

**Twin Rotor MIMO System  
Control Experiments  
33-949S**

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# Twin Rotor MIMO System Control Experiments

**33-949S**

(For use with MATLAB  
R2006b version 7.3)

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## Manual overview

The following manual refers to the Feedback Instruments Twin Rotor MIMO System Control application. It serves as a guide for the control tasks and provides useful information about the physical behaviour of the system. A nonlinear model is proposed and then later on identification algorithms are introduced. The models obtained are compared with the phenomenological model and the Twin Rotor MIMO System setup. Control algorithms are developed, tested on the Twin Rotor MIMO System (TRMS) models and then implemented in a real time application.

Throughout the manual various exercises are used to bring the user closer to the TRMS control problem. Depending on the knowledge level of the user some of the sections and exercises can be skipped. The more advanced users can try to model, identify and control the TRMS on their own from the beginning.

The relative difficulty of each exercise is indicated using the following icons:



easy level,



medium level,



expert level.

If any of the identification or controller design exercises appear to be too difficult or the results are not satisfactory you may go straight to the examples that are supplied and test them by changing the parameters of the controllers.



## Introduction

The TRMS workshop serves as a model of a helicopter. However some significant simplifications are made. First is the fact that TRMS is attached to a tower and second of great importance that the helicopter position and velocity is controlled through the rotor velocity variation. In the real helicopter the rotor velocity is more less constant and the propulsion is varied through the rotor blades angle modification.

Nevertheless the most important dynamic characteristics present in a helicopter are captured in the TRMS model. Like in a real helicopter there is a significant cross coupling between two rotors. If we activate the vertical position rotor the helicopter will also turn in the horizontal plane.

With two inputs (the voltages supplied to the rotors) and outputs (vertical and horizontal angles and angular velocities) the TRMS is an excellent MIMO plant for laboratory exercises.

## TRMS set description

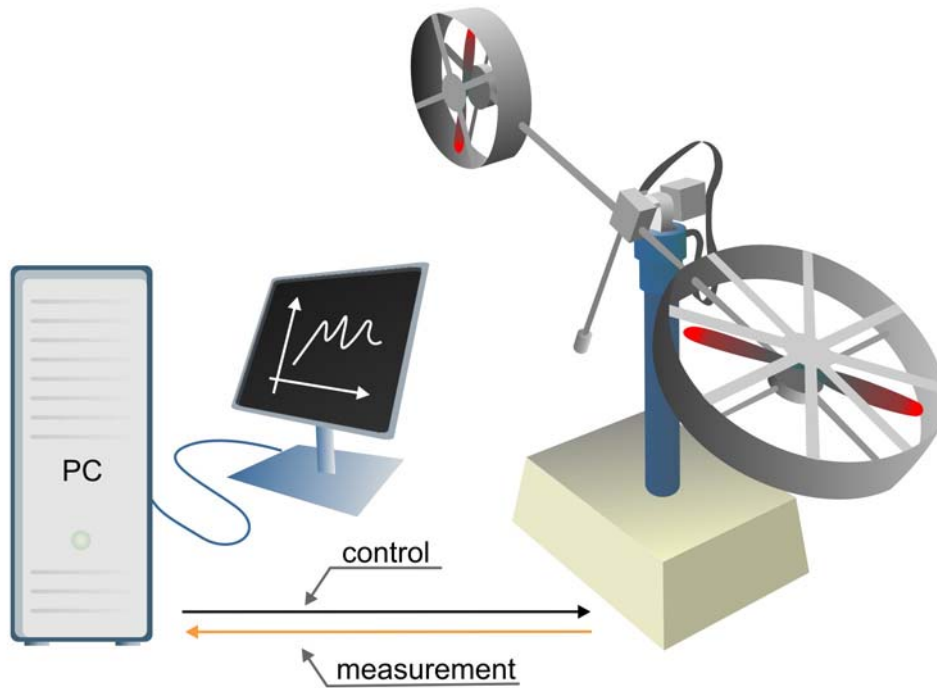
The description of the TRMS setup in this section refers to the mechanical part and the control aspect. For details on the mechanical and electrical connection, the interface and an explanation of how the signals are measured and transferred to the PC, refer to the '*Installation & Commissioning*' manual.

As shown in Figure 1, the TRMS mechanical unit consists of two rotors placed on a beam together with a counterbalance. The whole unit is attached to the tower allowing for safe helicopter control experiments.



**Figure 1 TRMS mechanical unit**

Apart from the mechanical units, the electrical unit (placed under the tower) plays an important role for TRMS control. It allows for measured signals transfer to the PC and control signal application via an I/O card. The mechanical and electrical units provide a complete control system setup presented in Figure 2.

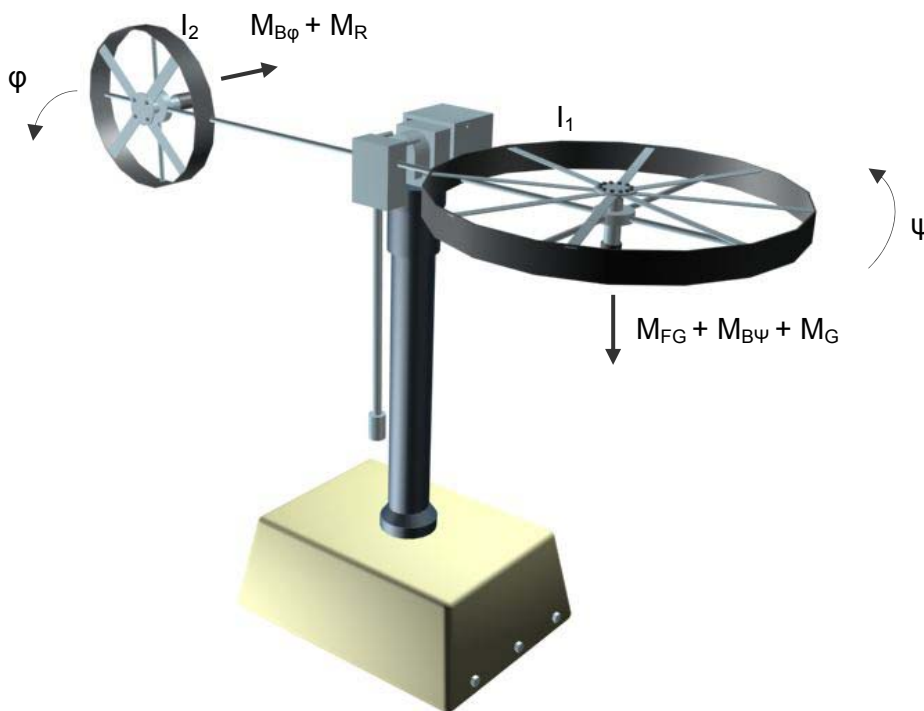


**Figure 2 TRMS control system**

In order to design any control algorithms one must first understand the physical background behind the process and carry out identification experiments. The next section explains the modelling process of the TRMS.

## TRMS model

Every control project starts with plant modelling, so as much information as possible is given about the process itself. The mechanical-electrical model of the TRMS is presented in Figure 3.



**Figure 3 TRMS phenomenological model**

Usually, phenomenological models are nonlinear, that means at least one of the states ( $i$  – rotor current,  $\theta$  – position) is an argument of a nonlinear function. In order to present such a model as a transfer function (a form of linear plant dynamics representation used in control engineering), it has to be linearised.

According to the electrical-mechanical diagram presented in Figure 3 the non-linear model equations can be derived.

As far as the mechanical unit is concerned the following momentum equations can be derived for the vertical movement:

$$I_1 \cdot \ddot{\psi} = M_1 - M_{FG} - M_{B\psi} - M_G, \quad (1)$$

where

$$M_1 = a_1 \cdot \tau_1^2 + b_1 \cdot \tau_1, \quad - \text{nonlinear static characteristic} \quad (2)$$

$$M_{FG} = M_g \cdot \sin \psi, \quad - \text{gravity momentum} \quad (3)$$

$$M_{B\psi} = B_{1\psi} \cdot \dot{\psi} + B_{2\psi} \cdot \text{sign}(\dot{\psi}), \quad - \text{friction forces momentum} \quad (4)$$

$$M_G = K_{gy} \cdot M_1 \cdot \dot{\phi} \cdot \cos \psi. \quad - \text{gyroscopic momentum} \quad (5)$$

The motor and the electrical control circuit is approximated by a first order transfer function thus in Laplace domain the motor momentum is described by:

$$\tau_1 = \frac{k_1}{T_{11}s + T_{10}} \cdot u_1. \quad (6)$$

Similar equations refer to the horizontal plane motion:

$$I_2 \cdot \ddot{\phi} = M_2 - M_{B\phi} - M_R \quad (7)$$

where

$$M_2 = a_2 \cdot \tau_2^2 + b_2 \cdot \tau_2, \quad - \text{nonlinear static characteristic} \quad (8)$$

$$M_{B\phi} = B_{1\phi} \cdot \dot{\phi} + B_{2\phi} \cdot \text{sign}(\dot{\phi}), \quad - \text{friction forces momentum} \quad (9)$$

$M_R$  is the cross reaction momentum approximated by:

$$M_R = \frac{k_c(T_o s + 1)}{(T_p s + 1)} \cdot \tau_1. \quad (10)$$

Again the DC motor with the electrical circuit is given by:

$$\tau_2 = \frac{k_2}{T_{21}s + T_{20}} \cdot u_2. \quad (11)$$

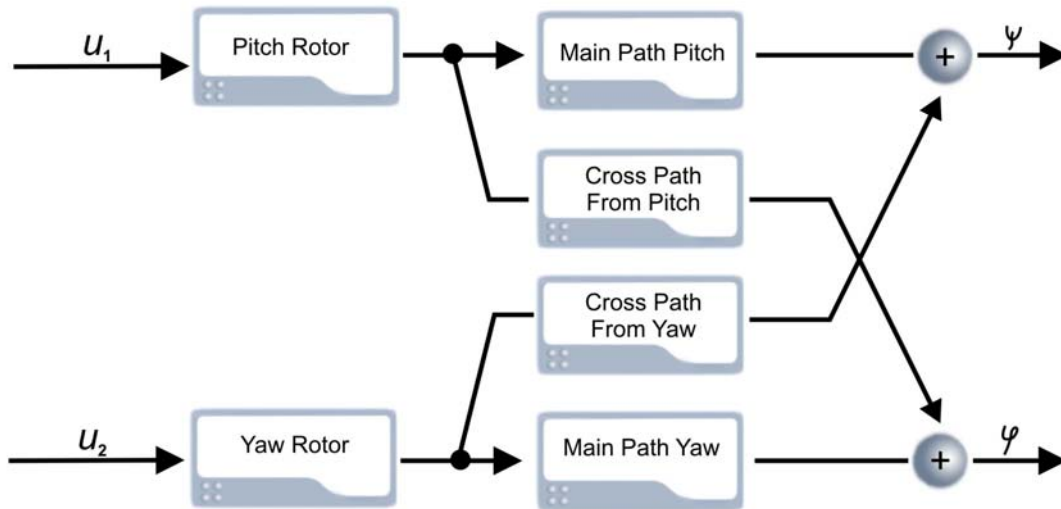
The phenomenological model parameters have been chosen more or less experimentally, which actually makes the TRMS nonlinear model a semi-phenomenological model. The following table gives their approximate values.

