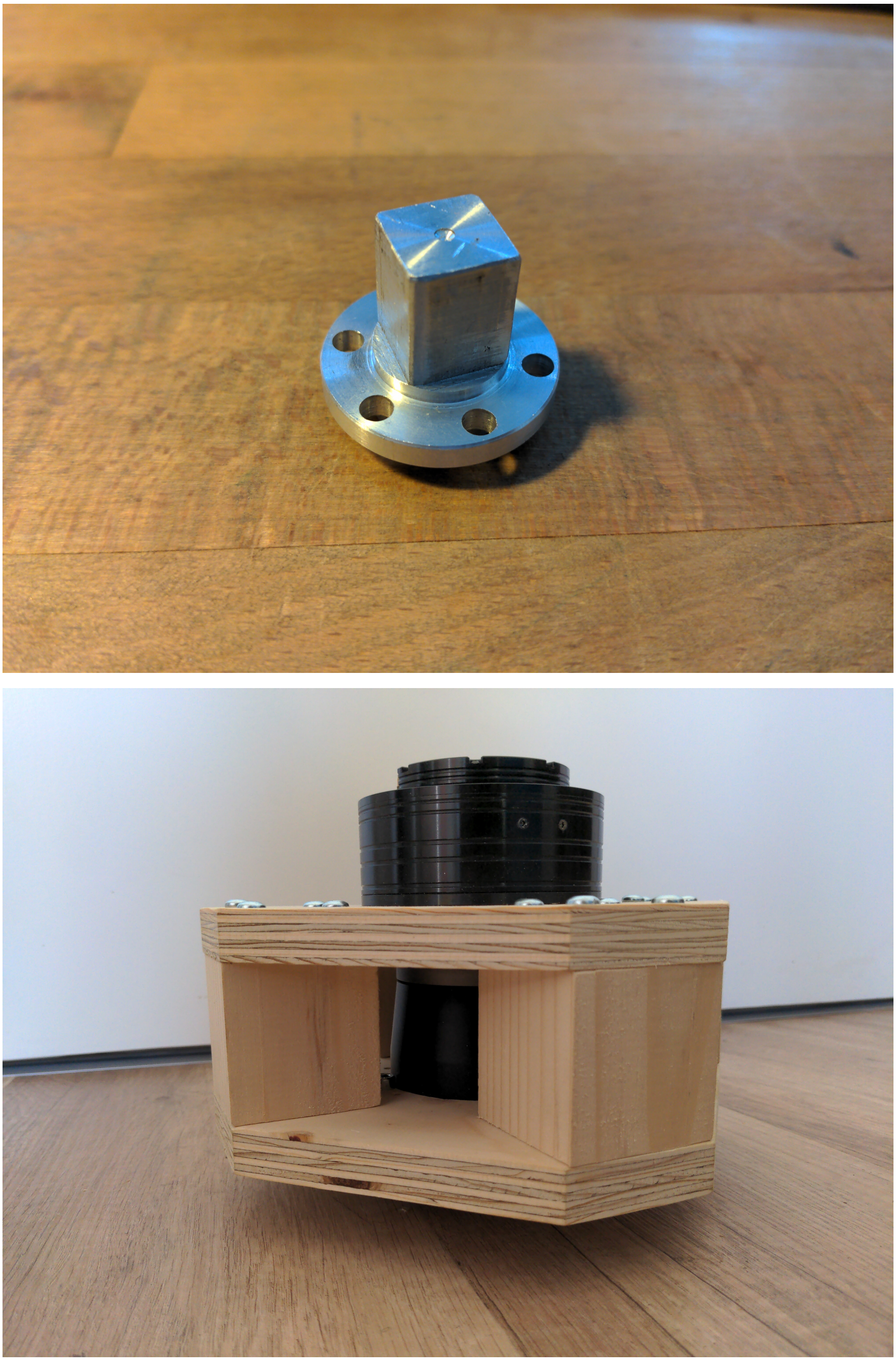


Figure 6: Torque-meter to motor coupling (top), wooden connecting frame (bottom) for the T-Motor AK10-9 v2.0 motor

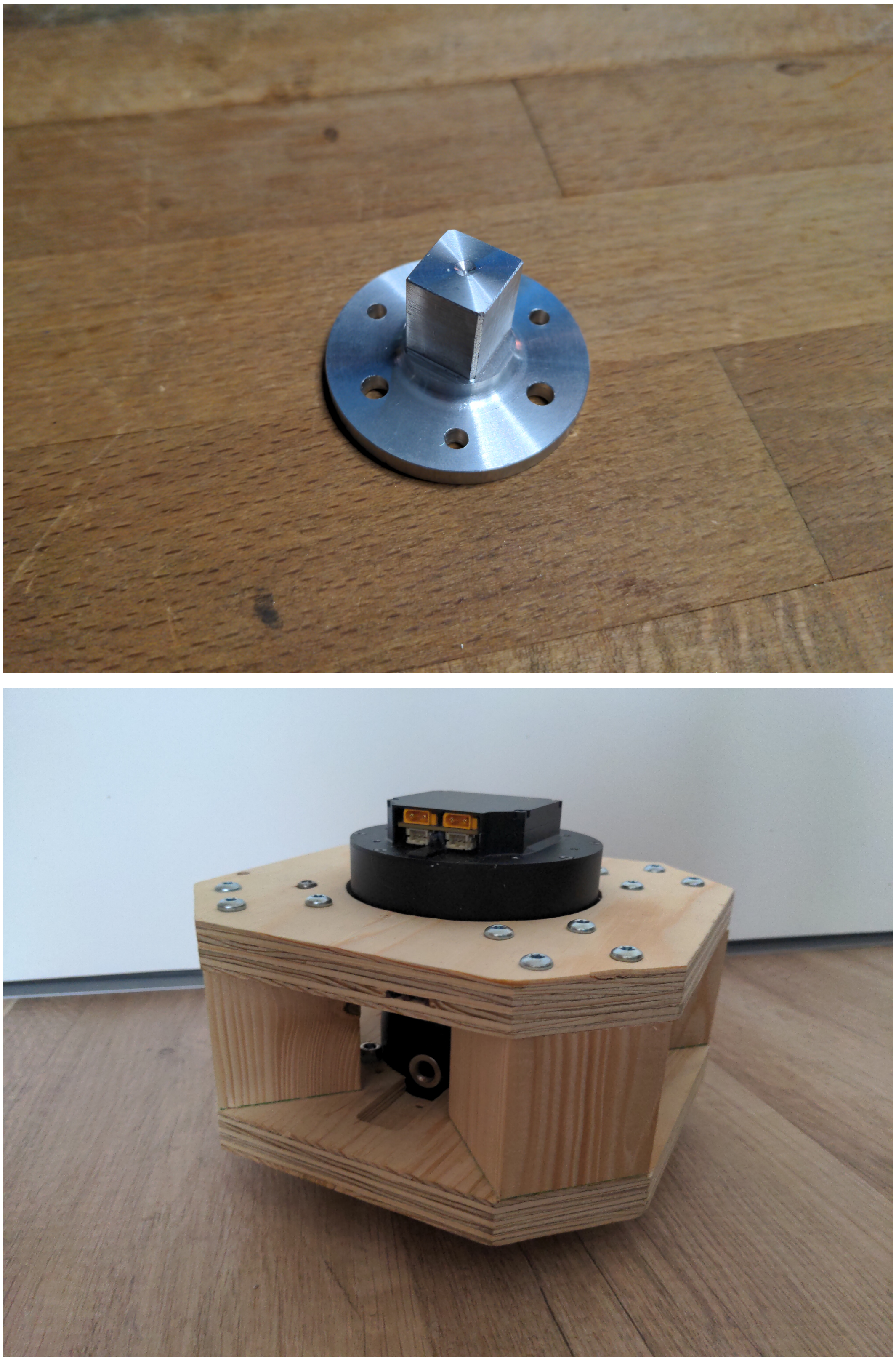


Figure 7: Torque-meter to motor coupling (top), wooden connecting frame (bottom) for the MJBots QDD100 beta 3 motor

4 Torque Tests Description

4.1 Static Steady-State Torque Test

In the static steady-state torque test, the static torque stand is used to measure the discrepancy between desired torque and measured torque while the motor is not moving and in steady-state. The chosen torque trajectory for these tests is a very slow ramp moving from the minimum to the maximum nominal torque and back for 4 repetitions. Lead-in/lead-out ramps are used before/after a run so that all trajectories start/end at 0Nm. The results are presented as a plot of measured torque error vs. desired torque and of measured torque vs. time.

A few variations of this test are used that can be useful in explaining anomalies found in the standard test described above.

- **Vary Motors**: To determine variations between motors of the same type, the standard test is performed with up to 4 distinct motors.
- **Vary Rotor Position**: To determine if the rotor position has an effect on the results, a single motor is tested with the rotor being rotated by 90° steps between each run (0°, 90°, 180°, 270°).
- **Vary Ramp Speed**: To check if the ramp speed is slow enough as to avoid transient effects, 4 tests are performed with decreasing ramp speed factors of 100%, 75%, 50%, 25% on a single motor.
- **Vary Ramp Amplitude**: To characterize any possible hysteresis, the ramp amplitude is decreased to 100%, 80%, 60%, 40%, while maintaining the same ramp speed, on a single motor.
- **Long Run**: To test if the results remain consistent over a long duration, the standard test is performed after 0h, 1h, 2h, 3h. Between the tests, the standard ramp is continuously repeated without data being recorded.
- **Vary Voltage**: The input voltage to the motor is set to various values within the supported range. This shows if the static steady-state torque output depends on input voltage.
- **Compare PD Control**: Compare the feedforward torque control to the PD feedback control by setting the Kp term to 1, 10, 100 and the angle setpoint such that the same torque is produced as in the feed-forward case, assuming the relation $q_{out} = q_{ff} + K_p * (r_{des} - r_{cur})$ holds. This tests if the PD control loop is implemented as would be expected.
- **Maximum Torque**: Since motors can far exceed their nominal output torque for short durations of time, a test can be performed up to the maximum torque.

In this case the ramp signal is repeated only once, and the motor allowed to cool to ambient temperature after each of four repetitions.

- **Vary Temperature**: To check the influence of temperature on the torque error, the motor is heated by requesting a constant torque until a self reported temperature of 30°C, 50°C, 70°C, 90°C is reached. After which the standard test is performed. The motor is insulated with a hand towel during the entire test, to minimize heat loss.

Each one of these variations can optionally be modified in the following ways.

- **Percentage Error**: The measured torque error is plotted as a percentage of the desired torque instead of an absolute value. This can help with visualization if the torque error increases with the desired torque.
- **Self Reported Torque**: The self reported torque provided by the motor is used instead of the measured torque from the torque-meter. This change can show if the motor controller is aware of any torque error.
- **Direct Drive**: All tested motors have a gearbox reduction stage before the output. To test the influence of the gearbox, it is removed and the internal motor coupled directly to the output. In the plots, the output torque is multiplied by the previous gear ratio, emulating a perfect gearbox, to keep them easily comparable.

