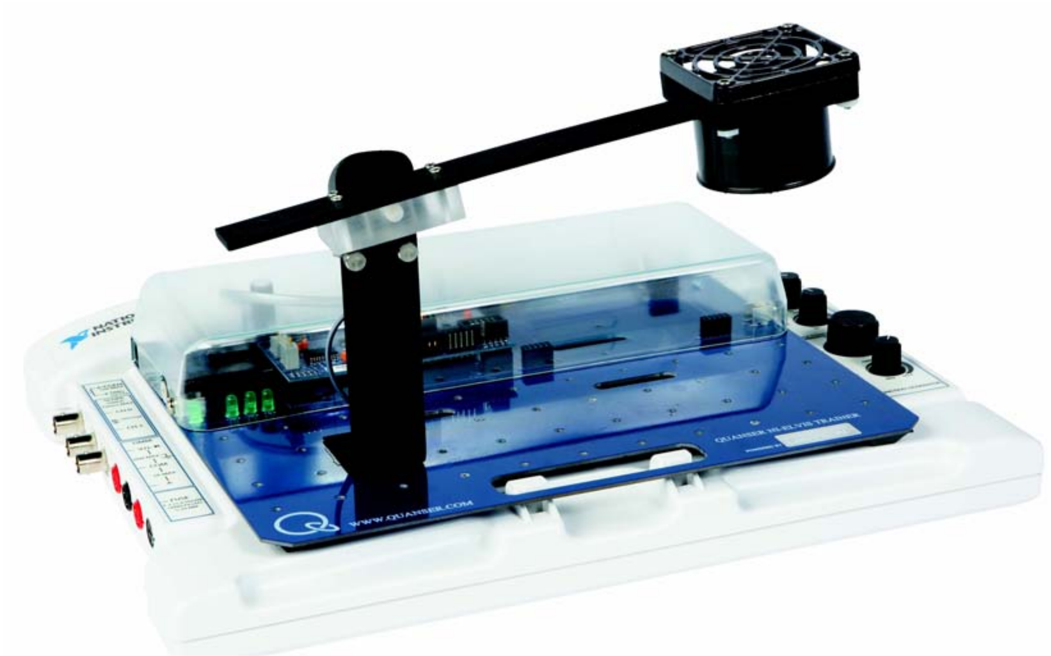
QNET-014 VTOL Trainer

Quanser Engineering Trainer for NI-ELVIS

QNET Vertical Take-Off and Landing Trainer



Student Manual

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1. Introduction

This manual contains experimental procedures and lab exercises for the QNET Vertical Take-Off and Landing (VTOL) Trainer, depicted in Figure 1. See Reference [2] for details about the hardware of this device.

Figure 1: QNET-VTOL Trainer on ELVIS II.

The prerequisites to run the LabVIEW Virtual Instruments (VIs) for the VTOL trainer are listed in Section 2 and described in Section 3. The in-lab procedures are given in Section 4 and split into three sections: current control, modeling, and flight control. In Section 4.1, a current controller is designed to compensate for the propeller motor dynamics. The current-torque thrust constant, moment of inertia, and stiffness parameters of the second-order VTOL model, which is presented in Reference [1], are experimentally derived in Section 4.2. In Section 4.3, a PID controller is designed to regulate the position of the VTOL to the desired pitch angle. The exercises are given within the lab procedures and labeled "**Exercise**". In that case, enter your answer in the corresponding exercises number in Section 5.

2. Prerequisites

The following system is required to run the QNET VTOL Trainer virtual instruments:

- ✔ PC equipped with either:
  - ✔ NI-ELVIS I and an NI E-Series or M-Series DAQ card.
  - ✔ NI ELVIS II
- ✔ Quanser Engineering Trainer (QNET) module.

- ✔ LabVIEW 8.6.1 with the following add-ons:
  - ✔ DAQmx
  - ✔ Control Design and Simulation Module
  - ✔ *When using ELVIS II*: ELVISmx installed for required drivers.
  - ✔ *When using ELVIS I*: ELVIS CD 3.0.1 or later installed.

⚠ **If these are not all installed then the VI will not be able to run!** Please make sure all the software and hardware components are installed. If an issue arises, then see the troubleshooting section in Reference [2].

3. VTOL Trainer Virtual Instruments

3.1. Summary

Table 1 below lists and describes the VTOL Trainer LabVIEW VIs supplied with the **QNET CD**.

VI	*Description*
QNET_VTOL_Current_Control	Control the current in the propeller motor.
QNET_VTOL_Modeling	Validate transfer function model and identify system parameters.
QNET_VTOL_Flight_Control	Control the pitch of the VTOL device using PID.

Table 1: VTOL Trainer VIs supplied with the QNET CD.

3.2. Description

3.2.1. Current Control

This VI is used to feed an open-loop voltage or current to the QNET-VTOL Trainer. The VI when in current mode is shown in Figure 2. In this mode, a current-controller is used to regulate the current in the motor and the user chooses the reference current. In voltage mode, shown in Figure 3, the voltage chosen is applied directly to the QNET amplifier, which in turn drives the motor. As a quick VI description, Table 2 lists and describes the main elements of the QNET VTOL Current Control VI. Every element is uniquely identified by an ID number located in Figure 2 and Figure 3, for both current and voltage mode.