**Table 1. TRMS model parameters**

Parameter	Value
$I_1$ - moment of inertia of vertical rotor	$6.8 \cdot 10^{-2} \text{ kg} \cdot \text{m}^2$
$I_2$ - moment of inertia of horizontal rotor	$2 \cdot 10^{-2} \text{ kg} \cdot \text{m}^2$
$a_1$ - static characteristic parameter	0.0135
$b_1$ - static characteristic parameter	0.0924
$a_2$ - static characteristic parameter	0.02
$b_2$ - static characteristic parameter	0.09
$M_g$ - gravity momentum	0.32 N·m
$B_{1\psi}$ - friction momentum function parameter	$6 \cdot 10^{-3} \text{ N} \cdot \text{m} \cdot \text{s} / \text{rad}$
$B_{2\psi}$ - friction momentum function parameter	$1 \cdot 10^{-3} \text{ N} \cdot \text{m} \cdot \text{s}^2 / \text{rad}$
$B_{1\phi}$ - friction momentum function parameter	$1 \cdot 10^{-1} \text{ N} \cdot \text{m} \cdot \text{s} / \text{rad}$
$B_{2\phi}$ - friction momentum function parameter	$1 \cdot 10^{-2} \text{ N} \cdot \text{m} \cdot \text{s}^2 / \text{rad}$
$K_{gy}$ - gyroscopic momentum parameter	0.05 s/rad
$k_1$ - motor 1 gain	1.1
$k_2$ - motor 2 gain	0.8
$T_{11}$ - motor 1 denominator parameter	1.1
$T_{10}$ - motor 1 denominator parameter	1
$T_{21}$ - motor 2 denominator parameter	1
$T_{20}$ - motor 2 denominator parameter	1
$T_p$ - cross reaction momentum parameter	2
$T_0$ - cross reaction momentum parameter	3.5
$k_c$ - cross reaction momentum gain	-0.2

The bound for the control signal is set to [-2.5V .. +2.5V].

The TRMS is a MIMO plant – multiple input multiple output. Figure 4 presents a simplified schematic of the TRMS.



**Figure 4 TRMS simplified system schematic**

The TRMS is controlled with two inputs the  $u_1$  and  $u_2$ . The dynamics cross couplings are one of the key features of the TRMS (Figure 4). The position of the beams is measured with the means of incremental encoders, which provide a relative position signal. Thus every time the Real-Time TRMS simulation is run one must remember that setting proper initial conditions is important.

**Exercise 1 – Model testing**



**Introduction**

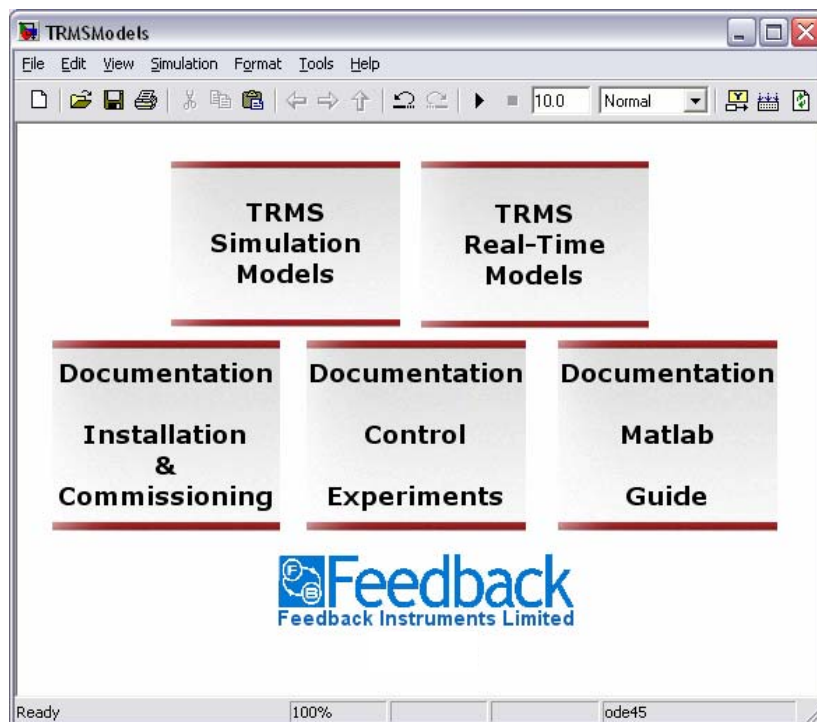
For the initial exercise the user has been provided with the TRMS nonlinear model described by equations (1)-(11).

Load Matlab and the menu system using the Windows Start menu (Figure 5).



**Figure 5 Start menu**

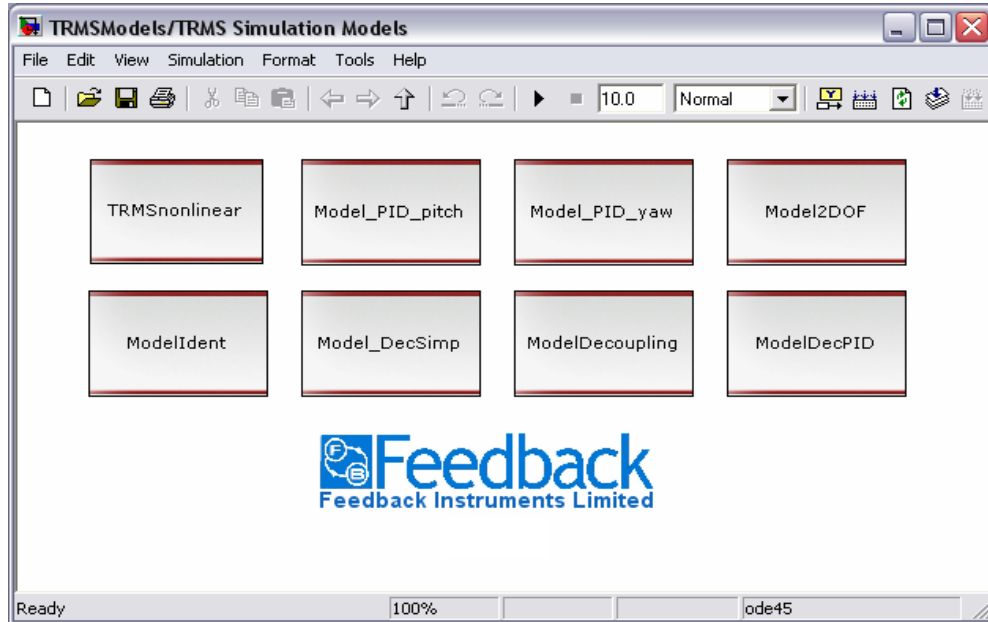
Matlab will run and the Simulink model menu will open (Figure 6). This contains links to the simulation-only models (TRMS Simulation Models), the real-time models (TRMS Real-Time Models) and the manual documents.



**Figure 6 Simulink model menu**

Double click on the 'TRMS Simulation Models' block in the main menu. A sub-menu containing all of the simulation-only models will open (Figure 7).





**Figure 7 Simulation models menu**

Double click the required model *TRMSnonlinear.mdl*. The Simulink model window will open.

**If necessary refer to the ‘Matlab Guide’ manual for Simulink model starting guide.**

### **Task**

To begin with the user is advised to check the responses of the TRMS nonlinear model alone (*TRMSnonlinear.mdl*) with zero, constant and sinusoidal voltages applied to both of the rotors ( $u_1, u_2$ ). You may change the values of the parameters to see how the response varies. Change the initial angle value for both of the rotors to see how that influences the response.

### **Example results and comments**

Figure 8 presents model response to step changes (from 1 to 0) of control voltages.

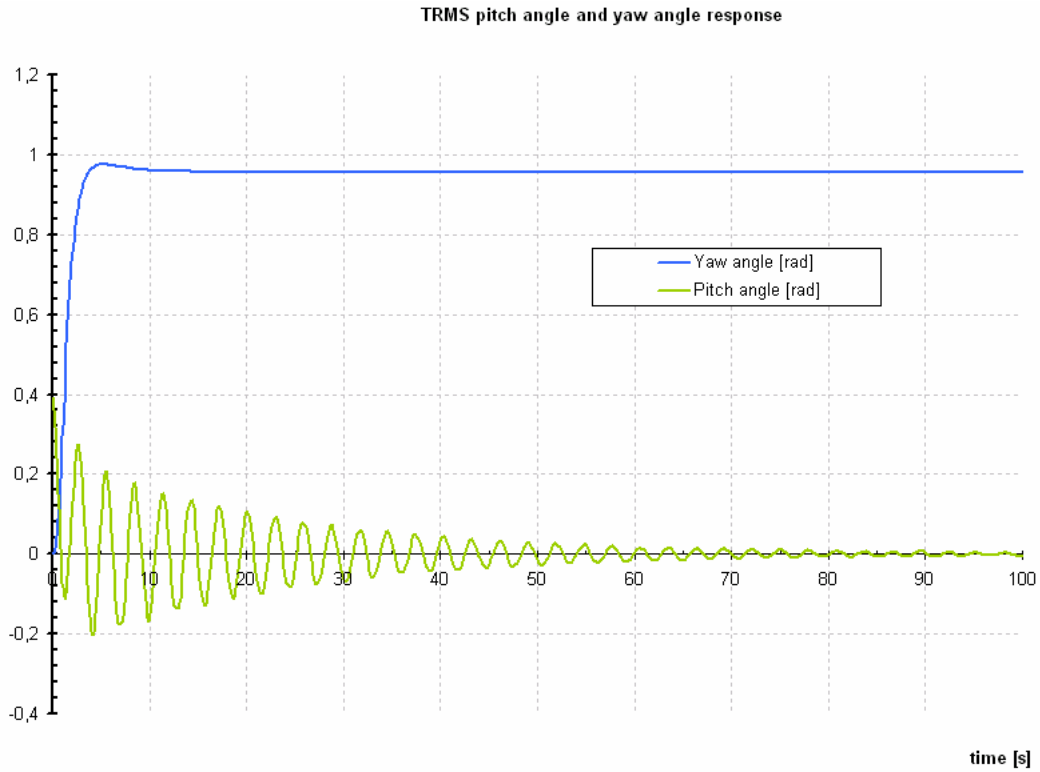


Figure 8 TRMS model response

## TRMS model identification

As mentioned in the previous section the MIMO is a nonlinear plant with significant cross couplings between the rotors (Figure 4). To keep the identification simple the model can be treated as two linear rotor models with two linear couplings in-between. Thus 4 linear models have to be identified: two for the main dynamics path from  $u_1$  to  $\psi$  and  $u_2$  to  $\phi$  and cross coupling dynamics paths from  $u_1$  to  $\phi$  and  $u_2$  to  $\psi$ . These models will be used for controller design and tests in the “TRMS Control” section.

There are a few important things that the control system designer has to keep in mind when carrying out an identification experiment:

- *Stability problem* – if the plant that is identified is unstable the identification has to be carried out with a working controller, which introduces additional problems that will be discussed later on. If the plant is stable and does not have to work with a controller the identification is much simpler.
- *Structure choice* – a very important aspect of the identification. For linear models it comes down to choice of the numerator and denominator order of the transfer function. It applies both for continuous and discrete systems.  
As far as the discrete models are concerned the structures are also divided in terms of the error term description: ARX, ARMAX, OE, BJ<sup>1</sup>.
- *Sampling time* – the sampling time choice is important both for identification and control. It cannot be too short nor can it be too long. Too short sampling time might influence the identification quality because of the quantization effect introduced by the AD. Furthermore the shorter the sampling time the faster the software and hardware has to be and more memory is needed. However short sampling time will allow for elimination of aliasing effects and thus anti aliasing filters<sup>2</sup> will not have to be introduced. Long sampling times will not allow for including all of the dynamics.
- *Excitation signal* – for the linear models the excitation choice is simple. Very often designers use white noise. In industrial applications it is often disallowed. White noise is attractive because of the fact that it holds very broad frequency content thus the whole dynamics of the plant can

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<sup>1</sup> More information about these structures can be obtained during System Identification courses.