4.2 Static Transient Torque Test

The goal of the static transient torque test is to capture any transient effects of the torque response while at zero velocity. All of these tests avoid crossing 0 Nm, as passing trough the gear backlash might damage the actuator. For a similar reason step signals are avoided. Instead a chirp signal is used, which consists of a sinusoidal function with exponentially increasing frequency. The frequency increases from 0.1Hz to 20Hz over a span of 120sec. Amplitude is chosen at 20% and center at 60% of nominal torque. The results are presented as normalized bode plots (removed scaling and offset), so that the influence of the steady-state error is largely removed.

Again a few variations of this test are used that can be useful in explaining anomalies found in the standard test.

- **Vary Motors**: Same as in static steady-state torque test.
- **Vary Chirp Center**: To check the linearity of the system the center torque value is varied at -80%, -40%, 40%, 80% of nominal torque on a single motor.

- **Vary Chirp Amplitude**: To check the linearity of the system the torque amplitude value is varied at 10%, 20%, 30%, 40% of nominal torque on a single motor.
- **Vary Rotor Position**: Same as in static steady-state torque test.

Each one of these variations can optionally be modified in the following ways.

- **Time Domain**: Instead of using bode plots (frequency-domain), sections of the time-domain measurements are plotted at 5Hz, 10Hz, 15Hz, 20Hz. Note that since scaling and offset were removed, these plots can only be used to interpret the shape of the sinusoidal response.
- **High Frequency**: The frequency range is increased at 0.1Hz to 80Hz and the runtime is doubled at 240sec. This test is far outside the typical application range and also outside the confirmed bandwidth of the torque-meter. Nevertheless it can be used to suggest a bandwidth of the motors and to better understand the response to instantaneous setpoint changes.
- **Self Reported Torque**: Same as in static steady-state torque test.

5 Torque Tests Results

5.1 T-Motor AK10-9 v2.0

The following tests results are for the T-Motor motors, model AK10-9 v2.0. The used supply voltage is 24V, unless otherwise noted. Nominal torque is ±16Nm, but ±10Nm is used instead, as the needed ±50Nm torque-meter was unavailable during the tests. The communication round-trip delay (delay from sending a CAN motor setpoint command to receiving the matching CAN motor state message) is measured at 60-80μs.

Some of the steady-state tests are performed with older versions of the driver code, using only a 400Hz refresh rate and with more jitter at up to 50μs. This is deemed to not have any significant influence on the results.

Static Steady-State Torque Test:

- **Vary Motors** (Fig. 8): A torque error of up to 1.5Nm is observed. Measurements are very consistent within the 4 repetitions of every motor. All motors exhibit some hysteresis with a height of approx. 1Nm depending on ramp direction.
- **Vary Motors - Percentage Error** (Fig. 9): The percentage error plot does not provide any new insights, as the torque error seems to be somewhat constant.
- **Vary Motors - Self Reported Torque** (Fig. 10): The motor controllers believe the torque error is always very close zero.
- **Vary Rotor Position** (Fig. 11): The same motor at a different rotor position behaves about as differently as an entirely different motor.
- **Vary Ramp Speed** (Fig. 12): The results are similar in all 4 tested speeds, strongly indicating that transient effects are not the cause of the hysteresis.
- **Vary Ramp Amplitude** (Fig. 13): Seemingly Unpredictable behaviour is observed after ramp direction changes, which gets reset after a 0Nm crossing.
- **Vary Voltage** (Fig. 15): All tested voltages from 16V, the minimum working, to 48V, the maximum rated, produced very comparable torque curves. It is fully expected, that in the dynamic test a high voltage is required to push the desired current into the motor, which in turn controls the torque.
- **Long Run** (Fig. 14): The steady-state response exhibits some drift over long durations (3h), although not as much as with changing rotor position. The temperature of the motor stabilizes at 44°C after the first hour.

- **Compare PD Control** (Fig. 16): Using the PD controller to "fake" torque-control instead of the feedforward term appears to neither improve nor deteriorate torque tracking significantly. This matches expectations.
- **Maximum Torque** (Fig. 17): For this test the supply voltage needed to be raised to the maximum of 48V, for the motor to be able to accept the 48Nm peak torque setpoint. During each test the temperature rose from ~30°C to ~60'C. It appears that the same behaviour as in the standad test persists up to about 30Nm, at which point both absolute error and hysteresis increase. This result indicates that it's not strictly necessary to redo all tests up to the nominal 16Nm, as results are likely not to change.
- **Vary Rotor Position - Direct Drive** (Fig. 18): The Gear ratio of 9:1 means that the gearbox-corrected measured torque meter accuracy is reduced to 0.45Nm (9*0.05Nm), which is a significant fraction of the observed torque error. Nevertheless the results are interpreted, as the measurement resolution is still sufficient and within each run the measurements seem very consistent. Only a slight improvement over the non-direct-drive case (Fig. 11) can be observed. Errors of 1Nm are still regularly reached. The only mayor difference is that the torque error appears less "wavy". Why this is the case could not be determined.
- **Maximum Torque - Direct Drive** (Fig. 19): Again, even at higher torques the gearbox does not appear to influence the steady-state torque error.
- **Vary Temperature** (Fig. 20): Varying the motor temperature appears to only have a slight effect on the torque error. By the end of the 30°C, 50°C, 70°C, 90°C runs, the temperature was observed to drop to to 30°C, 42°C, 58°C, 75°C. A highe frequency noise is observed on each run that was not present in any other test. This change was linked to the *50TW* torque-meter, used to facilitate fast heating at high torques. With the *10TW* torque-meter said noise is not present, but the higher temperatures can't be reached.

Static Transient Torque Test:

- **Vary Rotor Position** (Fig. 21): The results are very consistent across rotor positions and thus likely also across multiple motors (see steady-state tests). A slight increase in gain can be observed at higher frequencies with +1dB at 20Hz. This is likely due to an upcoming under-damped second order pole at higher frequencies. Since the gain increase is only minor, this is not further investigated. The phase plot shows a linear decrease, which is indicative of a constant time delay. Calculating said delay yields roughly 11ms. A small phase offset of about -7° at 0Hz is observed, which can't be explained.
- **Vary Rotor Position - Time Domain** (Fig. 22): With higher frequency, the measured torque starts to slightly loses its perfectly sinusoid shape after 10Hz.

- **Vary Rotor Position - Self Reported Torque** (Fig. 23): With the self reported torque, the gain increase disappears and so does the phase offset at 0Hz. The slope of the phase now indicates a delay of 6ms, meaning that 11ms - 6ms = 5ms of delay are unaccounted for by the motor controller.

- **Vary Chirp Center** (Fig. 24): The results are unchanged, suggesting that the transient response is independent of the desired torque.

- **Vary Chirp Amplitude** (Fig. 24): The results are unchanged, further suggesting that the transient response is independent of the desired torque. Although 0.5Nm amplitude inexplicably does not exhibit the gain increase.

- **Vary Rotor Position - High Frequency** (Fig. 26): This plot shows a peak gain of 12dB at a cutoff frequency of 42Hz. The test was aborted after the first run, as such a high gain makes the trajectory cross the 0Nm mark.

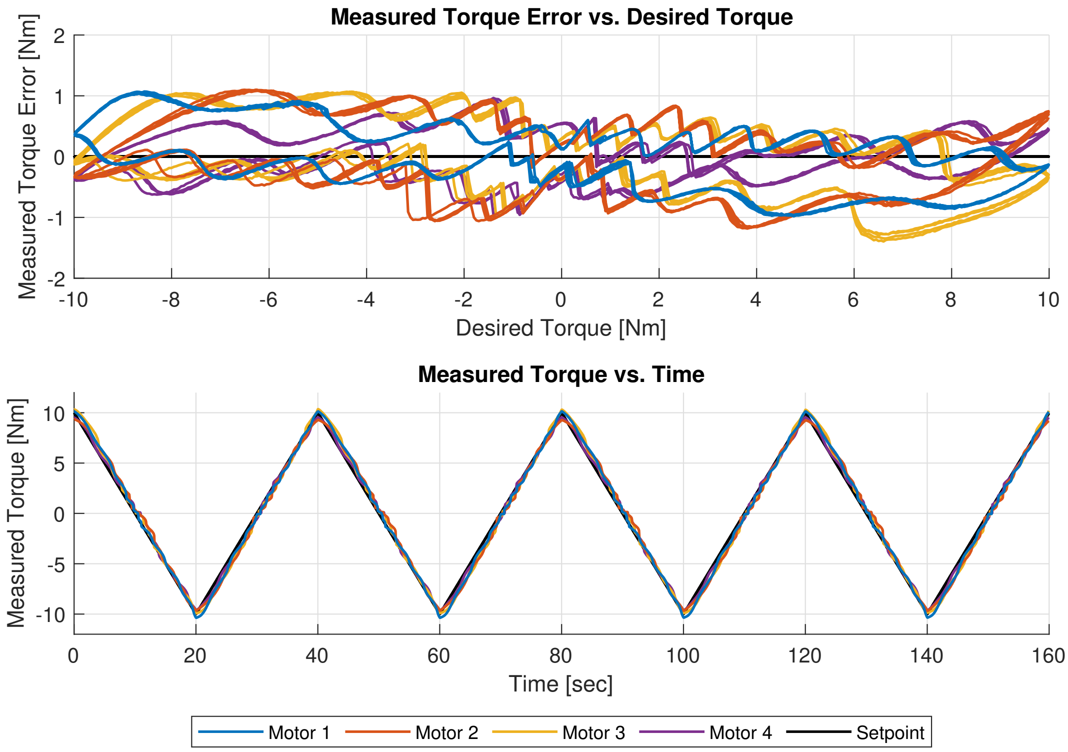


Figure 8: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Motors

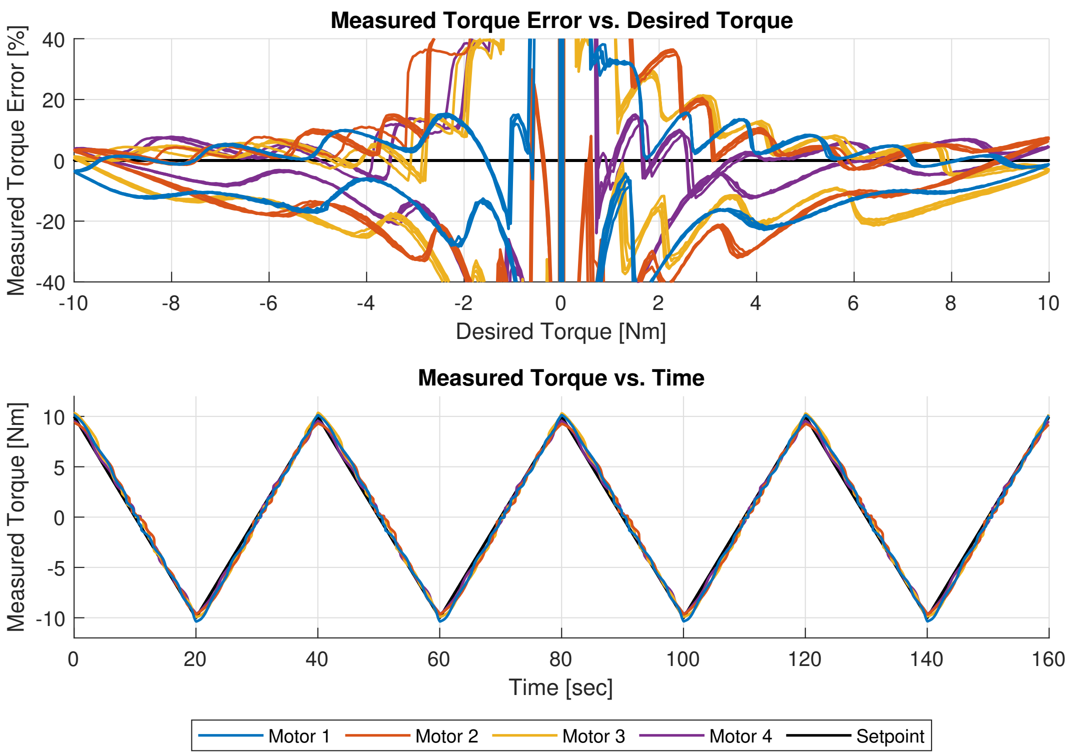


Figure 9: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Motors - Percentage Error

