PRACTICAL WORK OF

Modeling of Mechatronic Systems 1

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Master M2E2 1 time year

Hector Ramirez and Didace Habineza

Year 2014-2015

MSM1 labs for M2E2 1 masters time year take place in *room 106 B* and consist of two topics each corresponding to two four-hour sessions:

- Exercise 1: Modeling of a fl uidic system;
- Exercise 2: Modeling of an electromechanical system.

The students will be divided into 4 pairs. TP rotations are shown in the table in Fig. 1. S_i corresponds to the session *i, B_i* in pairs *i.*

	B_1	B_2	B_3	B_4
S_1	TP 1 TP	1 TP 2 TP	2 TP 1 TP	1 TP 2
S_2	TP 2 TP	2 TP 2 TP	1 TP 1 TP	2 TP 2
S_3	TP 1 TP	1		
S_4				

Figure 1: Table of TP rotations

A preparation is to be done *before* each TP session [1] and the report is due *at the end of the second session of each of the two practicals.* The TP grade will consist of a grade preparation and continuous monitoring during the session and a note on the practical work report.

1 This does not mean that you have to know how to do everything in the preparation (sections (preparation) of the handout) but that you should at least try to do everything ...

Content

Chapter 1

Modeling a system fluid

The aim of this practical work is to model a fluid device thanks to a network of systems with localized parameters. This fluid network will use an analogy with electrical networks. The model studied, brand INTECO, corresponds to an automatable system for filling and checking the water level in tanks. This model is made up of three tanks of di ff erent geometries, each of which can be emptied using a manual valve and an electrically controllable valve using a digital control system (PC + I / O card on PCI bus). An electric pump supplying the upper tank can also be controlled from the PC and from the I / O card (Fig. 1.1).

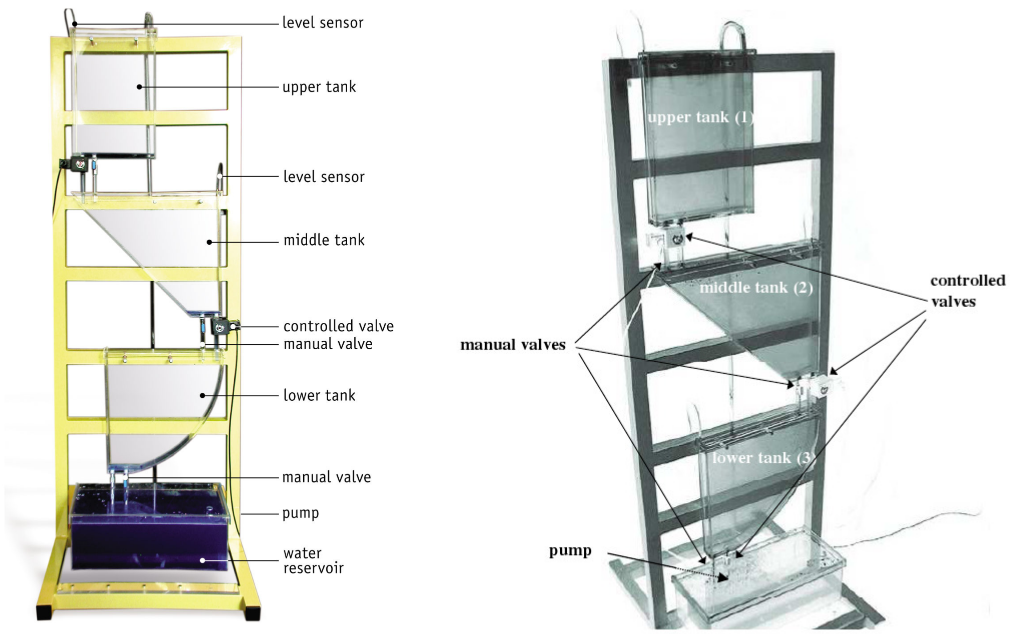


Figure 1.1: Description of the INTECO model comprising three tanks.

1.1 Some principles of fl uid mechanics

Under certain simplifying assumptions, it is possible to define an analogy between electrical systems and fluid systems and to model the latter by networks of systems with localized parameters. In order to simplify the study, we will assume for this lab that the fluid used is ideal and incompressible and that the flows are laminar (without turbulance). The Tab. 1.1 recapitulates the analogy between the variables *conservative, through, potential* and *across* for these two physical domains.