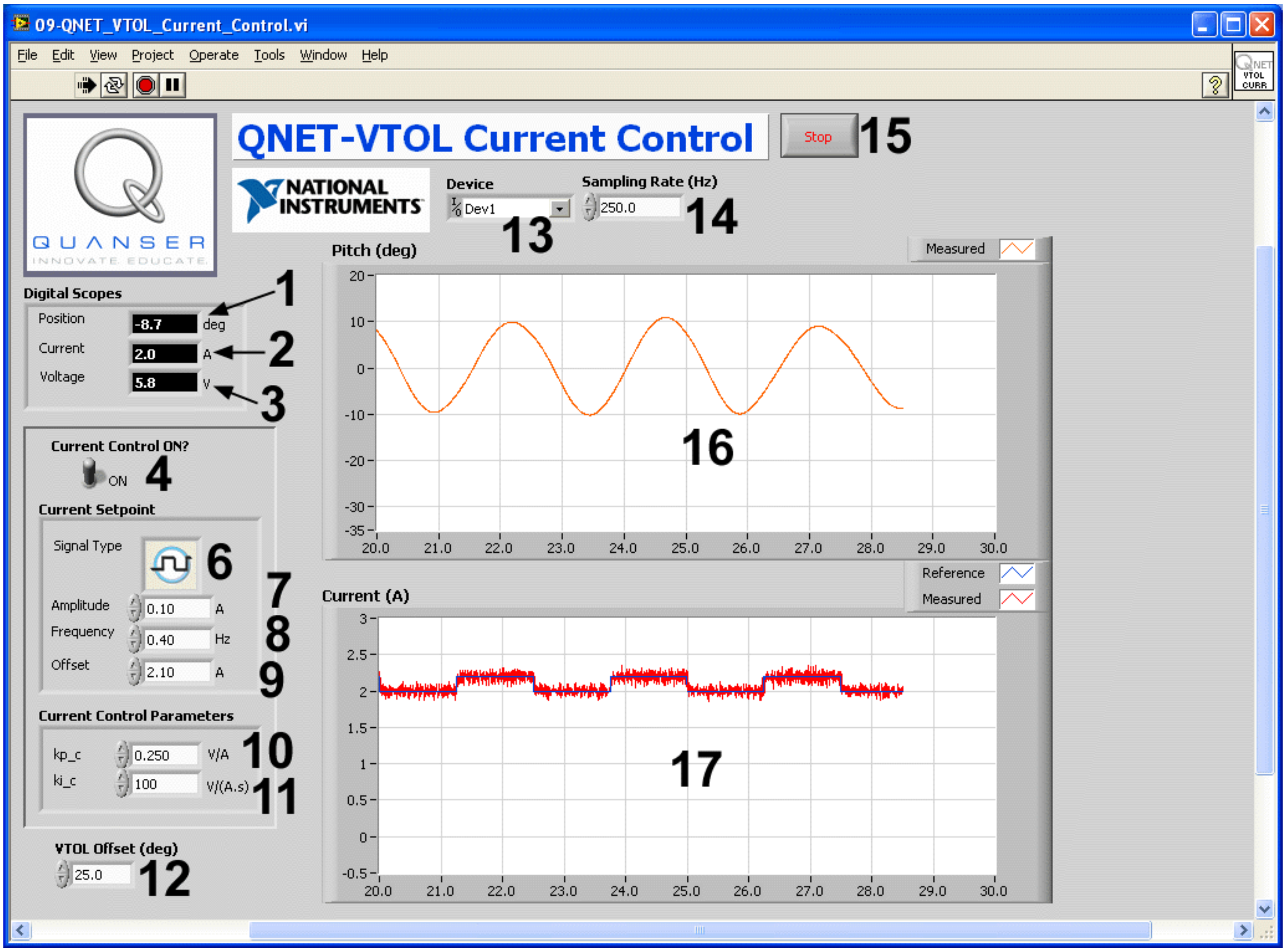

Figure 2: QNET-VTOL Current Control VI when in open-loop current mode.

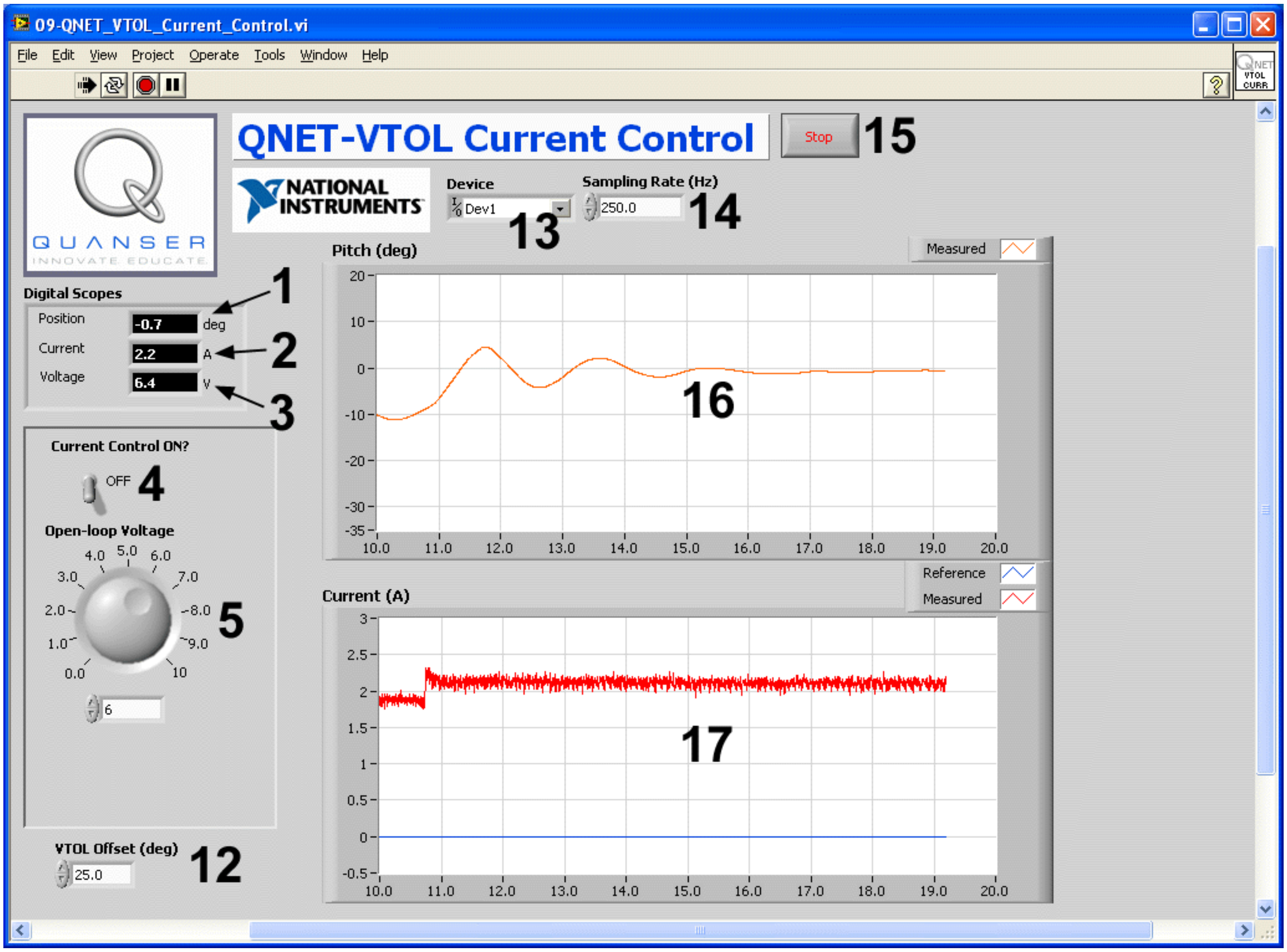

Figure 3: QNET-VTOL Current Control VI when in open-loop voltage mode.

ID #	Label	Parameter	Description	Unit
1	Position	θ	VTOL pitch position numeric display.	deg
2	Current	I_m	VTOL motor armature current numeric display.	A
3	Voltage	V_m	VTOL motor input voltage numeric display.	V
4	Current Control ON?		Turns current control on and off.	
5	Open-loop Voltage		Input motor voltage to be fed.	V
6	Signal Type		Type of signal generated for the current reference.	