<sup>2</sup> These are the basics of the Digital Signal Processing course. For more insight the user is asked to study more on signal processing and digital control.

be identified. If the dynamics are not too complex several sinusoids with different frequencies can be summed to produce a satisfactory excitation signal.

- *Identification method* – usually two methods are used, the Least Mean Square (LMS) method and the Instrumental Variable method. The LMS method is the most popular and is implemented in Matlab. This method minimizes the error between the model and the plant output. The optimal model parameters, for which the square of the error is minimal is the result of the identification.

## Main path pitch rotor identification

The following exercise uses all the information presented in previous section and provides an identification experiment, which results in a discrete model of the main path pitch rotor. The first model to be identified describes the relation between the control voltage  $u_1$  and the angle  $\psi$ .

### Exercise 2 – Main path pitch rotor identification



#### Introduction

All the real time simulations are carried out using a sampling time of  $T_s = 0.001$  [s]. However because discrete models are identified and plant dynamic response is relatively slow, the identification is carried out with the sampling time of  $T_s = 0.1$  [s]. For the identification the Matlab System Identification Toolbox is used.

The identification experiment is carried out using the model called *MainPitch\_Ident.mdl*. This model excites the TRMS and records its response. The excitation signal is composed of several sinusoids. Two signals are collected in the form of vectors and are available in the Workspace.

#### Task

Carry out the identification experiment and collect the data. Identify a discrete model using the Matlab identification interface. Specify the model structure to be for example oe241.

**Refer to the ‘Matlab Guide’ manual for description of how to use the system identification toolbox.**

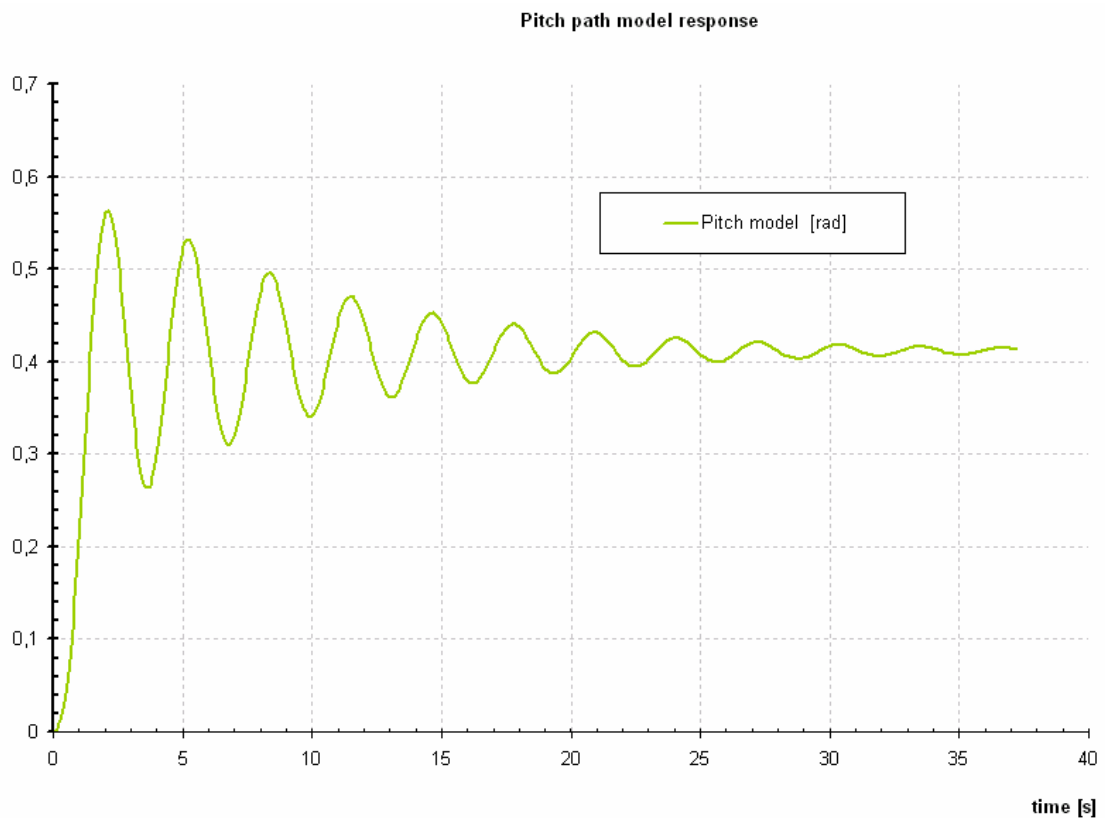
**TRMS IDENTIFICATION**

You can check the quality of the response of the identified model by the step response analysis, transient response, pole and zeros map, frequency response and model residuals.

**Example results and comments**

The step response of the identified system can be similar to the one presented in Figure 9. You can also transform the discrete models into their continuous equivalent with the means of 'd2c' command. The continuous model obtained is used in the first PID control exercise.

**Refer to the 'Matlab Guide' manual for description of how to use the system identification toolbox.**



**Figure 9 Step response of the pitch path model**

## Main path yaw rotor identification

### Exercise 3 – Main path yaw rotor identification



#### Introduction

This identification experiment is carried out using the model called *MainYaw\_Ident.mdl*. This model excites the TRMS and records its response. The excitation signal is composed of several sinusoids. Two signals are collected in the form of vectors and are available in the Workspace.

#### Task

Carry out the identification experiment and collect the data. Identify a discrete model using the Matlab identification interface. Specify the model structure to be `oe231`.

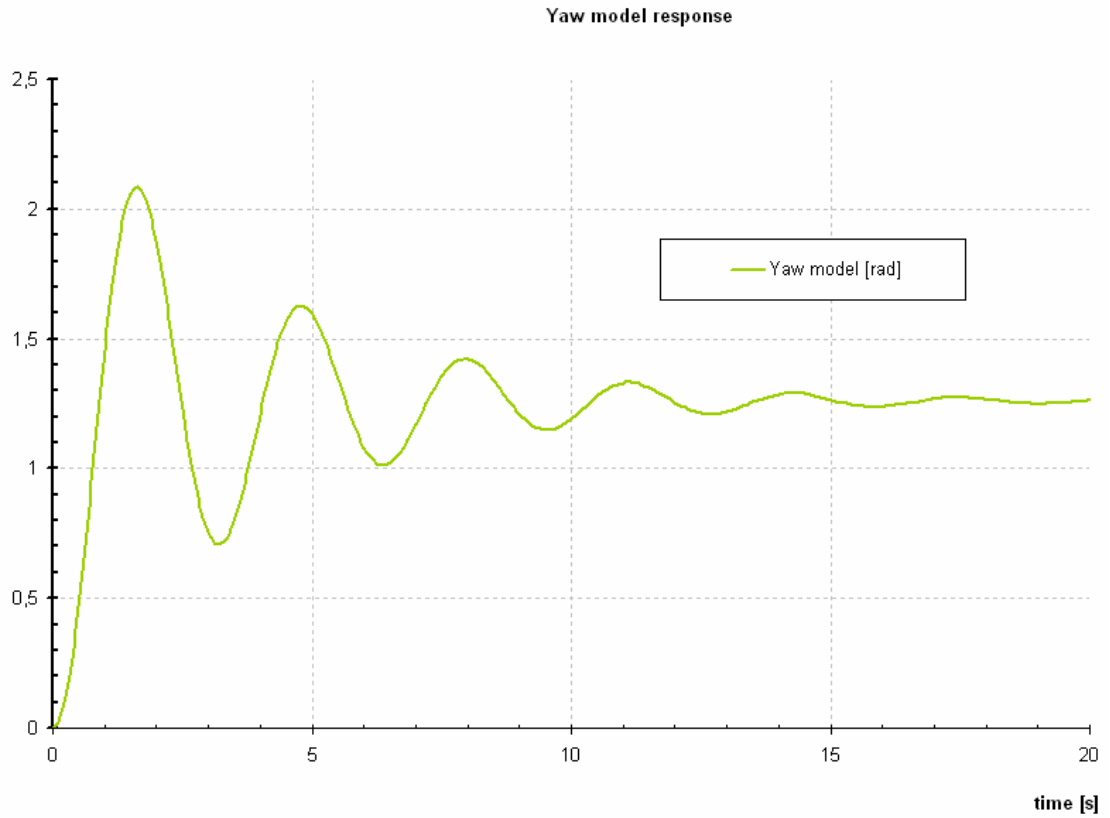
**Refer to the ‘*Matlab Guide*’ manual for description of how to use the system identification toolbox.**

You can check the quality of the response of the identified model by the step response analysis, transient response, pole and zeros map, frequency response and model residuals. Select any of the model views to view the results, for example the transient response.

#### Example results and comments

The step response of the identified system can be similar to the one presented in Figure 10. You can also transform the discrete models into their continuous equivalent with the means of ‘`d2c`’ command. The continuous model obtained is used in the PID control exercise.

**Refer to the ‘*Matlab Guide*’ manual for description of how to use the system identification toolbox.**



**Figure 10 Step response of the yaw path model**

## Cross path from pitch rotor identification

### Exercise 4 – Cross path from pitch rotor identification



#### Introduction

The identification experiment is carried out using the model called *CrossPitch\_Ident.mdl*. This model excites the TRMS with  $u_1$  and records its response  $\varphi$  – yaw angle. The excitation signal is composed of several sinusoids. Two signals are collected in the form of vectors and are available in Workspace.

#### Task

Carry out the identification experiment and collect the data. Identify a discrete model using the Matlab identification interface. Specify the model structure to be `oe121`.

**Refer to the ‘Matlab Guide’ manual for description of how to use the system identification toolbox.**

You can check the quality of the response of the identified model by the step response analysis, transient response, pole and zeros map, frequency response and model residuals. Select any of the model views to view the results, for example the transient response.

#### Example results and comments

The step response of the identified system can be similar to the one presented in Figure 11. You can also transform the discrete models into their continuous equivalent with the means of ‘*d2c*’ command. The continuous model obtained is used in the PID control exercise.