Variables	Electricity	Fluid mechanics [at]
Conservative	charge Q	mass = $\rho \cdot V$
Through	current i	mass flow $\rho \cdot q$
Potential	electric potential ϕ	absolute pressure p
Across	voltage $v_{12} = \phi_2 - \phi_1$	pressure di ff erence $p_{12} = p_2 - p_1$

[at] ρ is the density of this fl uid, V its volume and q its volume flow. Yes ρ remains constant (incompressible fl uid), the fl uid volume can also serve as a conservative variable and its volume flow as a through variable, this is what we will do in this lab.

Table 1.1: Summary table of the analogies between the variables *conservative, through, potential* and *across* for the electrical field and the fluidic field.

1.1.1 The fl uid reservoir: filling and emptying

Or a tank which can be supplied or emptied using a filling and a drain pipe. The volume flow rate of fl uid entering this reservoir is equal to
$q_{filling} - q_{emptying}$ and this fl uid is subjected to the force of gravity (acceleration of gravity
$g = 9,81$ m / s 2). The pressure at the top of the tank will be noted p_1 and the pressure at the bottom p_2. The height of the fluid in the tank will be noted h.

De fi nition 1.1 (Continuity equation (conservation of mass))
The mass m (t) of water stored in the tank is a conservative quantity:

$$\frac{dm(t)}{dt} = \rho \left(q_{filling}(t) - q_{drain}(t) \right) \tag{1.1}$$

In a constant section tank AT, We have $m(t) = \rho \cdot A_T \cdot h(t)$ and the continuity equation reduces to:

$$A_T \cdot \frac{dh(t)}{dt} = q_{filling}(t) - q_{drain}(t) \tag{1.2}$$

De fi nition 1.2 (Pascal's principle (Newton's law in statics))
If the vertical acceleration of the fl uid particles at the bottom of the tank is low enough to be neglected (emptying and filling relatively *slow), the sum of the vertical forces*
at the bottom of the tank is zero. The pressure di ff erence $p_{21} = (p_2 - p_1)$ between the bottom and the top of the tank is then due only to the weight P of the body of water:

$$\begin{aligned} & P - (p_2 - p_1) \cdot A = 0 \\ \Rightarrow \quad & p_{21} \cdot A = m \cdot g \\ \Rightarrow \quad & p_{21} \cdot A = (\rho \cdot A \cdot h) \cdot g \\ \Rightarrow \quad & p_{21} = \rho \cdot g \cdot h \end{aligned} \tag{1.3}$$

De fi nition 1.3 (Bernouilli's principle (energy conservation))
This principle is a direct application of the principle of conservation of energy to the emptying of a tank through a section orifice. S located at the bottom of the tank. If we assume that the leaks and losses are negligible - drain without loss of energy

-, the potential gravitational energy $V(h) = \rho \cdot g \cdot h$ of an elementary volume of drained fluid is then completely transformed into kinetic co-energy $T^*(v) = \frac{1}{2}$

the drain port (v is the velocity of the fl uid leaving the orifice of vi $\frac{1}{2} \cdot \rho v^2$ at the exit of dange):

$$V(h) = T^*(v) \tag{1.4}$$

For laminar flow, the drain flow is $q = \int_S v\, dS \approx v \cdot S$, Which give :

$$\rho \cdot g \cdot h = \frac{1}{2} \cdot \rho v^2 \Rightarrow q = S \cdot \sqrt{2 \cdot g \cdot h} \tag{1.5}$$

In practice, the flow leaving the orifice is never perfectly laminar and a flow rate coe ffi cient of this port $k_S < 1$ is then used [1]:

$$q = k_S \cdot S \cdot \sqrt{2 \cdot g \cdot h} \tag{1.6}$$

1.2 Modeling (preparation)

Question 1.1 *Using the equations recalled in the previous section (continuity and Pascal's principle) and considering the following electrical / fluid analog:*

1. $Q \Leftrightarrow V$;
2. $i \Leftrightarrow q$;
3. $v_{12} \Leftrightarrow p_{12}$,

show that there is a complete analogy between a tank of constant section AT and a conden-
electric sator. Then indicate the value of VS_f, the capacity of the tank. Express its constitutive law for an ideal component (incompressible fluid and constitutive law of the
linear tank). What changes if the section of the tank is not constant?