ID #	Label	Parameter	Description	Unit
7	Amplitude		Current setpoint amplitude input box.	A
8	Frequency		Current setpoint frequency input box.	Hz
9	Offset		Current setpoint offset input box.	A
10	kp_c	$k_{p,c}$	Current control proportional gain.	V/A
11	ki_c	$k_{i,c}$	Current control derivative gain.	V.s/A
12	VTOL Offset		Pitch calibration	deg
13	Device		Select the NI DAQ device.	
14	Sampling Rate		Sets the sampling rate of the VI.	Hz
15	Stop		Stops the LabVIEW VI from running.	
16	Pitch	θ	Scope with measured (in red) VTOL pitch position.	deg
17	Current	I_m	Scope with reference (in blue) and measured (in red) current.	A

Table 2: Nomenclature of QNET-VTOL Current Control VI.

3.2.2. Modeling

This VI is used for model validation and parameter identification and is shown in Figure 4. A transfer function is ran in parallel with the actual system and enables users to confirm whether their derived model is correct. Using the LabVIEW *System Identification Toolkit*, the VTOL Trainer transfer function model can be identified automatically by collecting the measured stimulus (i.e. current) and response (i.e. measured pitch angle) signals and specifying the order of the transfer function process model. The main components of the QNET VTOL Modeling VI front panel are listed and described in Table 3. Every element is given an ID number which is used to uniquely identify the VI components in Figure 4.

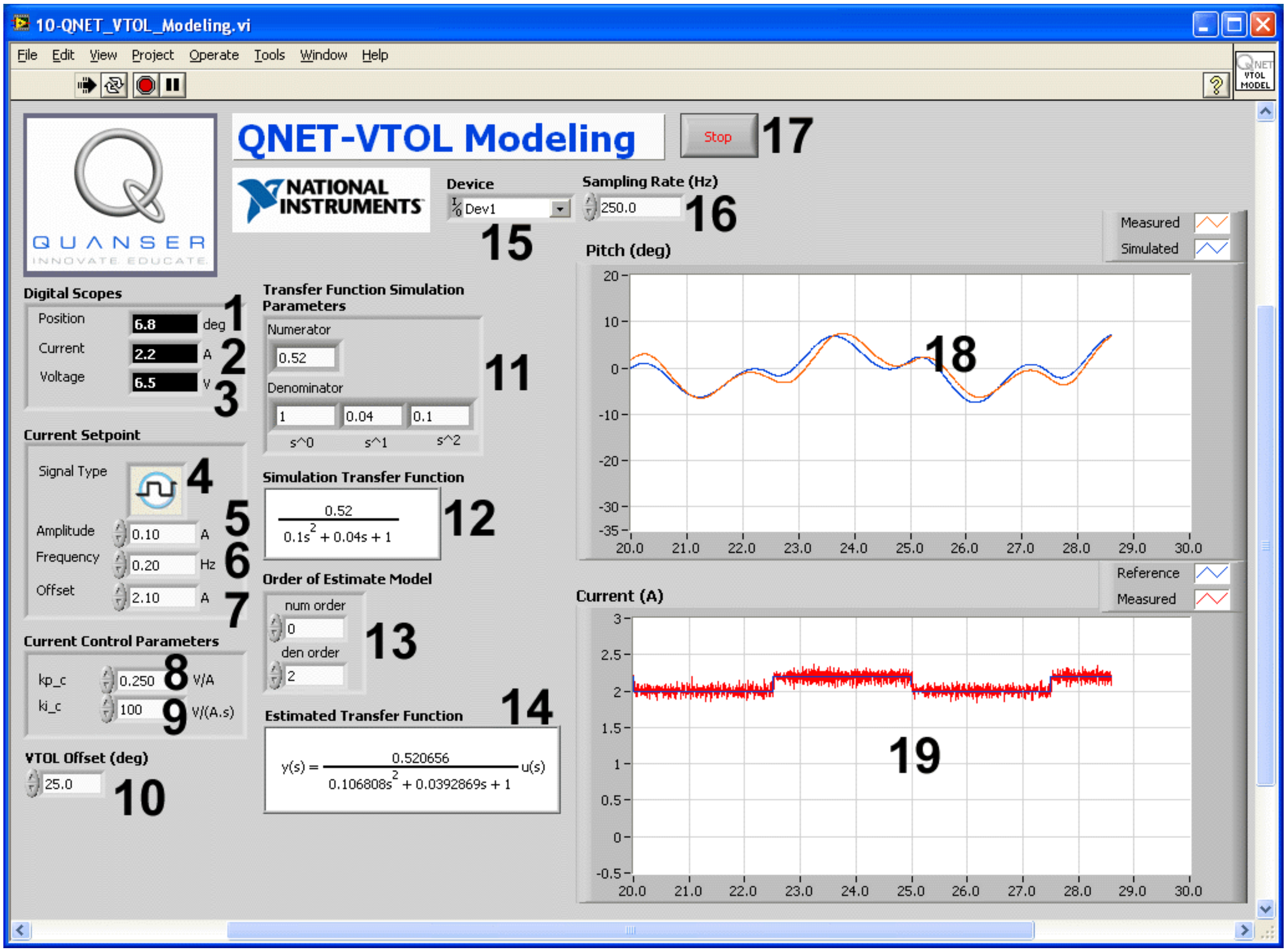

Figure 4: QNET-VTOL Modeling VI.

ID #	Label	Parameter	Description	Unit
1	Position	θ	VTOL pitch position numeric display.	deg
2	Current	I_m	VTOL motor armature current numeric display.	A
3	Voltage	V_m	VTOL motor input voltage numeric display.	V
4	Signal Type		Type of signal generated for the current reference.	
5	Amplitude		Current setpoint amplitude input box.	A
6	Frequency		Current setpoint signal frequency input box.	Hz
7	Offset		Current setpoint signal offset input box.	A
8	kp_c	$k_{p,c}$	Current control proportional gain.	V/A
9	ki_c	$k_{i,c}$	Current control derivative gain.	V.s/A
10	VTOL Offset		Pitch calibration	deg
11	Transfer Function Simulation Parameters		Transfer function used for simulation.	
12	Simulation Transfer Function		Displays the transfer function currently begin simulated.	
13	Order of Estimated Model		Order of transfer function to be estimated using the *System Identification Toolkit*.	
14	Estimated Transfer Function		Transfer function estimated using the *System Identification Toolkit*.	
15	Device		Selects the NI DAQ device.	
16	Sampling Rate		Sets the sampling rate of the VI.	Hz
17	Stop		Stops the LabVIEW VI from running.	
18	Pitch	θ	Scope with simulated position (in blue) and measured VTOL pitch position (in red).	deg
19	Current	I_m	Scope with reference (in blue) and measured (in red) current.	A

Table 3: Nomenclature of QNET-VTOL Modeling VI.

3.2.3. Flight Control

This VI runs the PID-based cascade control system, which is described in Reference [1], to control the position of the VTOL pitch. As a quick VI description, Table 4 lists and describes the main elements of the QNET VTOL Flight Control VI and every element is uniquely identified by an ID number in Figure 5.

