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Thesis WIP

RICHARD ODELL

Master's Thesis at ITM
Supervisor: Lars Svensson
Examiner: Lei Feng

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Abstract

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Acknowledgements

I would like to thank...

Acronyms

ABS	Anti-lock Braking System
DC	Direct Current
ITRL	Integrated Transport Research Lab
KTH	The Royal Institute of Technology
MBD	Model-Based Design
MPC	Model Predictive Controller
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
RCV	Research Concept Vehicle

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Chapter 1

Introduction

This chapter will give an introduction to the thesis.

1.1 Background

The Research Concept Vehicle (RCV) at The Royal Institute of Technology (KTH) is a platform for research in vehicle autonomy and vehicle dynamics. For precise autonomous operation, accurate actuation of steering input and wheel torque is critical. The electrical wheel motors of the RCV can produce torque for acceleration and braking up to a limit. However, for hard braking maneuvers, regenerative braking is not sufficient and a hydraulic brake system actuated by electric linear actuators is used in addition. In the current configuration, the hydraulic brakes actuate fairly slow (>1s before braking request is met). Thus, a redesign of the control software and the mechanical assembly is needed. The task is challenging due to the non-linear and environment dependent dynamics of the hydraulic system.

1.2 Purpose

The vehicle industry as well as industry in general is moving towards automation to lower costs, risks, lead times and work load for employees. Today there already exists some form of autonomous driving in vehicles, such as Tesla's Auto pilot and Volvo which are conducting tests with autonomous high way driving around Gothenburg. For the technology to be accepted by the masses it need to be safe and not put people, animals or other things at risk. Since the RCV is built for autonomous driving, but lacks an efficient friction brake, the purpose of this thesis will be to evaluate and improve the performance of the friction brake system. The updated braking system on the RCV will be discussed how they can be applied in general autonomous vehicles,
To fulfill the purpose a couple of research questions was set up. These are as follows:

- Which are the most common methods used in friction brake controllers in brake-by-wire systems and autonomous vehicles?
- How does the chosen control method enhance how the torque request are met, compared to the original hardware setup and controller?
- Can the controllers achieve an error of a maximum of 5% of the requested torque at all times?

1.3 Delimitations

A lot of aspects affects the behavior of the brakes, and to achieve a properly functioning brake with good reaction time will consume much time. Therefore delimitations must be made in order to make the thesis feasible within the limited time frame. The focus of this thesis will be on making an existing braking system faster in terms of reaction time of reaching the requested braking torque.
Wheel slip and Anti-lock Braking System (ABS) are both important factors while designing a modern brake, but this will not be implemented or considered in this thesis due to the fact that there is simply not enough time. Split mu, meaning when there is different friction coefficients acting on the the wheels, for example when one wheel travels over a slip of ice or gravel, will not be considered either. The parts that has been left out will be seen as future work that can be made to further improve the brakes on the vehicle.

1.4 Research design/Methodology

The methodology used for this project will be a case study of how to implement one or more brake controllers, which works best for solving the problem stated together with a comparison of the controllers advantages and disadvantages. The case study will have its focus on qualitative research, as there's extensive work already done within this area. The testing will also have a qualitative orientation in the end to validate the brake model as well as how the controller performs.

1.5 Ethics

Brakes is one of the most vital part to the safety of a vehicle. Although this project handles the brakes while in autonomous drive mode, there will still be one or two people in the car monitoring the autonomous driving, whom might be susceptible to great risks if the brakes do not work. To keep the safety of the vehicle at acceptable levels there is a manual brake pedal that overrides the autonomous drive mode, and brakes the vehicle if necessary. This brake pedal is controlled by the person in the drivers seat, who has experience with the vehicle and is much aware of the risks and behavior of the car.

The vehicle is not legal to drive in regular traffic, and thus is only driven in big closed off areas, such as a rented runway on Arlanda or in a closed off parking lot, where it is driven at low speeds of up to 45 km/h. The vehicle is also equipped with seat belts dimensioned for racing. It is an electric car so the people around wont be exposed to any harmful exhausts.