Question 1.2 *Explain the operation of a proportional solenoid valve then, using the equations recalled in the previous section (Bernouilli and Pascal principle), give the constitutive law of a solenoid valve in the form of a relation between the flow rate obtained at the valve outlet and its two control quantities:*

- *the pressure di ff erence p_{21} at its ends;*
- *its opening section S (function of the control voltage for a solenoid valve).*

What is the type of this component (active / passive, conservative / dissipative) and its associated causality?

Question 1.3 *Find the linear graph associated with the network of the three tanks of the INTECO model and deduce from its rank and its nullity.*

[1] $k_S \approx 0,62$ for a single hole and $k_S \approx 0,98$ for a nozzle.

Question 1.4 *Recall the constitutive laws of the di ff erent subsystems making up this model as well as their causality. Deduce the dynamic order of this system and propose variables allowing to model its state.*

Question 1.5 *According to the constitutive laws of the di ff erent subsystems, choose a tree and the associated co-tree respecting the causality of these components. Deduce from the interconnection matrices* Q *and* B *then the corresponding generalized Kirchho ff laws. What is the dimension of the vector space of the volume flows* [2] *and that of the vector space of the pressure di ff erences?*

1.3 Identi fi cations and experimental verifications

The INTECO model is controlled by a PC and an I / O card connected to its PCI bus. The latter is programmable and controllable by means of *Matlab Simulink.* Converting and compiling the schema *Simulink* in a C program is performed using the *Real Time Workshop toolbox* by Matlab. The program is launched and controlled in real time on the PC processor by using the *Real toolbox*

Time Windows Target by Matlab.

Launch the Matlab software. Go to a directory (*directory)* that you will have created in the directory C: \ students \ Master_M2E2_1 \ MSM1 \ then launch the toolbox
(*toolbox)* Simulink (> simulink). Open the original fi le model_driver_level.mdl
(cf. Fig. 1.2) then save it under a new name in your directory.

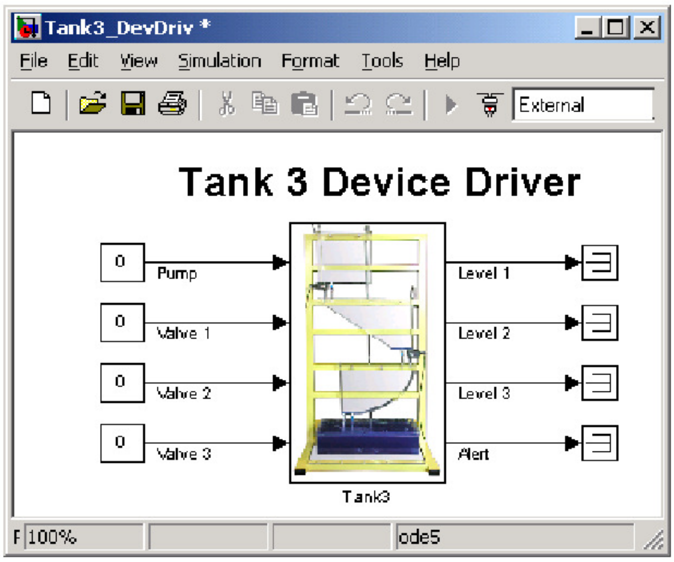


Figure 1.2: Screenshot of the original command fi le of the INTECO model. You can compile your fi le using the

following menus:
→ Tools → Real-Time Workshop → Build Model

[2] The dimension of the vector space of the volume flows is the number of independent volume flows in the graph associated with this system.

You can start your circuit program using the following menus:

→ Tools → External Mode Control Panel

You can see the components of the block Tank3 by carrying out the manipulation: Click right button → Look under Mask

1.3.1 Identification of the elements of the upper tank

Question 1.6 *From the geometric dimensions measured on the tank or from manufacturer data, determine the behavior law of the upper tank. From this result, propose an experimental protocol to determine the constitutive law*

pump flow q_p / control voltage u_p. Draw the curve $q_p = f(u_p)$ for $0 \leq u_p \leq 1$.
What can you say about the behavior of the pump?

Question 1.7 *Propose an experimental protocol making it possible to determine the laws of behavior of the two drain valves of the upper tank (manual valve and solenoid valve). Carry out the corresponding experiments for these two types of valves and trace their characteristics. Compare the results obtained experimentally with the laws determined in the preparation. Deduce from the physical parameters of manual valves and solenoid valves.*

1.3.2 Identification of the laws of behavior of other tanks

Question 1.8 *From the geometric dimensions measured or from the manufacturer's data, determine the constitutive laws of the other two tanks. Based on the results of the previous questions, propose an experimental protocol to measure the laws of behavior of these two tanks. Draw the corresponding characteristic curves and compare them to the theoretical results. Conclude*

1.4 Simulation of the dynamic behavior of the fl uidic model

At first, you will only take into account the upper tank. The operation of the model comprising the three tanks will only be studied later if you have time.

Question 1.9 *By reduction of the behavioral and interconnection equations, propose a state model of this fluid system. The inputs to this status model will be the control (or flow) of the pump and / or the control of valves and solenoid valves. The outputs of this model will be the level (s) in the di ff erent tanks.*

Question 1.10 *Propose a method or a computer program making it possible to solve these equations of state and therefore to simulate the dynamic behavior of this model. You can use one of the following software: matlab, simulink, scilab.*

Question 1.11 *Using the model obtained, simulate various dynamic behaviors and experimentally verify the concordance between the theoretical results (simulations) and practical results (experimental).*

Chapter 2

Modeling a system electromechanical

The goal of this practical work is to model an electromechanical energy conversion system and a motion transmission system. A model of the company INTECO (cf. Fig. 2.1 and 2.2), made up of a direct current motor (MCC), several transmission devices (couplings, inertias, reducers ...) and several sensors (position and speed) will be used in this lab. The first part of the subject consists in modeling and then in experimentally identifying the operation of the DC motor. In a second step, the same work will be carried out on the mechanical transmission. Finally in the last part, these di ff erent subsystems will be interconnected in order to obtain a complete electromechanical drive in rotation. Modeling in the form of a state will then be used to carry out simulations. These will then be compared to the actual dynamic behavior of the model.

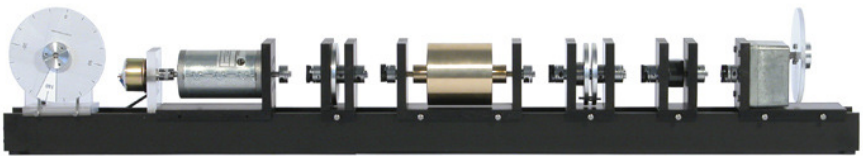


Figure 2.1: Description of the INTECO model.

2.1 Some principles of electromechanical energy conversion

The DC motor of the INTECO model is *permanent magnets.* His *stator* - the fixed part of the motor -, is thus made up of permanent magnets which generate a constant magnetic field $\vec{B}$ in the central part of the machine (cf. Fig.

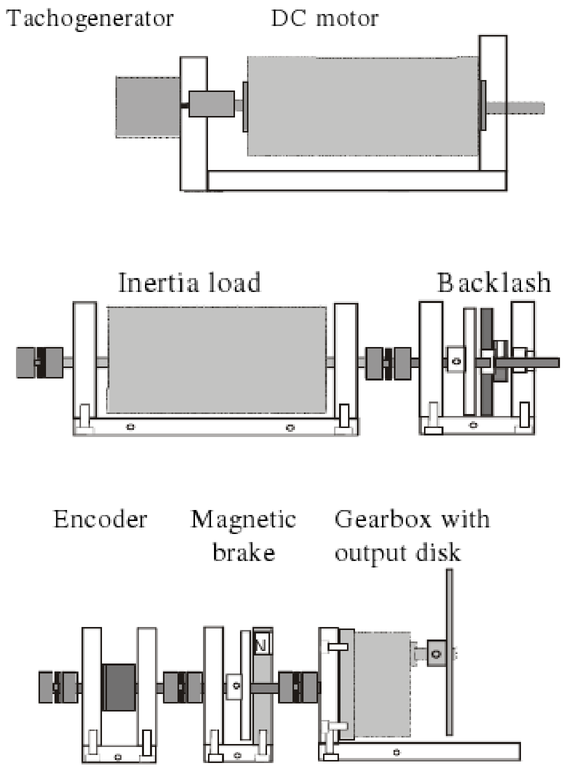


Figure 2.2: Description of di ff erent constituents of the INTECO model.

2.3). A winding supplied by a direct current i is fixed on the *rotor* - the mobile part of the motor. As the winding of this rotor is *square* in the stator field $\vec{B}$, each of the conductors of this winding undergo a Laplace force:

$$\vec{F} = i \cdot d\vec{l} \times \vec{B} \tag{2.1}$$

$d\vec{l}$ is the unit vector carried by the conductor and it is oriented in the direction of the current.
When the winding is in the at_1- b_1 (Fig. 2.4 (a)) or in position at_3- b_3 (Fig. 2.4 (c)), the force and torque resultants created by the two conductors of the winding cancel each other out. However, when the winding is in the at_2- b_2 (Fig. 2.4 (b)), a negative torque is created and when the winding is in the position at_4- b_4 (Fig. 2.4 (d)), a positive pair is created. These last two positions allow the rotor to rotate.
one way or the other.

A system called *collector + brushes* allows this coil to be fed in a different way for each of these positions:

- position at_1- b_1: the winding is not supplied;
- position at_2- b_2: the winding is fed in the negative direction ($i \leq 0$) therefore a positive couple is created;

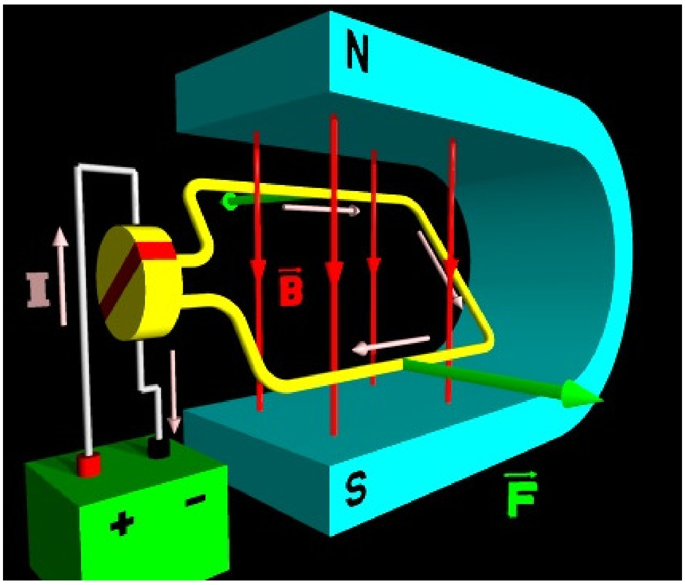
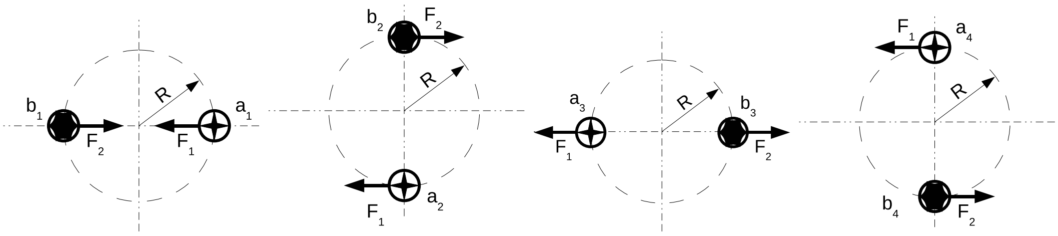


Figure 2.3: Simpli fi ed constitution of an MCC.



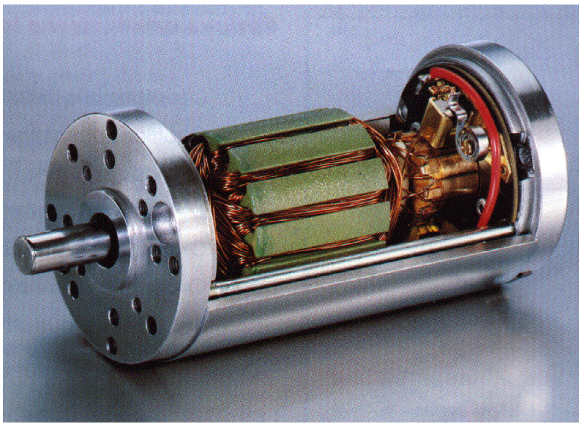
(a) In position at_1- b_1, (b) In position at_2- b_2, (c) In position at_3- b_3, (d) In position at_4- b_4,
forces F_1 and F_2 strength F_1 produced the forces F_1 and F_2 strength F_1 produced the
are equal and negative torque - $F_1 \cdot R$ are equal and positive couple $F_1 \cdot R$
opposites. They don't and strength F_2 product opposites. They don't and strength F_2 product
do not produce the negative couple do not produce the positive couple
couple because their - $F_2 \cdot R$. The couple couple because their $F_2 \cdot R$. The couple
directions go through resulting is therefore worth directions go through resulting is therefore
the axis of rotation of the $c = - (F_1 \cdot R + F_2 \cdot R)$. the axis of rotation of the $c = (F_1 \cdot R + F_2 \cdot R)$.
rotor. rotor.

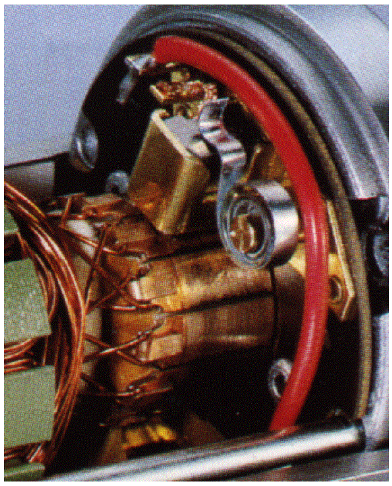
Figure 2.4: Creation of the torque in an MCC as a function of the position of the rotor conductors with respect to the stator field.

- position at_3- b_3: the winding is not supplied;
- position at_4- b_4: the winding is supplied in the positive direction (reversal of the direction of the current in relation to the at_2- b_2: $i \geq 0$) therefore a positive couple is created.

The torques created in these four positions being positive or zero, the average torque is overall positive. If the machine is made up of many conductors distributed over the entire periphery of the rotor (cf. Fig. 2.5), the oscillations of couples around its mean value

become weak and therefore negligible. With this assumption, the instantaneous torque no longer depends on the position of the rotor winding with respect to the magnets but only on the current.
i, of the field $\vec{B}$ produced by stator magnets and machine geometry.





(at) (b)

Figure 2.5: Construction of a direct current motor: (a) exploded view, (b) detail of the system *collector + brushes.*

In this case, for a control $\vec{B}$ constant (permanent magnets), the torque produces *c (t)* East proportional to current *i (t)* circulating in this winding:

$$c(t) = K_{vs} \cdot i(t) \tag{2.2}$$

K_{vs} is called the machine torque constant.

When the rotor rotates relative to the stator at the speed $\omega(t)$, there is also a variation of the magnetic coupling flux $\lambda(t)$ in the rotor winding. This flux depends on the magnetic field generated by the permanent magnets of the stator and the angle between rotor and stator (which defines the projection coupling surface). According to Faraday's law, there will then be creation of an electromotive force (fem) *and)* induced at the terminals of this winding.

This is of the form $e(t) = -\frac{d\lambda(t)}{dt}$. This fem depends on the variation of the flux of coupling, therefore of the rotational speed on the ends. Thus, the induced emf is proportional at rotational speed $\omega(t) = \frac{d\theta(t)}{dt}$ of the motor :

$$e(t) = K_e \cdot \omega(t) \tag{2.3}$$

K_e is called the machine's emf constant.