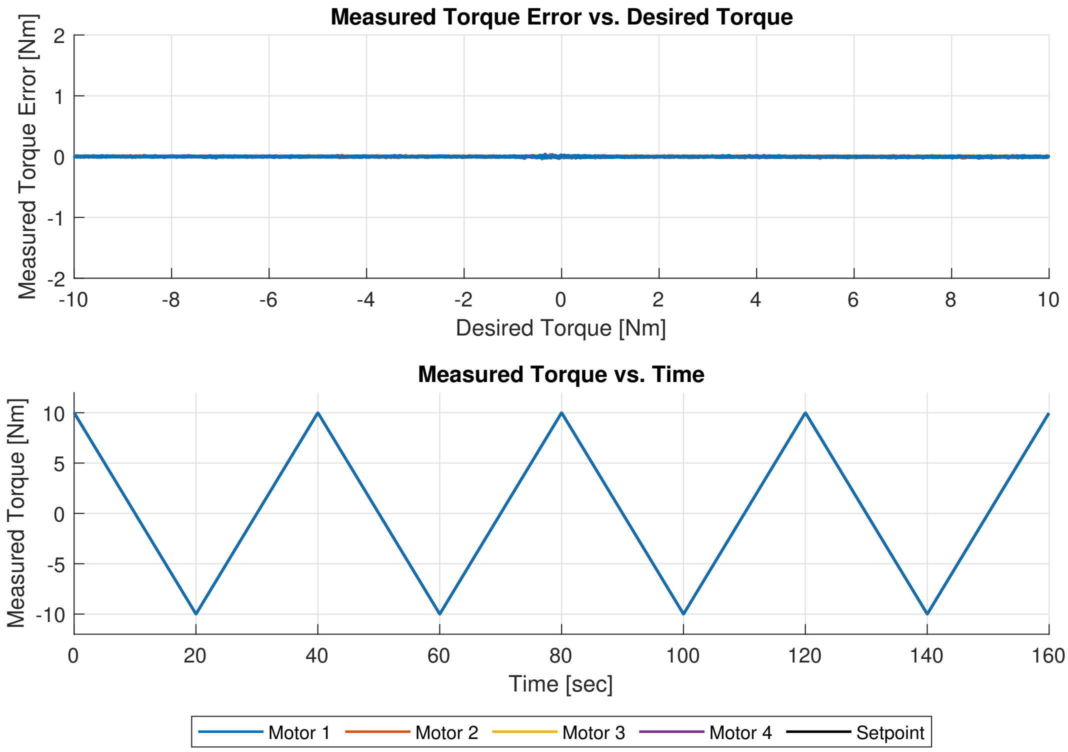


Figure 10: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Motors - Self Reported Torque