1.6 Risk assessment

The risks that is involved with this project include the availability of the RCV as well as that ordered hardware gets here on time. Concerning the availability of the RCV is mainly concerning test. I do not know how to drive the vehicle or how the whole system works, so I will need help doing the tests. Since the testing phase and later parts of the thesis takes place during summer, I might need to change my plan to match peoples vacation.

Concerning the hardware, the actuators that are mounted on the vehicle is relatively slow, and the system will need to be upgraded to achieve a fast enough response time. The lead times in deliveries must be taken into considerations in the time plan.

1.7 Requirements?

- Speed of the actuators, in ms before request to actual torque meet.
- Should it be optimized for torque meet, or regeneration? that is, should the regenerative me used as torquefill or as main brake? Probably torque fill.
- Maximum negative acceleration/ deceleration.

1.8 Outline

What does the report discuss? This chapter discusses this, this other chapter discusses that...

Chapter 2

Background study

This section presents the background study that was conducted in the early parts of this project.

2.1 Frame of reference

The literature search began with searches in the IEEE Xplore database, but ended up using Google Scholar as the main search engine for articles, papers and reports that was of value to this thesis. The search began with broad definitions such as 'braking system autonomous driving' as well as 'braking control methods in autonomous driving' trying to get reports that included everything in the braking system, such as the hardware as well as software and controllers. As stated before the main idea in the beginning was to just make a new controller to the brakes on the RCV, but this was broadened to also include the implementation of new hardware. This resulted in that the background study had to be oriented towards hardware as well.
The literature searches showed that there where a few methods of controlling a brake actuator or braking system that appeared more frequently than other. These methods where then included in the search, together with searches solely for that method. This way each search only resulted in a few certain articles or papers where most of them where relevant or at least semi-relevant to this thesis project. These articles and their contents are discussed in the following sections withing this chapter.

2.1.1 Hardware setup

Yu et al. [1] discusses differences in a linearly actuated system vs a hydraulic pump system. The linearly actuated system uses a linear actuator that press directly on a hydraulic cylinder, while a hydraulic pump system uses an electric pump to build up pressure and controls the pressure in the system by valves and/or solenoids. The linear actuators are simpler and more fail safe, since it doesn't have as many valves from where there can be a leakage of hydraulic fluid.

Line, Manzie and Good [2] has constructed a electro-mechanical brake-by-wire system, which utilizes an electrical motor in the calipers as actuator that controls the pressure between the brake pads and the rotor. There is also a brake pedal that sense the pedal position which in turn sends the brake request to a controller. They compare two different controllers in this paper, a cascaded Proportional-Integral (PI) controller and a Model Predictive Controller (MPC). The cascaded PI controller has three control loops for force, motor angular velocity and motor current. The PI controller works, but due to the systems nonlinearity it is somewhat inconsistent in different situations. The MPC performs better in this case, but in order for it to work this efficiently a very good model of the system is needed as ground work, and this is time consuming.

Xiang et al. [3] writes that a electro-mechanical system is preferable over a electro-hydraulical system, due to the simplicity, the efficiency and stability, the enhanced diagnostic capabilities, cost reduction, space and weight saving as well as the elimination of environmental concerns associated with traditional hydraulic braking systems.

Line, Manzie and Good [4] as well as in Ahn et al. [5] are articles about using a cascaded PI controller to control a electro-mechanical brake-by-wire system. Here they present requirements on a electromechanical braking system. They discuss the influence of friction, which makes the system nonlinear. The nonlinearity is discussed in the conclusion, where the nonlinear system is the explanation why the cascaded pi controller does not work as fast in the lower brake pad force spectrum as it does for the higher part of the spectrum.

Frede, Khodabakhshian and Malmquist [6] has done a state-of-the-art report on by-wire systems, with an extensive part about brake-by-wire. They present an overview of brake blending strategies as well as control strategies to regulate braking torque. Most reports discuss brake blending control, but reports where brake torque control is achieved by fuzzy logic is presented as well. Isermann [7] also describes the strengths of a fuzzy logic controller, due to its ability to handle nonlinear systems.