2.2 Modeling of a DC motor (preparation)

In the previous section we showed that a DC motor is a converter of energy from the electrical form to the mechanical form. We showed than the torque of the rotor *c (t)* is created by the interaction between a stator magnetic field generated by a permanent magnet attached to the stator and a rotor magnetic field generated by the current *i (t)* circulating in the rotor winding (creation of a Laplace force). The rotor current is *switched* by a system *brushes + mechanical collector*

so that the rotor field remains fixed and perpendicular to the stator field and so that the torque does not depend on the position of the rotor. We have also shown that due to the rotation of the rotor coil at the speed $\omega (t)$ in front of the fixed stator field created by the permanent magnet, an fem *and)* is induced in the rotor winding. The equations of

this electromechanical coupling are: {

$$c (t) = K_{vs} \cdot i (t) \; e (t) = K_e \cdot \omega (t) \tag{2.4}$$

These two equations describe the behavior of *electromechanical transduction.* The sub system S_T ensuring the conversion of electrical energy $p_{e(}\, t) = e (t) \cdot i (t)$ into mechanical energy $p_{m(}\, t) = c (t) \cdot \omega (t) ($ and vice versa) is shown on the Fig. 2.6.

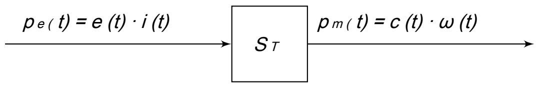


Figure 2.6: Representation of the transducer subsystem $S_{T.}$

The previous modeling allows us to obtain the energy loss during the electromechanical conversion:

$$\begin{aligned} p_{e(}\, t) - p_{m(}\, t) &= e (t) \cdot i (t) - c (t) \cdot \omega (t) \\ &= K_e \cdot \omega (t) \cdot i (t) - K_{vs} \cdot i (t) \cdot \omega (t) \\ &= (K_e - K_{vs)} \cdot i (t) \cdot \omega (t)) \end{aligned} \tag{2.5}$$

However, the subsystem S_T is generally regarded as a perfect energy conversion system and therefore as a purely conservative (lossless) system. Now, for
that this energy conversion is lossless, it is necessary that $p_{e(}\, t) - p_{m(}\, t) = 0$, which means
$K_{e} = K_{vs.}$ If the couple $c (t)$ is expressed in Nm, the current $i (t)$ in A, the fem *and)* in V and the
rotation speed $\omega (t)$ in rad.s $_{-1}$ the constants K_{vs} and K_e are therefore equal in order to respect the principle of conservation of energy during perfect transduction (without loss).

In order to also be able to model the mechanical and electrical losses as well as the stored magnetic and mechanical energies, the model of the direct current machine must also include conventional electrical and mechanical subsystems. The additional elements of the electromechanical network of the direct current machine are as follows:

- a resistance R to take into account the energy dissipated by e ff and Joule in the windings;
- an inductance L to take into account the electromagnetic phenomena of self-induction in the coils (stored magnetic energy);
- a coefficient of friction D to take into account the energy dissipated by viscous friction in the air and the motor bearings;

- inertia J to take into account the mechanical phenomena of accumulation of kinetic energy in the rotor.

In addition a power supply - voltage source *u (t)* - is connected on the electrical side and a mechanical load - source of resistive torque $vs_{r}(t)$ - is connected on the mechanical side.

Question 2.1 *Represent the lumped-parameter network used to model the dynamic behavior of a DC motor. Find the linear graph associated with this electromechanical system and deduce its rank and its nullity.*

Question 2.2 *Recall the constitutive laws of the di ff erent subsystems of this network as well as their causality. Deduce the dynamic order of this system and propose variables allowing to model its state.*

Question 2.3 *Depending on the constitutive laws and the causalities of the di ff erent subsystems, choose a tree and the associated co-tree. Deduce from the interconnection matrices*
Q *and* B *then the corresponding Kirchho laws ff.*

2.3 Identi fi cation of DC motor parameters

Some modeling parameters of this engine are given by the manufacturer (see attached documentation) but all the information is generally not available. This part proposes to identify them experimentally.

The INTECO model is controlled by an I / O card connected to the PCI bus of the PC. The latter is programmable and controllable by means of *Matlab Simulink*.
Converting and compiling the schema *Simulink* in a C program is performed using the *Real Time Workshop toolbox* by Matlab. The program is launched and controlled in real time on the PC processor by using the *Real Time toolbox*

Windows Target by Matlab.