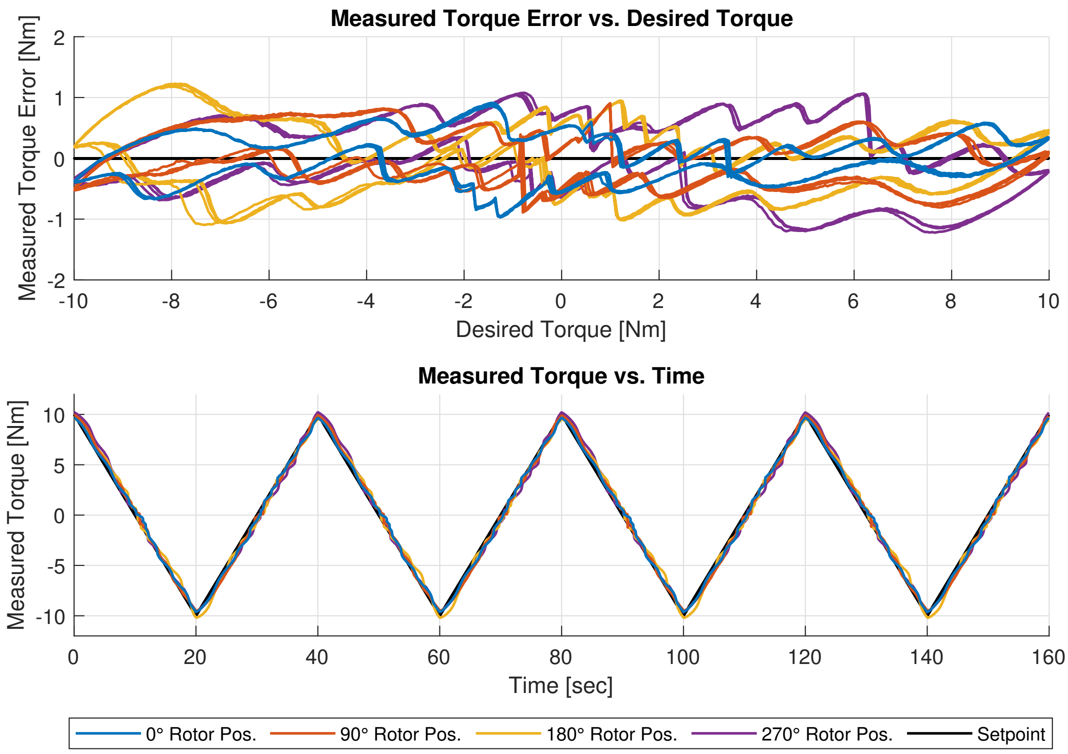


Figure 11: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Rotor Position

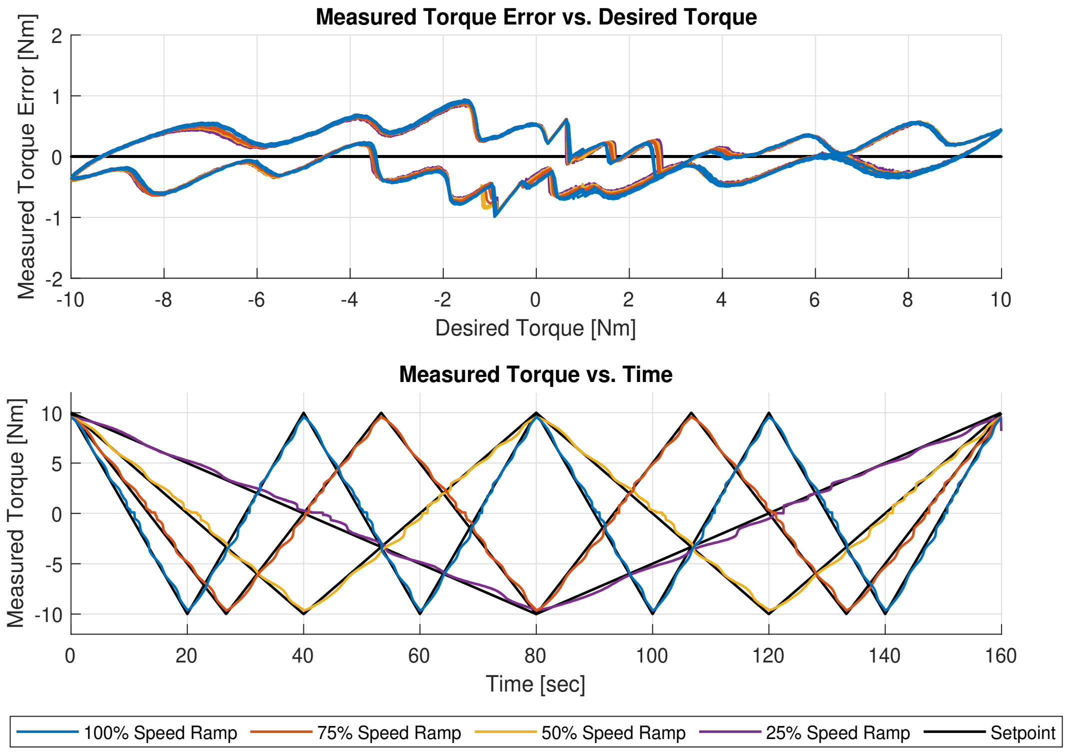


Figure 12: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Ramp Speed

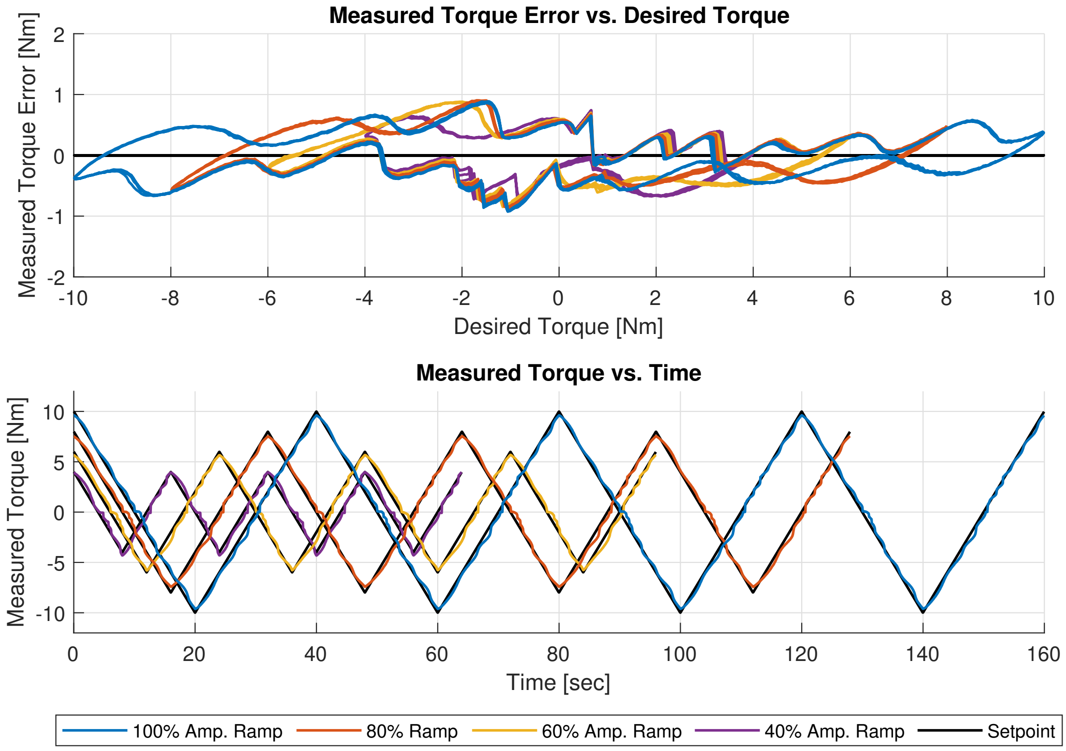


Figure 13: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Ramp Amplitude

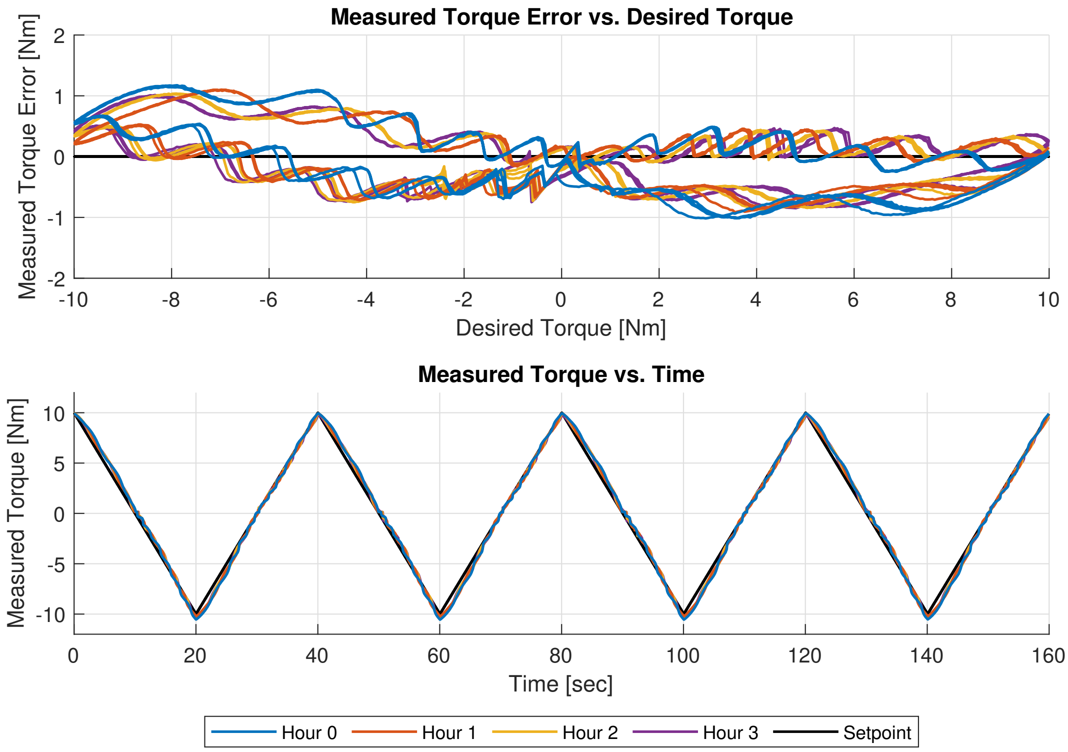


Figure 14: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Long Run

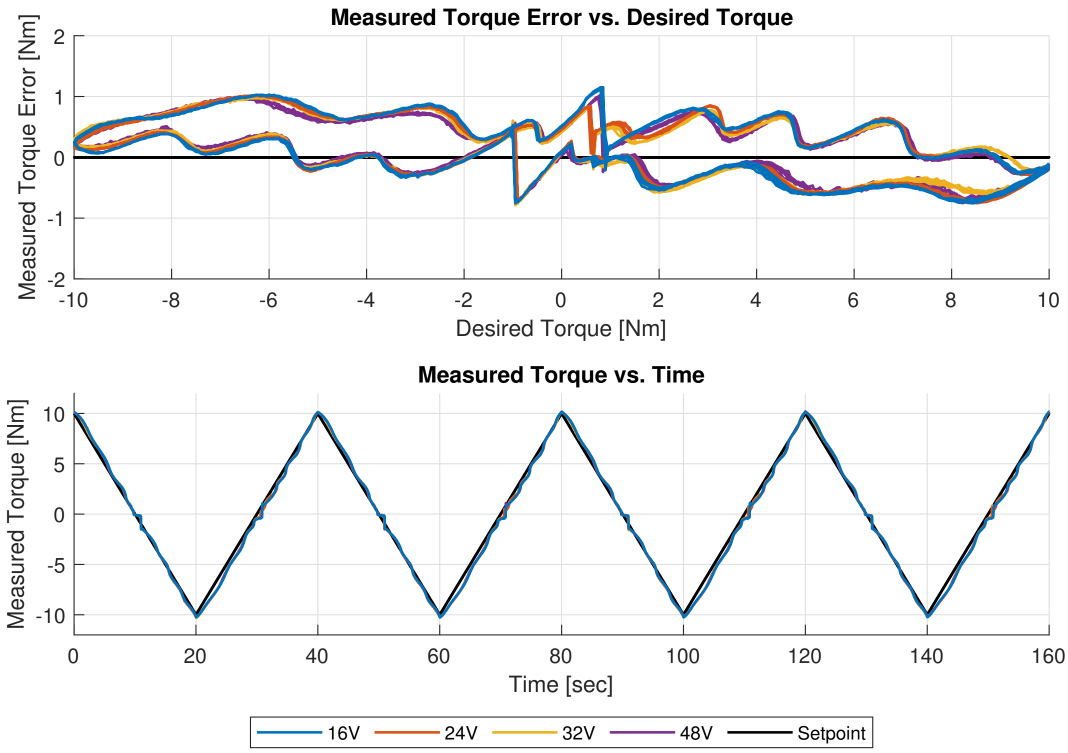


Figure 15: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Voltage

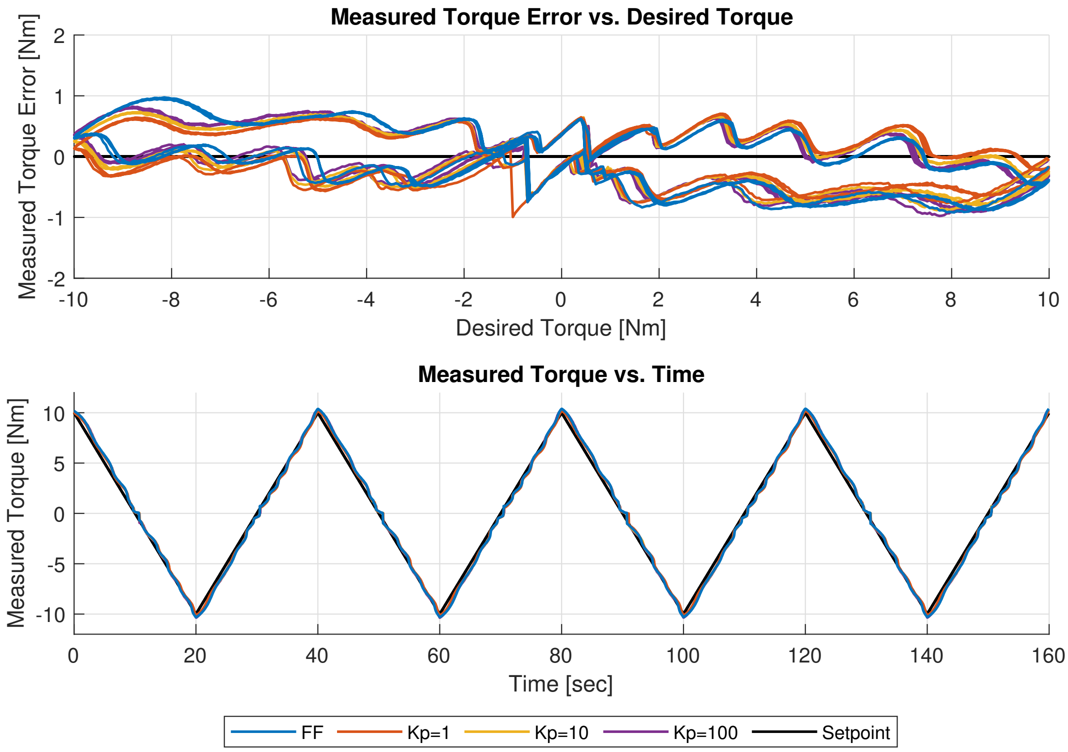


Figure 16: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Compare PD Control