Milanés et al. [8] presents in an article how an autonomous braking system is implemented into a ordinary road car. The car is already fitted with a hydraulic braking system with a manually controlled braking pedal, and the autonomous braking system is added on to that, resulting in a electro-hydraulic autonomous braking system similar to that on the RCV. Although the actuator in this car is a electric pump compared to a linear actuator on the RCV, this report shows that a electro-hydraulic system is satisfactory, even though other reports state that electro-mechanical systems are preferable [9] [3].

The brake blending will be done by a simple function where the regenerative brakes brakes as much as possible, and when they have reached their maximum braking power, the friction brakes steps in to fill in the missing torque, as described by Troung [10].

2.2 Results/Conclusions from background study

The results from the literature study is that the two friction brake controllers will consist of a Proportional-Integral-Derivative (PID) controller and a fuzzy logic controller. The brake blending algorithm will be a simple one where the regenerative brakes brake as much as possible, and the friction brakes fills in the missing torque.

Chapter 3

Implementation

This chapter could present how the brake is implemented, this in terms of how it is set up in Simulink/Simscape and how the new mounts was made together with why the decision was made to order new ones.

3.1 Original setup?

The friction braking system that is used in the RCV in the beginning of this thesis project is a electro hydraulic brake system. The braking system is made up of two linear actuators which are controlled by current from an [escon??] driver, which in turn get its signal from a —dSpace controller— (write more about this), which is the main computer in the RCV. The linear actuators acts on hydraulic cylinders that transfers the force to the calipers on each wheel, where the force acts on the rotors which brakes the vehicle. The reason there are two linear actuators is due to the fact that there are two completely separated friction braking systems in the vehicle, one system that acts on the two front wheels, and the other that acts on the two rear wheels. This is done to incorporate a higher level of safety, whereas if one of the systems breaks down, there will still be braking abilities on two of the four wheels.

There is also a manually operated braking pedal that acts on the hydraulic system, controlling the brakes on all four wheels. This braking pedal which is mechanically connected directly to two hydraulic cylinders is located between the calipers and the hydraulic cylinders connected to the linear actuators. If the manual brake pedal is pressed, the autonomous braking system is mechanically disconnected, and all braking is controlled by the driver.

[Picture of brake system setup]

3.2 Brake actuators and other hardware

At the start of the thesis project the idea was to use the original hardware setup that existed in the RCV, but after testing and reading up on the original actuators a decision was made to change to a new set of actuators that are faster and stronger.

3.2.1 Original actuators and lever arm

The original actuators was of an acme screw type, which involves a lot of dynamic friction where up to 80% of the input power can be dissipated in friction losses [SOURCE]. This means that the motor within the actuator has to work hard to move the rod in each direction. The static friction is also very high, which raises a problem when it come to the control of the actuator. The actuator requires a high current to start moving to overcome the static friction, and when it has overcome that static friction the need of current to keep the motion going is not as high. Thus, the steps in current that is needed to make the actuator move offers a problem in controlling it, since it is hard to control with the step in current that is needed and very small movements in the actuator rod can have large effects to the pressure of the hydraulic system.

However, one feature that could be useful in the acme leadscrew actuators is that the configuration is, within certain forces, self locking. They function in such a way that it moves easily if force is applied from one direction , while if it is applied in the other direction it has to be very high in order for the piston to move. Thus, they can be used as parking brake when the vehicle is turned of, if no other means of parking brake is present. Since the ballscrew actuator has lower internal friction, it cannot be relied upon as parking brake. Though, a parking brake can easily be realized by other means, such as a lever connected to the manual parking brake etc., and is therefore not included in the scope of this thesis

The hardware setup, in terms of mounts and lever arm, that was originally mounted on the RCV needed revision as well, especially the lever arms that transferred the force from the actuator to the hydraulic cylinder. As can be seen in picture [SOURCE TO PICTURE], there is a lever arm that transfers the force from actuator to hydraulic cylinder. This arm is over dimensioned, the lever arm is to long. Tests showed that the acme screw actuators reaches their stroke limit when the request for braking torque reaches a certain point, which means that the actuators is able to provide higher force than originally is possible, hence, the lever arms can be shortened in order to make the system faster while keeping the amount of force that can be delivered.