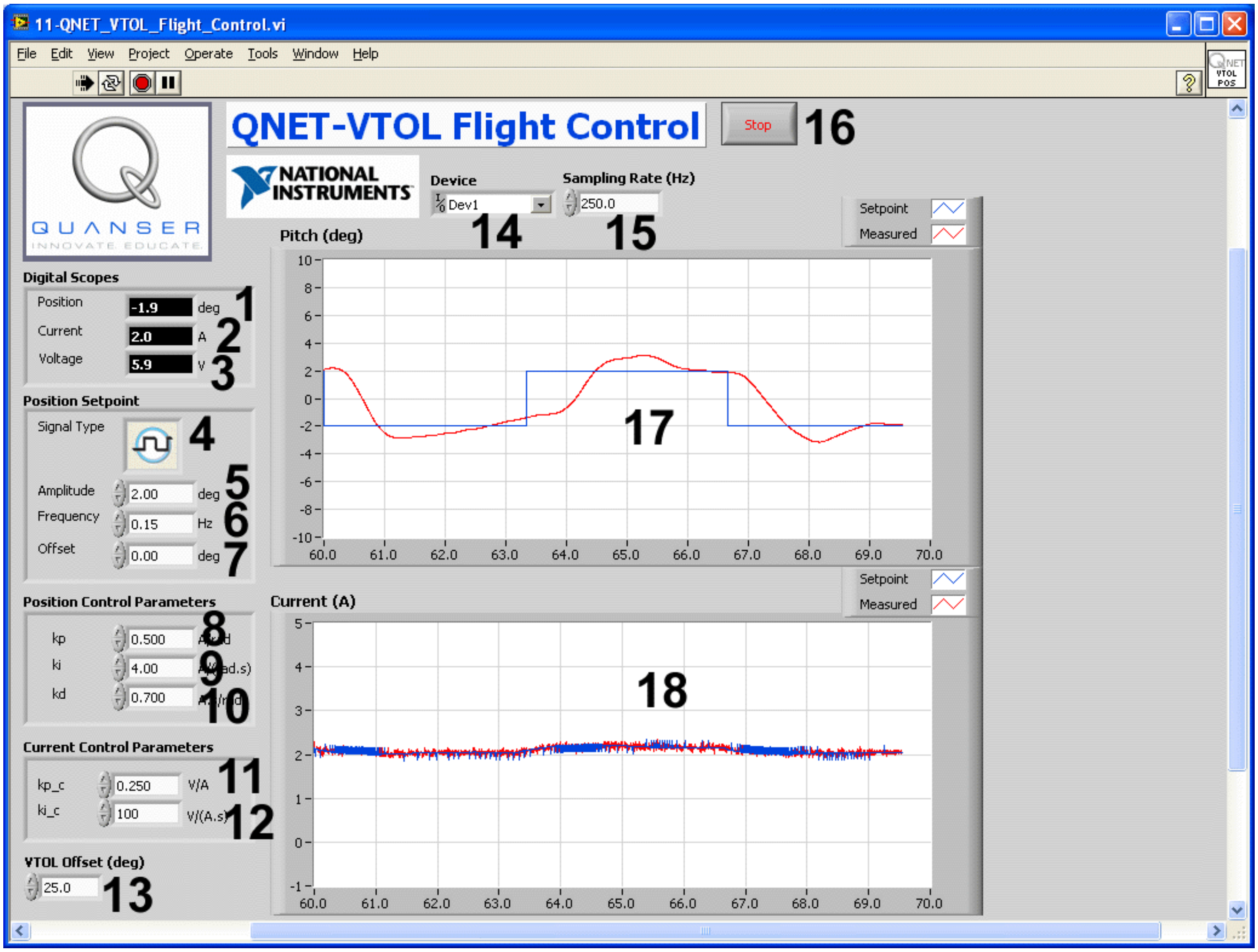

Figure 5: QNET VTOL Flight Control VI.

ID #	Label	Parameter	Description	Unit
1	Position	θ	VTOL pitch position numeric display.	deg
2	Current	I_m	VTOL motor armature current numeric display.	A
3	Voltage	V_m	VTOL motor input voltage numeric display.	V
4	Signal Type		Type of signal generated for the current reference.	
5	Amplitude		Pitch setpoint signal amplitude input box.	A
6	Frequency		Pitch setpoint signal frequency input box.	Hz
7	Offset		Pitch setpoint signal offset input box.	A
8	kp	k_p	Position control proportional gain.	A/rad
9	ki	k_i	Position control integral gain.	A/(rad.s)
10	kd	k_d	Position control derivative gain.	A.s/rad
11	kp_c	$k_{p,c}$	Current control proportional gain.	V/A
12	ki_c	$k_{i,c}$	Current control derivative gain.	V.s/A
13	VTOL Offset		Pitch calibration	deg
14	Device		Selects the NI DAQ device.	
15	Sampling Rate		Sets the sampling rate of the VI.	Hz
16	Stop		Stops the LabVIEW VI from running.	
17	Pitch	θ	Scope with reference position (in blue) and measured VTOL pitch position (in red).	deg
18	Current	I_m	Scope with reference current (in blue) and measured current (in red).	A

Table 4: Nomenclature of QNET-VTOL Flight Control VI.

4. In-Lab Experiments

4.1. Current Control

4.1.1. Finding Resistance

1. Open the QNET_VTOL_Current_Control.vi shown in Figure 7, below.
2. Ensure the correct *Device* is chosen, as shown in Figure 6.

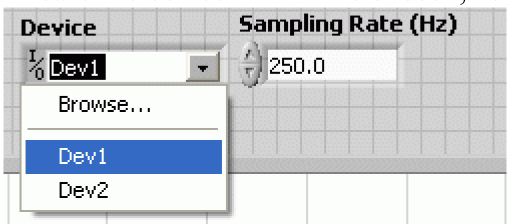

Figure 6: Selecting correct device.

3. Run the VI.
4. Set the *Current Control ON* switch to OFF.
5. Set the *Open-loop Voltage* knob to 4.0 V. The VTOL Trainer propeller should begin turning as a voltage is applied to the motor.
6. **Exercise 1**: Vary the voltage between 4.0 and 8.0 V by steps of 1.0 V and measure the current at each voltage. Enter the results in the table.
7. Click on *Stop* button to stop the VI.