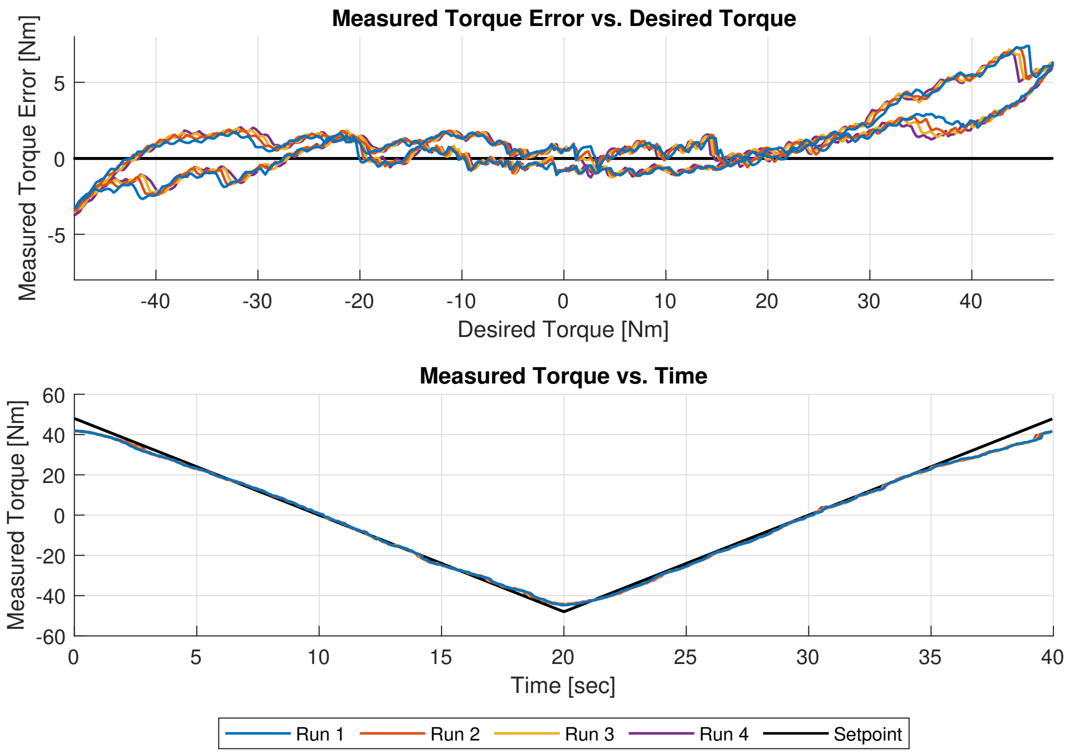


Figure 17: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Maximum Torque

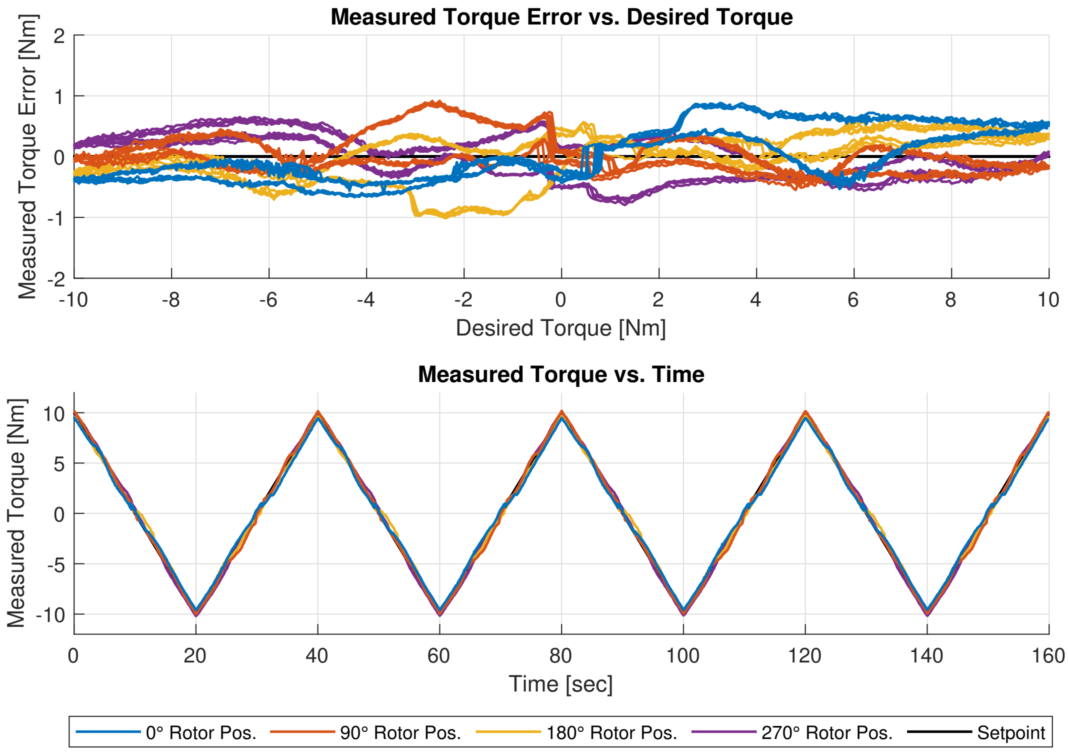


Figure 18: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Rotor Position - Direct Drive

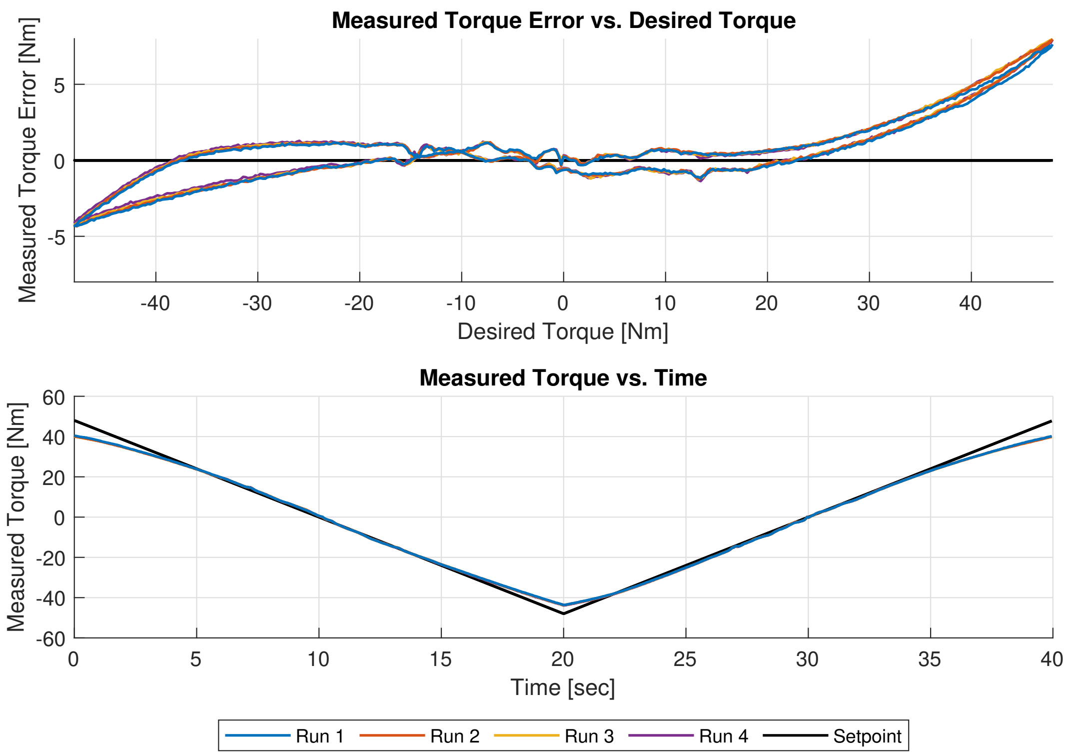


Figure 19: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Maximum Torque - Direct Drive

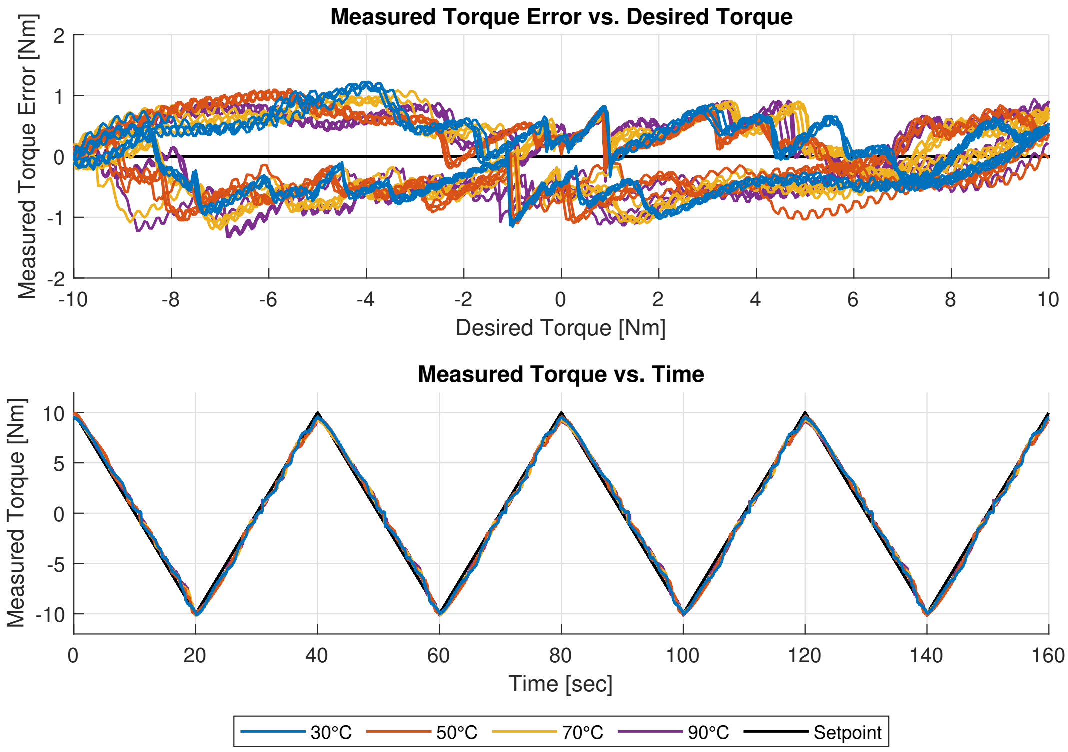


Figure 20: T-Motor AK10-9 v2.0 - Static Steady-State Torque Test Varying Temperature

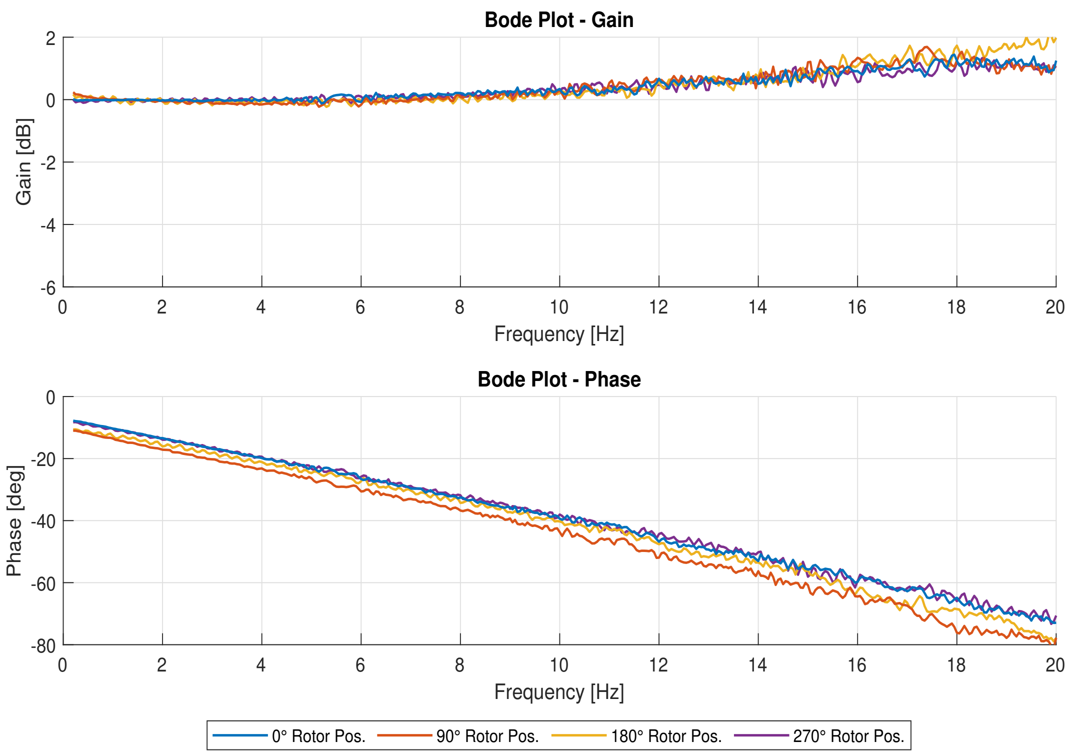


Figure 21: T-Motor AK10-9 v2.0 - Static Transient Torque Test Varying Rotor Position