3.2.2 New actuators

New actuators was needed to make the system faster, and the decision fell on the MAXJACCCC SOMETHING, which

3.2.3 Mounts for new actuators

A decision was made to change the original actuators to a pair of new ones. The new actuators are of ball screw type, which incorporate lower friction, both static and dynamic. This will help a lot when constructing the controller for the brakes, since we wont have as high step in the current needed to start moving the actuator rod.

New mounts had to be made to fit the new actuators, which are slightly larger than the original lead screw actuators. These mounts where modeled in the 3D CAD program Solid Edge, and can be seen in 3.1 [AND MORE]. These parts where then manufactured by water jet cutting by the machine department at KTH. The parts that where constructed where new mounts to the actuators, mounts to the hydraulic cylinders as well as a new connection between the actuator and lever arm. The hydraulic cylinders has not been changed during the thesis project, but since the actuator mounts has been made wider as the actuators are wider, the cylinders had to be wider apart as well to get everything to line up properly.

The connection between the actuator and lever arm was made with regards to the possibility to change the position of the connection on the lever arm, to be able to change the leverage. The connection consists of a T-shaped part that is mounted on the actuator while also clamping on to the lever arm with the help of another piece of metal with holes drilled, two screws and bolts.

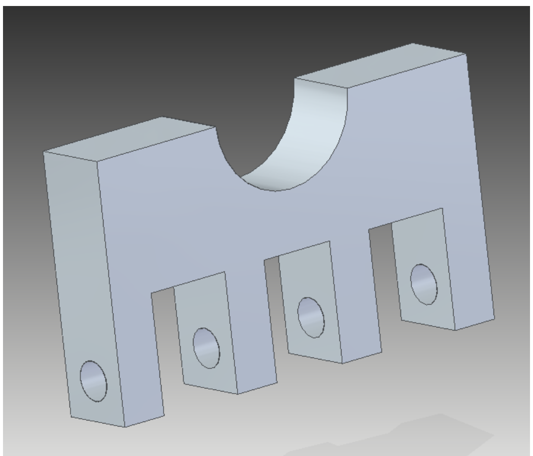

Figure 3.1. CAD picture of mount

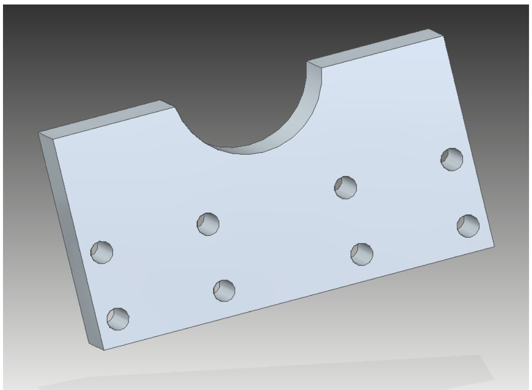

Figure 3.2. CAD picture of the hydraulic cylinder mount

3.3 Implementation and tuning in simulink/simscape

The development of the controller was made using Model-Based Design (MBD), where the model was made using the graphical programming environment Simulink. Primarily the tool box Simscape was used, which is a tool box useful while designing physical systems. The model was then VERIFIED, and used while tuning the brake controller.

3.3.1 Simscape model (and MBD?)

The plant model was constructed in Simulink, mostly using the Simscape toolbox. The plant is made up of a few different parts which are the hydraulic system, the brake calipers, electric actuators and mechanical force translation such as lever arm. All of these parts are made up of Simscape blocks that are tuned by measured or calculated values as well as values derived from data sheets. The choice of using MBD was due to the fact that it is an easy and fast.
This way of solving a problem by making a software plant model and designing the controller from there is called MBD, which has become a very popular method of solving engineering problems, since when a plant model has been made it is easy, fast and cheap to develop and improve the controls[11].

3.3.2 Verification of simscape model

When the simscape model was done the plant need to be verified before the of the controlled is done. The verification was made by running the physical system with the new actuators and all necessary hard ware mounted at certain current requests and the compare the results with from the same cases of current request on the plant model. The results can be seen in [FIGURE].

3.3.3 Tuning controller

The PID controlled was tuned using pole placement design.

A feed forward was also incorporated

Something about anti windup

Chapter 4

Results

This chapter presents the results of the thesis.