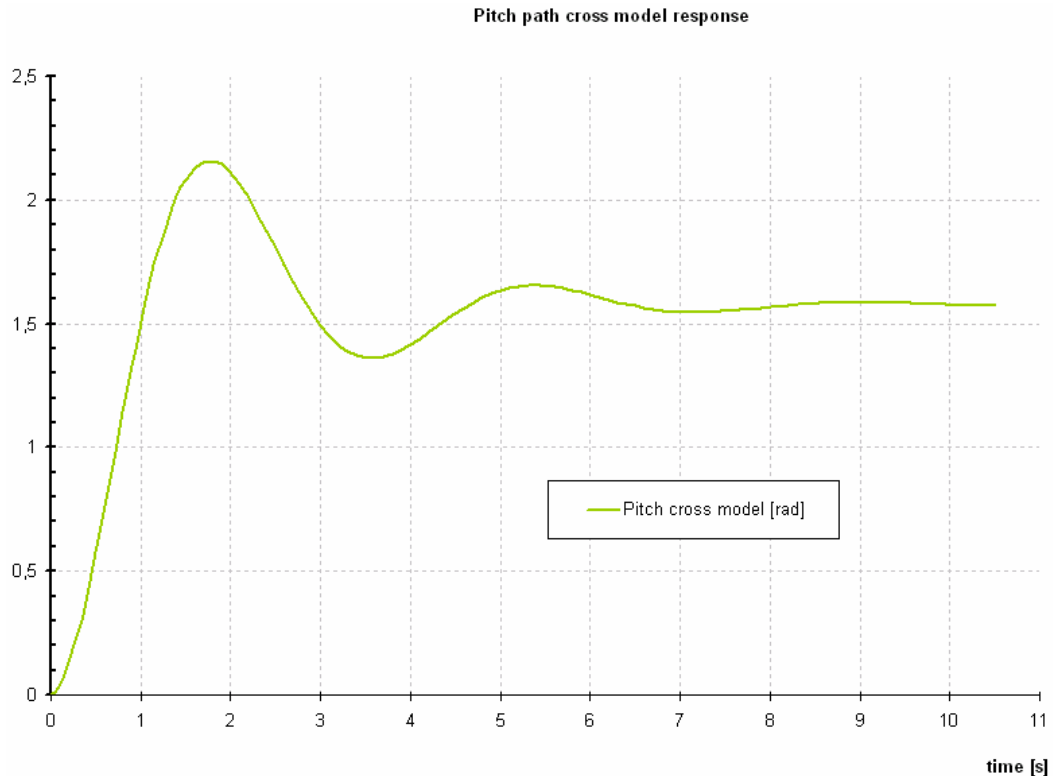


Figure 11 Step response of the pitch cross path model

## Cross path from yaw rotor identification

### Exercise 5 – Cross path from yaw rotor identification



#### Introduction

The identification experiment is carried out using the model called *CrossYaw\_Ident.mdl*. This model excites the TRMS with  $u_2$  and records its response  $\psi$  – *pitch angle*. The excitation signal is composed of several sinusoids. Two signals are collected in the form of vectors and are available in Workspace.

#### Task

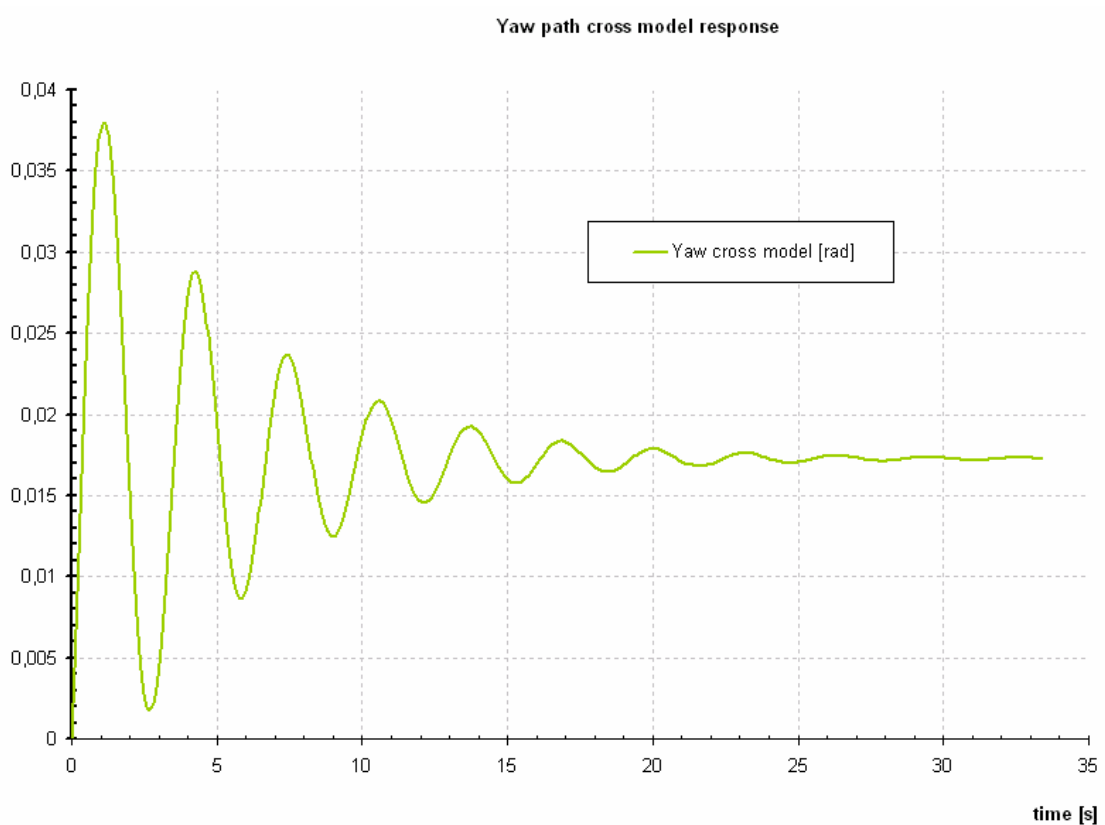
Carry out the identification experiment and collect the data. Identify a discrete model using the Matlab identification interface. Specify the model structure to be `oe221`.

**Refer to the ‘Matlab Guide’ manual for description of how to use the system identification toolbox.**

You can check the quality of the response of the identified model by the step response analysis, transient response, pole and zeros map, frequency response and model residuals. Select any of the model views to view the results, for example the transient response.

**Example results and comments**

The step response of the identified system can be similar to the one presented in Figure 12. You can also transform the discrete models into their continuous equivalent with the means of 'd2c' command. The continuous model obtained is used in the PID control exercise.



**Figure 12 Step response of the yaw cross path model**

## TRMS setup control

The TRMS control aspect covers three main control areas:

- 1 Degree of freedom (DOF) rotor control,
- 2 DOF rotor control,
- Dynamics decoupling,
- Control with decoupled dynamics.

Each of these control problems has its characteristic. Two 1 DOF control systems ignore the dynamics cross coupling and control the rotors separately. 2 DOF system ignores the couplings but controls both of the rotors. Control with dynamics decoupling constitutes the best control system in terms of performance.

Matlab provides various analysis methods for linear systems as far as dynamics are concerned (root locus, frequency analysis tools – Bode diagrams, Nyquist plots, pole and zero maps etc.). With the information, which Matlab provides about the dynamics of the system, controllers can be designed. The following sections explain how the PID controller works, and how it can be tuned.

### Plant control

There are numerous control algorithms. The PID control algorithm is popular because of its simplicity. A general schematic of a simple control closed loop system is presented in Figure 13.

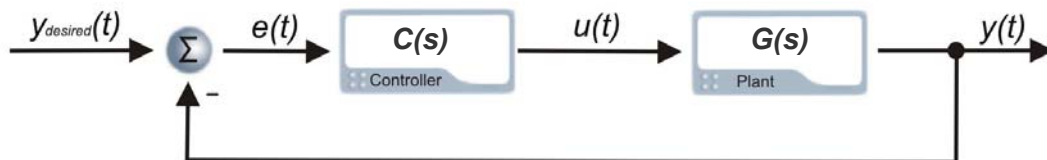


Figure 13 Simple control system – closed loop

Assuming that the plant is represented by its linear model its transfer function can be described as:

$$G(s) = \frac{B(s)}{A(s)} \quad (12)$$

where  $s$  is the Laplace operator.

The idea of control algorithms is to find a controller (transfer function, discrete transfer function, any nonlinear), which will fulfil our requirements (certain dynamic response, certain frequency damping, good response to the dynamic changes of the desired value etc. ). Every controller's input is the  $e(t)$  error signal. Sometimes disturbance signals are also measured. Depending on the present and past values of the error signal, the controller performs such an action (changes the  $u(t)$  control signal) that the  $y(t)$  is as close to the  $y_{desired}(t)$  value as possible at all times.

There are many controller design and tuning methods. All of them consider the behaviour of a 'closed loop system' (plant with a controller Figure 13) and provide controller parameters according to the assumed system characteristics. With the known plant transfer function  $G(s)$  it is possible to find satisfactory parameters of the  $C(s)$  controller such that the closed loop system will have the desired characteristics described by the transfer function  $T_c(s)$ :

$$T_c(s) = \frac{C(s) \cdot G(s)}{1 + C(s) \cdot G(s)} \quad (13)$$

## PID controller

PID controller consists of 3 blocks: **P**roportional, **I**ntegral and **D**erivative. The equation governing the PID controller is as follows:

$$u(t) = P \cdot e(t) + I \cdot \int e(t)dt + D \cdot \frac{de(t)}{dt} \quad (14)$$

$$e(t) = y_{desired}(t) - y(t) \quad (15)$$

With the means of the Laplace transform such a structure can be represented as a transfer function:

$$U(s) = \left( P + \frac{I}{s} + D \cdot s \right) \cdot E(s) \quad (16)$$

$$C(s) = \frac{U(s)}{E(s)} = \left( P + \frac{I}{s} + D \cdot s \right) = \frac{Ds^2 + Ps + I}{s} \quad (17)$$

Each of the PID controller blocks ( $P, I$  and  $D$ ) plays an important role. However for some applications Integral or Derivative part has to be excluded to give satisfactory results. The **P**roportional block is mostly responsible for the speed of the system reaction. In some plants the oscillations may occur if the value of  $P$  is set to be too large.

The Integral part is very important and assures 0 error value in steady state, which means that the output will be exactly what we want it to be. Nevertheless the Integral action of the controller causes the system to respond slower to the desired value changes and for systems where very fast reaction is very important the integral action may have to be omitted. Certain nonlinearities will also cause problems for the integration action.

The Derivative part has been introduced to make the response faster. However it is very sensitive to noise amplitude increase and may cause the system to react very nervously. Thus very often it is omitted in the controller design. Derivative part output filtering may reduce the nervous reaction but also slows the response of the controller down and sometimes undermines the sense of using the Derivative part at all. Proper filtering can help to reduce the high frequency noise without degrading the control system performance in the lower frequency band.

There are several PID tuning techniques. Most often Ziegler-Nichols rules are used or a relay experiment is undertaken. Very often the closed loop system roots are analysed and set in the desired position with the means of  $P$ ,  $I$  and  $D$  parts proper choice. Matlab delivers a root locus tool, which helps in such design. To get the feeling of root locus controller design and its effects on the system motor velocity control exercise is proposed.

## TRMS 1 DOF pitch rotor control

As a first control task TRMS 1 DOF pitch rotor control is chosen. The following exercises will guide you through controller design and testing on the model and in real time application.

### Exercise 6 – 1 DOF pitch rotor control



#### Introduction

To design a PID controller a model of the plant is needed. For this purpose we can use a linearised plant model or use a model obtained in the identification experiment and design a PID controller based on that model.

#### Task

Design a PID controller for the model obtained in the identification experiment ('Main path pitch rotor identification' section). Make sure you transform the discrete model into continuous form. Use the root locus tool to select proper PID parameters values.

**Refer to the 'Matlab Guide' manual for PID design guide.**

### Example results and comments

The root locus of the identified model with the PID control with  $P = 5$ ,  $I = 8$ ,  $D = 10$  is presented in Figure 14.

