Modelling and simulation of a measurement robot

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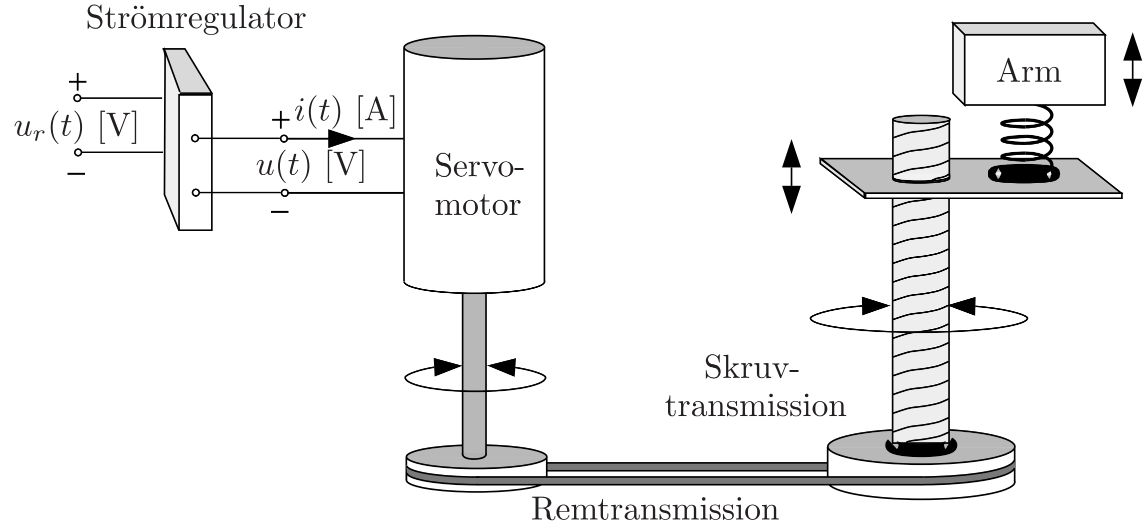

REGLERTEKNIK
AUTOMATIC CONTROL
LINKÖPING

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Chapter 1

Introduction

In this lab we will create a model of the robot in Figure 1.1. The robot's primary use is to perform accurate distance measurements. The robot arm is equipped with a sensor, which is activated if it contacts an object. By moving the robot between two surfaces, the distance between these can be computed.

The lab is divided into two parts. First, you will build and simulate a model of the motor component. Two types of modeling, namely block-oriented modeling in SIMULINK and object-oriented modeling in the MODELICA language, are compared. In the second part of the lab, a model of the complete robot will be built and simulated, using the object-oriented approach (MODELICA). This will entail more complex modeling, using hierarchical models and sub-components. The tasks of both parts of the lab should be finished during the same four-hour session. Therefore, the exercises must be well prepared, and the **preperatory exercises** will be checked before the session starts.