4.1 Hardware

The highest needed braking torque on each wheel was calculated with respect to the maximum negative acceleration that is stated in the requirements. If the acceleration is known, as well as the mass of the vehicle the total force that needs to act on the vehicle can be calculated with Newtons second law,

$$F_{tot} = m \cdot a, \tag{4.1}$$

where F_{tot} is the total force needed to achieve acceptable deceleration, m is the mass of the vehicle and a is the acceleration. The vehicle has four wheels and the force is considered to be divided evenly distributed on each wheel. Hence, this gives us

$$F_{wheel} = \frac{F_{tot}}{4}, \tag{4.2}$$

where F_{wheel} is the force needed on each wheel. The torque needed on that wheel can then be calculated by

$$M = F_{wheel} \cdot r, \tag{4.3}$$

where M is the torque and r is the radius of the wheel. The required torque on each wheel was calculated to 350 Nm.

Beskriva hur Pressure—>Torque gått till under mätning??

Chapter 5

Conclusion

This is what a chapter looks like.

Chapter 6

Discussion

This is what a chapter looks like.

Chapter 7

Future work

This is what a chapter looks like.

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Appendix A

First Appendix

A.1 Appendix A, Max Jac datasheet

Max Jac

12 and 24 Vdc - load up to 30 lb

» Ordering Key - see page 60
» Glossary - see page 61

Standard Features and Benefits

- Designed for industrial applications
- Rugged aluminum housing with IP69K
- High efficiency
- Long life
- Hard coat anodizing for high corrosion resistance
- Virtually maintenance free
- Worm or ball screw models
- Non contact analog position feedback signal

General Specifications

Parameter	Max Jac
Screw type	worm or ball
Internally restrained	no
Manual override	no
Dynamic braking	no
Self locking worm screw models ball screw models	 yes no
End of stroke protection	no
Mid stroke protection	no
Motor protection	no
Motor connection	flying leads or cable with connector
Motor connector	AMP Superseal Series 1,5
Certificates	CE
Options	Encoder position feedback

Performance Specifications

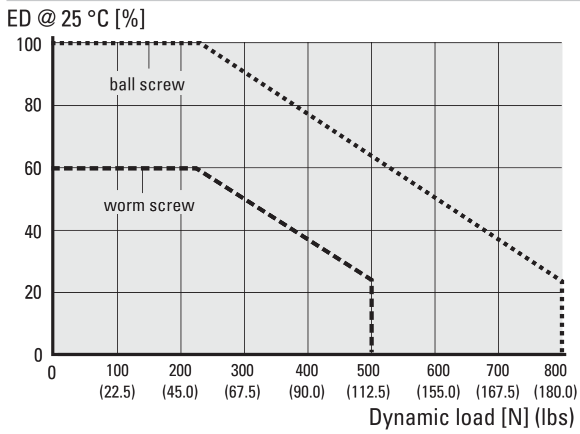
Parameter		Max Jac
Maximum load, dynamic / static MX • • W (worm screw) MX • • B (ball screw)	[N]	 500 / 2000 800 / 100 - 350 (1)
Speed, at no load / at maximum load MX • • W (worm screw) MX • • B (ball screw)	[mm/s]	 33 / 19 60 / 30
Available input voltages	[VDC]	12, 24
Standard stroke lengths	[mm]	50,100,150 200, 250 (2), 300 (2)
Operating temperature limits	[°C]	-40 to +85
Full load duty cycle @ 25 °C	[%]	25
End play, maximum	[mm]	0,3
Restraining torque	[Nm]	2
Lead cross section	[mm^2]	1
Standard cable lengths	[mm]	300, 1600
Protection class		IP66/IP69K
Salt spray resistance	[h]	500
Life	[cycles]	500000 (3)
Analog position feedback signal	[VDC]	0,5 - 4,5
Encoder position feedback option Supply voltage Pulses per mm, worm / ball screw Channels	[VDC]	 5 9,86 / 5,84 A, B

(1) The static force (i.e. the backdriving force) for a ball screw unit varies and is dependant on the number of cycles it have been running and at wich loads.

(2) Strokes possible for ball screw models only.

(3) For ball screw actuator with 100 mm stroke, average load of 500 N and changing load direction.

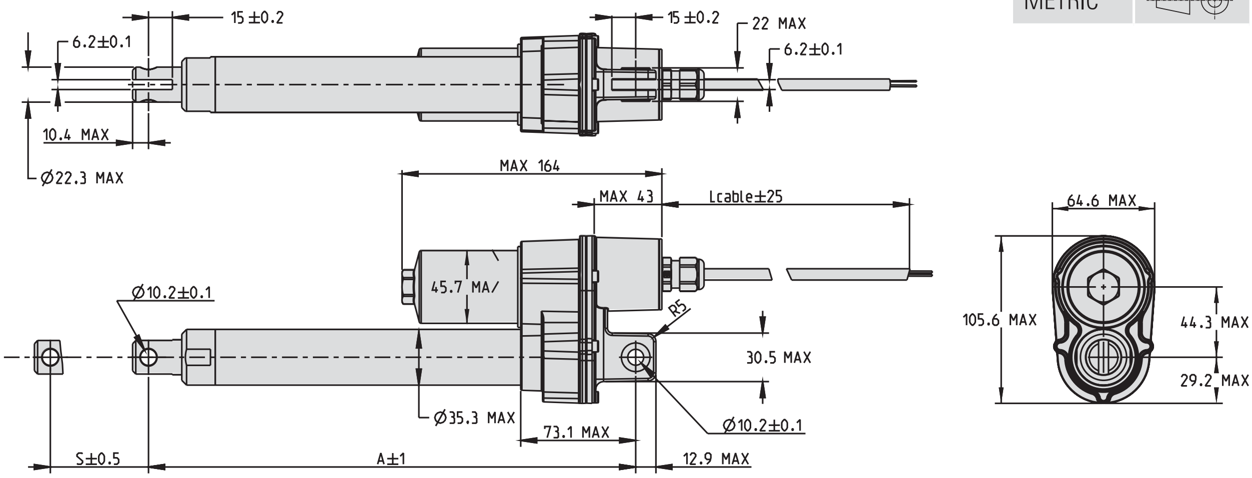
Duty Cycle vs. Load



Max Jac

12 and 24 Vdc - load up to 30 lb

Dimensions	Projection
METRIC	

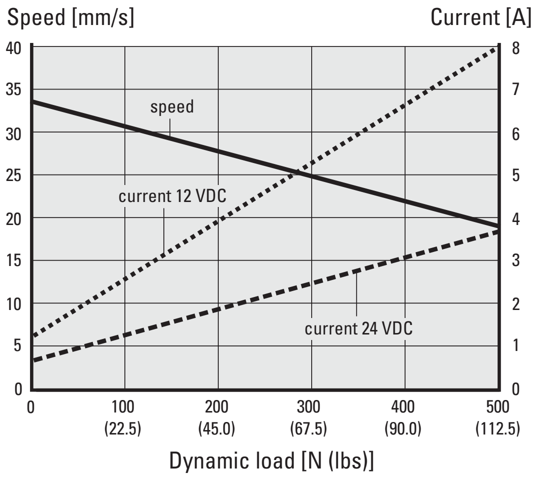


Stroke (S)	[mm (inch)]	50 (1.97)	100 (3.94)	150 (5.91)	200 (7.87)	250 (9.84) *	300 (11.81) *
Retracted length (A)	[mm (inch)]	206 (8.11)	256 (10.08)	306 (12.05)	356 (14.02)	406 (15.98)	456 (17.95)
Weight	[kg]	1,5	1,7	1,9	2,1	2,2	2,4

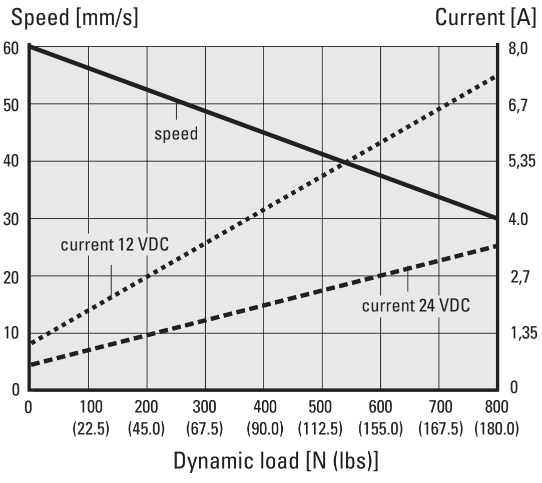
* Strokes possible for ball screw models only.