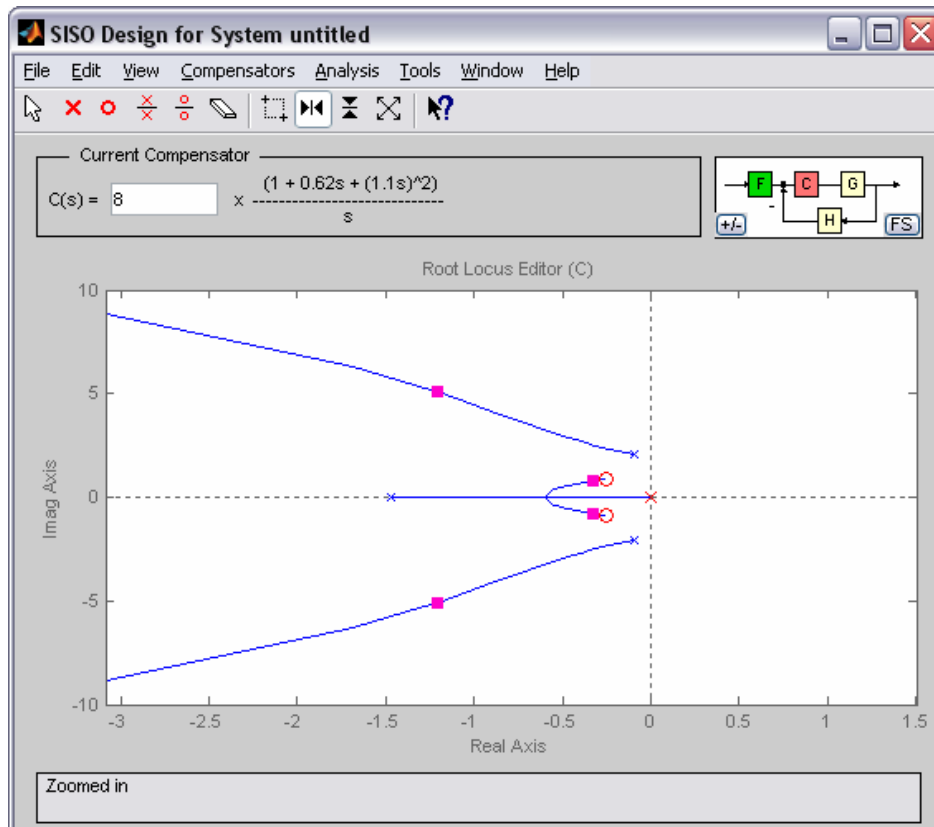


Figure 14 Root locus with PID controller

You can test the controller on the nonlinear model with *Model\_PID\_pitch.mdl* or on the model that you have identified.

Use a sinusoidal signal for the set value of the pitch position  $\psi_{desired}(t)$ . Change the frequency and see how the output will follow the desired value. Decrease and increase the values of the proportional, integral and derivative gains in the PID controller. See how that influences the tracking of the desired value. You should observe that  $I$  part – assures 0 steady state error but slows the system reaction,  $D$  part makes the system faster but causes the controller to behave nervously – observe the controller output.

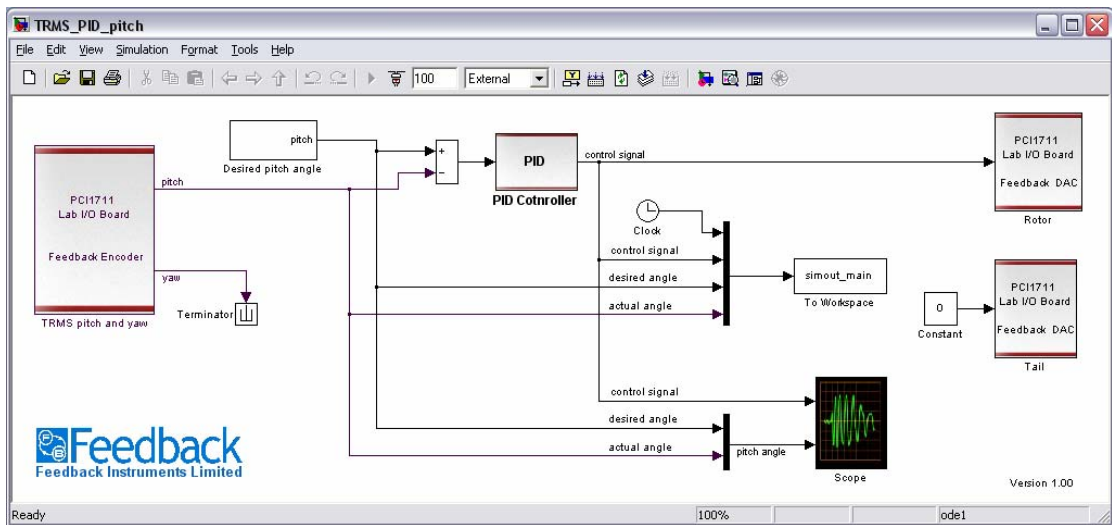
The controller that has been obtained in the above exercise can be tested on the TRMS setup. The following exercise will guide you through it.

**Exercise 7 – Real time 1 DOF pitch rotor control**



**Introduction**

Just as in exercise 6 the pitch rotor position will be controlled. This time it will be tested in real time. For this exercise use the *TRMS\_PID\_pitch.mdl* presented in Figure 15.



**Figure 15 Real time TRMS pitch position control**

As you open the *TRMS\_PID\_pitch.mdl* you will notice that this simulation is directed to an external module, which is indicated in the upper part of the simulation window. The PID controller has been already designed, however you can change its parameters according to the results obtained in exercise 6.

Before you run the real time simulation make sure the TRMS setup is properly connected and that the Power Source is turned off. Refer to the '*Installation & Commissioning*' manual for more instructions on real time simulations.

**Task**

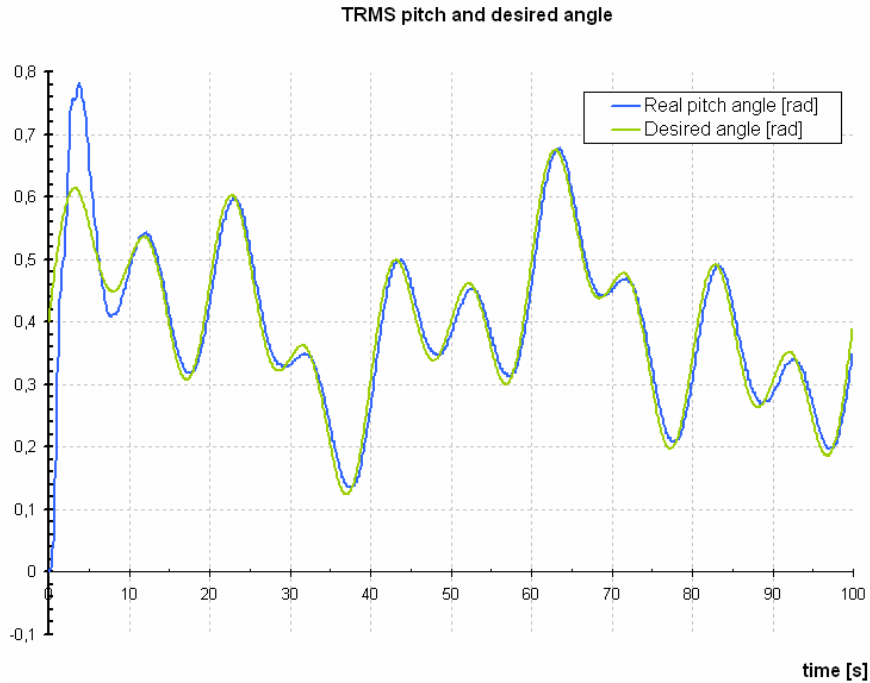
The task is to change the sinusoidal  $\psi_{desired}(t)$  signal frequency and see how the cart reacts to it. Change the controller *P*, *I* and *D* values to see how the signal  $\psi_{desired}(t)$  is tracked by the system output.

Make sure the changes of the *P*, *I* and *D* gains will not have a destructive effect on the TRMS. You should already gain some experience in exercise 6 on how the values of these gains can be changed.

**Example results and comments**

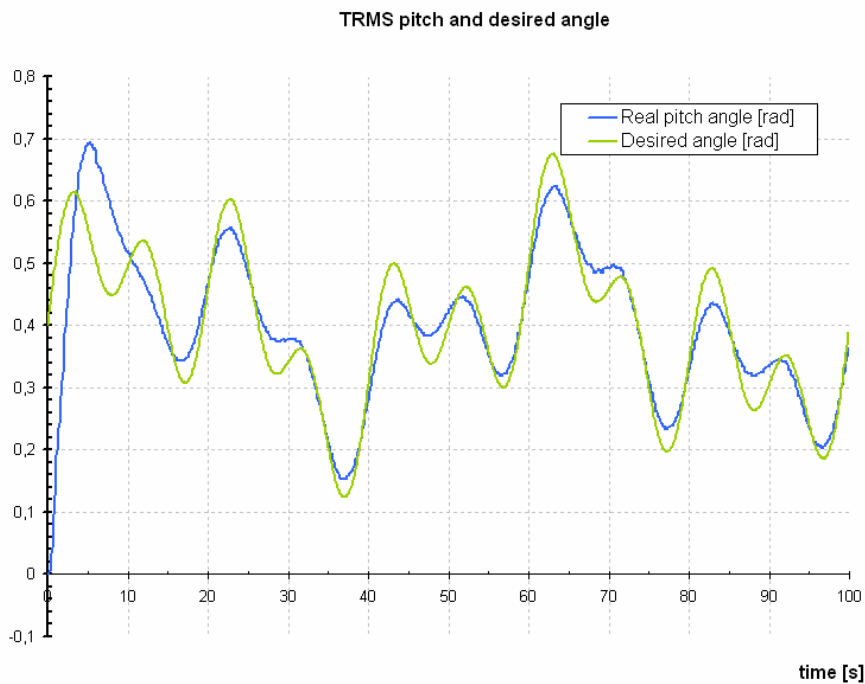
Figure 16 and Figure 17 present real time simulation results of the pitch position PID control. Two  $I$  and  $D$  gain values have been selected. The simulation proves that the  $I$  value increase may slow the system down and cause bigger overshoot. You should also be able to notice that the bigger the  $D$  value the faster the response but the more nervous the control signal  $u_1$ . Very energetic control signal changes can often lead to control unit brake down.





**Figure 16 PID control with  $P = 5, I = 8, D = 10$**

The result presented in Figure 16 proves how efficient controllers can be when identification experiment is incorporated in their design. Figure 17 shows how wrong controller tuning may degrade the system performance.



**Figure 17 Real time control simulation results, with  $P = 3, I = 4, D = 15$**

## TRMS 1 DOF yaw rotor control

Similar to pitch control a 1 DOF yaw rotor control system is created.

### Exercise 8 – 1 DOF yaw rotor control



#### Introduction

To design a PID controller a model of the plant is needed. For this purpose we can use a linearised plant model or use a model obtained in the identification experiment and design a PID controller based on that model.

#### Task

Design a PID controller for the model obtained in the identification experiment ('Main path yaw rotor identification' section). Make sure you transform the discrete model into continuous form. Use the root locus tool to select proper PID parameters values.

Refer to the '*Matlab Guide*' manual for PID design guide.

#### Example results and comments

The root locus of the identified model with the PID control with  $P = 2$ ,  $I = 0.5$ ,  $D = 5$  is presented in Figure 18.

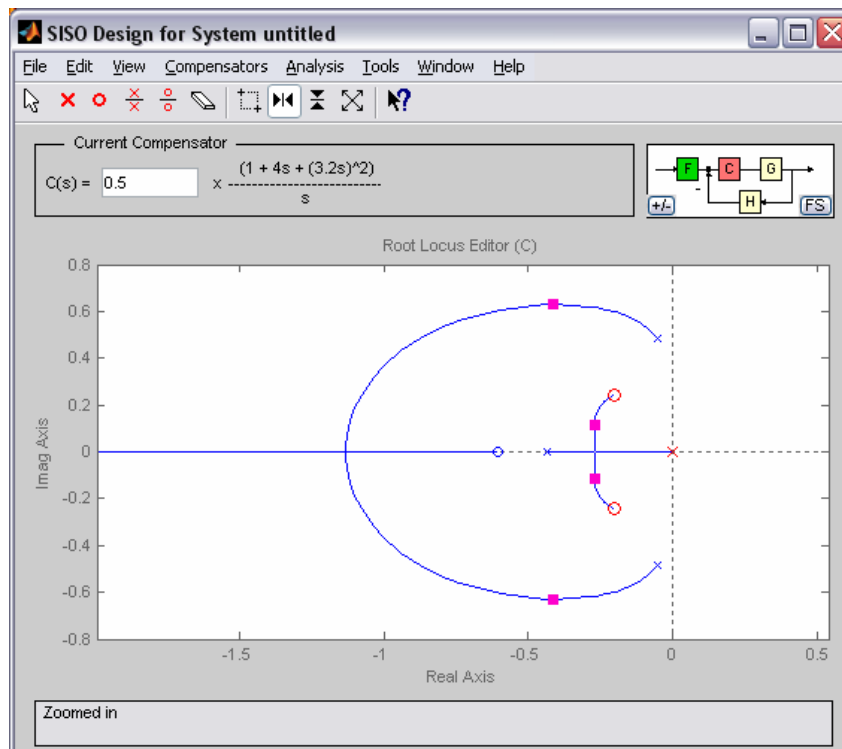


Figure 18 Root locus with PID controller

You can test the controller on the nonlinear model with *Model\_PID\_yaw.mdl* or on the model that you have identified.

Use a sinusoidal signal for the set value of the yaw position  $\varphi_{desired}(t)$ . Change the frequency and see how the output will follow the desired value. Decrease and increase the values of the proportional, integral and derivative gains in the PID controller. See how that influences the tracking of the desired value. You should observe that *I* part – assures 0 steady state error but slows the system reaction, *D* part makes the system faster but causes the controller to behave nervously – observe the controller output.

The controller that has been obtained in the above exercise can be tested on the TRMS setup. The following exercise will guide you through it.

### Exercise 9 – Real time 1 DOF yaw rotor control



#### Introduction

Just as in exercise 8 the yaw rotor position will be controlled. This time it will be controlled in real time. For this exercise use the *TRMS\_PID\_yaw.mdl*. The PID controller has been already designed, however you can change its parameters according to the results obtained in exercise 8.

Before you run the real time simulation make sure the TRMS setup is properly connected and that the Power Source is turned off. Refer to the '*Installation & Commissioning*' manual for more instructions on real time simulations.

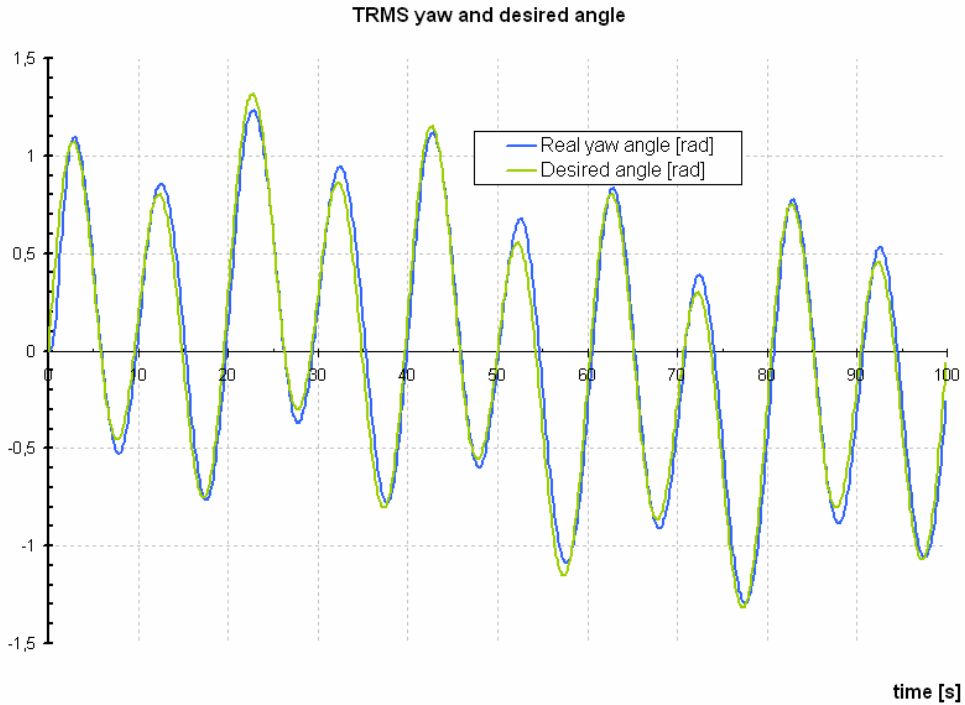
#### Task

The task is to change the sinusoidal  $\varphi_{desired}(t)$  signal frequency and see how the cart reacts to it. Change the controller *P*, *I* and *D* values to see how the signal  $\varphi_{desired}(t)$  is tracked by the system output.

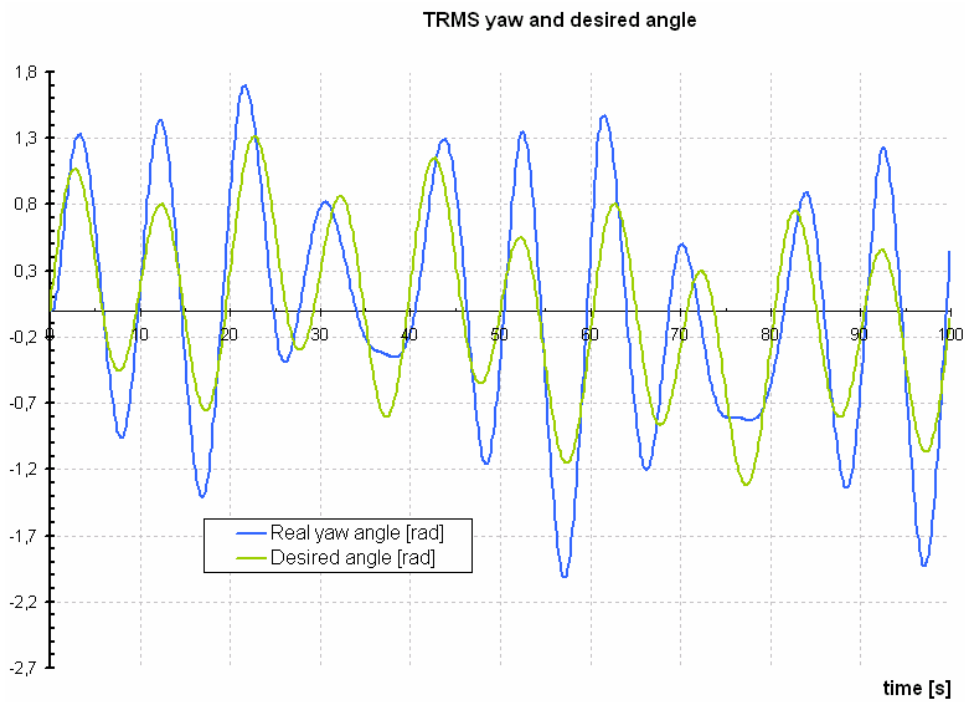
Make sure the changes of the *P*, *I* and *D* gains will not have a destructive effect on the TRMS. You should already gain some experience in exercise 8 on how the values of these gains can be changed.

#### Example results and comments

Figure 19 presents real time simulation results of the yaw position PID control. Figure 20 gives an example of badly tuned PID controller.



**Figure 19** PID control with  $P = 2, I = 0.5, D = 5$



**Figure 20** Badly tuned PID control  $P = 1, I = 2, D = 5$

## TRMS 2 DOF position control

In 1 DOF only one rotor has been used for control. The 2 DOF control includes 2 controllers working in parallel. For some MIMO plants such solution gives satisfactory results. If the cross coupling dynamics are significant, extra algorithms have to be incorporated. Either a decoupling scheme is introduced or multidimensional controllers should be designed.

The two controllers that have been designed in the previous sections are first tested in parallel. Secondly a dynamics decoupling scheme is introduced.

## TRMS 2 parallel controllers

In this section two of the designed PID controllers will be tested on the phenomenological model and on the real plant. The application allows for control scheme switching. The user has the possibility of choosing 1 DOF and 2 DOF control schemes.

### Exercise 10 – Model 2 DOF control



#### Introduction

Use the *Model2DOF.mdl* for this exercise.

#### Task

You can change the control scheme using the 'control scheme switch'. You may also change the desired position signal parameters and see how the model responds. Change the controller  $P$ ,  $I$  and  $D$  values to see how the signals  $\varphi_{desired}(t)$ ,  $\psi_{desired}(t)$  are tracked by the model outputs.

Do not make significant changes of the  $P$ ,  $I$  and  $D$  gains as that may destabilise the system.

#### Example results and comments

Figure 21 and Figure 22 present simulation results of pitch and yaw model control for sinusoidal reference signals.