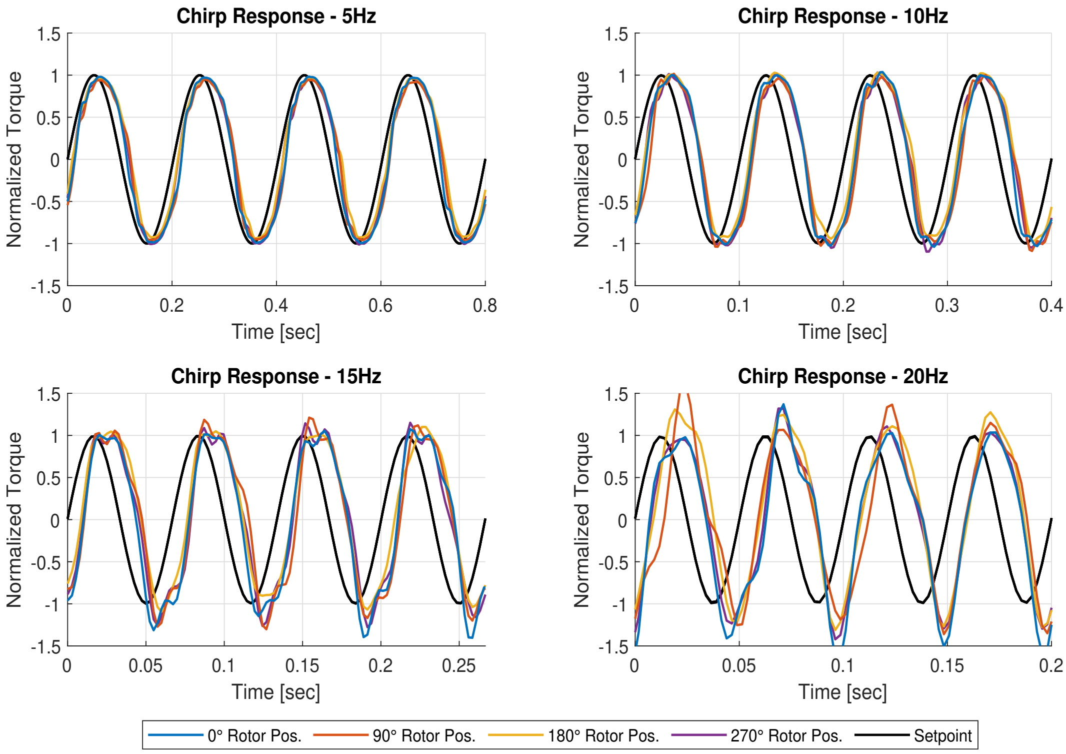


Figure 22: T-Motor AK10-9 v2.0 - Static Transient Torque Test Varying Rotor Position - Time Domain

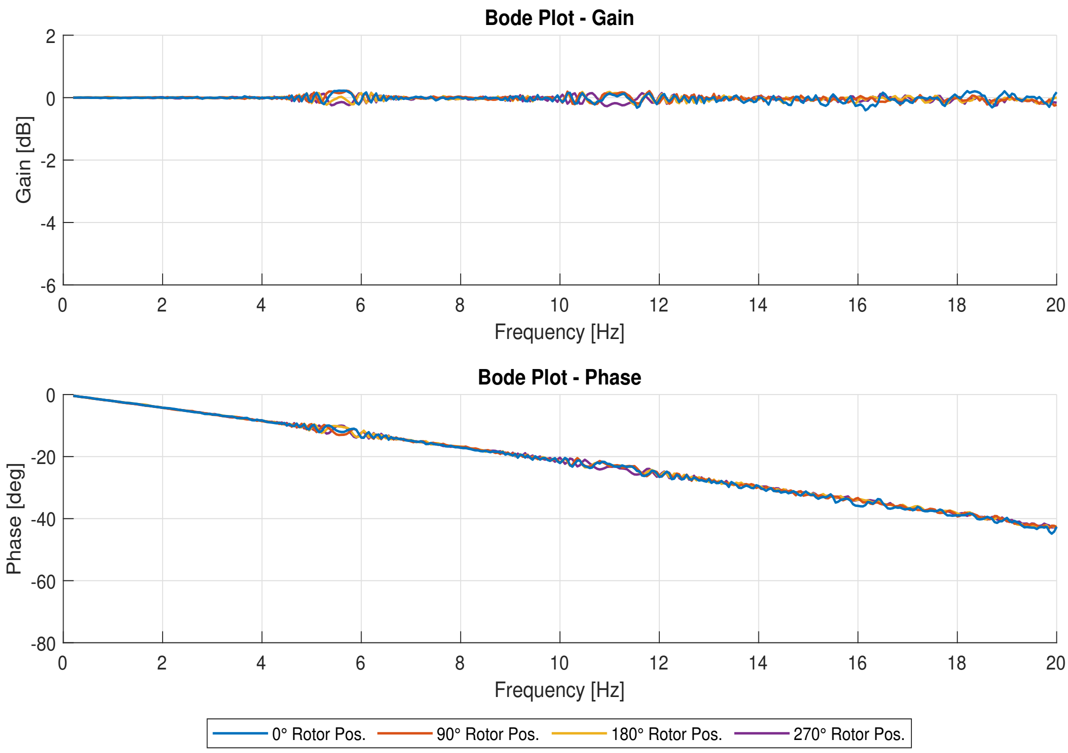


Figure 23: T-Motor AK10-9 v2.0 - Static Transient Torque Test Varying Rotor Position - Self Reported Torque

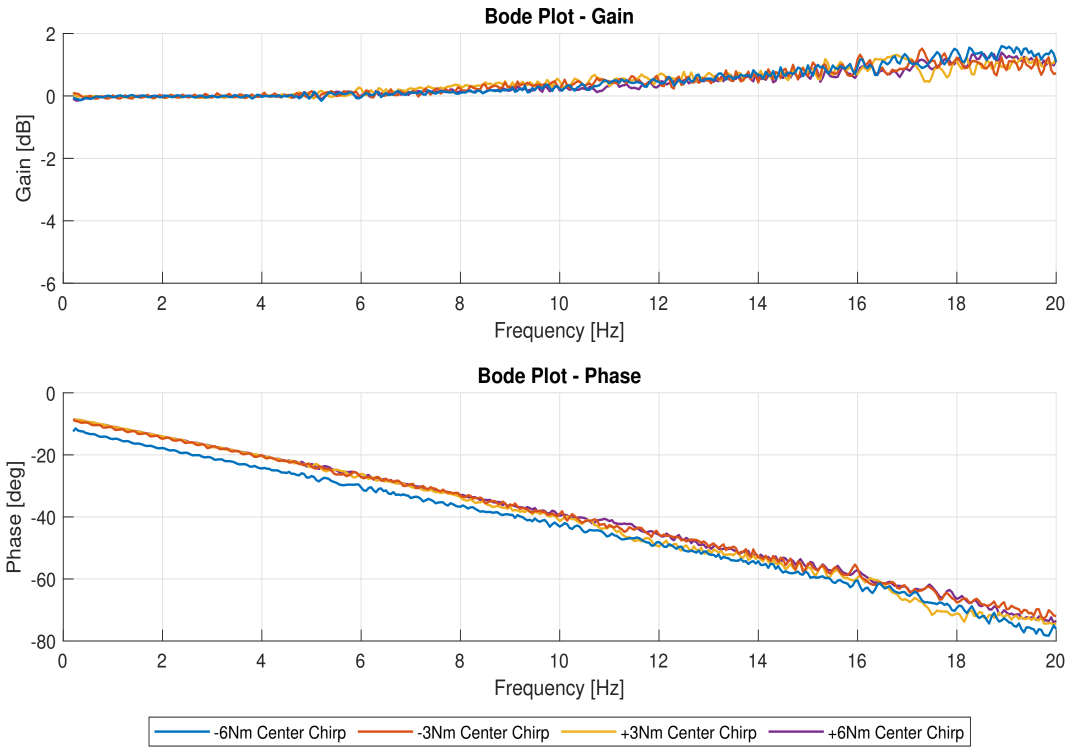


Figure 24: T-Motor AK10-9 v2.0 - Static Transient Torque Test Varying Chirp Center

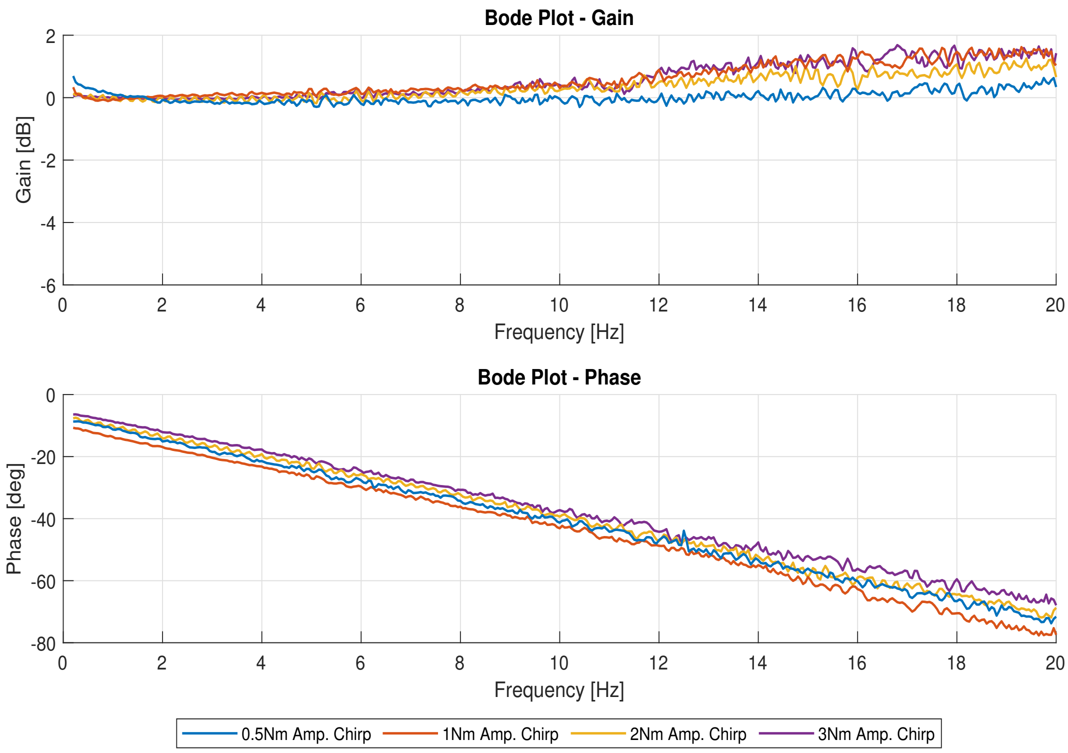


Figure 25: T-Motor AK10-9 v2.0 - Static Transient Torque Test Varying Chirp Amplitude