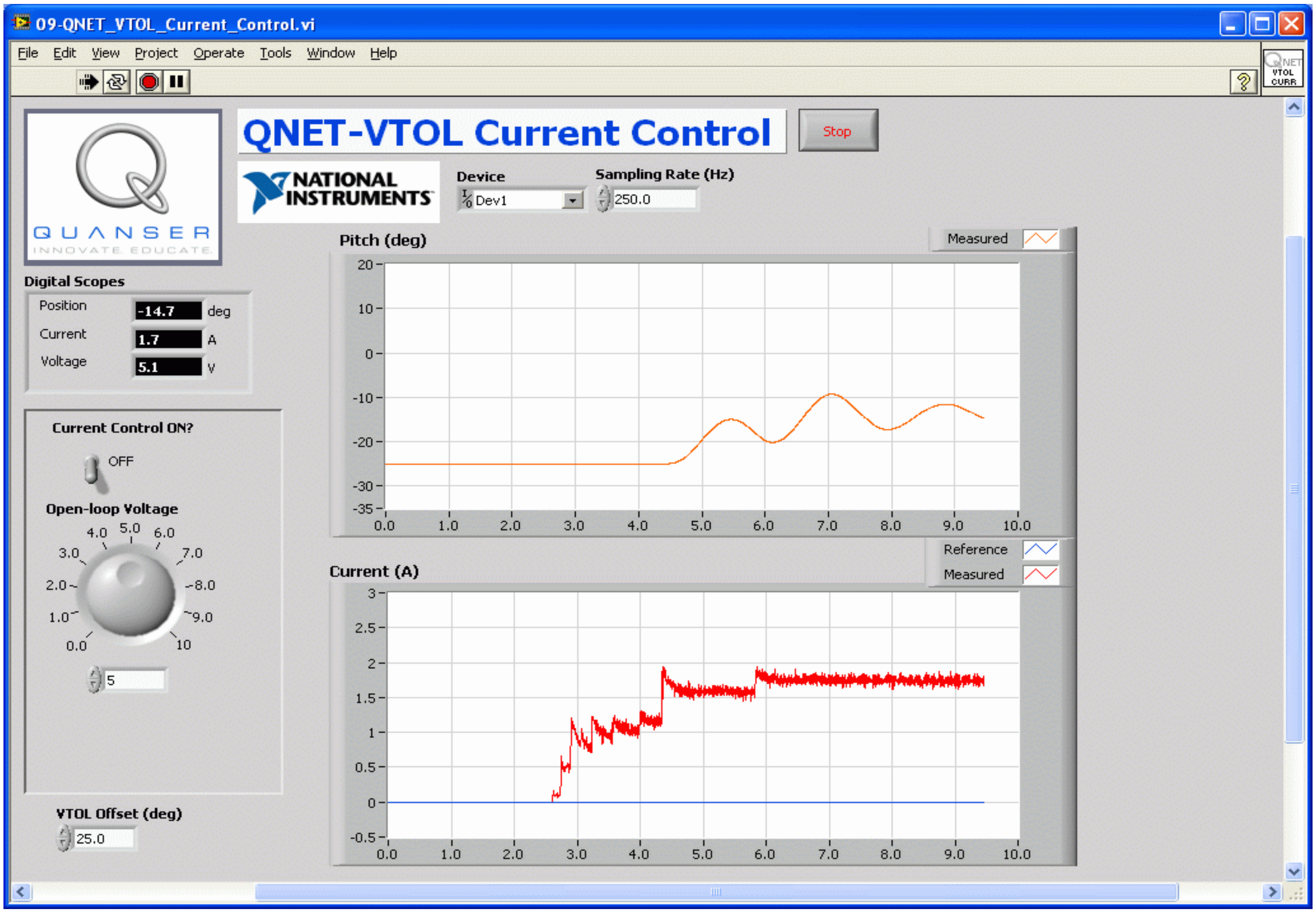

Figure 7: Running QNET-VTOL Current Control in open-loop voltage mode.

4.1.2. Qualitative Current Control

1. Open the QNET_VTOL_Current_Control.vi as shown in Figure 8, below.
2. Ensure the correct *Device* is chosen.
3. Set the *Current Control ON* switch to ON.
4. Run the VI.
5. In the *Current Setpoint* section set:
   - *Amplitude* =0.20 A
   - *Frequency* =0.40 Hz
   - *Offset* =0.90 A
6. In the *Control Parameters* section set the PI current gains to:
   - *kp_c* = 0.250
   - *ki_c* =10

   The VTOL Trainer propeller should begin turning at various speeds according to the current command. Examine the reference and measured current response obtained in the *Current (A)* scope. They should be tracking as shown in Figure 8, below.

7. **Exercise 2**: Show and explain the effect of not having any integral gain. Attach a sample response.
8. In the *Control Parameters* section set the PI current gains to:
    - *kp_c* = 0
    - *ki_c* =100
9. **Exercise 3**: Show and explain the effect of not having any proportional gain. Attach a sample response.
10. Click on *Stop* button to stop the VI.

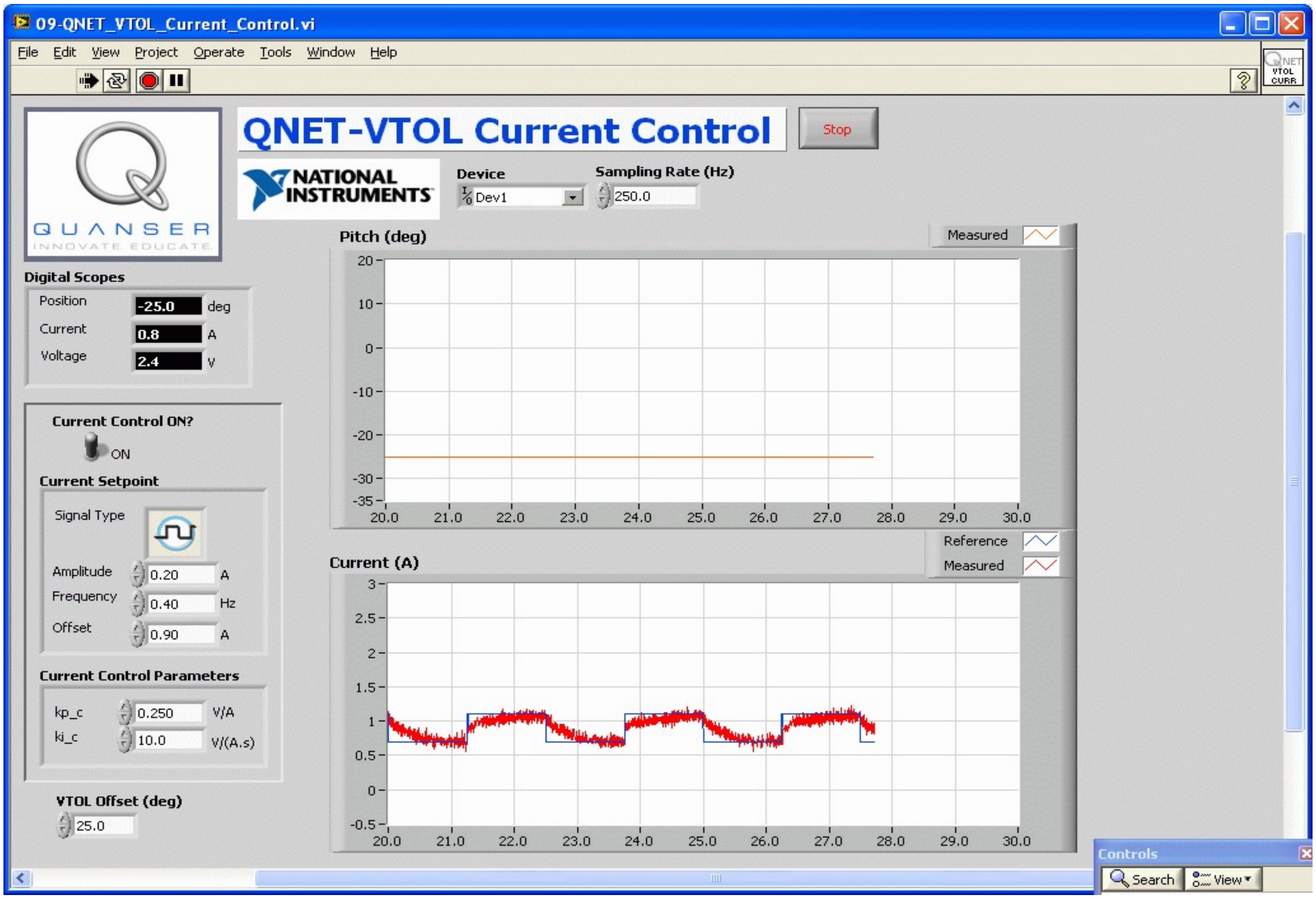

Figure 8: Running the QNET-VTOL Current Control VI with the current-controller.

4.1.3. Current Control Design

1. **Exercise 4**: Calculate the PI gains, k_p and k_i, necessary to satisfy the natural frequency and damping ratio specifications:
    - $\omega_n = 42.5$ rad/s
    - $\zeta = 0.70$

See Reference [1] for more information on designing a current controller. To compute the gains, you will need the resistance found in Section 4.1.1 and assume the inductance of the motor is L_m =53.8 mH. Enter your results in Table 5.

2. Open the QNET_VTOL_Current_Control.vi as shown in Figure 8, above.
3. Ensure the correct *Device* is chosen.
4. Set the *Current Control ON* switch to ON.
5. In the *Current Setpoint* section set:
   - *Amplitude* =0.20 A
   - *Frequency* =0.40 Hz
   - *Offset* =0.90 A
6. In the *Current Control Parameters* section, set the PI current gains to what you found.
7. Run the VI. The VTOL Trainer propeller should begin turning at various speeds according to the current command. Examine the reference and measured current response obtained in the *Current (A)* scope. They should be tracking.
8. **Exercise 5**: Include a plot showing the current response with your designed PI gains.
9. Click on *Stop* button to stop the VI.

4.2. Modeling

The VTOL Trainer model parameters are found by performing the experiments instructed in Section 4.2.1, 4.2.2, and 4.2.3 and doing some computations. Once this model is validated, the LabVIEW *System Identification Toolkit* is used in Section 4.2.4 to determine the VTOL Trainer transfer function. The manually derived model and the model found through the system identification software tool are then compared.

4.2.1. Measure the Equilibrium Current

1. Open the QNET_VTOL_Current_Control.vi as shown in Figure 8, above.
2. Ensure the correct *Device* is chosen.
3. Set the *Current Control ON* switch to ON.
4. Run the VI.
5. In the *Current Control Parameters* section, set the PI current gains found in Exercise 4.
6. In the *Current Setpoint* section set:
   - *Amplitude* =0.00 A
   - *Frequency* =0.40 Hz
   - *Offset* =1.00 A
7. Gradually increase the offset current until the VTOL Trainer is horizontal.
8. The pitch should read 0 degrees when the VTOL Trainer is horizontal. You may need to adjust the pitch offset by varying the *VTOL Offset* control. By default this is set to 25.0 degrees.
9. **Exercise 6**: The current required to make the VTOL Trainer horizontal is called the equilibrium current, I_{eq}. Capture the pitch and current response and record this current. Enter the value in Table 7.
10. Click on *Stop* button to stop the VI.
11. **Exercise 7**: Using the equations presented in Reference [1] and the equilibrium current just found, calculate the thrust current-torque constant K_t. Enter the value in Table 7.

4.2.2. Find Natural Frequency

1. Open the QNET_VTOL_Current_Control.vi as shown in Figure 8, above.
2. Ensure the correct *Device* is chosen.
3. Set the *Current Control ON* switch to ON.
4. In the *Current Control Parameters* section, set the PI current gains found in Exercise 4.
5. In the *Current Setpoint* section set:
   - *Amplitude* =0.00 A
   - *Frequency* =0.40 Hz
   - *Offset* =I_{eq} (equilibrium current found in Exercise 6)
6. Run the VI.
7. **Exercise Error: Reference source not found**: When the VI starts and the equilibrium current step is applied, the VTOL Trainer will shoot upwards quickly and then oscillate about its horizontal. Capture this response and measure the natural frequency. Fill out Table 6 with the various measured values.
8. Click on *Stop* button to stop the VI.

4.2.3. Model Validation

1. **Exercise 9**: Using the VTOL Trainer model given in Reference [1] and the specifications listed in Reference [2], compute the moment of inertia acting about the pitch axis. Enter the value in Table 7.
2. **Exercise 10**: Based on the natural frequency found in Exercise 8 and the moment of inertia calculated in Exercise 9, find the stiffness of the VTOL Trainer. Enter the value in Table 7.
3. **Exercise 11**: Compute the VTOL Trainer transfer function coefficients based on the previously found parameters: K_t, J, B, and K.
4. Open the QNET_VTOL_Modeling.vi as shown in Figure 9, below.
5. Ensure the correct *Device* is chosen.
6. In the *Current Control Parameters* section, set the PI current gains found in Exercise 4.
7. In the *Current Setpoint* section set:
   - *Amplitude* =0.00 A
   - *Frequency* =0.20 Hz
   - *Offset* =I_{eq} (equilibrium current found in Exercise 6)
8. Run the VI.
9. Let the VTOL Trainer stabilizes about the horizontal.
10. In the *Current Setpoint* section set:
    - *Amplitude* =0.10 A
11. **Exercise 12**: In the *Transfer Function Simulation Parameters* section, enter the parameters computed in Exercise 11. Is the simulation matching the measured signal? Capture the response.
12. Click on *Stop* button to stop the VI.