Performance Diagrams

Worm Screw Models (MX • • W)



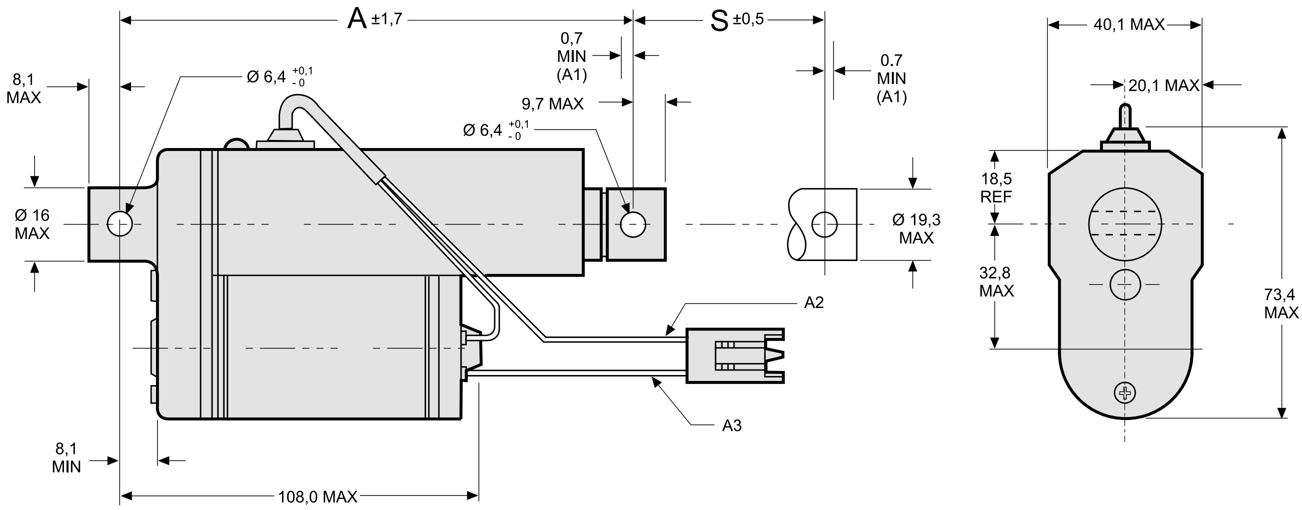
Ball Screw Models (MX • • B)



A.2 Appendix B, Electrak 1

Electrak® 1

12, 24 and 36 Vdc - load up to 340 N



S: stroke
A: retracted length
A1: installation must include at least this much coast beyond limit switch shut off

A2: red lead
A3: yellow lead

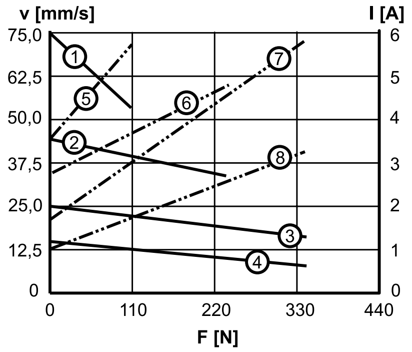
Ordering stroke	[inch]	1	2	3	4	5	6
Electrical stroke (S) *	[mm (inch)]	20,8 (0,82)	46,2 (1,82)	71,6 (2,82)	97,0 (3,82)	122,4 (4,82)	147,8 (5,82)
Retracted length (A)	[mm]	134,5	159,9	185,3	210,7	236,1	261,5
Weight	[kg]	0,52	0,54	0,60	0,63	0,66	0,68

* The electrical stroke is the stroke when the internal limit switches switch off the power to the motor. The installation then must allow the extension tube to coast at least 0,7 mm beyond that position before it becomes mechanically blocked to travel any further (distance A1). If there is no mechanical block the extension tube coasting distance will depend on the load, no load means the longest coasting distance while the distance becomes shorter as the load becomes higher. The exact coasting distance depends on the load, in which direction the load acts (push or pull), the mounting orientation of the actuator and any added friction to the system by guides or other installations and has to be determined on a case to case basis.

Performance Diagrams

Speed and Current vs. Load

12 Vdc

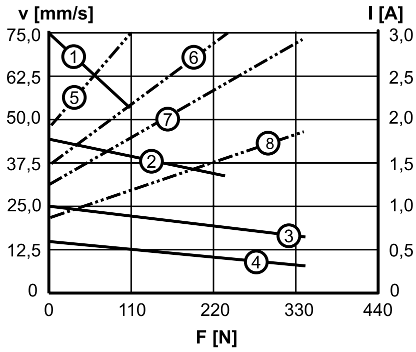


V: speed I: current F: load

1: speed S12-09A04
2: speed S12-09A08
3: speed S12-17A08
4: speed S12-17A16
5: current S12-09A04
6: current S12-09A08
7: current S12-17A08
8: current S12-17A16

Speed and Current vs. Load

24 Vdc

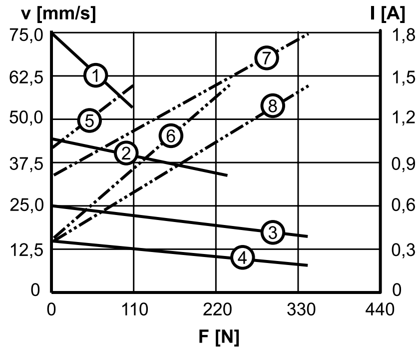


V: speed I: current F: load

1: speed S24-09A04
2: speed S24-09A08
3: speed S24 -17A08
4: speed S24-17A16
5: current S24-09A04
6: current S24-09A08
7: current S24-17A08
8: current S24-17A16

Speed and Current vs. Load

36 Vdc



V: speed I: current F: load

1: speed S36-09A04
2: speed S36-09A08
3: speed S36-17A08
4: speed S36-17A16
5: current S36-09A04
6: current S36-09A08
7: current S36-17A08
8: current S36-17A16

Electrak® 1SP

12, 24 and 36 Vdc - load up to 340 N

» Ordering Key - see page 74
» Glossary - see page 85
» Electric Wiring Diagram - see page 56

Standard Features and Benefits

- Very compact and lightweight
- Potentiometer feedback
- Corrosion resistant housing
- Self-locking acme screw drive system
- Maintenance free
- Internally restrained extension tube
- Ideal for replacement of comparable size pneumatic and hydraulic cylinders

General Specifications

Parameter	Electrak 1SP
Screw type	acme
Internally restrained	yes
Manual override	no
Dynamic braking	no
Holding brake	no, self-locking
End of stroke protection	no
Mid stroke protection	no
Motor protection	auto reset thermal switch
Motor connection	flying leads and connector
Motor connector	Packard Electric Pack-Con male 8911773 with terminal 6294511. Mating connector: 8911772 with terminal 8911639 (p/n 9300-448-001)
Certificates	CE
Options	none

Performance Specifications

Parameter		Electrak 1SP
Maximum load, dynamic / static	[N]	
SP • • -09A04		110 / 1300
SP • • -09A08		225 / 1300
SP • • -17A08		340 / 1300
SP • • -17A16		340 / 1300
Speed, at no load / at maximum load	[mm/s]	
SP • • -09A04		75 / 52
SP • • -09A08		45 / 33
SP • • -17A08		26 / 17
SP • • -17A16		14 / 7
Available input voltages	[Vdc]	12, 24, 36
Standard stroke lengths	[inch]	2, 4, 6*
Operating temperature limits	[°C]	-25 – +65
Full load duty cycle @ 25 °C	[%]	25
End play, maximum	[mm]	0,9
Restraining torque	[Nm]	0
Lead cross section	[mm²]	1
Lead length	[mm]	110
Protection class		IP65
Potentiometer	[kOhm]	10**

* Six inch stroke lenght not possible for SP • • -17A16.
** See table on page 19 for resistance change per mm.

Compatible Controls

Control model	See page
DPDT switch	61
AC-247 ELS	64
DCG-150	66