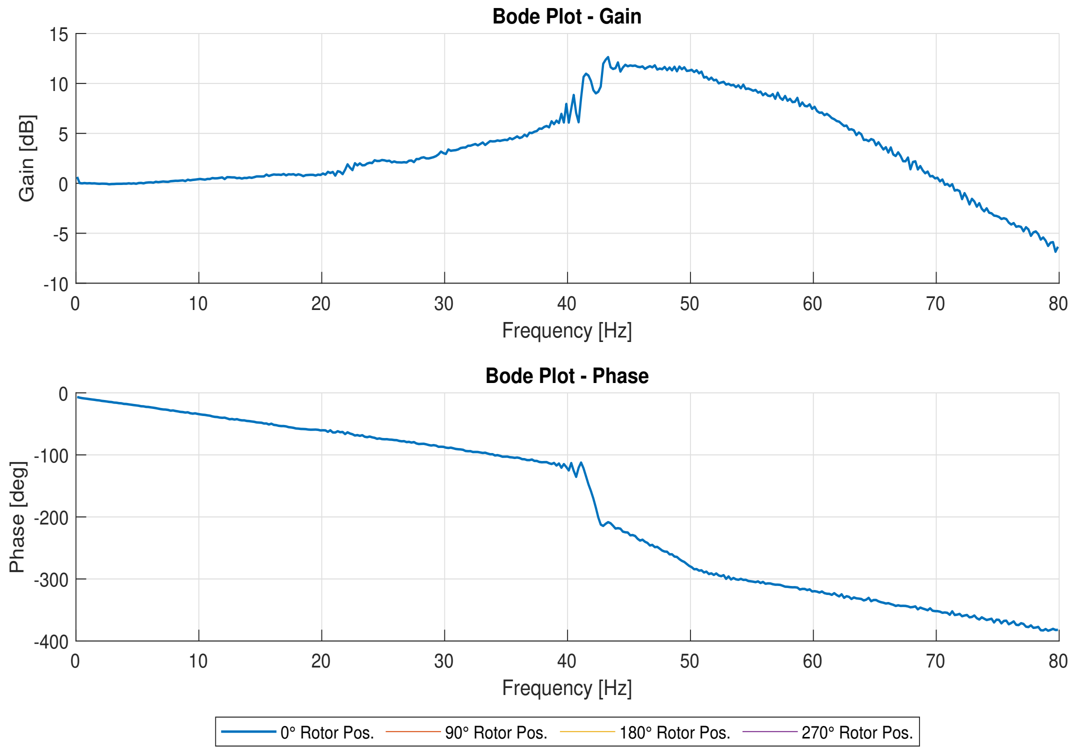


Figure 26: T-Motor AK10-9 v2.0 - Static Transient Torque Test Varying Rotor Position - High Frequency

5.2 MJBots QDD100 beta 3

The following tests results are for the MJBots motor, model QDD100 beta 3. The supply voltage used is 44V and nominal torque is ±5Nm. To note is that the automatic calibration process fails to accurately estimate the torque constant and that it was corrected manually to 1.33Nm/A.

Static Steady-State Torque Test:

- **Vary Rotor Position** (Fig. 27): The behaviour of the MJBots QDD100 motor largely matches the T-Motor AK10-9 v2.0, only that the torque error is reduced to ∼0.6Nm from ∼1.0Nm. This can be explained by the changed gearbox ration to 6:1 from 9:1, reducing any error by 6/9=0.67. Again, this points towards the gearbox having negligible influence on the torque error. This result also suggests that all motors perform somewhat similarly, as two motors from two manufacturer with entirely different components performing so similarly by chance seems very unlikely.
- **Vary Ramp Speed** (Fig. 28): The results are similar in all 4 tested speeds, strongly indicating that transient effects are not the cause of the hysteresis.
- **Vary Ramp Amplitude** (Fig. 29): Seemingly Unpredictable behaviour is observed after ramp direction changes, which gets reset after a 0Nm crossing.
- **Long Run** (Fig. 30): The duration between recordings is reduced to 8min, as interesting changes are observed over that time-frame. It appears that the motor controller is derating to hold a temperature of 70°C, which is reached after the first interval. This is unexpected as the *continuous* rated torque is 3.3Nm.

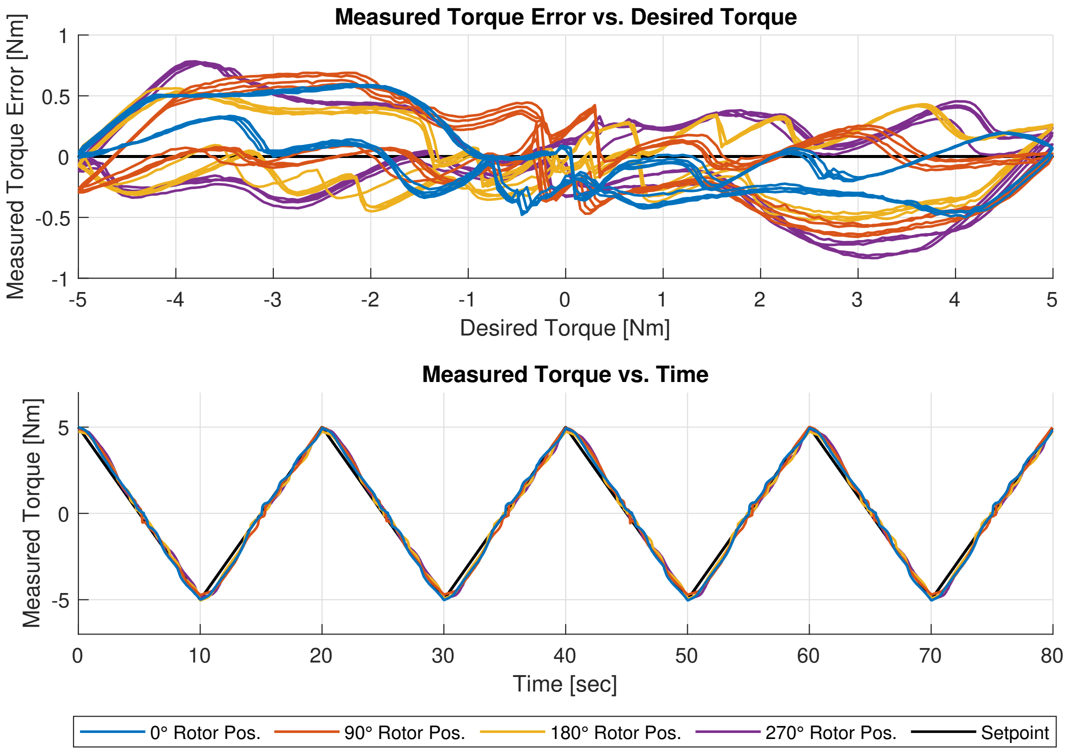


Figure 27: MJBots QDD100 beta 3 - Static Steady-State Torque Test Varying Rotor Position

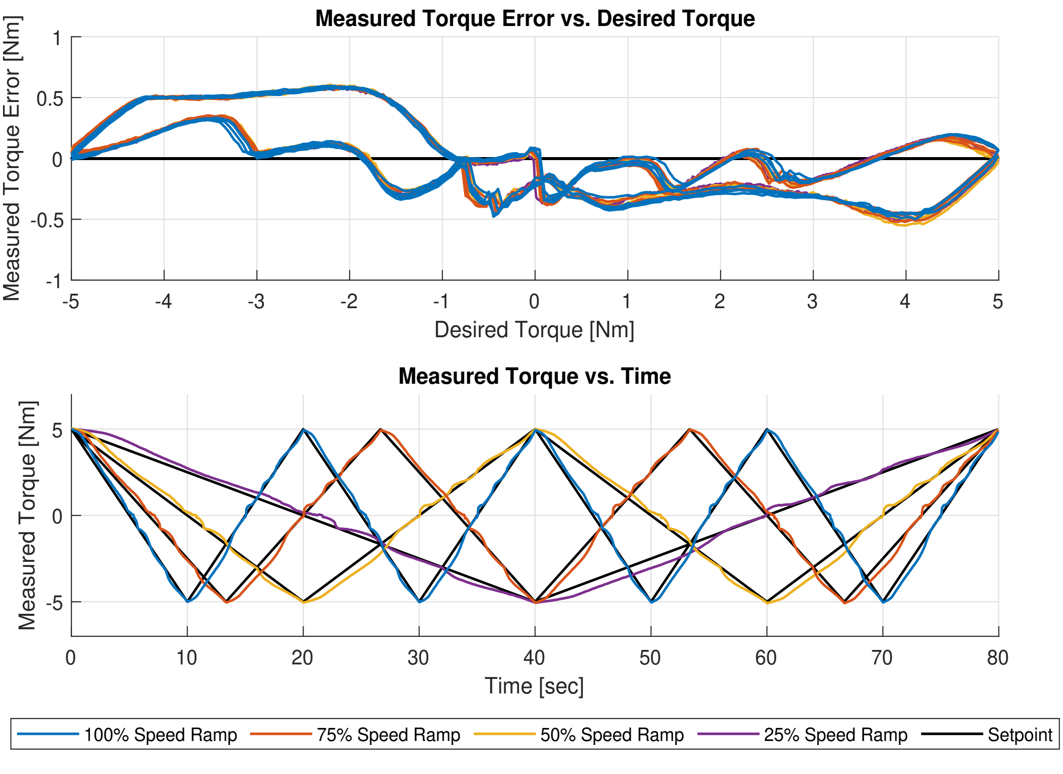


Figure 28: MJBots QDD100 beta 3 - Static Steady-State Torque Test Varying Ramp Speed