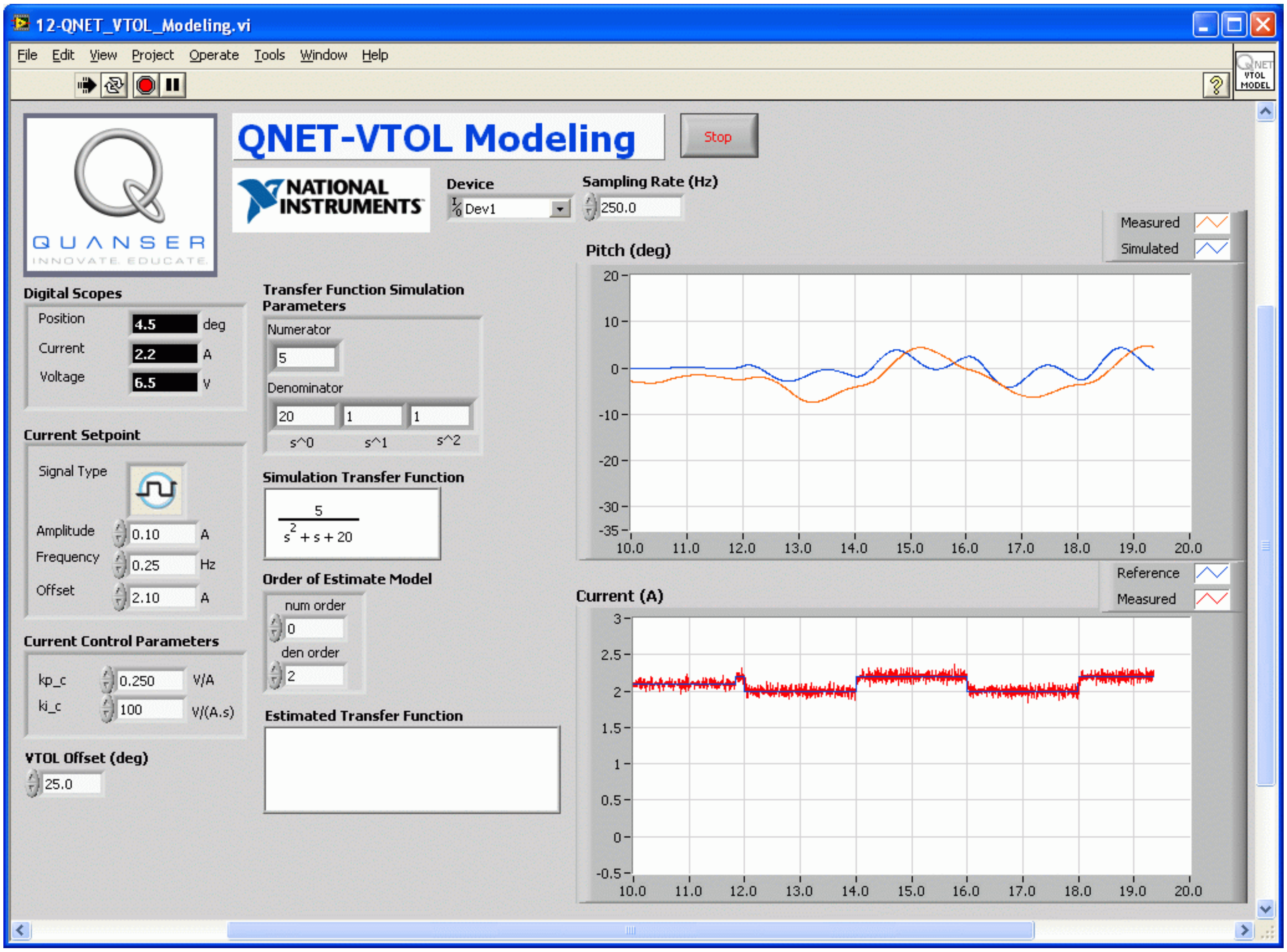

Figure 9: QNET-VTOL Modeling

4.2.4. Using the System Identification Tool

1. Run the QNET_VTOL_Modeling.vi with the *Current Setpoint* section set:
    - *Amplitude* =0.10 A
    - *Frequency* =0.20 Hz
    - *Offset* =I_{eq} (equilibrium current found in Exercise 6)

   So the VTOL Trainer is about its horizontal with a current amplitude of +/- 0.10 A, as described by steps 4-10 in Section 4.2.3.
2. Let the VI run for at least 20 seconds.
3. Click on *Stop* button to stop the VI. When the VI is stopped, the *Estimated Transfer Function* displays a newly identified transfer function of the VTOL system based on the last 20 seconds of current (i.e. stimulus signal) and pitch angle (i.e. response signal) data.
4. **Exercise 13**: Enter the identified transfer function.
5. Enter the identified TF parameters into the *Transfer Function Simulation Parameters* section.
6. Go through steps 7-10 to in Section 4.2.3. That is, bring the VTOL Trainer up to 0 degrees and then feed +/- 0.1 A.

7. **Exercise 14**: In the *Transfer Function Simulation Parameters* section, enter the parameters computed in Exercise 13. How is the simulation matching the measured signal compared to the transfer function with the manually estimated parameters? Capture the response.
8. Click on *Stop* button to stop the VI.
9. **[Optional] Exercise 15**: Assume the moment of inertia is as calculated in Exercise Error: Reference source not found. Then from the identified transfer function, find the stiffness (K_{id}), the viscous damping (B_{id}), and the current-torque constant ($K_{t,id}$). How do they compare with the parameters you estimated manually? Enter identified values in Table 7.

4.3. Flight Control

4.3.1. PD Steady-State Analysis

1. **Exercise 17**: Calculate the theoretical VTOL Trainer steady-state error when using a PD control with $k_p = 2$ and $k_d = 1$ and a step amplitude of $R_0 = 4.0$ degrees. Enter value in Table 8.
2. Open the QNET_VTOL_Flight_Control.vi as shown in Figure 10, below.
3. Ensure the correct *Device* is chosen.
4. Run the VI.
5. In the *Position Setpoint* section set:
    - *Amplitude* =0.0 rad
    - *Frequency* =0.15 Hz
    - *Offset* = 0.0 rad
6. In the *Position Control Parameters* section set:
    - *kp* = 1.0 A/rad
    - *ki* = 2.0 A/(rad.s)
    - *kd* = 1.0 A.s/rad
7. Let the VTOL system stabilize about the 0.0 rad setpoint. Examine if the VTOL Trainer body is horizontal. If not, then you can adjust the pitch offset by varying the *VTOL Offset* control. By default this is set to 25.0 degrees.
8. To use a PD control, in the *Position Control Parameters* section set:
    - *kp* = 2.0 A/rad
    - *ki* = 0 A/(rad.s)
    - *kd* = 1.0 A.s/rad
9. In the *Position Setpoint* section set:
    - *Amplitude* = 2.0 rad
    - *Frequency* = 0.40 Hz
    - *Offset* = 2.0 rad

   The VTOL Trainer should be going up and down and tracking the square wave setpoint.
10. **Exercise 18**: Capture the VTOL device step response when using this PD controller and measure the steady-state error. Enter the measured PD steady-state error value in Table 8. How does it compare with the computed value in Exercise 17?
11. In the *Signal Generator* section set *Amplitude (rad)* to 0 rad and slowly decrement *Offset (rad)* to -8.0 rad.
12. Click on the *Stop* button to stop running the VI.