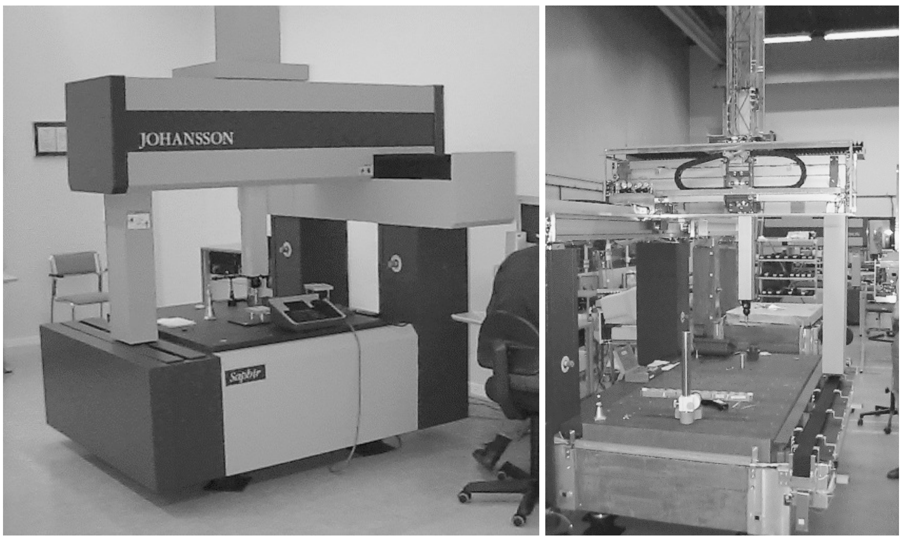


Figure 1.1: The robot, with and without cover.

1.1 The tools

As mentioned, this lab is carried out in SIMULINK and OPENMODELICA. The goal is to understand and appreciate different ways to approach a modeling task. Specific instructions to SIMULINK and OPENMODELICA, as well as examples on how to get started are available on the course homepage.

SIMULINK:

SIMULINK is a MATLAB-based programming environment for modeling, simulating and analyzing dynamical systems. Through its primary graphical interface, block-oriented models can be easily established. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. SIMULINK is widely used in automatic control and digital signal processing for multidomain simulation and model-based design.

MODELICA:

The modeling and simulation environment OPENMODELICA is based on the MODELICA Language, which is an object-oriented, equation based language to describe complex physical systems of various types. OPENMODELICA offers different libraries from which we will use the MODELICA Standard Library. It provides model components and standard component interfaces from many engineering domains. The MODELICA Standard Library consists of sub-libraries, among those we will use the following:

- Electrical.Analog
- Mechanics.Rotational
- Mechanics.Translational

All exercises can be completed with the sub-libraries above, but you are free to use additional ones. Information, examples and tutorials are available on this web page:

https://build.openmodelica.org/Documentation/Modelica.UsersGuide.Overview.html

OPENMODELICA is installed on the computers used during the lab and can be opened with the following commands written in the terminal:

```
» module add courses/TSRT92
» OMEdit &
```

1.2 Description of the system

A sketch of the robot is shown in Figure 1.2.

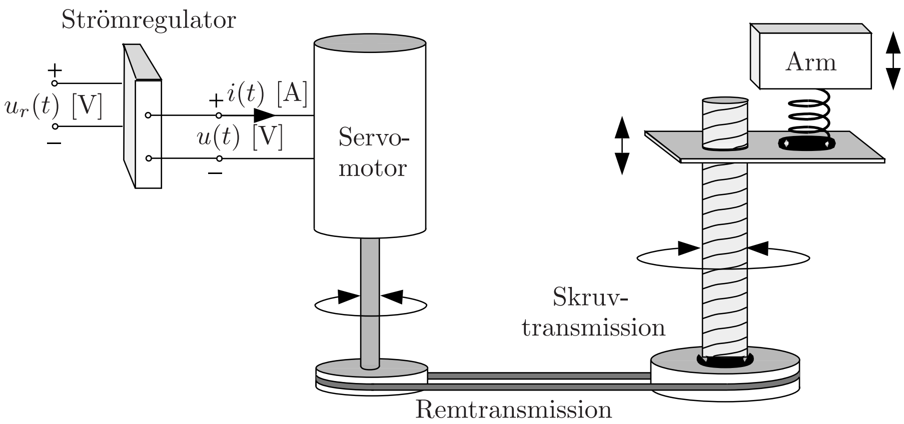


Figure 1.2: The robot system.

The system consists of five components, connected according to Figure 1.3. A short description of every subsystem follows below.

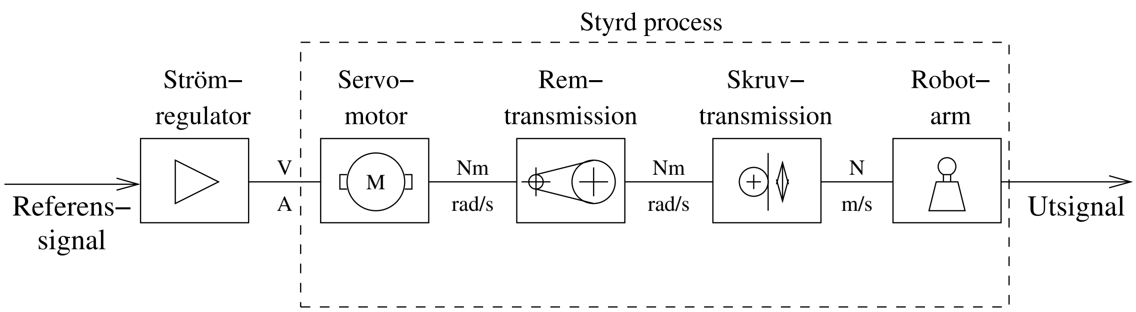


Figure 1.3: Main components in the system and their interactions.

1.2.1 Current controller (strömregulator)

Inputs to the current controller are both a voltage, which constitutes a reference signal for the motor current, and the measured motor current. The output is the voltage driving the motor and the current drawn from the reference source.

For simplicity, on the second part of the lab we will use a current source instead of a current controller. This means that we assume that we have an ideal controller where the motor current always equals the desired one. However, note that if we use an ideal current source we cannot have any inductance in the circuit. (Why?)

1.2.2 Servo-motor

The servo motor is a simple DC-motor mechanically connected to a tachometer. The current controller is electrically connected to the servo motor in accordance with Figure 1.4. The tachometer allows for yet another feedback loop, because the motor angular velocity is proportional to the tachometer voltage. This feedback is not used in our model of the robot, so the modeling of the tachometer can be seen as an optional exercise. Another extension could be to design a controller which controls the motor angular velocity by feedback from the tachometer.

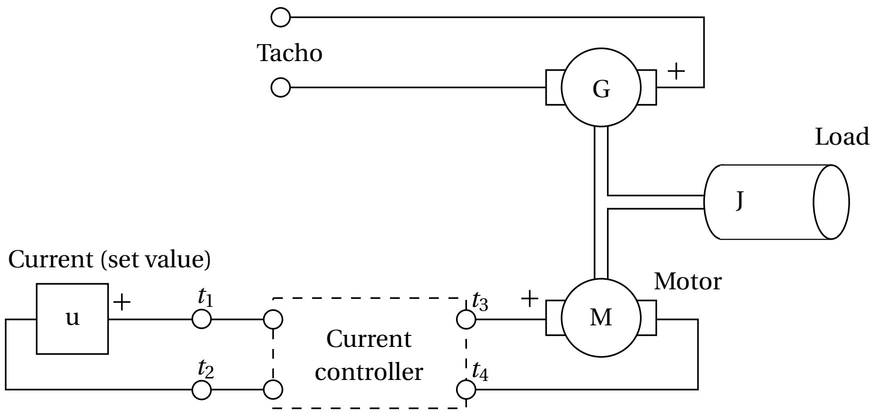


Figure 1.4: Electrical components sketch.

Data for the motor and the tachometer can be found in Figure A.3, in Appendix A. The used motor has model number M-586-0585. The plot shows the relation between revolutions per minute (RPM) and torque. The upper curve is limiting the working area of the motor. From the curve we can see 3 different limitations; the motor has an upper speed limit of 6000 RPM, a maximum torque of 1.05 Nm, and a maximum power. The lower curve shows the relation between torque and angular velocity on the motor axle when the motor current is kept constant. This constant current can be found as *Continuous stall current*, i.e., 3.9 A.

Under *Winding specifications* in Figure A.3 there are two resistors and one inductor. The reason for this is that the coil can not be viewed as ideal and is both inductive and resistive. With the notation in Figure 1.5, the *Armature resistance* is $\mathrm{R_I}$, the *Terminal resistance* is given by $\mathrm{R}_r + \mathrm{R_I}$ and the *Armature inductance* is $\mathrm{I_I}$.

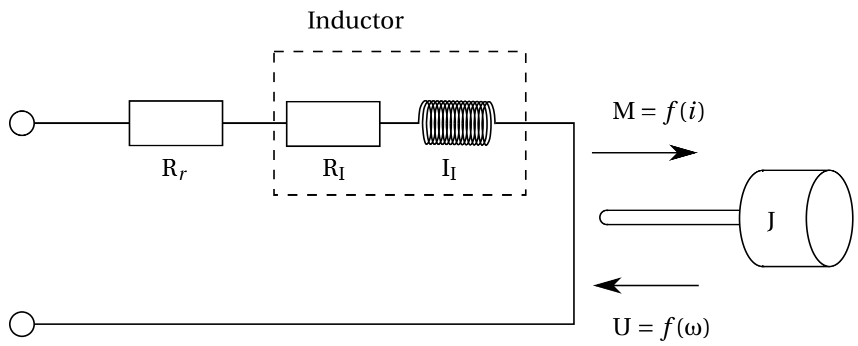


Figure 1.5: Motor sketch.

1.2.3 Belt transmission (remtransmission)

The servo is connected to a toothed cylinder-shaped belt disc with outer diameter 20 mm and thickness 10 mm. A rubber belt drives another belt disc with outer diameter 80 mm and thickness 15 mm. The length of the belt is 750 mm. The belt is elastic and elongates 0.4 % of its full length at max load 200 N. In the Physics Handbook you can find out how to compute inertia for the discs. The discs are made out of aluminum (density $2.7 \cdot 10^3$ kg/m^3). Moreover, energy losses happens at both discs which need to be modeled; the smaller disc has a friction coefficient of $2 \cdot 10^{-5}$ Nms/rad while the larger one has a friction coefficient of $5 \cdot 10^{-5}$ Nms/rad.

1.2.4 Screw transmission (skruvtransmission)

The larger disc on the belt transmission drives a screw with pitch 1 revolution/inch. The screw in turn drives the vertically operating robot arm. The screw used in the robot is of B-8000 type and data for the screw transmission is found in Figure A.1 [1] in Appendix A. The screw is connected to the robot arm through a spring with spring constant 75 kN/m. The length of the screw [2] is 1 m. Friction in the screw is assumed negligible.

1.2.5 Robot arm (robotarm)

The robot arm is driven by the screw via the spring and moves vertically. The mass of the arm is 5.5 kg and the friction is 25 Ns/m. Note that we ideally want to control the velocity of the arm, but for practical reasons we instead use the velocity of the motor, which is connected to the tachometer, as feedback signal.

[1] 16 oz = 0.45359 kp, 1 kp = 9.81 N and 1 in = 25.4 mm according to the Table

[2] Note that the inertia is given per unit length in the table.

1.3 Some modeling hints

Subsequently, some general hints follow in order to simplify the modeling.

Sub-models: To begin with, divide the large model into smaller models and test every sub-model separately. This will also give you a better feeling for how the different parts work.

Start with a simple model: Start with the most basic properties. As an example, if you model two gearwheels with different radii, the most important property is that they scale torque and angular velocity. Properties that might be relevant at a later stage are friction and possibly elasticity in the cogs.

Slow dynamics first: Extend the simple model with slow dynamics first. If a gearwheel is attached to a long aluminum shaft, the shaft flexibility has slower dynamics than the wheel. In other words, the weakness of the shaft is more important to model than the weakness of the cogs.

Changing standard blocks in OPENMODELICA: In the scope of this lab, it will not be necessary to change the equations in a standard block offered by OPENMODELICA. If you wish to do a change anyway, it is easiest to copy the block and save it under a new name. You can then edit the copy.

OPENMODELICA gives compilation errors: There is obviously something wrong in your model. A few common faults to check are:

- Try compiling each subsystem individually to see wich one is faulty.
- Make sure that all connections are between the same sort of motion, i.e. rotational to rotational movement (round flanges) and translational to translational movement (square flanges).
- Only the upper connections on the `IdealGearR2T` should be used.
- All the damper should have one end fixed.
- When connecting the subsystems, make sure that the name of the file is different from the name of the subsystem.

Chapter 2

The lab

2.1 Motor modeling

During the lab, two models of the robot motor are built and verified by simulations.

- A *block-oriented* model in SIMULINK.
- An *object-oriented* model in OPENMODELICA.

We assume here that the motor is driven by a voltage source.

2.1.1 Preparations

Preparation 1 *Write down the motor component of the robot (Figure 1.5) in state-space form. Use the motor current i and the engine speed ω as state variables, and the motor voltage u_m and the motor load T_{load} as input signals.*

Hint 1: *The voltage denoted by U in the figure should not be confused with the input voltage u_m.*
Hint 2: *The functions $M = f(i) = k_\tau i$ and $U = f(\omega) = k_u \omega$ are linear in i and ω, respectively.*
Hint 3: *See the textbook about gyrators.*
Hint 4: *The static friction can be neglected and the viscous friction is linear in ω.*

Preparation 2 *Implement a model of the motor using* SIMULINK-*blocks.*

Hint: *To see how the signals are connected we recommend blocks such as* `Integrator`, `Gain` *and* `Sum` *in the model. For students not familiar with Simulink, a small guide is available in the course web page.*

Preparation 3 *Think through what an object-oriented model should look like in* OPENMODELICA *and which standard blocks you need.*

Preparation 4 *Find all numerical constants required for the motor model. Be careful with the units!*

Hint: *For the mechanical friction coefficient, use the diagram in Figure A.3. In particular, the slope of the straight line is relevant to study.*

2.1.2 Exercises

The electrical time constant for the motor is defined as the time constant for the current when a voltage step is made with the axle held still. The mechanical time constant is defined as the time constant for angular velocity during a voltage step without engine torque. These two time constants are given in Figure A.3.

Task 1 *Implement the model in* OPENMODELICA *and validate the result by comparing the simulated time-constants with the ones in the data sheet. Note that one will be less accurate than the other. Why?*

Hint 1: *The time constant is defined as the time it takes for the output to reach* 63% *of its final value.*
Hint 2: *You will need the following* MODELICA *blocks:* `VoltageStep`, `Resistor`, `Inductor`, `Ground`, `RotationalEMF`, `Inertia`, `Damper` *and* `Fixed`.
Hint 3: *The friction can be modeled as a damper between the motor axle and fixed.*
Hint 4: *The axle could be held still by connecting it to a fixed.*

Task 2 *See what time-constants you get with the block-oriented model from Preparation 2. Do you get the same results? Why/why not?*

Hint: *By multiplying* ω *by zero the axle is fixed.*

Task 3 *Make sure that the* MODELICA*-model of the motor can be reused. A good solution is to make the motor a sub-system, and thus allowing hierarchical modeling. This can be done by inserting flanges in each sub-model for connecting them in the main model.*

2.2 Modeling the whole robot

Now we model the whole robot in OpenModelica. For simplicity we use a current source instead of a current controller.

2.2.1 Preparations

Preparation 5 *Using an ideal current with an inductance can cause problems — how? In this lab we avoid the problem by not including the inductance in the model.*

Preparation 6 *Find all numerical constants needed for the belt transmission. Be careful with units!*

Hint: *The gear ratio should be calculated for both belt discs separately.*

Preparation 7 *Find all numerical constants needed for the screw transmission. Be careful with units!*

Preparation 8 *Find all numerical constants needed for the robot arm. Be careful with units!*

Preparation 9 *Plan which sub-components you'll need in addition to the motor model, and how the sub-models should be assembled in order to get a complete model of the robot system. The models should be constructed with the object-oriented approach used by* MODELICA *(hierarchical modeling).*

2.2.2 Exercises

Task 4 *Modify your* MODELICA *model of the motor to use a current source.*

Task 5 *Implement a* MODELICA *model for the belt transmission.*
Hint: *You will need the following* MODELICA *blocks:* `Inertia`, `Damper`, `IdealGearR2T`, `Spring` *and* `Fixed`.

Task 6 *Implement a* MODELICA *model for the screw and robot arm.*
Hint: *You will need the following* MODELICA *blocks:* `Inertia`, `IdealGearR2T`, `Spring`, `Damper`, `Fixed`, `Mass` *and* `ConstantForce`.

Task 7 *Combine the subsystems to create a* MODELICA *model for the whole robot.*
Note: *The subsystems can't have the same names as the filenames.*

Task 8 *Simulate the system with a step in the current at t=2s, the amplitude of the step should be the continuous stall current defined in Figure A.3. What is the behaviour of the robot arm?*

Task 9 *Which simplifications have been made? (For example we assume that all voltages are within limits.)*

Task 10 *When a system is extended with more dynamics, simulations will take longer. Sometimes the difference in time can be larger than what can be explained from having a larger system. What other explanations could there be? Which dynamics should be included in a model first, the fast or the slow ones?*

Task 11 *The real system is very oscillatory which is the reason that the control group has studied this robot. Can this be seen in the simulations? What causes the oscillation?*

Task 12 *Play around by increasing and decreasing parameters to see if you can reduce the oscillations. Which parameters affect the oscillations? Why is it not suitable to do these changes on the real robot?*

Bibliography

[1] L. Ljung, T. Glad and A. Hansson. *Modeling and identification of Dynamic Systems.* Studentlitteratur, 2021.

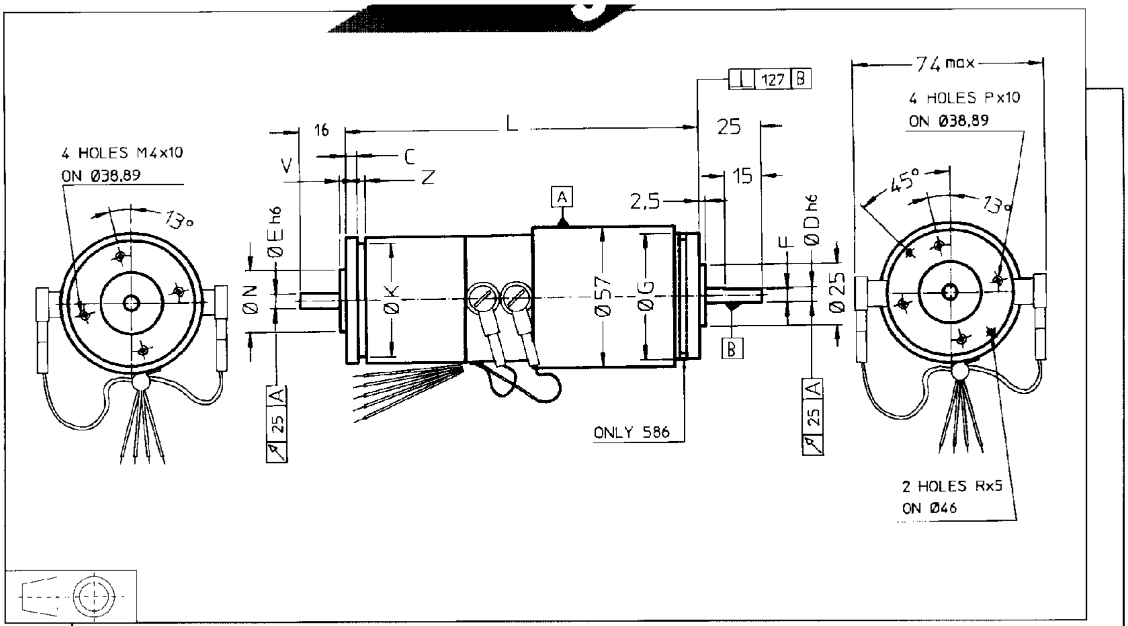
[2] T. Glad and L. Ljung. *Reglerteknik: Grundläggande teori.* Fjärde upplagan, Studentlitteratur, 2006.

Appendix A

Data Sheets

MECHANICAL PROPERTIES				
Screw/Nut Series	Static Frictional Drag Torque oz.-in. (NM)	Screw Inertia oz.-in.-sec.^{2}/in.	Anti-Backlash Life	Anti-Backlash Life w/TFE Coating
B 4000		$.3 \cdot 10^{-5}$	N/A	N/A
B 6000		$1.5 \cdot 10^{-5}$	Typical	Typical
B 7000		$3.5 \cdot 10^{-5}$	Backlash	Backlash
B 8000	Free	$5.2 \cdot 10^{-5}$	.003"-.010"	.003"-.010"
B 10000	Wheeling	$14.2 \cdot 10^{-5}$	(.076-.25mm)	(.076-.25mm)
B 12000		$30.5 \cdot 10^{-5}$		
B 14000		$58.0 \cdot 10^{-5}$		

Figure A.1: Mechanical data for the screw transmission.



Dimensioni in mm Tolleranze in micrometri - *Dimensions in mm Tolerances in micrometer*

TIPO/*TYPE*	L	D	E	F	G	V	C	Z	N	P	R	K
M 586 0585 0606 01 TBU	142	6	6	5,5	51	2,5	4,83	3,18	25	M4	/	46,23
M 586 0585 0606 02 TBV	142	6	6	5,5	51	2,5	4,83	3,18	25	M4	/	46,23
M 586 0585 0606 03 TPU	145	6	6	5,5	51	/	/	/	/	/	M2,5	/
M 588 1100 0606 01 TBU	167	6	6	5,5	51	2,5	4,83	3,18	25	M4	/	46,23
M 588 1100 0808 02 TBU	167	8	8	/	57	2,5	4,83	3,18	25	M4	/	46,23
M 588 1100 0606 04 TBV	167	6	6	5,5	51	2,5	4,83	3,18	25	M4	/	46,23
M 588 1100 0808 03 TBV	167	8	8	/	57	2,5	4,83	3,18	25	M4	/	46,23
M 589 1270 0808 01 TBU	180	8	8	/	57	2,5	4,83	3,18	25	M4	/	46,23
M 589 1270 0806 02 TPU	183	8	6	/	57	/	/	/	/	/	M2,5	/

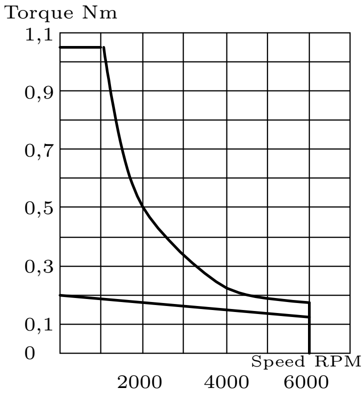
La serie 500 DT appartiene ad una più vasta famiglia di servomotori a corrente continua con eccitazione a magnete permanente, particolarmente studiati per soddisfare le esigenze in un ampio campo di applicazioni industriali e professionali, quando siano richieste alte prestazioni di precisione, di velocità e/o posizionamento.

The series 500 DT belongs to a large family of permanent magnet DC servomotors, they were studied to satisfy the demands of a broad range of industrial and professional apllications, where highly precise speed and/or positioning perfomances are required.

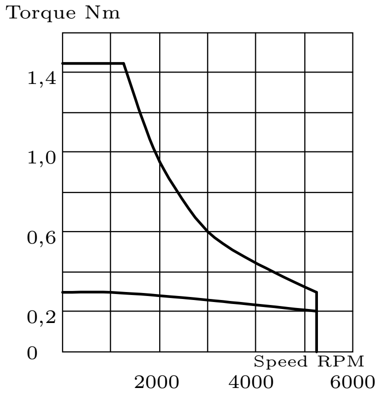
FORMA (secondo IEC 34-7) IMB5 (fissaggio con flangia)
PROTEZIONE (secondo IEC 34-5) IP 44
EQUILIBRATURA (secondo DIN 45665) classe N
POLI n. 2
MATERIALI ISOLANTI in classe F ed H
CAMPO DI FUNZIONAMENTO altitudine < 1000 m. s.l.m.
TEMPERATURA AMBIENTE MAX 40° C
TEMPERATURA AMBIENTE MIN 0° C

CONSTRUCTION (according to IEC 34-7) IMB5 (flange mounting)
PROTECTION CLASS (according to IEC 34-5) IP 44
BALANCING (according to DIN 45665) class N
POLE NUMBER 2
INSULATION CLASS F and H
OPERATING RANGE below 1000 m above sea level
MAXIMUM OPERATING AMBIENT TEMPERATURE 40° C
MINIMUM OPERATING AMBIENT TEMPERATURE 0° C

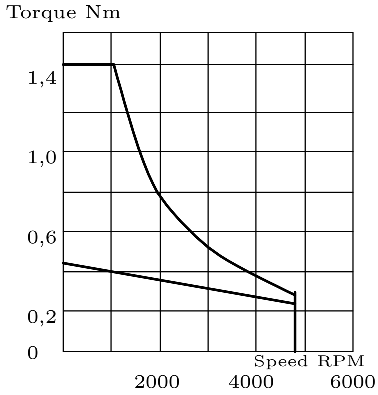
Figure A.2: Servo motor.



M 586 0585



M 588 1100



M 589 1270

SPECIFICATIONS (1)		**M 586 0585**	**M 588 1100**	**M 589 1270**
Operating Specifications				
Continuous stall torque	Nm	0,2	0,35	0,40
Peak Stall torque	Nm	1,05	1,50	1,44
Continuous stall current	A	3,90	3,30	3,30
Maximum pulse current	A	18,7	14,2	11,9
Maximum terminal voltage	V	60	60	60
Maximum speed	RPM	6000	5200	4700
Mechanical data				
Rotor moment of inertia (including tachometer)	kg m^2	$3{,}88 \cdot 10^{-5}$	$5{,}5 \cdot 10^{-5}$	$6.8 \cdot 10^{-5}$
Mechanical time constant	ms	10,2	10	8
Motor mass (including tachometer)	kg	1,3	1,7	1,9
Thermal data				
Thermal resistance (armature to ambient)(2)	°C/W	5	4,2	4
Maximal armature temperature	°C	155	155	155
Winding specifications				
Torque constant (3) K_τ	Nm/A	0,056	0,105	0,12
Voltage constant (back emf)(3)	V/kRPM	5,8	11	12,7
Armature resistance (4)	Ω	0,8	1,6	1,8
Terminal resistance (4)	Ω	1,15	2	2,2
Armature inductance	mH	3,39	5,2	6,4
Electrical time constant	ms	2,95	2,6	2,9
Tachometer data				
Linearity (maximum deviation)	%	0,2		
Ripple (maximum peak to peak)	%	5,0		
Ripple frequency	cycles/rev	11,0		
Temperature coefficient	%/°C	-0,05		
Output voltage gradient	V/kRMP	14±10 %		

(1) Ambient temperature (if not otherwise specified): 40 °C.
(2) Test conducted with unit heatsink mounted on a 254x254x6 mm.
(3) Tolerance ±10%
(4) At 25°C.

Figure A.3: Data for servo motor.