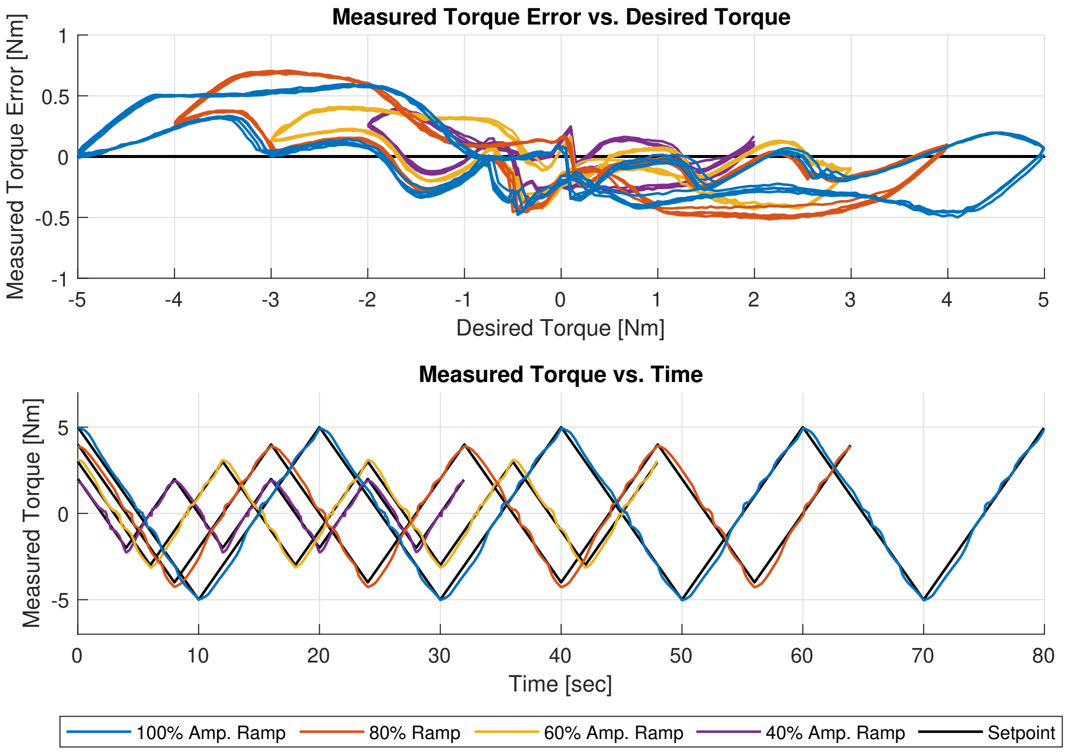


Figure 29: MJBots QDD100 beta 3 - Static Steady-State Torque Test Varying Ramp Amplitude

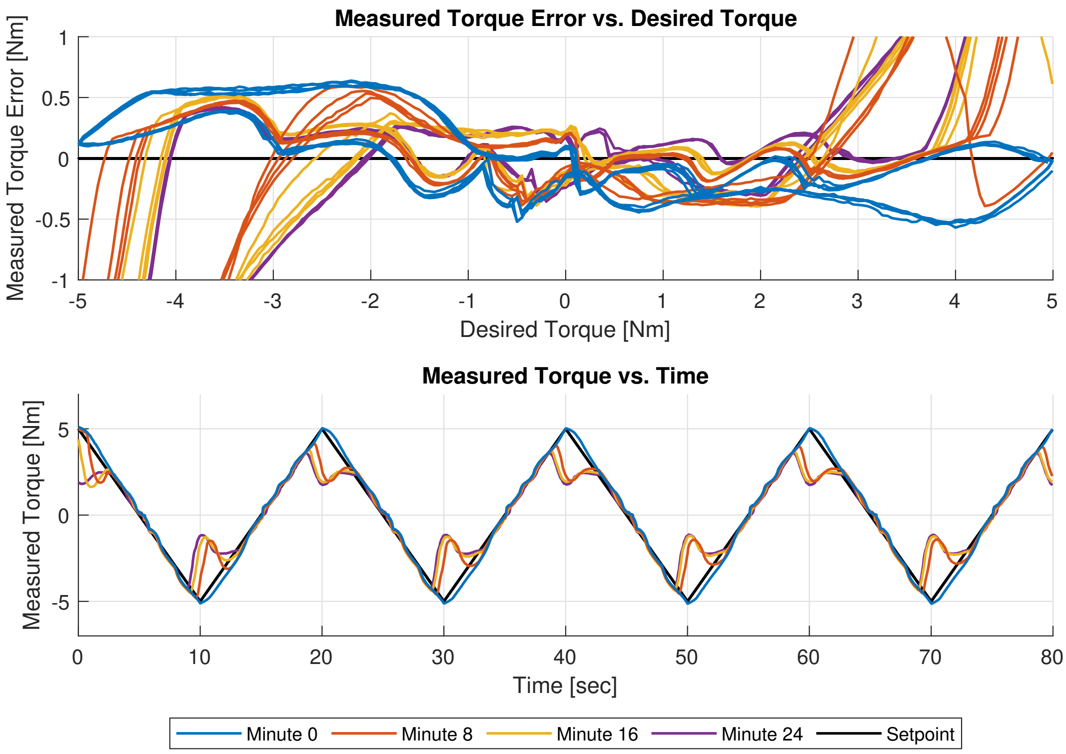


Figure 30: MJBots QDD100 beta 3 - Static Steady-State Torque Test Long Run

6 Appendix

6.1 High Torque Motor Selection Guide

There is a common misconception, that choosing the motor with the lowest KV will produce the highest torque. This is not necessarily true.

A quick reminder: The KV constant of a motor is the number of RPM produced for each Volt applied to the windings under no load ($KV : RPM/V$). Whereas the KT constant is the torque produced by the motors for each Ampere applied to the windings ($KT : Nm/A$). Meaning, the same current will ideally produce the same torque, no matter the rotation speed of the motor. KV and KT are inversely proportional to each other ($KT = 1/KV$), although special care must be given to unit conversions when calculating one from the other.

One could then reason that a low KV means a high KT, and a high KT means more torque for each Ampere, and that means more torque can be produced. The last part of the reasoning is not necessarily true. The reason being, that a high KV motor can take a higher maximum current than an otherwise equivalent low KV motor.

An explanation can be found in that the limiting factor for maximum torque is heat dissipation of the motor. For two motors that are equivalent besides their KV, the heat dissipation capacity is the same. Heat generation can be split up into two categories, copper losses and iron losses. Iron losses are disregarded here as they mostly play a role at high RPM, which is not the typical application of high torque motors. Copper losses are losses caused by the resistance of the copper windings. Now it can be noted, that high KV motors have a low winding resistance. Reason being, that for higher KV a lower number of windings are used, and so the copper wires are shorter and thicker to fill the same space, both lowering the resistance. The effect is that a high KV motor produces less copper loss than a low KV motor for the same winding current. Or viewed differently, a high KV motor can take more current before the copper loss matches the maximum heat dissipation capacity. It then so happens that a high KV motor, which consequently has a low KT, can fully offset the low KT by being able to support a higher current, and ends up producing the same maximum torque $T_{max} = KT * I_{max}$.

The question might then arise on what is a good criterion for selecting high torque motors, if a low KV is not necessary. The easiest way is to hope the motor datasheet provides a maximum torque rating. Otherwise the relevant variables are:

- Large volume of copper windings (large motor)
- Good heat dissipation

- Copper with low resistivity
- Core with high permeability
- Strong permanent magnets
- High gear reduction (although this also amplifies any torque error)

A different source of confusion might be on what role the motor input voltage plays. Internally these motor control the current to the windings, and subsequently the torque, by chopping the input voltage. A shunt resistor is used to measure the current and as feedback for setting the duty cycle of the chopping. At the windings, this controlled current results in some voltage, that is not necessarily the same as the input voltage. This voltage is given by the sum of the winding resistance voltage ($U = R * I$) and the back-EMF voltage. The back-EMF voltage is induced by the permanent magnets moving relative to the windings and increases with motor speed. At some speed the back-EMF voltage will match the input voltage, and it will become impossible to push current trough the windings, consequently it will be impossible to produce torque that could further accelerate the motor speed. This is the maximum motor speed, and even before reaching it, the capacity to produce current/torque will be lowered. The maximum supported input voltage is limited by the electrical components used in the controller and by the insulation rating of the windings.

good single source for this information??

6.2 Possible Future Tests

- **Dynamic Tests**: Perform all presented tests while the motor is moving at a fixed RPM. The Robotic Systems Lab (RSL) owns a teststand suitable for these tests.
- **Resiliance Tests**: Stress test a motor until it breaks, either with aggressive step inputs causing impact loading, exceeding torque limits, or similar.
- **Efficiency Tests**: Check how efficient a motor is at producing torque under various conditions.
- **Varying KV**: Test how a changed KV impacts the torque output on otherwise equal motors, to experimentally confirm the statements in the motor selection guide.
- **Different Motors**: Test more different motors, like the UniTree A1.

6.3 T-Motor AK10-9 v2.0 - Direct Drive Modifications

To run the T-Motor AK10-9 v2.0 as a direct drive motor, the built in planetary gearbox is modified. The planet gears are removed and replaced by a 3D printed carbon-fiber reinforced PET-G part, that rigidly connects the sun gear (input) to the planet carrier (output). 3D printing is chosen as it would be difficult to manufacture an inside gear matching the sun gear in metal. After some maximum torque tests the printed part is unchanged, indicating that it is strong enough and likely also rigid enough. Nevertheless, prolonged high torque tests are avoided, as temperatures above 80°C would soften the part.

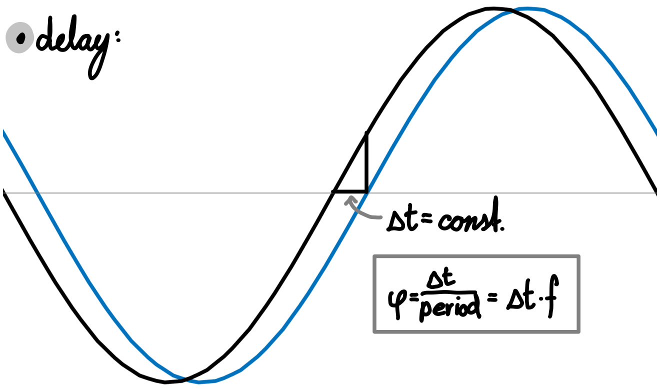
Figure 31: Images illustrating the direct-drive modification of the AK10-9 v2.0

phase plot explaination

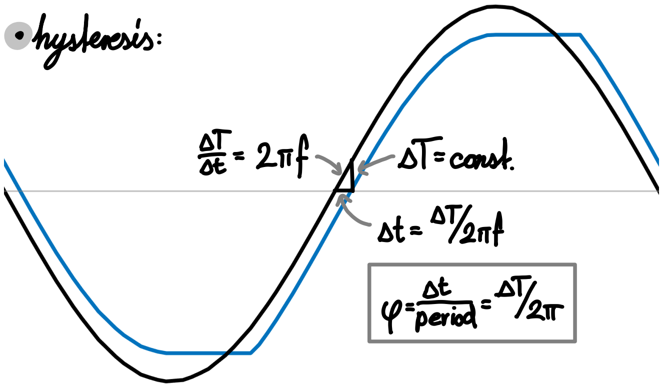
const. time delay Δt + torque hysteresis ΔT : can explain observed phase plot!

- ↳ reason for delay: protocol delay, current sensing/control delay, others?
- ↳ reason for hysteresis: magnetic hysteresis in motor core? (apparently not gearbox friction, see DD test)

• delay:



• hysteresis:



• default FD identification test results explained with 9ms time delay and 0.45Nm torque hysteresis: