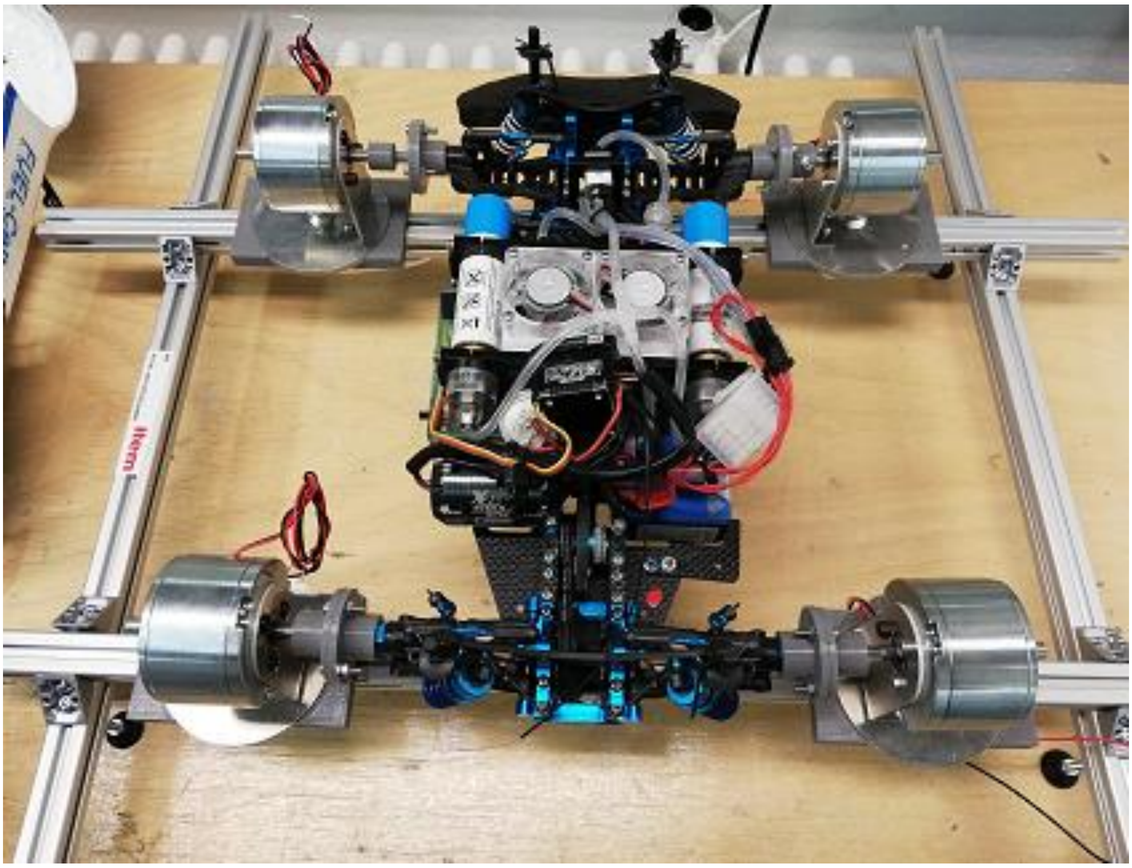
Graduation Assignment

Test stand design and automated sequenced implementation



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MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Master of Automotive Engineering**

Branch of study: **Advanced Powertrains**

II. Master's thesis details

Master's thesis title in English:

Test stand design and automated sequences implementation

Master's thesis title in Czech:

Konstrukce a automatizace zkušebního stanoviště

Guidelines:

1. Literature and market survey of car dynamometer, the suppliers and working principle.
2. Survey of mechanical and electrical solution suiting a 1:10 car test stand. Choice of test stand parts (for e.g. sensors, actuators) to assess power and energy consumption in accordance to given criteria (for e.g. reliability, feasibility, accuracy)
3. Mechanical design of the test stand with PTC Creo. Ordering of the necessary parts, assembling of the test stand.
4. Automation of the test stand including the measurement inaccuracies using real-time automation software: PA tools TX from Kratzer Automation.
5. Implementation of driving test cycles based on WLTP and NEDC.

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Assignment valid until: ____________

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Abstract:

The actual methods to provide an average consumption of a certified vehicle are the standard driving test. As different standards exist according to the country, they have in common to test vehicle on laboratory on test benches. The use of test benches is motivated since it allows to simulate the road conditions in a repeatable way and under specific conditions providing consistency of the measurement. The emulation of the road conditions has to be transferred to the bench were the car can spend its power. The use of chassis dynamometer allows to produce a resistive torque to the car's wheel in accordance with the road load simulation model.

This master's thesis aims in his turn to assess car consumption on driving test but specifically for a 1:10 RC electric car. This car has basically been built for an endurance race. Given that it is a specific vehicle, no standards are defined, and this thesis proposed a simplified driving cycle which give specifications to design an adapted chassis dynamometer car allowing to emulate a road load conditions. The use of an industrial PLC computer allows the automation of the tests as the same time as the assessment of the mechanical and electrical power.

The presented results report the chassis dynamometer design under PTC CREO, assembly and test. The simulation of the road load adapted to a 1:10 car along a driving cycle. The acquisition of the motor rotational speed, battery voltage, under TwinCAT PLC using the I/O communication EtherCAT. Further, method of system identification has been tested with Simulink toolbox for PMSM/converter speed control.

Keywords: chassis dynamometer, road load, speed control, driving cycle

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

TECHNISCHE UNIVERSITÄT CHEMNITZ

Acknowledgment

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Maxime WACH
Chemnitz, Germany
11/01/19

Table des matières

List of abbreviation

PAU	Power Absorption Unit
TUC	Technische Universität Chemnitz
PMSM	Permanent Magnetic Synchronous Motor
ESC	Electronic Speed Controller
SOC	State Of Charge
I/O	Input/output
PLC	Programmable Logical Controller
RLS	Road Load Simulation
PWM	Pulse Width Modulation
RC	Radio Controlled
HB	Hysteresis brake

List of nomenclature

Je	**D**riveline inertia in kg m^2
Cpm	Prime mover torque in N
Cmt	Resistive torque of the trunnion mounted brake in N
τ	Shear stress in MPa
T	Torque in N
D	Diameter in m
m_{eff}	Equivalent mass in kg
v	Speed in m/s
F_{mot}	Wheels effort in N
F_{aero}	Drag resistance in N
F_{roll}	Rolling resistance in N
F_{grade}	Grade resistance in N
S	Surface in m^2
ρ	**A**ir density in kg/m3
C_x	Drag coefficient
m_{car}	Car mass in kg
g	Gravity in
f_{roll}	rolling coefficient
ϑ	grade of the road in degree
r	wheel rim in m
J_w	inertia km m^2
J_{drive}	inertia kg m^2
N_f	gear transmission
N_t	gear transmission
J_M	motor inertia in kg m^2
J_{eff}	equivalent inertia in kg m^2
w	Wheel speed in rpm
C_w	Wheel torque in Nm
Cr	Resistive torque in Nm
$Crdyn$	resistive torque of the dynamometer in Nm
J_{bench}	Inertia of the bench

J_{mot}	Motor inertia in kg m^2
k	Gear transmission of the car
$J_{rotating}$	inertia of the real rotating part in kg m^2
C_{dyna}	Dynamometer torque in Nm

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1 Introduction

Over the last decades, the observation of the scientific community regarding the evolution of pollution and global warming has led the automotive industry to the hardening of car certification's standards. The establishment of driving cycle recognized as standards, provides a common test estimating the car consumption available on the European roads. In the facts, many driving cycles exist throughout the world, those tests are performed in certain circumstances. The essence of the measurement's results highly relies on repeatable conditions and fixed test settings. Those reasons have motivated the introduction of the new WLTP providing tests more adapted to real road conditions.

As the department of the TUC works on automotive test for the industry, the future settlement of a chassis dynamometer in the laboratory will be used as test bench automated with a real time PLC. In extension, the master's thesis has been proposed to work on a test bench to implement automated sequences by means of an industrial PLC.

Dimension, design and assemble a chassis dynamometer suited a 1:10 electric touring car able to provide an estimated mechanical power and allowing the operator to implement future automated driving sequences.

To meet the objectives, we will first model the road load simulation for a given driving cycle allowing the test bench's design. After the assembly of the test stand, we will try to enslave a PMSM motor and his controller to perform the future automation of the driving sequences.

1.1 Statement of the problem:

To provide the assessment of the power at the cars wheels directly, test laboratories use what is called a chassis dynamometer. Generally, it is composed of a brake and a torque sensor to assess the power but in this case the lack of

The first part of the master's thesis aims to:

In the following sections, we define the specifications with the test requirements. We model the vehicle to propose a road load adapted to the driving cycle. Then we study the principle of a chassis dynamometer, we explain the problematic associated to the measurement of the dynamo power. After doing a basic market research of the existing benches, we chose a solution with the selecting method and finally with dimensioned component responding our specifications, we will build the bench.

1.2 Outlines

The general advancement to meet the master's thesis requirement is organized as follow:

Chap 2: Chassis dynamometer

In this chapter, the principle of the chassis dynamometer is explained so does our methodology to assess the torque without torque sensor. After a short survey of the market, the existing solutions allow us to provide criteria for designing a chassis dynamometer according mechanical requirement.

Chap 3: Road load simulation

This chapter treats the mechanical model uses to determine the road load to simulate on the brakes. With the help of a defined driving cycle, the theoretical power and torque is computed and will be used as criteria to select a PAU.

Chapter 4: Design of the bench

This chapter deals with the selection of components according the previous criteria such as the PAU. It deals with PTC CREO simulation to design some specific part such as the connection wheel to brake.

Chapter 5: Speed regulation

This chapter deals with the motor and ESC control. After defining the principle, some experiments are done as pwm control with Arduino and with TwinCAT.

Chapter 6: Energy consumption

The definition of the SOC is studied and it is proposed two methods to determines the SOC of the battery

Chapter 7: Data acquisition

This chapter deals with the acquisition of the data such as the speed, the voltage and the current from the car. The choice of the cards is made thanks to signal analysis and the basic automation test are done

Chapter 8 : It presents some results about speed.

2 Chassis dynamometer

2.1 Principle of a dynamometer

A dynamometer is a device for measuring the force or mechanical power transmitted by a rotating shaft. The principle of a dynamometer lies on the measurement of the resistive torque of the brake connected to the prime mover. The brake absorbs the power of the prime mover. With the knowledge of the rotational speed, the power is assessed.

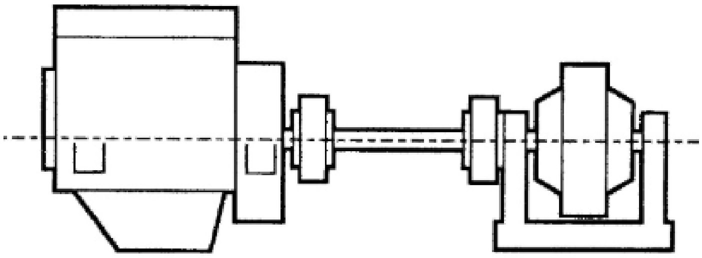


Figure 2-1. Simple for of dynamometer/engine driveline

In the case of the trunnion-mounted dynamometer (figure 1-2), the PAU is mounted on bearings coaxial with the shaft of the prime mover. This former develops its power into the PAU which when it brakes produced a resistive torque measured by the load cell acting tangentially at a known radius from the axis. The effort measured at the load cell drives to the knowledge of the resistive torque.

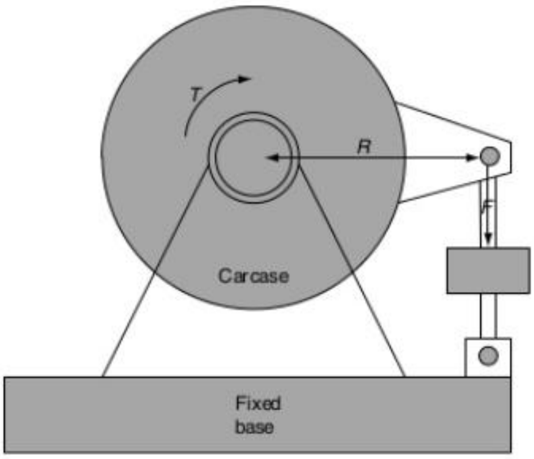


Figure 2-2. Diagram of a trunnion-mounted dynamometer measuring torque with a load cell

The law of dynamic (1.1) applied on the axis of the system {prime mover + PAU shaft} highlights the fact that the torque from the prime mover is the torque measured when the state is permanent.

$$Je\frac{d\Omega c}{dt} = Cpm - Cmt \quad (1.1)$$

But in case of transient states with accelerating and decelerating conditions, which are the most common measurements during the driving cycle, the torque must be corrected by the knowledge of $Je\frac{d\Omega c}{dt}$. Thus, the simple torque measurement in not sufficient to know the output torque unless there is no inertia. It is as well understood that the prime mover put in movement this inertia and spend energy to accelerate it. But in a test bench, to assess the exact consumption of the car on road condition, the inertia as to imitate the one of the car, if not, we spend extra energy not representing the true consumption of the car.

Based on those fact, the criteria of **inertia** is basics requirement for test bench design. It will attempt to be minimized.

2.2 Torque measurement

Currently, several technologies for torque measurement exist in the automotive industry. We are not going to details all the existing solution, but they turn out expensive, difficult to set up and to calibrate. As the design of the bench doesn't aim to be marketed but to be used as a tool for automated sequences the budget is limited and the buying torque sensor or load cell or equivalent precision technology is not permitted.

To balance this problem, let us understand the motivation of the use of a torque sensor. As it was discussed previously, the brake is controlled, and the torque is measured from the resistive torque of the brake. In general, the torque law related to the brake's command is unknown and when it is known, the torque is highly dependent on external parameters such as speed and temperature. Preventing the measurement to be repeatable.

But in the situation where the PAU offers known torque law with few dependencies over test parameters, we can obtain a torque estimation on the brake output just by knowing the command.

In addition, the knowledge of the command and the acceleration terms ($Je\frac{d\Omega c}{dt}$) provides the power of the prime mover. In the case where such a PAU is available and calibrated for specific conditions it is an alternative to measure the torque.

Based on those fact, we are provided two other criteria which are the knowledge of the **torque law** of the PAU and the possible **automated control** of this PAU as we are going to run automated sequence.

2.3 Pau market analysis

The following paragraphs gathered some existing technologies of chassis dynamometer for industrial purpose and for 1:10 RC car. This section is not going to explain in detail every technology but gives general knowledge and critical view to build a methodology for chassis dynamometer design

The study describing the different dynamometer technologies and torque measurement is reported in **[1]** Moreover, as we don't need a torque sensor, we will not study the torque sensor principle neither the existing solution

2.4 Rotronics solution

Rotronics is specialist in motor and vehicle test bench design. It proposes solution adapted to assess power

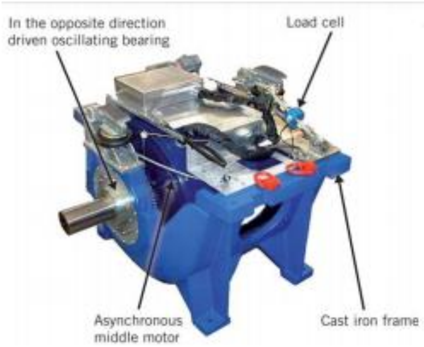


Figure 2-3: Eddy current brake trunnion mounted

The presented dynamometer is provided of an Eddy current PAU acting as a trunnion mounted torque measurement device. The eddy current is a spread technology in the chassis dynamometer industry thanks to its low inertia, good torque/power range over speed matching a large range of motor. However, this solution is well adapted to provide higher torque than our request even if it allows good control, it is generally temperature sensitive and has low dynamic performances.

This is to give three additional criteria:

- The first one is the **matching torque** over the speed. Actually, the PAU need to be oversized compared to the measured power to fully range the measurement possibilities.
- The second criteria is the **high dynamic** performances. This is justified with the high acceleration abilities of the car which can accelerate till 8m/s^2

2.4.1 AVL solution

AVL is one of the powertrain system world leader. This engineering Austrian company has recently developed a chassis dynamometer for F1 testing

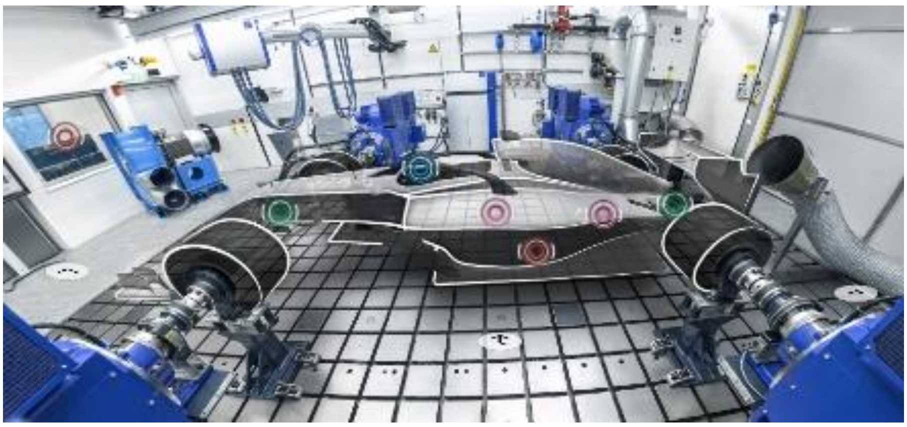


Figure 2-4: AVL Racing chassis dynamometer

The figure depicts a high controlled environment with precise F1 position on the test stand. As previously, the connection coupled a hub elastically., preventing vibration. The torque is measured with a torque flange directly connected between the brake and the hub.

The solution proposed uses AC dynamometers as brakes, their advantage is that they act on the 4 quadrants also as regenerative brakes. AC brakes ensures lower inertia, robustness yet it requires a precise electronic control.

The use quadrant won't be decisive as we won't require 4 quadrants working but only on the 1/3 (figure down). The brakes as not necessary regenerative. However, the convenience to control the brake with **few electronics** is a criteria.

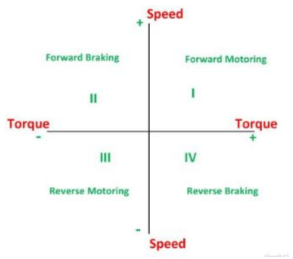


Figure 2-5: Quadrant

This picture also depicts the use of hub connection for power transmission.

Hub connection has several advantages as the allows no wear, few inertias. However, they need to be accurately aligned.

The criteria of inertia and wear are used for chassis bench type selection.

2.4.2 Crea Technologie RC 1:10 bench

The actual test bench used for the RC car is a roller bench of 4 connected inertia providing the same speed at each wheel.

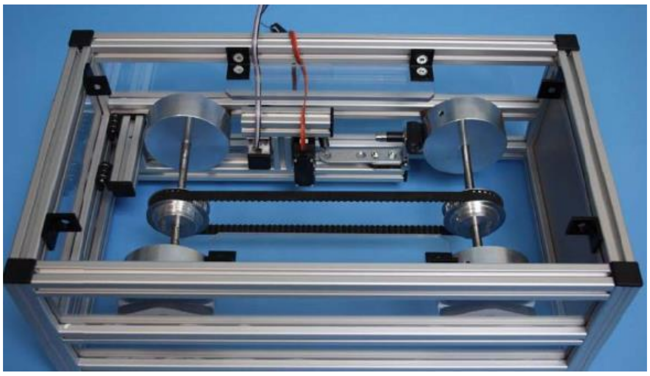


Figure 2-6: Crea technologie 1:10 RC test bench

Braking principle lies on friction actuated by a servomotor whose position is controlled. This solution has the main problem of wheel slip leading to inaccurate measures as the hall effect sensor provides one time per round. The advantage of this bench is the compacity of the test environment and the lifetime of its components.

However, the friction lead to wear and doesn't allow torque's law establishment since it is highly temperature dependent.

Unlike the previous solution, this chassis offers rolling inertia as interface between the wheels and the brakes. The main advantages of the rolling chassis is that they provide easy setup, However, the it prevents good repeatability because of interaction between the wheel and the rolling part which is an area of temperature variation and rolling resistance. For this reason, hub connection will be chosen.

2.5 Mechanical for hub connection

Although the hub connection seems to provide better measurement conditions, the built up of the coupling device must be dimensioned in counterpart.

The nature of the problem when coupling two shaft is inherent tendency to develop torsional oscillations. Those one must be properly aligned. In case of misalignment, excessive vibration can lead to lifetime shorten and damage of the transmission.

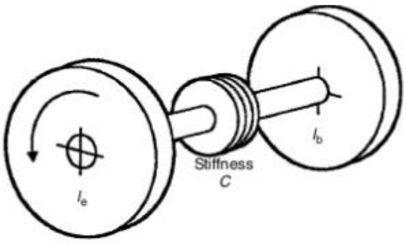


Figure 2-7: Inertia coupling

A way to prevent from misalignment, techniques such as dial indicator mounting. It ensures the unalignment measurement from a shaft to the other. Laser techniques or vibrational survey can also be done but are not topic for this study.

To resist the developed torque by the prime mover, the shaft must be dimensioned. In case of a full cylinder according to [3], the maximum shear stress is computed and provide the minimum diameter.

$$\tau = \frac{16T}{\pi D^3} \tag{1.2}$$

In the RC car model tests, a simple diameter simulation with PTC CREO FEM is complete. As a lot of part act as damps, the vibrational analysis is not treated.

criteria	weight
Price	5
Torque law	5
Automated control	5
Matching torque	4
Inertia	3
High dynamic abilities	3

Tableau 2-1: PAU Criteria

3 Road load simulation

3.1 Vehicle model

On a test bench no road conditions are available and need to be emulate as effort to the wheels. This is the role of the brake. This emulation is possible by applying the desired load thanks to the brake of the dynamometer.

The brake has to emulate the effort the car is facing on the road but also the simulated inertia of the car as it has no motion on the test bench.

The next section gives the mechanical model of the effort that the brake must provide.

The dynamic equation (1.3) describes the motion of the car in a longitudinal road on a steep with a grade ϑ

$$m_{eff}\frac{dv}{dt} = F_w - F_{aero} - F_{roll} - F_{grade} \quad (3.1.1)$$

- The air drag is given with:00

$$F_{aero} = \frac{1}{2}\rho S C_x v^2 \quad (3.1.2)$$

The parameters are chosen according hand measurement and Cx is chosen from a race car as the shape is similar.

- The rolling resistance is taken with standard rolling coefficient for rubber classic tires:

$$F_{roll} = m_{car} g f_{roll} \cos(\vartheta) \quad (3.1.3)$$

- The gravity effort is given with:

$$F = m_{car} g \sin(\vartheta) \quad (3.1.4)$$

The effective mass of the car with the rotating components is given according to the car transmission:

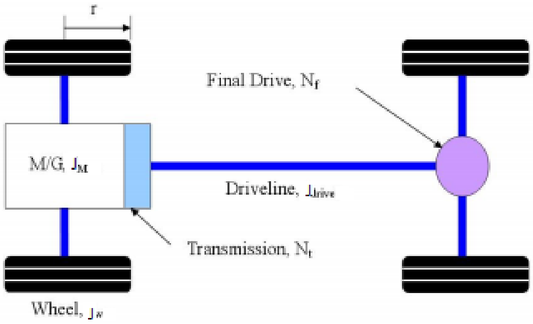


Figure 3-1: Vehicle model

$$m_{eff} = m_{car} + \frac{4J_w}{r^2} + \frac{J_{drive}{N_f}^2{N_t}^2}{r^2} + \frac{J_M{N_f}^2{N_t}^2}{r^2} \quad (3.1.5)$$

Approximation:

- The driveline components are mostly in plastic and are considered with $J_{drive} = 0$, same approximation for the wheels which are only the external roll for holding the tire.
- As the differential is blocked, $Nf = 1$

3.2 Wheel model on the bench

The mechanical model of the computed torque to provide to emulate the road load needs to consist several parameters on the bench. the inherent additional inertia of the bench and the dragging torque of the brakes: $Crdyn$

The following equation gives the motion of the wheel when coupled to the dynamometer:

$$J_{eff}\frac{dw}{dt} = C_w - Cr - Crdyn \quad (3.2.1)$$

The 1/10 car being a 4WD, the resistive torque is computed for 1/4 of the resistance of the car:

$$Cr = r \times \frac{1}{4} \times (mgf_{roll} + \frac{1}{2}\rho SC_x v^2 + m_{car}g\ sin(\vartheta) + m_{car}gf_{roll}\cos(\vartheta)) \quad (3.2.2)$$

The inertia seen at the wheel is the car's inertia corrected with the rotating masses of the bench.

$$J_{eff} = \frac{mr^2}{4} + J_{bench} + \frac{J_{mot}k^2}{4} \quad (3.2.3)$$

However, the car mass doesn't exist since the car has no motion on the chassis and needs to be simulate as a torque.

The only terms considered is the inertia J_{BENCH} and the motor inertia. As it exists resistive torque in the dynamometer Crb, the torque to provide is equal to:

$$C_{dyna} = Cr + (J_{eff} - J_{rotating})\frac{dw}{dt} - Crdyn \tag{3.2.4}$$

The lack of torque sensor leads us to use the formula to assess the developed torque at the wheel:

$$C_w = C_{dyna} + J_{bench}\frac{dw}{dt} \tag{3.2.5}$$

The parameters are proposed according to the shape of the car, the rubber tires of the car:

Parameter	Value
m_{car}	$2.05kg$
r	$3.3\ cm$
N_t	4.5
J_M	$46\ mg \cdot cm^2$
S	$0.85\ \text{cm}^2$
C_x	0.3
ρ	1.225 kg/m3
f_{roll}	0.01
g	9.81

Tableau 3-1: Value of car parameters

3.3 Specific Driving cycle:

In Europe, the actual test used to assess emissions and consumption of certified cars is the NEDC, currently replaced by the WLTP. The NEDC cycle is divided in two sections: one urban cycle repeated 4 times and an extra urban. The acceleration is smooth with its $0.9\ \text{m/s}^2$ and the tests has the general characteristics. In accordance with the performances of the RC car, the proposed NEDC has no peculiar meaning. Although the purpose of the Master thesis is not to scale the problem of an electric car to compare a consumption to a real car, we will even so propose a cycle inspired from the NEDC because of its convenience with constant acceleration and flat speed.

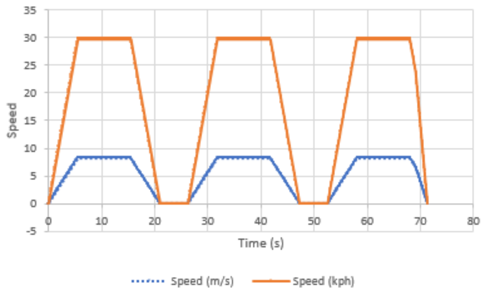


Figure 3-2: Driving cycle

Acceleration	+/- 1.5 m/s^2
Top Speed	8.25 m/s
Time of on cycle	21 s

Tableau 3-2: Test conditions

We decide arbitrarily according to the tests performed on the car (figure down) to drive with the characteristics table X. In the future, the specifications of the tests will change according our needs.

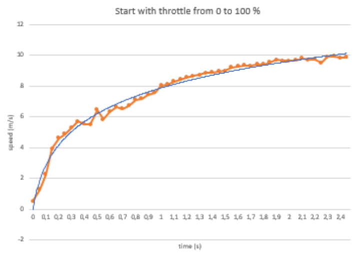


Figure 3-3: Acceleration test

The theoretical road load simulation allows to compute the following torque and power under flat road and no wind conditions.

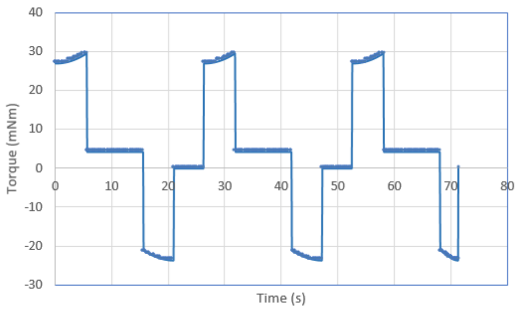


Figure 3-4: Torque estimated

As we notice the low influence of the wind effect, and the low torque provide at constant speed.

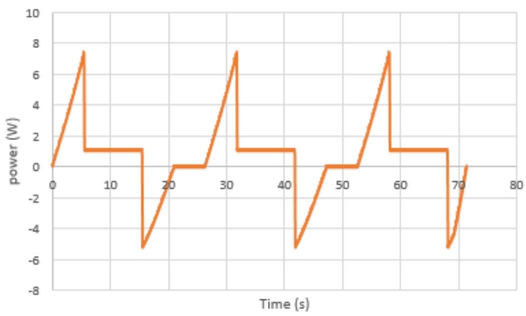


Figure 3-5: Power estimated

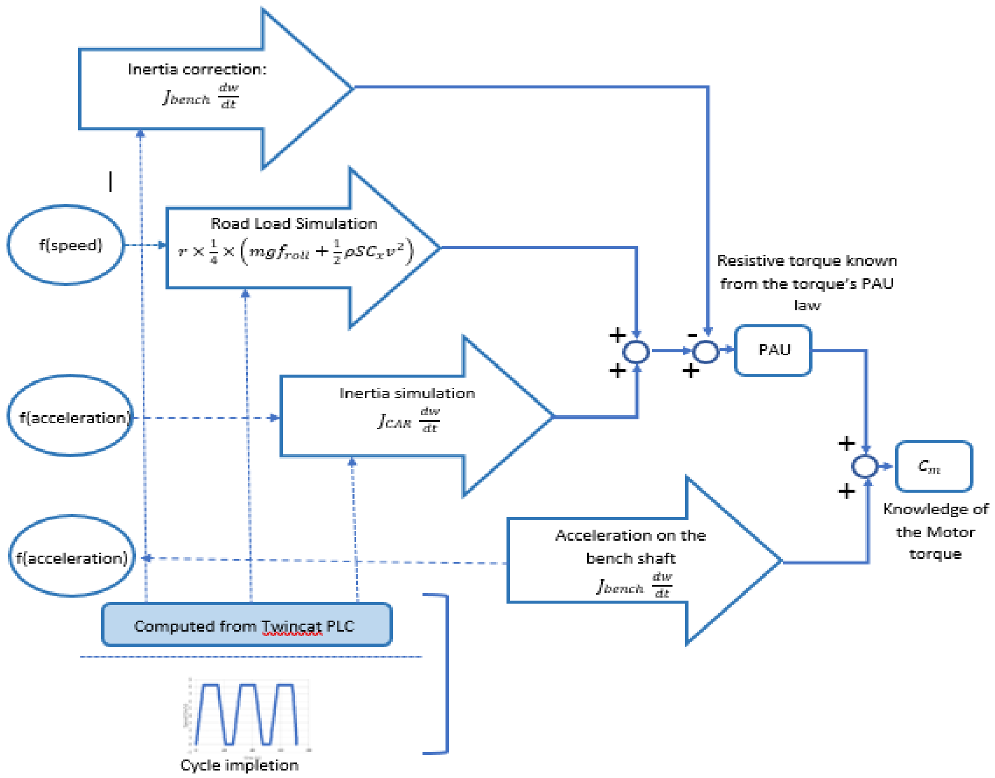
Those graphics defines the requirements for PAU dimensioning. According to the graphics 1, the terms of dynamics seems to dimension the brake, it represents around 30 mNm where the drag effect required 5 mNm.

parameter	value
top speed	3000 rpm
max Torque	30 mNm (resolution:1 à 2mNm)
Min max power	7.5 W
Dynamics behaviour	High dynamics changes

Tableau 3-3: Requirements

In conclusion of this part, we have proposed some requirements to build the test bench as it should follow a driving cycle. In reality, we would perform test but as well power estimation to compare the power of the car and the battery's power to deduce some efficiency. The power chosen for the PAU will be secured with a minimal power of half the motor's power meaning 77.5W to enable future test with a 2WD-car.

The next figure explains the emulate torque to provide to emulate the road and the computed torque of the wheel process.



4 Design of the test bench

The design of the chassis dynamometer is based according to primary criteria studied. A survey about PAU fitting the RC 1:10 performances has been carried out.

4.1 PAU

4.1.1 Hysteresis brakes

Principle:

A hysteresis brakes is made of two primary members: the pole structure and the rotor which, both interact magneticaly to produce a braking force. The pole structure is the assembly of the case, the inner pole, the bearings and the coil. It is the stator part of the brake. The rotor part is affixed to the shaft is suspended with an air gap between the pole and the case.

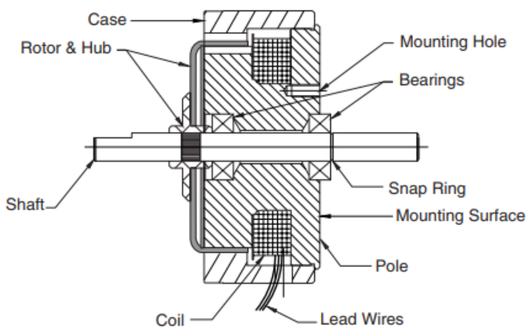


Figure 4-1: Hysteresis brake

As the coil receives the current, a magnetic field (figure 2) proportional to this formr is established in the air gap. In his turn, the rotor becomes magnetized. Due to the hysteresis phenomenon, the rotor resists movment creating the braking torque according the law:

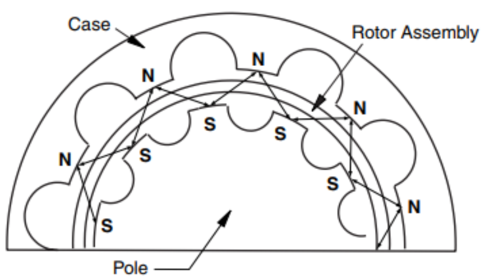


Figure 4-2: Magnetic phenomenon

Advantages :

- Smooth torque
- Easy set up
- Low inertia
- Very low torque for high dynamics possibilities and good sensibility
- Independent speed torque
- No wear
- No noise
- Torque's : T= f(Current), as hysteresis law
- Low dragging torque
- Automation with current control

As drawbacks, it appears a cogging torque when turning at high speed while unpowered. In addition, the law depend on the temperature as the resistance of the coil change.

4.1.2 Powder magnetic brakes

A powder magnetic brakes, not to be confond with the previous technology, consists of a stator containing a coil (figure 3) and a rotor with a shaft with free magnetic powder in the arounds.

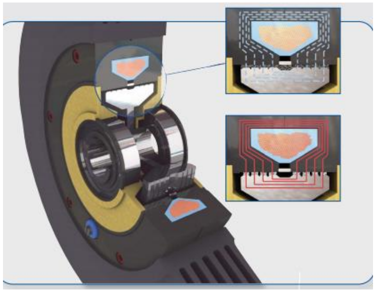


Figure 4-3: Powder brake

When a current is applied to the coil, the particules are aligned along the magnetic field creatting a resistive motion thus a torque between rotor and stator within a linear law. When the current is removed, the powder is pushed thanks to centrifugal forces realising the rotor.

Main advantages of this technology are:

- Linear Torque=f(current) law
- No noise
- Few wear
- Good dynamics torque/speed changes
- Automation with current control

As counter part, the brakes has an important dragging torque and heats fast.

4.1.3 Rheostatic DC motor

When using a separated excitation DC motor as Generator is it possible to create a torque with the change or the resistance in the armature.

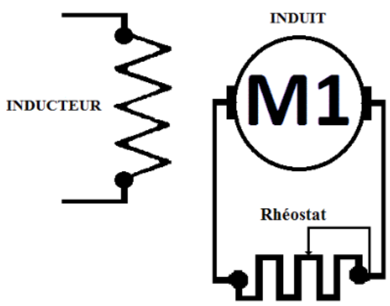
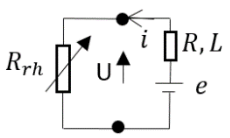


Figure 4-4: Armature and field magnet

The armature rotates in the magnetic field B created by the field magnet. The appaearance of the emf on the armature occurred.

The emf being proportional the the speed, for a given resistor, the current is proportionnal to the emf and thus to the resistor. When reducing the resistance, I rises as B, creating a bigger torque then reducing the speed. The power is dissipated in the resistor. The equation shows the influence on the torque for a DC motor.



In permanent state, we obtain the torque proportional to the resistance:

$$T = Ki = \frac{k1 * k2 * \omega}{(R + R_{rh})} \quad (4.3.1)$$

The main advantages of this PAU :

- Easy to set up
- Classic parameters of a DC
- High dynamics abilities
- Possible control in 4 quadrants

However, the control is more complex given that it needs to be control with adaptative resistor with a large range in automated way and the Torque law depends on several factor such as speed.

4.1.4 Final choice

The next matrix permits the choice with marks from 1 to 5

criteria	weight	Hysteresis	Powder	Rheostatic brake
Price	5	10	10	15
Torque law independent with external parameters	5	20	10	15
Possible automation	5	25	25	25
Matching torque with low sensibility	4	20	12	8
Inertia	3	15	9	15
total		90	66	78

Tableau 4-1: Critera choice

Our choice is finally the hysteresis brake. Over those main criteria, the hysteresis brake even if it has a hysteresis cycle, has a very good resolution while controling the torque over the current. The company has provide the assessed curves

As chosen part, the hysteresis brake offer a very compact with low smooth torque.

model	Max Torque	Supply voltage	Rotating speed	Max continuous power	Power for 5 min	Residual torque	Rotor inertia
HB-50M	350 mNm	24 V	15000 RPM	23 W	90W	1.55 mNm	4.1 mg cm^2

Tableau 4-2: HB characteristics

To know exactly the law Torque=f(Current), we asked the company to provide in addition, the exact torque low speed under peculiar condition for our tests requirements

The tables are provided in appendix and only concern partial range from 20 to 130 mA for our automated sequences.

The conditions of the tests are provided by the company given in appendix.

Nonetheless, the hysteresis phenomenon offers unknown law in the middle of the cycle but offers a precise low torque for a rising torque know and the same till 85 mNm. The possibility with such a brake is convenient when we want to provide a rising torque as in the drving cycle rising is the first state then provide a zero torque on the dearasing speed of the cycle.

4.2 Speed sensor

This section deals with the choice of a speed sensor with a short presentation of different technologies.

4.2.1 Hall effect speed sensor

The hall effect speed sensor are active sensor working withmagnetic field detection. The principle consists in sensing the ferromagnetic components like in the ferromagnetic material wheel. Contrary to the inductive passive sensor, the detection is a square signal which give the presence of the magnetic field or not.

The advantages of this sensor :

- Easy signal sensing with PNP or NPN with TTL mesureament
- Compact solution
- high frequence sensing
- Fast rising voltage

However, the hall effetc sensor need a ferromagnetic wheel to work, which means adding inertia on the axis. The air gap has to be mastered such as the geometry of the wheel. Indeed, those former parameters impacts the magnetic field, thus, the real detection of a tooth.

4.2.2 Optical sensor

The optical sensor is based on laser detection principle as exemple of the diffuse optic sensor..

The sensor has the advantage :

- measure surface states of components presence
- it limits the inertia with only lighy surface for exemple
- very fast frequency of sensing
- fast rising voltage

However this solution can turn out very volatile and are often expensive.

4.2.3 Encoder

An encoded is based on light detection with code track described figure

It has the advantage :

- high sampling speed
- cheap
- sensing both rotating sens

However, in the axial position of the encoder must be very accurate under <1mm precision. In addition, It requires coupling so adding inertia.

4.2.4 Selection:

The next matrix with criteria help to chose the hall effect speed sensor, the criteria

Criteria	Weight	HE sensor	Optical sensor	encoder
Price	5	15	10	15
Added Inertia	5	10	10	10
Set up	3	9	12	3
Signal frequency	3	12	12	15
total	16	46	44	43

The speed sensor has been bought on RS-online. The datasheet provides the geometry of the wheel for magnetic field correct detection. It has been designed in the workshop according to the geometry with 4 teeth for enough speed acquisiton per round.

4.3 Bench simulation

4.3.1 Coupling

As we consider our plastic transmission as torsional damping, the use of a coupler remains basics The coupling axis is mostly the place where all effort are concentrated. When coupling. As is this in the interface brake/car's hubs has been simulated with PTC creo with FEM method. Indeed, the axis diameter is dimensionned as is need to resist the torque response but not to be overdimensionned to avoid PAU's damage.

Condition	Results
Torque 0.35 Nm	Von mises : 17 MPa

Tableau 4-3: Simulation

The material considerer is the PLA, material used for 3D-printer. The shear has been chosen according to the study [3]. This material offers low inertia and being a spare part, it can be changed and rebuild fastly in case of break. The convergence of the H-type mesh is provided with 3.8%

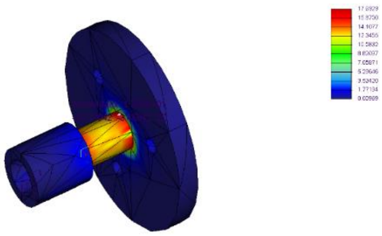


Figure 4-5: connection simulated

Comparison of the computed diameter with the shear stress formula and the fem study.

Fem method	According to (1.2)
3.8mm	4.1 mm

Tableau 4-4: diameter computed

In case of misalignment of overload, we want the spare part to brake first.The diameter is limited at 6mm while it provides a coefficient of 1.33 compared the previous measure.

4.3.2 Chassis structure

The part holding the brake are dimensionned with PTC creo.

On the figure 3.3 are the hysteresis brakes hold with bend alu sheet in dark blue. Those aluminium sheet have been designed with fem study to avoid unalignement with the axis of the hub. The proposed structure(aluminium sheet) simulates a misalignement of 10^-3 degres.

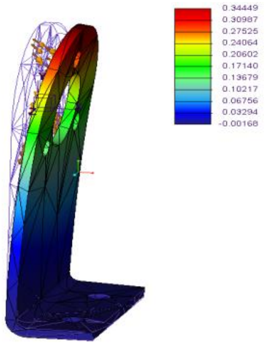


Figure 4-6: PAU holding part

In grey are the aluminium profil chosen for there light mass, cheap price and easy use.

4.4 First results

Despite of the design, the proposed diameter has mostly not fit the tests. The 3-D printing depends on layers' melting temperature, of the direction of the printing. As it is unknown, the diameter is finally chosen with 18mm. The figure shows the 6mm and the 18 mm connecting parts.

As the first part is to connect with the PAU, the other part screwable is mounted on the car.

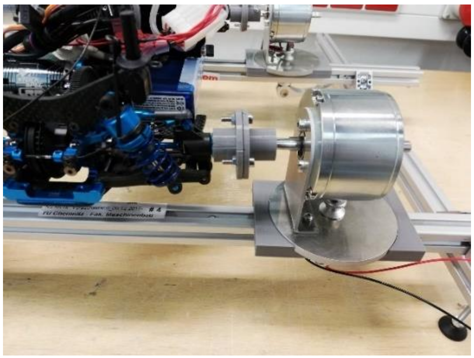


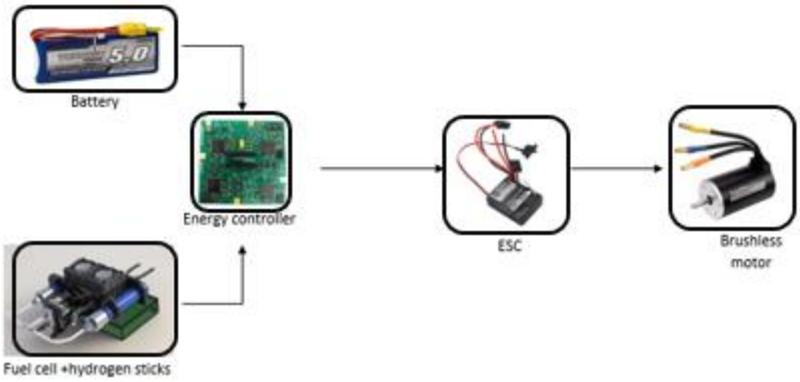
Figure 4-7:RC coupling wheel to HB

The chassis structure showed figure 4-7 consists of the assembly of the brake providing vertical axis dynamometer is mounted in a way enabling track and wheelbase adjustment.adjustment for wheels' toe-in.

5 Motor control

This section presents the second purpose of the master's thesis dealing with the vehicle speed control. As it is aimed to enslave the car along a driving cycle, the knowledge about brushless motor control and electronic speed controller are the basics for a possible regulation. The major part of the thesis has attempted to model mathematically the system PMSM/controller then simulating it's model with matlab/simulink according to the previous work thesis [3]. However this attempt was not successful to give valuable control. Such a modell required several electronic knowledge and the precise datasheet of the PMSM altough some parameters can be estimated. The alternative proposed consists to model a motor controller with experiments.

5.1 Overview of the electric power transmission:



The current car is an hybrid car receiving its power from fuell cell sitcks and 2 cells Lithium polymer battery. Both powers are transmitted to a controller that is linked to the ESC. The ESC finally adapts the power to the brushless motor going to the wheels by mechanical transmission. The understanding of the fuell cell is not the topic of the masterthesis and we will only establish the consumption from the battery. The brushless motor on the car is a permanent magnetic synchronous motor not to mistake with a brushless DC motor whose control his different.

5.2 Motor control

PMSMs are widely spread in the industrie thanks to their high power density , low inertia, high dynamics capacities, high efficiency , low maintenance which make them good cost-effective solution therefore, it is highly integrated in the RC world car.

The vocabulary of RC world car defines the motor in turns and Kv.

The definition of kV is the rotating speed capacities of the motor for 1V. Our PMSM is a 1700 Kv. Which means for a provided battery voltage of 7.4V, we have a top speed of 12580 theoretically. This is a very fast speed soution for a compact actuator. Moreover, it reveals the direct impact of the SOC of the battery which means the voltage provideS by the battery against the speed abilities. T

The number of turns refers to how many times the copper wire is wound around each pole of the armature.

The usage of the PMSM on RC car reveals a power over weight solution very effective as we have 155W for a 2kg-car.

5.2.1 PMSM

The Permanenet Magnet synchronous machine consists in alternatively feeding with a sinusoidal current 3 phases. This alternative current creates a rotating magnetic field on the stator which origines the movement of the permanent magnet. To maximize the torque, the angle between the rotor and stator field tends to be maintain in a precized position, requiring an advanced monitoring with feedback control.

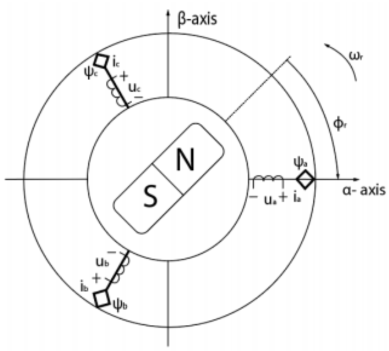


Figure 5-1: PMSM representation

The permanent magnet motor can be separated in two categories. One sees its winding excitated with a sinusoidal voltage wave (a). The other one has a trapezoidally wave..

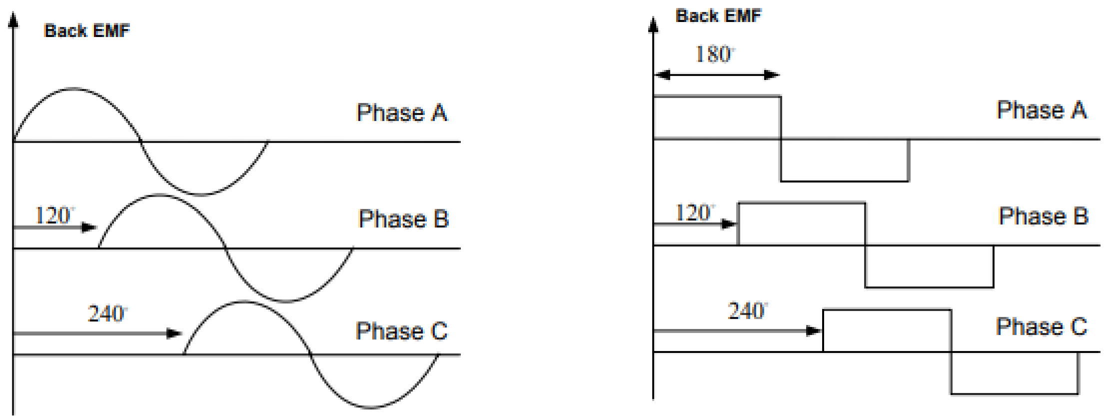


Figure 5-2: Sinusoidal and trapezoidal back emf

The sinusoidal excitated motor oparates with a rotating field and are called PMSM. As we see on the graph, the all are fed with current ithout interruption.

Unlike the PMSM, the motor fed with a trapezoidal wave. This precise synchronization is generally controlled with the angular position of the rotor. As the commutation is similar to a DC motor, it is called BLDC.

As it requires a complex control in 3 axis, modelling of 2 axis problem with Clark and Parl transformation are the state of the art of the PMSM model control.

The general caracteristic of the PMSM TorqueVSSpeed and Power Vs speed is given figure

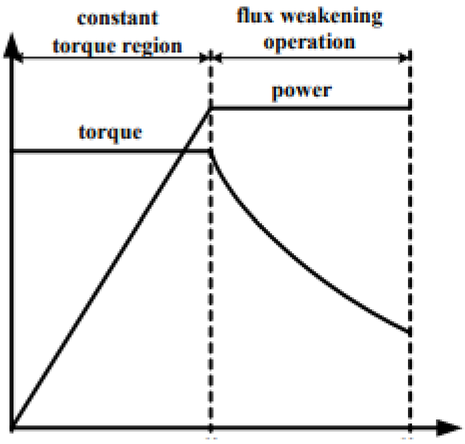


Figure 5-3: Torque/speed characteristic

Generally, the excitation flux Is controlled with the variation of the dc current through the field winding. The torque is proportional to the excitation flux and to the armature current while the voltage is proportionnal to speed and flux. In the low speed, the rated current and flux allow to produce a constant torque. At the same time, the voltage is rising proportionnaly with the speed. At a certain speed, the voltage reaches the rated voltage and can't increase. To overtake this speed, as a rated voltage, the flux has to decrease. This drop is responsible for the torque deacrease while the speed rise providing a constant power.

In the case of a PMSM, the permanent magnet creating its own magnetic permanent field doesn't permit any flux variation, a complex control by injection of a negative current allow to provide a similar torque/power VS speed characteristics.

5.2.2 Motor controller

The commutation's command of the current in the stator coil is made tanks to a 3-phase inverter (DC/AC) which interface the power supply (DC battery) and the motor.

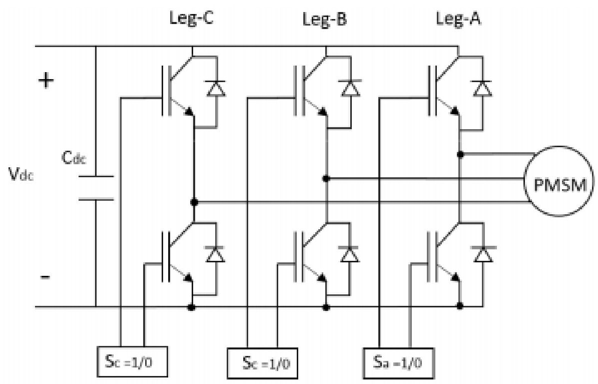


Figure 5-4: simplified controller wiring

The switching positions of the transistors allows the DC voltage from the battery to feed sequencely the phases of the PMSM turning the DC input voltage into an AC voltage to the PMSM.

The inverter's switching is performed thanks to a PWM signal The PWM methodology described and the control switching are described in 16. The logical signal Sa, Sb and Sb are triggers in a sinusoidal waveforms providing the AC voltage to the phases according to the diferrence of a carrier triangular wave and a reference sinusoidal signal given from the current controller explained in [4]

After the theoretical explanations of the inverter/motor control, experiments have been carried out on our system {ESC+ motor}.

When triggering the radio controler we noticed a PWM signal as input of the controller:

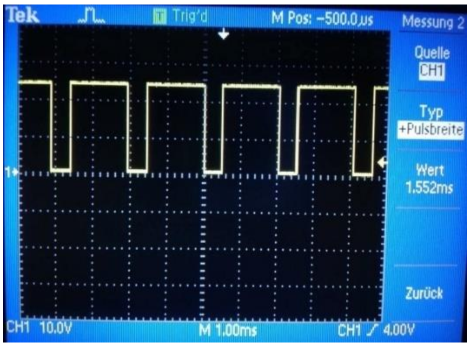


Figure 5-5: Pwm signal

The pusle width has been measuring thanks to an oscilloscope and we notice a signal star

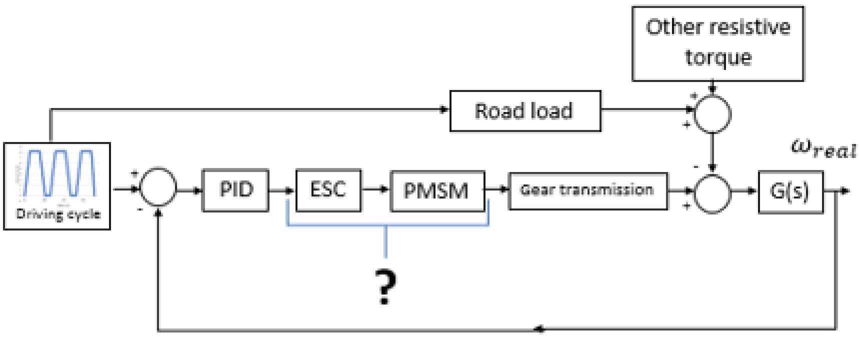
Pulse width	Motor speed
1.5 ms	0 rpm
1.8 ms	Top speed

Tableau 5-1: Pwm/speed range

According the signal, a special attention must be given to the sensitivity of the pulse width as it is to play with a period time variation of the µs.

1. Speed controller Design

The method to simulate the speed control in the case of the knwoledge of the ESC+MOT equations would give the speed control loop by feedback:



The classic method to face a perturbation as the road load is given with

- Blackbox model
- Implementation of the perturbation
- PID tuning

Nevertheless, the missing knowledge of the ESC/PMSM equations, leads us to use a system identification method

5.3 Modeling approach

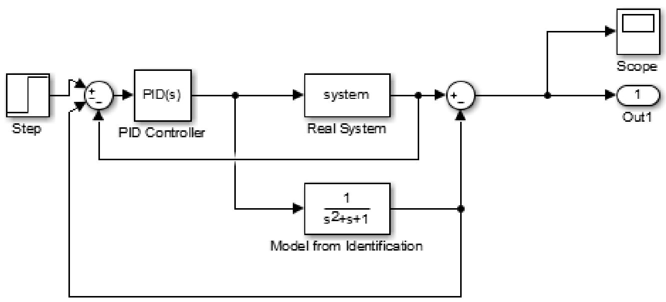
As the are considerered as grey boxes, a method based on tests is used to determined the model of the ESC+Motor. It consists in :

- collect experimental input (pusle width) and output (speed) data
- estimation of the model with

To do so, the system identification toolbox proposed by Matlab/Simulink is a mathematical method developped to model dynamics system thanks to the measurment of input/output data. This help simplify complex model such as the ESC+Motor system we require.

This method provides several structure model as

- state space control
- transfert function model estimation
- validation of the model with error minimization with simulink (figure 3)

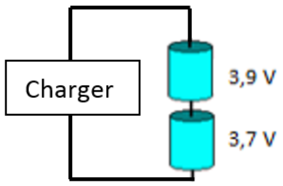


6 Energy consumption

6.1 Introduction

The battery is the keystone of the EV. It is the fuel of the car which gives energy to all electrical components especially the engine according to the demand. In the case of our car, it represents not only 15% of the mass but as well 10% of the price. The lifetime of the battery is shorter than the Car itself which means that taking care of the battery means to improve the durability of the all car. The purpose of the next sections is to show two methods to determine the state of charge of the battery to assess the consumption. In the later, both are to be tested.

When using a battery, we want to ensure efficient and safe operation, long autonomy and longest possible lifetime. To satisfy these criteria, the cells showed figure X must be continuously monitored.



The measurement of the SOC is the state of the art to deal with the current state of the battery. Different methods exist to assess the battery SOC such as voltage measurement and coulomb counting which are to be the presented methods.

The knowledge of the SOC is primordial E.G it allows the system to know when to disconnect the battery to protect it lifetime first and prevent danger as battery tends to burn as heating reactions occurred. In practice we don't use the full charge to prevent the damage of the battery because of chemical undesired products

Assessing the stage of charge is difficult because of the volatility of the parameters that change with the battery ageing and external conditions for e.g. temperature.
The performances of the battery are temperature sensitive since it impacts parameters e.g. the temperature reaction in the cell and internal resistance.

The control called Battery Management System (BMS). it allows the battery to perform its charge/discharge in the best and safest operation conditions such as the balancing of the cell voltage for example. The present car is derived from BMS meaning a care must be taken when running the tests.

6.2 Battery characteristics

The presented battery of the car is a Li-Polymer, derived from lithium technology. This Lipo battery has the advantage to have good energy characterisics despicted oh the figure

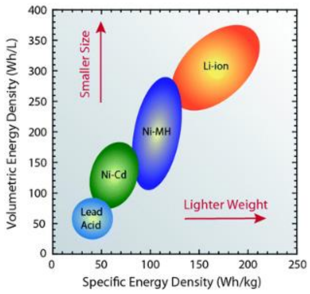


Figure 6-1: Characteristics

The nominal voltage as charge battery is around 3.7V. or two-cell battery provides at rated voltage 7.4V.

The C-rate defining the charge/discharge rate of the battery's current. When the battery works on 1C, it means that the battery would discharge in 1/C hour. Eg when our battery is a 7400 mAh, the discharge at 2C is a current of 14.8A.

6.3 Measurement of the SOC

6.3.1 Voltage measurement method

Measuring the state of charge with voltage is easy to set up but can turn out inaccurate because it is affected by the temperature and the discharge C-rate of the battery.

A representative measurement can be obtain with the discharge at constant C rate. This is seen. Moreover it is often difficult to assess a voltage change, as the general characteristics are flat along 80% of the discharge and drop as example from figure 3 from [2]

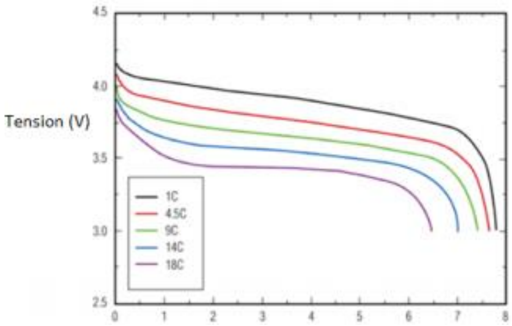


Figure 6-2:Tension for a li ion in open circuit

However, the measurement of the voltage in open circuit voltage provides satisfaying results. It is therefore mainly use because of it's simplicity.

6.3.2 Coulomb couting

The Coulomb counting is a method widely spread as eg in the computer, to estimate the SOC by measuring the in- and out- flowing current.

The integration of the measured current along the discharge provides the energy that has been sent. The measured of the output depict partially the consumption of the motor as losses are not considered.

6.4 Current sensor

The measurement of the current will be perfomed with a magnetoresistive current sensor provides in the labo of the TU Chemnitz whose characteristics are given in appendix.

According to the battery of 8000 mAh, with a range of C-rate tests between 0.5C and 5-C, the choice of a sensor with a range of 50A with a sensitivity of

7 Data acquisition

This section focuses on the general set up for our data acquisition system and use of a PLC for tests automation. In the frame of driving cycle implementation, the real time automation requires sequenced task execution and defined period time for each tasks. Depicted figure X

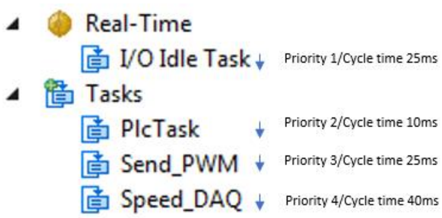


Figure 7-1: TwinCAT Sequence

The use of a PLC is a suitable solution for a multitask control environment with fast exectution. Several PLC makers e.g. ABB, Siemens, Beckhoff, Kratzer, propose diffent PLC solutions. However, the embedded software is standardized from one PLC brand to another according to the IEC 61131-3 standard which provides a common programming language e.g. structure text, function block diagram. The TUC working with Kratzer and Bekchoff Automation has at disposal two PLC technologies. The use of Beckhoff TwinCAT automation software as a fast learn interface has finally been prefered on Kratzer. However, unlike Kratzer, TwinCAT is not a Physical PLC but turn a normal pc into a real time controller. A standard computer with 4 CPU doesn't offers the same computing ressources as Kratzer PLC. During the tests several timing issues has been declared because of CPU overload.

The principle of the data transmission between the PLC and the signal to measure or acquire is showed . The PLC reveives and outputs data through a field bus.

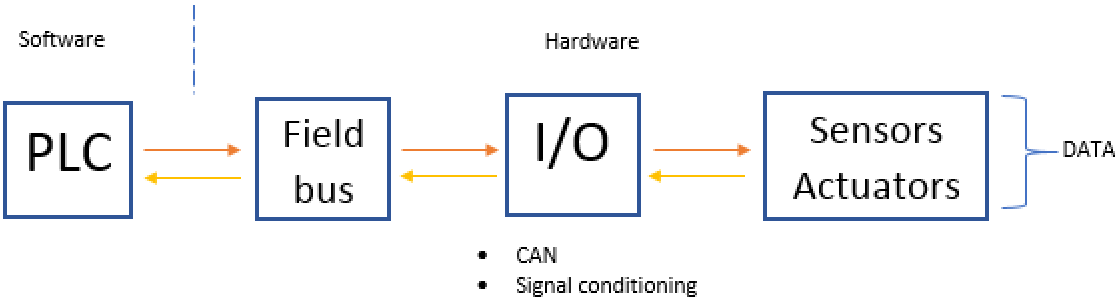


Figure 7-2: Acquisition system

A field bus is a industrial network system dealing with real time control. It connects both device called master and slave. As the field bus has been recently standardized, protocols exists providing differents advantages for e.g. RS 232, Profibus, Profinet.

The solution proposed by Beckhoff automation which is used for our tests: EtherCAT (ethernet for control Automation Technology) is an ethernet based protocol providing high speed communication for real time automation system.

EtherCAT uses a master/slave architecture with a processing 'on the fly" principle to ensure high speed data transmission. The master sending the telegram read by the slave. At the same moment, the slave adds its data, also called Process data object (PDO), to the frame.

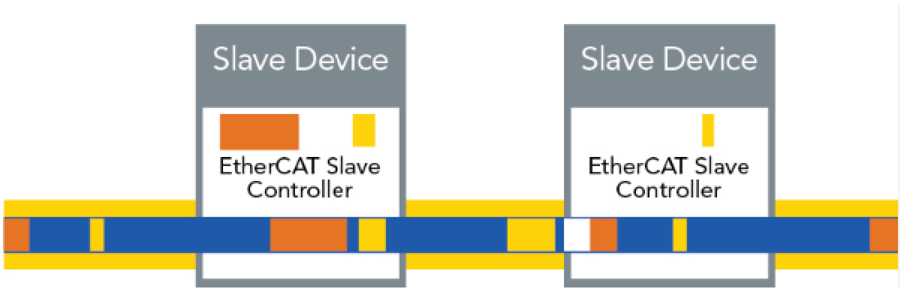


Figure 7-3: Information transport

7.1 I/O COMMUNICATION

The connection between our sensors, actuators and the field bus is done thanks to I/O cards proposed by Beckhoff Automation. We have chosen the card The channel supports several signal types that are gather

The cards are connected each other with one 24V source and the power is flowing in between the cards:

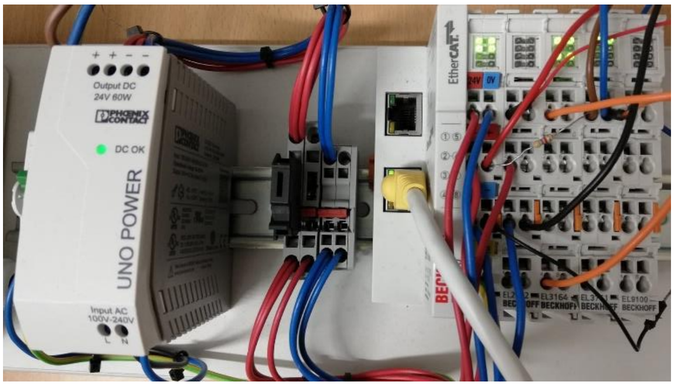


Figure 7-4:Beckhoff cards aquisiton

Acquisition of the measurment :

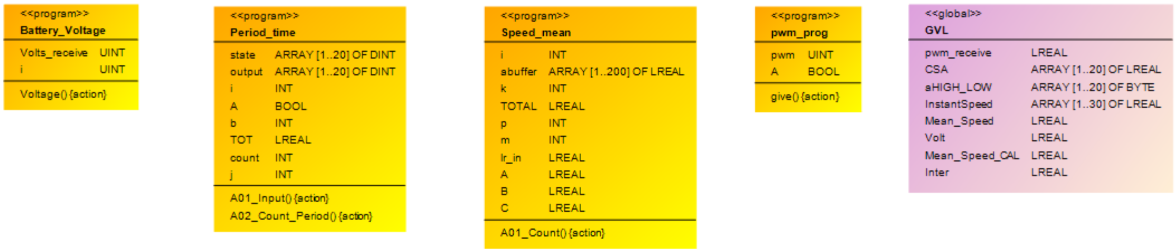
<u>Votlage:</u>

The acquisition cards provide a 0 to 10V measurement as unsigned integer on 15-bit which means the range in given from 0 to +32767dec:

The output signal is linked to the voltage with:

$$Volt = \left(\frac{voltage}{10}\right) * \frac{2^{16}}{2} - 1$$

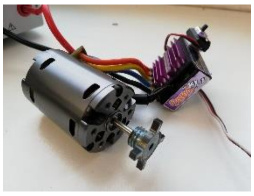
To provide speed tests, the UML structure is described as follow:



8 Results

1.1 Speed tests:

The following picture depicts the used {motor+ controller} set up powered by a Teensy 3.2 micro controller (Arduino):



The teensy provides a PWM signal whose pulse width is adjusted with a potentiometer. The code is given in appendix. The following graphs showed the drop and rising delays of the speed sensor:

While changing the pull up value, the signal considerably changes.

However the pull resistor will be chosen as **4.6 kohm** as the first speed sensor was damaged.

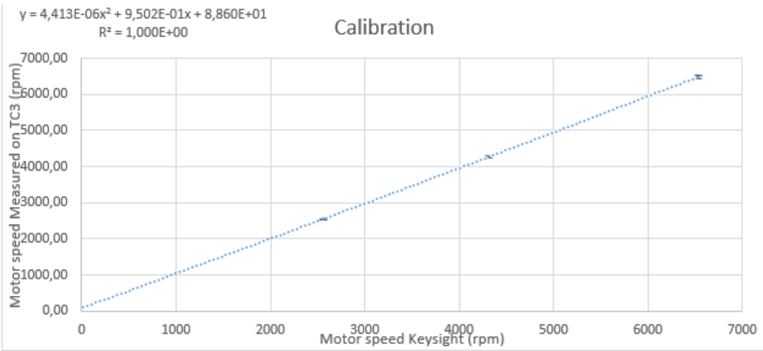
This results confer inaccuracies of the down/up sensing. The analogic signal will be coded as TTL signal.

The code's principle lies on the detection of the signal between two rising, Thus, the speed is acquired four times a round. The speed sensor signal is oversampled with an acquisition period of 400µ with adjustement of the time sequence of the TwinCAT tasks code. The limit of the analogic cards reveals code error with sampling period <400µs. The code is given in appendix

In essence, the measurement showed with TwinCAT (figure 3) computes the frequence of the output sensor signal but with the delay of the acquisition, the measurement device noise and the code limit.

To estimate the precision of the measurmeent, areference a measurement of the frequence of the output speed sensor signal is sampled. This is performed with a (6½ digit) Keysight multimeter. The results are showed with the standard deviation method. However, the sampling is done for the middle range of the speed. Some undesired measurment are not considered especially at low speed were the effect of the magnetic field is sensed enough to prevent a good measurment especially as the distance between the wheel and the sensor is around 1mm.

The speed example figure 3.



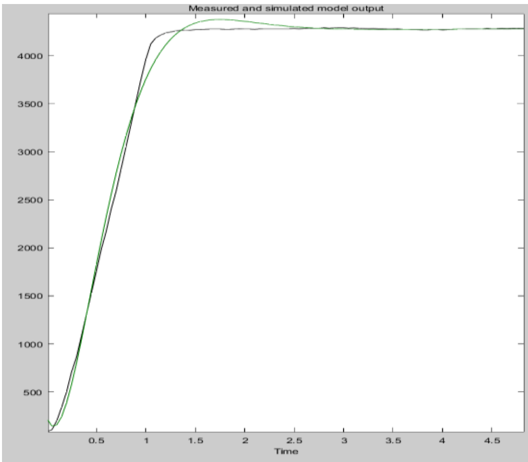
The set 3 values are taken as exemple

PWM representation	$Motor\ Speed\ \ rmp$	$Precision\ rmp$
	2565.00	$\pm 0.19\ \%$
	4313.55	$\pm 0.45\ \%$
	6525.14	$\pm 0.24\ \%$

A. <u>test for model identification</u>

As it has been explained previously with the attempt to model the PMSM+control, tests have been set up with several data sampling as Input/output: PWM/Speed step values with 50 ms sampling which fits the dynamic evolution noticement of the system.

Sampled data are collected and tested on identification toolbox



Conclusion

This master's thesis deals with a global topic for car data assessment. The design of the bench has been done and works on car tests from the full speed range.

Discussion

Because of lack of time and delay in the order with the beckhoff I/O and PAU, few tests could have been performed even if speed regulation, power assessment and eletrical SOC are to do as all sensor are now available.

Appendix

```
//°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°
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// Control of the PWM signal of the motor controler thanks to the potentiometer.
int voltage;
const int moteur=3;
int ESC;

//initialisation
void setup(){
  pinMode(moteur,OUTPUT);
  pinMode(15, INPUT);
  Serial.begin(38400);
  analogWriteFrequency(moteur,488);
}

 //implementation
void loop(){
    voltage = analogRead(15);                     // read the potentiometer
    ESC = map(voltage, 0, 1023, 185, 235);        // range the potentiometer values to the pulse width
    analogWrite(moteur,ESC);                      // Output the pulse width
    Serial.print("ESC:");
    Serial.println(ESC*100/255);                  // Value in ms
    Serial.print("value:");
    Serial.println(voltage*5/1023,2);             // Value in volt
    delay (200);
}
//°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°
//°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°
```

Drehmoment-Strom-Verlauf /Torque-current course

14.12.2018

Hysteresebremse / Hysteresisbrake HB-50M-2DS S.-Nr. 0549

Messmittel /test equipment : **Mobac Prüfstand Nr.01 – (0 – 2,0 Nm)**

- Drehmomentsensor / Torque Sensor : Lorenz - DR-2477 (ser. no 107976)
  (Genauigkeitsklasse / Accuracy class): (0,25 %)
- Datenlogger / Data logger: Lorenz - GM-80 (ser. no 18137)
  (Genauigkeitsklasse / Accuracy class): (0,1 %)
- Netzteil / Powersupply: Mobac / NT-IIC-A 0-2 A (ser. no 100816)
  (Genauigkeitsklasse / Accuracy class): (0,2 %)
- Raumtemperatur / Room temperature: + 20 °C (+/-1,0°C)

ext. Netzteil / Power supply : -/-

Tabellenwerte / Characteristic

Strom / current +	Drehmoment / torque
mA	Nm
20	0,003
21	0,003
22	0,003
23	0,003
24	0,003
25	0,003
26	0,003
27	0,003
28	0,003
29	0,003
30	0,003
31	0,003
32	0,003
33	0,003
34	0,003
35	0,003
36	0,004
37	0,004
38	0,004
39	0,004
40	0,004

Strom / current -	Drehmoment/ torque
mA	Nm
130	0,083
129	0,082
128	0,082
127	0,081
126	0,080
125	0,079
124	0,078
123	0,076
122	0,075
121	0,073
120	0,072
119	0,070
118	0,069
117	0,067
116	0,066
115	0,065
114	0,063
113	0,061
112	0,06
111	0,058
110	0,056

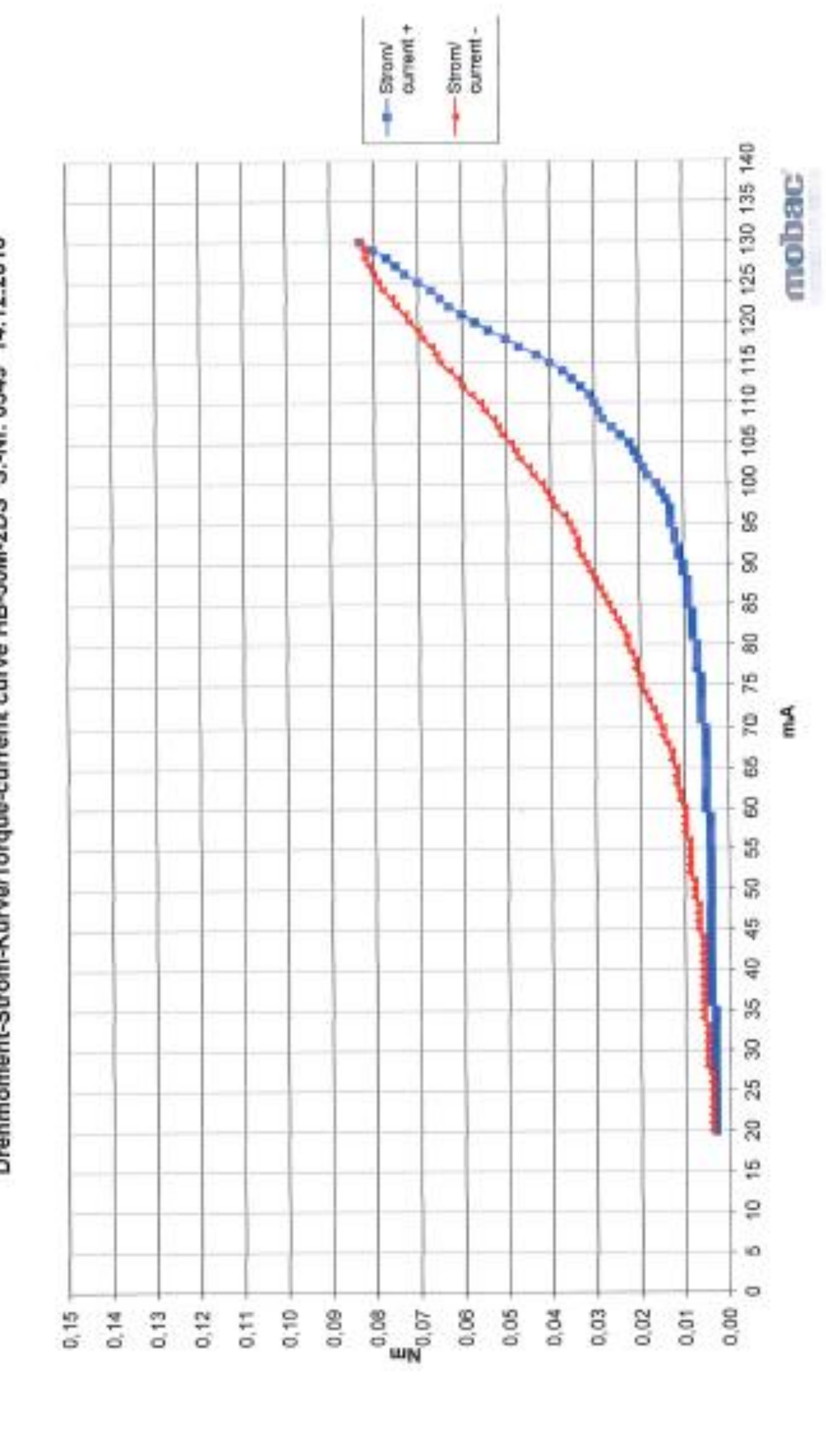
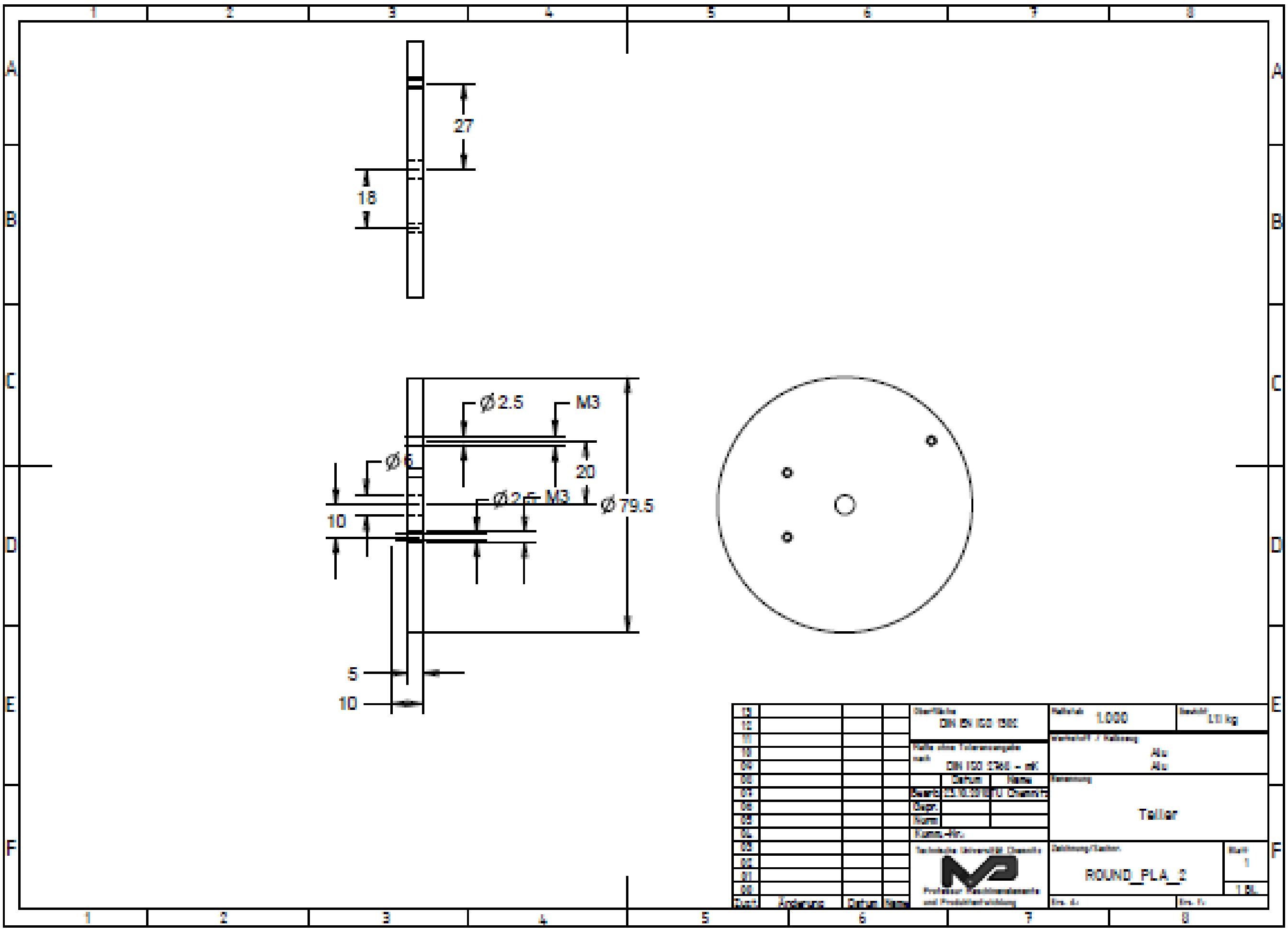
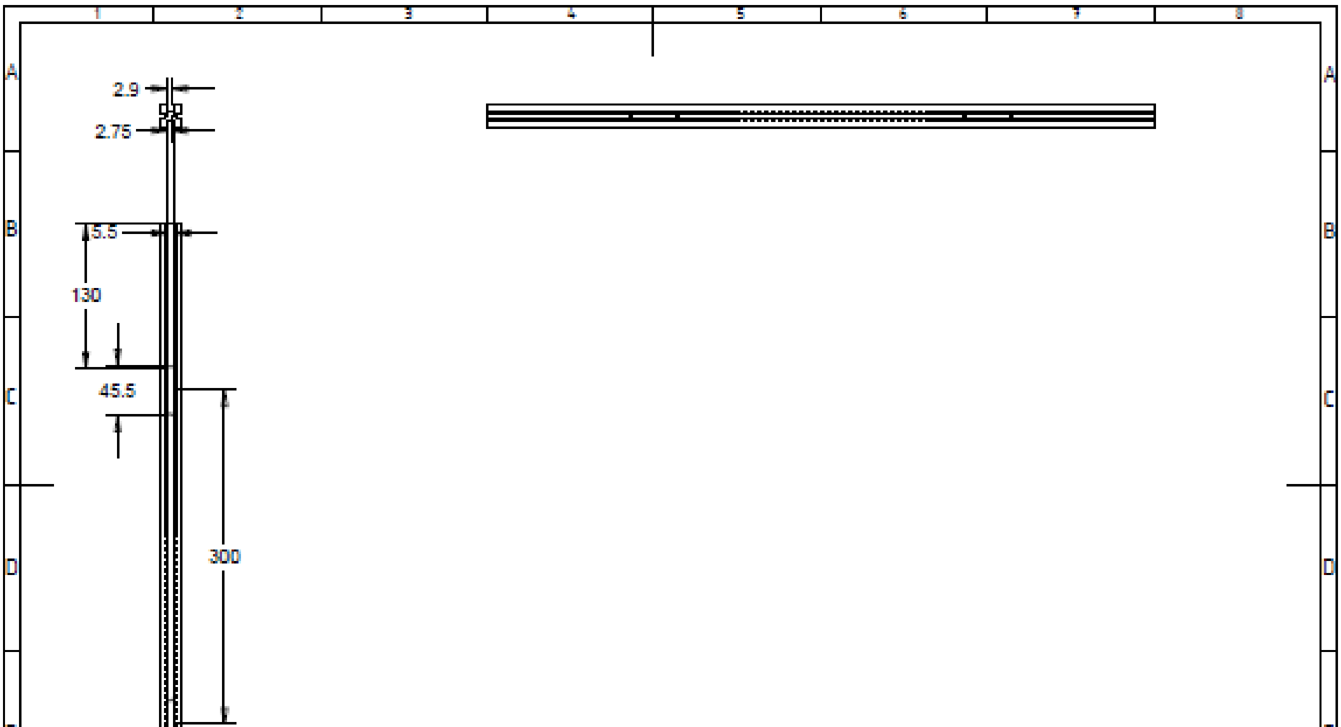

Drehmoment-Strom-Kurve/Torque-current curve HB-50M-2DS S.-Nr. 0549 14.12.2018
Strom/ current +
Strom/ current -
Nm
mA
mobac

Figure 8-1: Torque =f(I)





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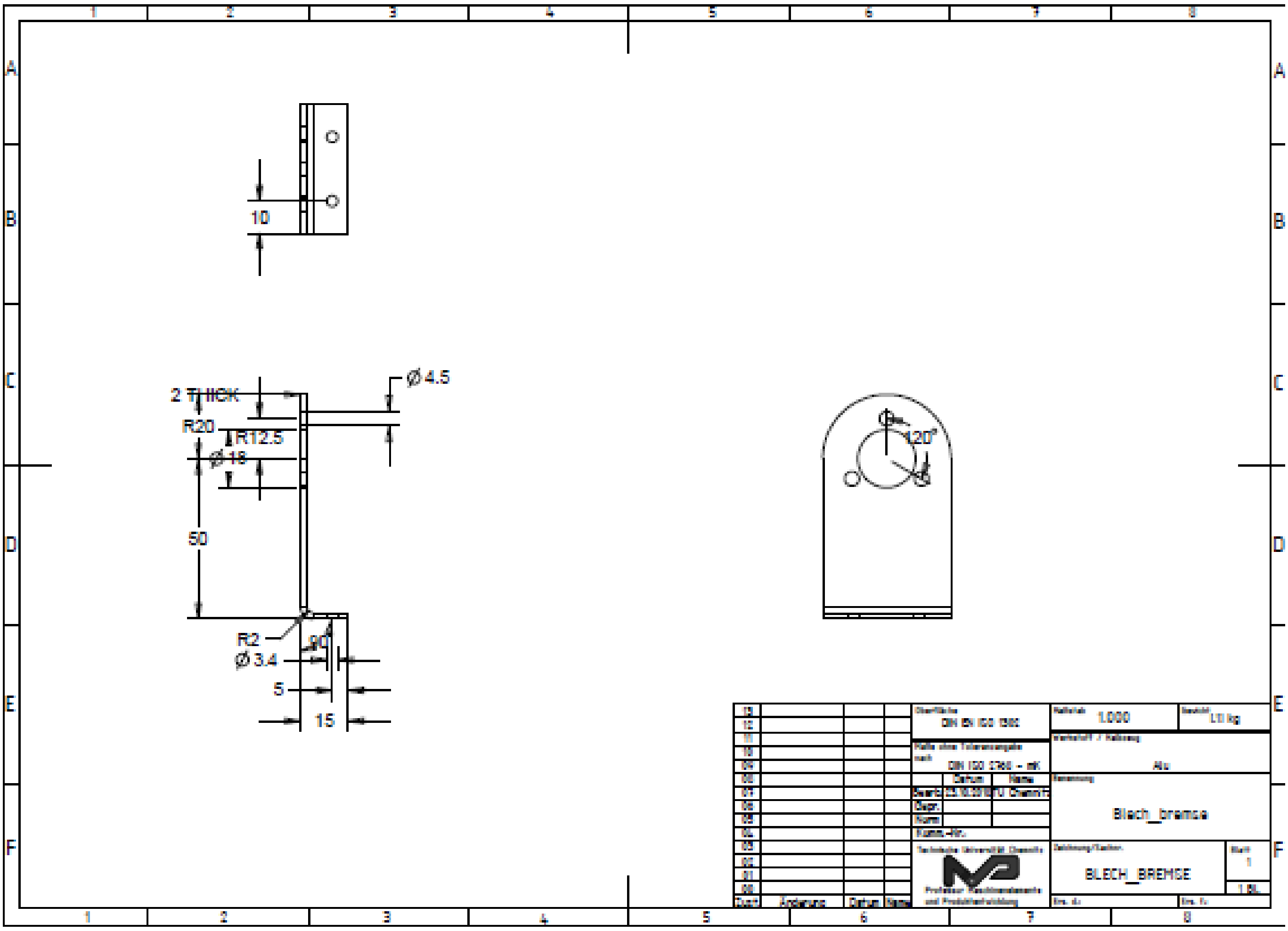
TECHNISCHE UNIVERSITÄT CHEMNITZ



Drehzahlsensor / Speed Sensor

1-Kanal Hall-Differenz M12 Baureihe /
1-Channel Differential-Hall M12 series

Technisches Datenblatt / Technical Data Sheet

IP67

Kurzdaten	
Versorgung	10 VDC ... 36 VDC
Frequenzbereich	0,5 Hz ... 20 kHz
Betriebstemperatur	-40 °C ... +125 °C
Schutzart (EN 60529) bei gestecktem Stecker	IP67

Data summary	
Power supply	10 VDC ... 36 VDC
Frequency range	0.5 Hz ... 20 kHz
Operation temperature	-40 °F ... +257 °F
Degree of protection (EN 60529) at connected plug	IP67

Anwendung

- Drehzahlerfassung an Zahnrädern mit kleinem Modul und hoher Auflösung
- Anwendung in Fahrzeugen, mobilen Arbeitsmaschinen und hydraulischen Antrieben

Applications

- Speed detection of gearwheels with small module and high resolution
- Applications in vehicles, mobile operating machines and hydraulic drives

Versorgung / Power supply	10 VDC ... 36 VDC
Stromaufnahme / Current consumption	<20 mA
Frequenzbereich / Frequency range	0,5 Hz ... 20 kHz
Max. Ausgangsstrom / Max. outptu current	500 mA @ 24 VDC, +25 °C / 50 mA @ 36 VDC, +125 °C
Kurzschlussfest / Short circuit immunity	ja, gegen alle Leiter / Yes, against all terminals
Verpolungsschutz Versorgungsleitungen / Reverse polarity protection power supply lines	ja, gegen alle Leiter / Yes, against all terminals
Ausgangssignalpegel / Output signal level	Low: ≤ 2 V; High: ≥ Ub-2V
Berechnung der maximalen Last / Calculation of maximum load	$R_L = U_b$ (VDC) / I_{max} (mA)

Anschlüsse / Connections

Anschlussbelegung Stecker / Plug terminal assignment (SDN2.GI02.SB / SDP2.GI02.SB)	1: VDC 2: nicht belegt 3: Masse 4: Signal		1 Red: VDC 2 Blue: not connected 3 White: Ground 4 Black: Signal	
Anschlussbelegung Kabel / Cable terminal assignment (SDN2.GI02.E2 / SDP2.GI02.E2)	**ABGEKÜNDIGT: Nachfolger auf Anfrage** **DISCONTINUED: Replacement on request**			

References

[1] A.J. Martyr, M.A. Plint, “ Engine Testing, Theory and Practice”, Third edition

[2]