Launch the Matlab software. Go to a directory (*directory)* that you will have created in the directory C: \ students \ Master_M2E2_1 \ MSM1 \ then launch the toolbox
(*toolbox)* Simulink (**>** simulink). Open the original fi le mcc.mdl_model_driver then
save it under a new name (cf. Fig. 2.7).
You can compile your fi le using the following menus:
→ Tools → Real-Time Workshop → Build Model
You can start your circuit program using the following menus:
→ Tools → External Mode Control Panel
You can see the components of the block Servo by carrying out the manipulation: Click right button → Look under Mask

Question 2.4 *Take the electrical equations of the direct current motor and indicate the equations that use the three electrical parameters R, L and* K_e*. Using these equations judiciously, propose an experimental protocol to determine these parameters independently of each other. Carry out the corresponding test to obtain the experimental value of each of these parameters. Compare the experimental values with the theoretical values provided by the manufacturer.*

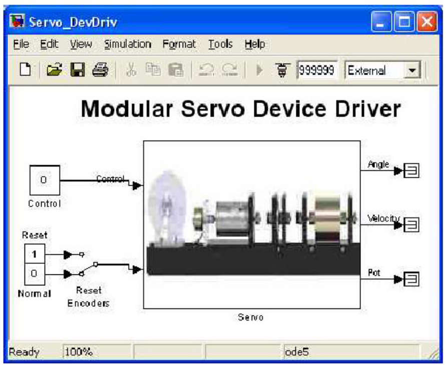


Figure 2.7: Screenshot of the original model command fi le.

Question 2.5 *Take the mechanical equations of the direct current motor and indicate the equations that use the three electrical parameters D, J and K vs. Using these equations judiciously, propose an experimental protocol to determine these parameters independently of each other. Carry out the corresponding test to obtain the experimental value of each of these parameters. Compare the experimental values with the theoretical values provided by the manufacturer.*

2.4 Modeling and identi fi cation of the electromechanical drive system

The mechanical transmission of the model will first be studied before coupling it to the direct current motor.

Question 2.6 *For each of the mechanical transmission subsystems, propose a constitutive law. Indicate each time, the type of subsystem (passive / active, conservative / dissipative, static / dynamic) and the associated causality.*

Question 2.7 *When possible, propose an identi fi cation method making it possible to experimentally determine the value of the parameters entering into these laws of behavior. Then perform the corresponding test on the model to identify these parameters.*

The DC motor is now mated to the entire mechanical transmission without using mechanical clearance (this hysteretic non-linear subsystem is not modelable by a standard state model or by a bijective input / output model.).

Question 2.8 *Find the linear graph associated with the complete electromechanical transmission system and deduce its rank and its nullity.*

Question 2.9 *Recall the constitutive laws of the di ff erent subsystems as well as their causality. Deduce the dynamic order of this system and propose variables allowing to model its state.*

Question 2.10 *Depending on the constitutive laws of the di ff erent subsystems, choose a tree and the associated co-tree respecting the causality of these components. Deduct in* *interconnection matrices* Q *and* B *then the corresponding Kirchho laws ff. Is there a problem with the causality of these subsystems? Why ? How to cure it ?*

2.5 Simulation of the dynamic behavior of the electromechanical model

At first, you will only consider the DC motor. The operation of the complete model will only be studied later if you have time.

Question 2.11 *By reduction of the behavioral and interconnection equations, propose a state model of this electromechanical system. Two inputs will be used, the voltage*
motor power u (t) (control input) and the resistive torque - load - vs $_{r\,(}$ *t)*
(disturbance input). Exit speed $\omega_{s\,(}$ *t) will be chosen as the output of this model.*

Question 2.12 *Propose a method or a computer program making it possible to solve these equations of state and therefore to simulate the dynamic behavior of this model. You can use one of the following software: matlab, simulink, scilab.*

Question 2.13 *Using the model obtained, simulate various dynamic behaviors and experimentally verify the concordance between the theoretical results (simulations) and practical results (experimental).*