TRMS model pitch and desired angle

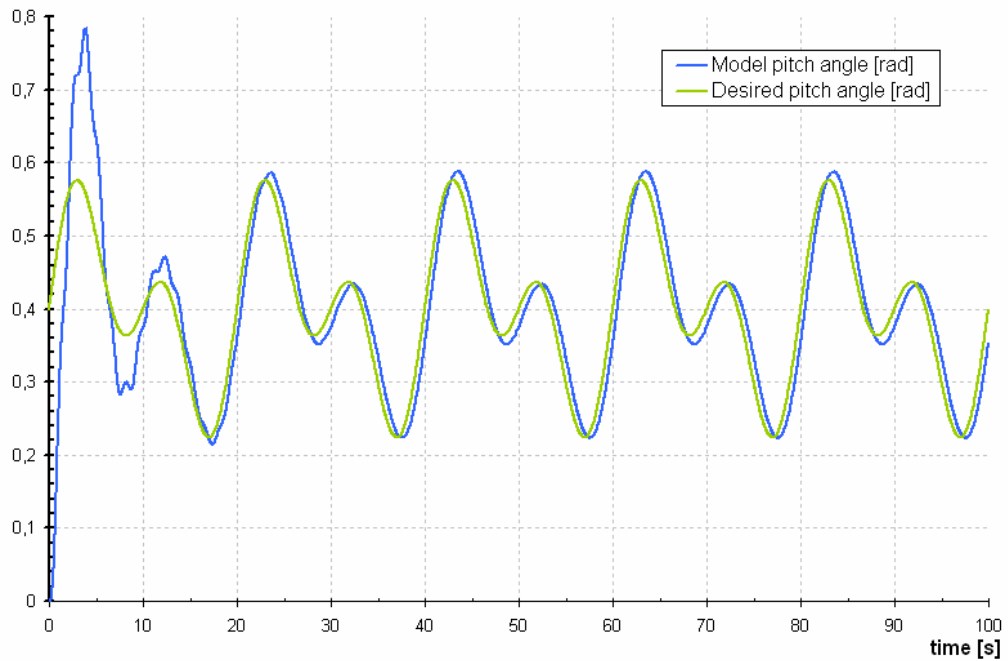


Figure 21 Pitch for 2 DOF model PID control

TRMS model yaw and desired angle

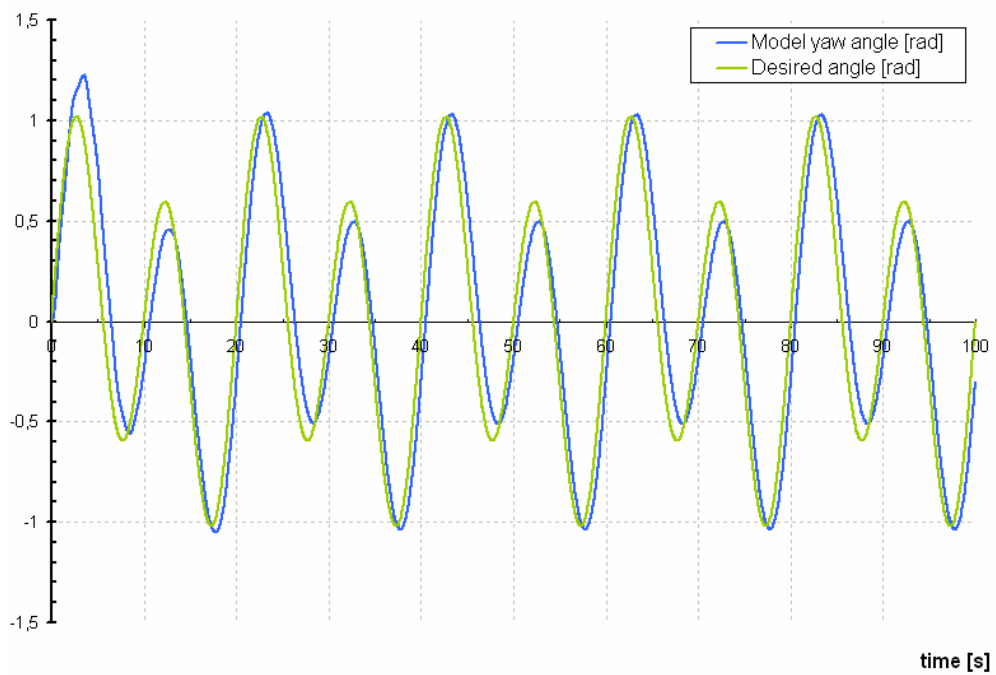


Figure 22 Yaw for 2 DOF model PID control

**Exercise 11 – Real time 2 DOF control**



**Introduction**

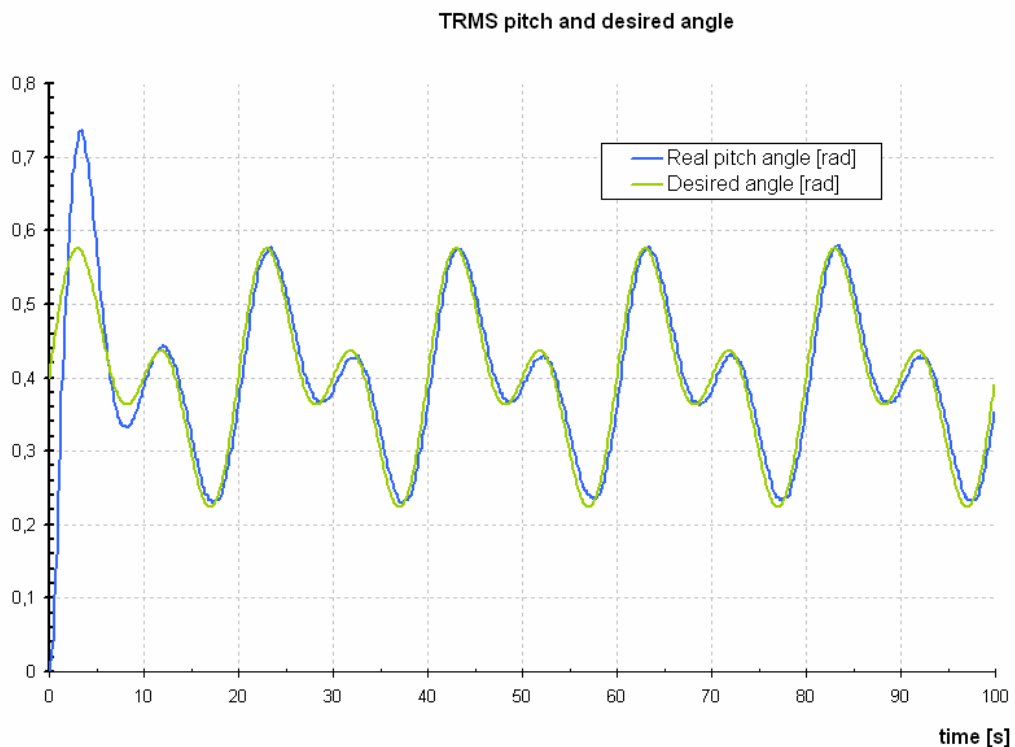
Use the *TRMS2DOF.mdl* for this exercise. Previously designed control scheme is now used for the real time application.

**Task**

You can switch the control scheme using the ‘control scheme switch’. You may also change the desired position signal parameters and see how the model responds.

**Example results and comments**

Figure 23 and Figure 24 present simulation results of pitch and yaw TRMS control for sinusoidal reference signals.



**Figure 23 Pitch for 2 DOF TRMS PID control**

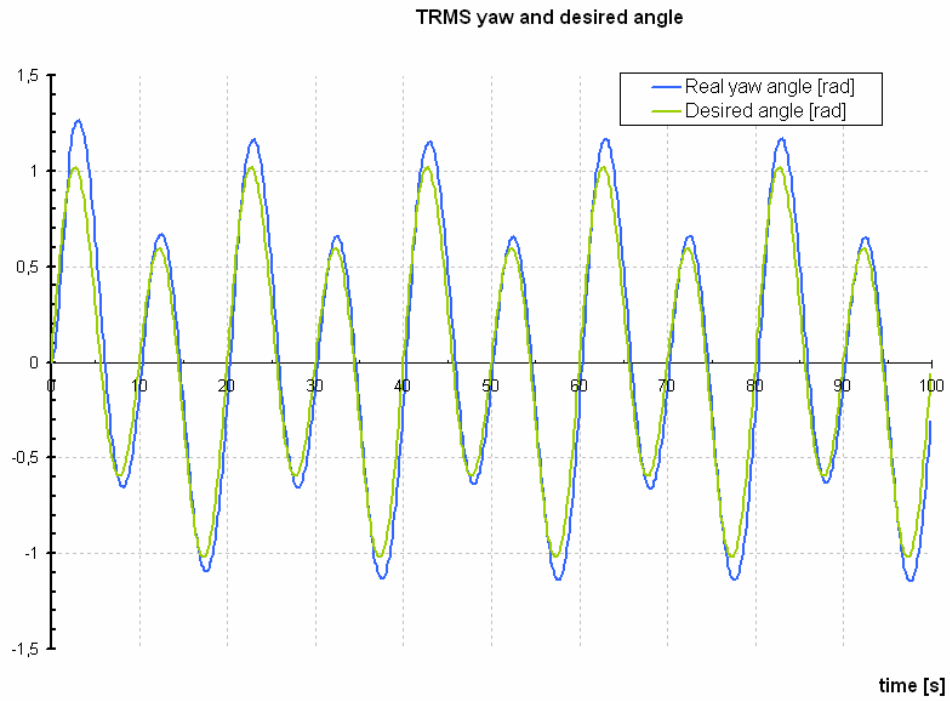


Figure 24 Yaw for 2 DOF TRMS PID control



### Dynamics decoupling

As mentioned in the modelling and control sections the key feature of the TRMS plant is the cross coupling dynamics. If pitch rotor is activated its movement has its effect on the vertical axis position. Furthermore the yaw rotor activation will influence the position of the helicopter in horizontal position. These effects are represented by functional blocks in the TRMS diagram (Figure 25).

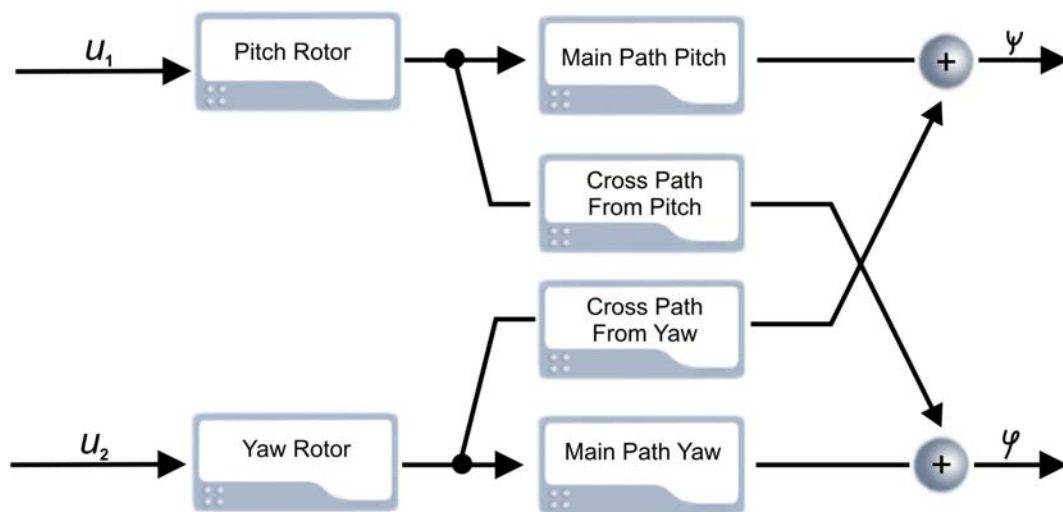
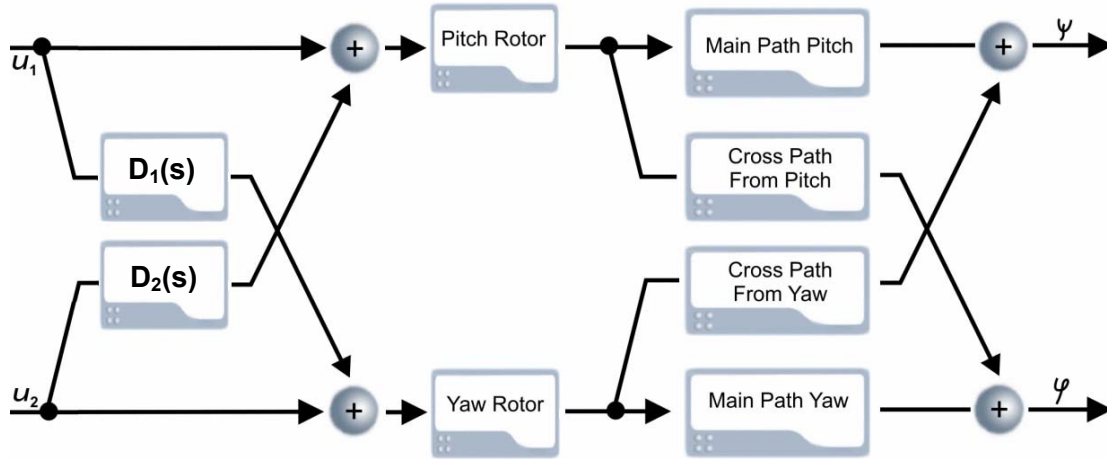


Figure 25 TRMS with dynamics coupling

If the dynamics coupling is significant two 1 DOF controllers might not manage to control the plant. Even if they do manage the decoupling can be incorporated to upgrade control system performance.

In order to separate the dynamic paths in the TRMS system decoupling functions have to be introduced (Figure 26).



**Figure 26 Dynamics decoupling**

If there are 2 main paths and 2 cross coupling paths just as in the TRMS only 2 functions are needed. In that case the transfer functions representing the decouplers are calculated based on the linear models that are obtained in the model identification section:

$$D_1(s) = -\frac{C_{12}(s)}{C_{11}(s)}, \quad (18)$$

$$D_2(s) = -\frac{C_{21}(s)}{C_{22}(s)}. \quad (19)$$

It may occur that a decoupler is of a high order or in worst case may even be unstable. Such transfer functions should be simplified. The easiest way to do that is to carry out an identification experiment in Simulink where one of the decouplers is the identified plant.

The decouplers for the TRMS had also been simplified through the identification to an oe111 model. The *TRMS\_DecSimp.mdl* has been prepared for that purpose. The simplified transfer functions are then used according to the schematic presented in Figure 26.

The following exercise will help you design decouplers and use them on the model and TRMS in real time.

**Exercise 12 – Model dynamics decoupling**



**Introduction**

According to the previous description you can test the decoupling method using a model. Follow the instructions given below.

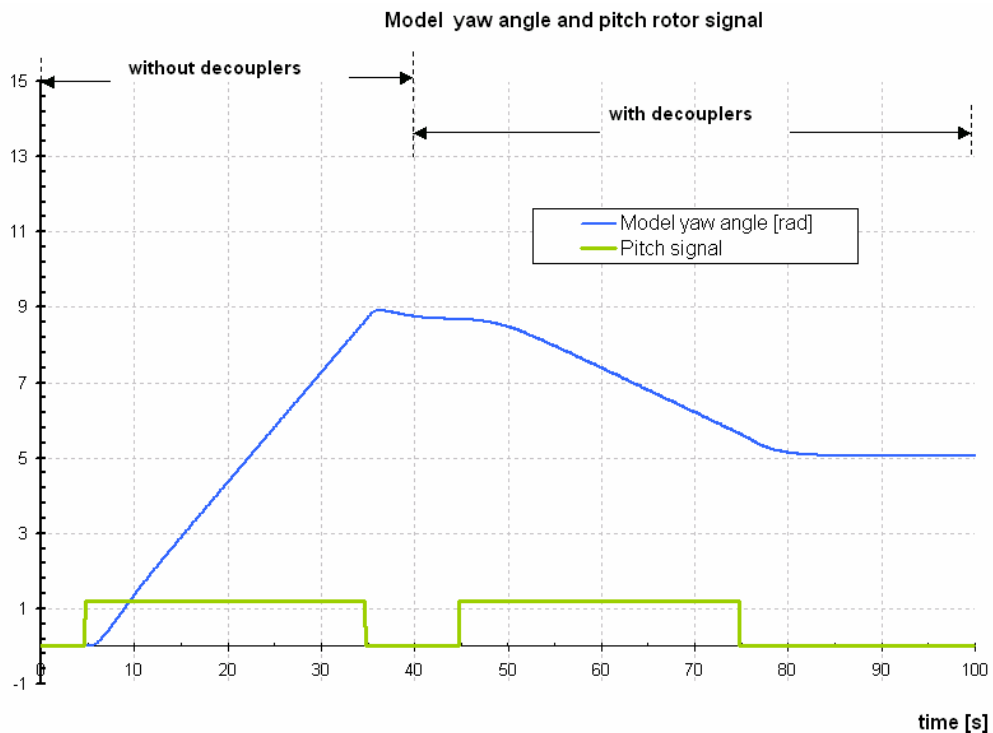
**Task**

To test the decoupling method on the model carry out the identification experiment of the proper paths in the model. Use the *ModelIdent.mdl*. Assign the identified transfer functions according to the schematic presented in Figure 25. Create the transfer functions described by equations (18) and (19). Carry out a simplification experiment through identification. You may use the *Model\_DecSimp.mdl*. Apply the simplified decouplers to the model and test their performance. Use the *ModelDecoupling.mdl* for that purpose.

**Refer to the ‘Matlab Guide’ manual for guide in case any difficulties arise.**

**Example results and comments**

Figure 27 presents simulation results for decoupling being switched on and off. Slower yaw position changes can be seen with decouplers turned on.



**Figure 27 Model decoupling test**

**Exercise 13 – TRMS dynamics decoupling**



**Introduction**

Just as in exercise 12 the decouplers are designed and tested. This time the work is being done on the TRMS plant.

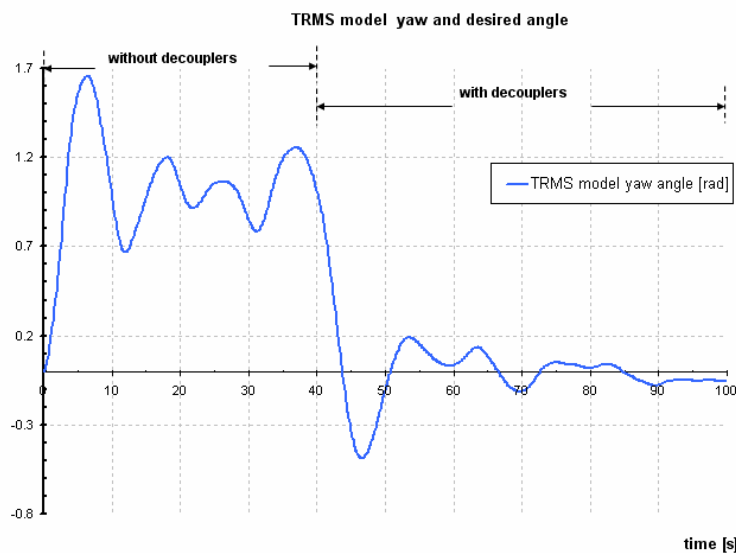
**Task**

Use the models identified in the identification section for decouplers design. Assign the identified transfer functions according to the schematic presented in Figure 25. Create the transfer functions described by equations (18) and (19). Carry out a simplification experiment through identification. You may use the *TRMS\_DecSimpl.mdl*. Apply the simplified decouplers to the model and test their performance. Use the *TRMSDecoupling.mdl* for that purpose.

**Refer to the ‘Matlab Guide’ manual for guide in case any difficulties arise.**

**Example results and comments**

Figure 28 present simulation results for decoupling being switched on and off.



**Figure 28 TRMS decoupling test**

## Plant control with decoupled dynamics

With the decouplers designed the control system performance with dynamics decoupling can be tested. The following exercises will guide you through it.

### Exercise 14 – Model control with dynamics decoupling



#### Introduction

The decouplers performance can now be tested with controllers.

#### Task

To test the decouplers use the *ModeDecPID.mdl*. Compare the results with the decouplers being turned on and off. Use the provided ‘decoupling switch’ for that purpose.

#### Example results and comments

Figure 29 present simulation results for decoupling being switched on and off.

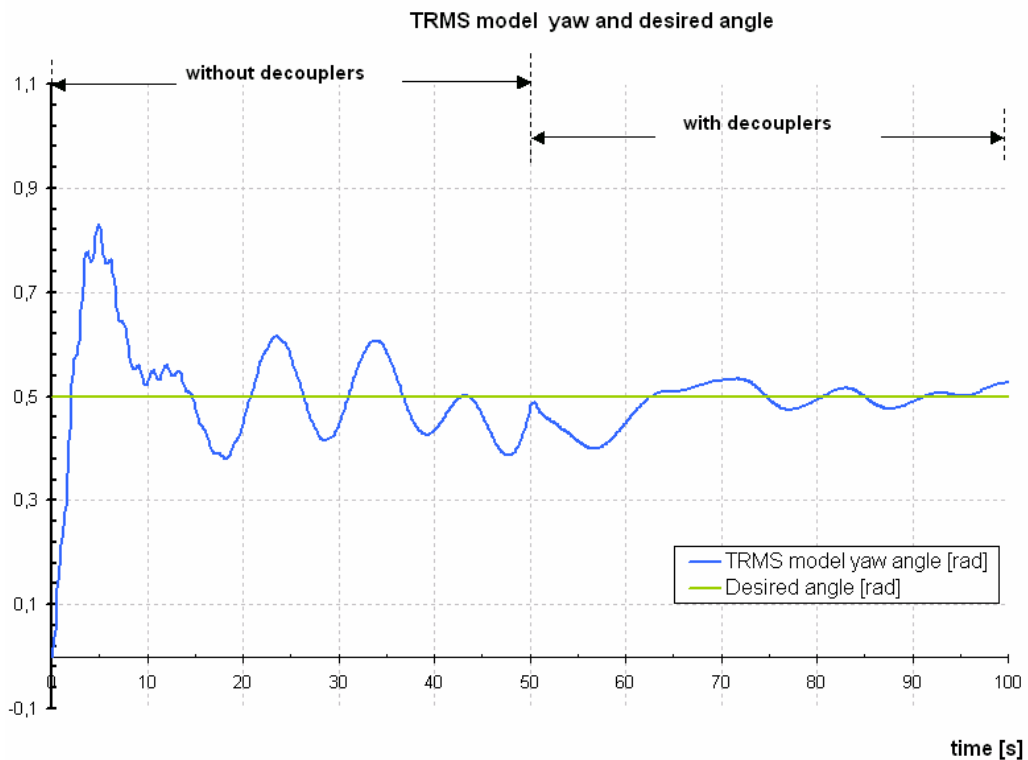


Figure 29 Model control with decoupling

**Exercise 15 – TRMS control with dynamics decoupling**



**Introduction**

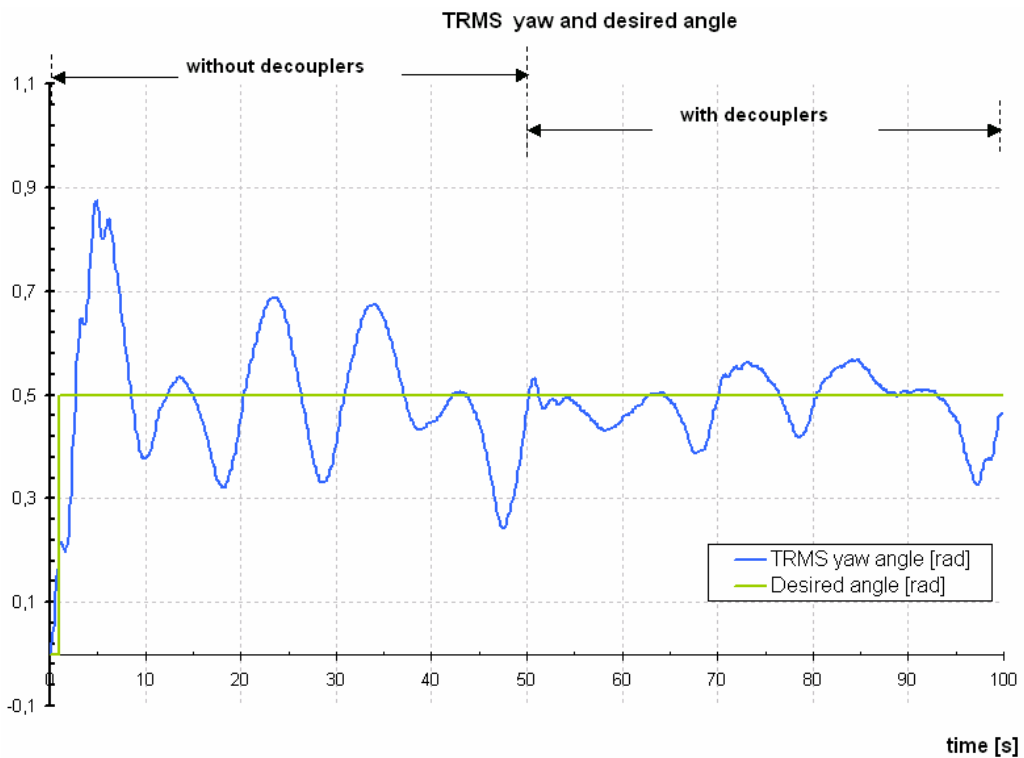
The decouplers performance can now be tested with controllers on the plant in real time.

**Task**

To test the decouplers use the *TRMSDecPID.mdl*. Compare the results with the decouplers being turned on and off. Use the provided ‘decoupling switch’ for that purpose.

**Example results and comments**

Figure 30 presents simulation results for decoupling being switched on and off.



**Figure 30 TRMS control with decoupling**