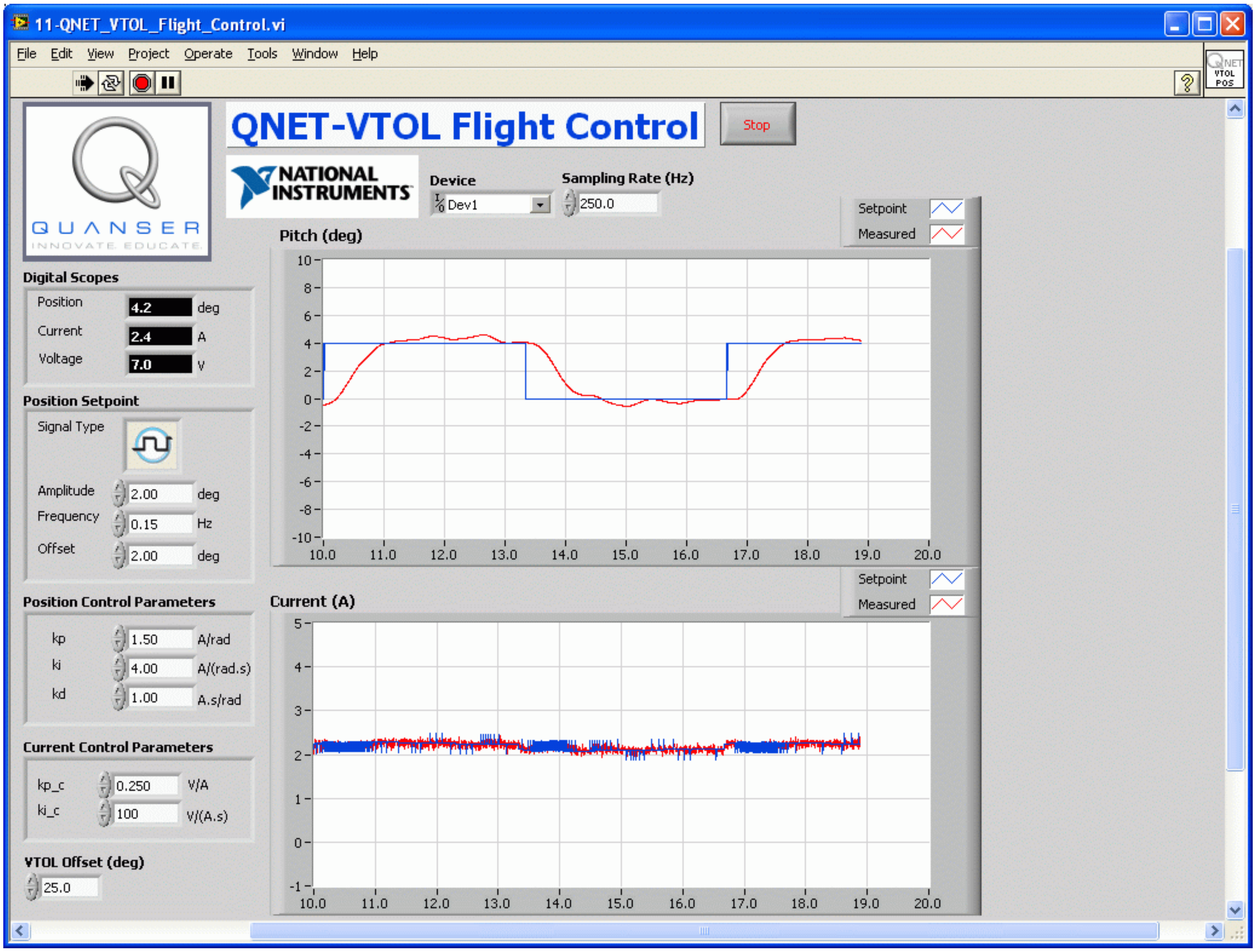

Figure 10: QNET-VTOL Flight Control VI.

4.3.2. PID Steady-State Error Analysis

1. **Exercise 19**: Calculate the VTOL Trainer steady-state error when using a PID controller. Enter the value in Table 8.
2. Go through steps 2-9 in Section 4.3.1 to run the PD controller.
3. In the *Position Control Parameters* section, increment the integral gain until you reach *ki* = 4.0 A/(rad.s).
4. **Exercise 20**: Capture the VTOL Trainer step response when using a PID controller and measure the steady-state error. Enter value in Table 8. How does it compare with the expected value found in Exercise 19?
5. To stop the control, in the *Signal Generator* section set *Amplitude (rad)* to 0 rad and slowly decrement *Offset (rad)* to -8.0 rad.
6. Click on the *Stop* button to stop running the VI.

4.3.3. PID Control Design

1. **Exercise 21:** Find the natural frequency, ω_n, and damping ratio, ζ, required to meet a peak time of 1.0 seconds and a percentage overshoot of 20%. Enter values in Table 8.
2. **Exercise 22:** Calculate the PID gains k_p, k_i, and k_v, needed to meet the VTOL Trainer specifications.
3. Open the QNET_VTOL_Flight_Control.vi as shown in Figure 10, above. Enter values in Table 8.
4. Ensure the correct *Device* is chosen.
5. Run the VI.
6. In the *Position Setpoint* section set:
    - *Amplitude* =0.0 rad
    - *Frequency* =0.15 Hz
    - *Offset* = 0.0 rad
7. In the *Position Control Parameters* section, enter the PID gains found in Exercise 22.
8. Let the VTOL system stabilize about the 0.0 rad setpoint. The VTOL Trainer body should be horizontal. If not, adjust the pitch offset by varying the *VTOL Offset* control. By default this is set to 25.0 degrees.
9. In the *Position Setpoint* section set:
    - *Amplitude* = 0.0 rad
    - *Frequency* = 0.40 Hz
    - *Offset* = 2.0 rad

   The VTOL Trainer should be going up and down and tracking the square wave setpoint.
10. **Exercise 23**: Capture the response of the VTOL system when using your designed PID controller.
11. **Exercise 24**: Measure the peak time and percentage overshoot of the measured response. Enter the values in Table 8. Are the VTOL Trainer response specifications satisfied?
12. In the *Signal Generator* section set *Amplitude (rad)* to 0 rad and slowly decrement *Offset (rad)* to -8.0 rad.
13. Click on the *Stop* button to stop running the VI.

5. Exercises

Exercise 1: Find Resistance

Input Voltage (V)	*Measured Current (A)*	*Resistance (Ω)*
4		
5		
6		
7		

8		
Average Resistance: $R_{m,avg}$ =		

Exercise 2: Current Response with Low Integrator Gain

Exercise 3: Current Response with No Proportional Gain

Exercise 4: PI Current Control Design

Parameter	***Value***	***Units***
R_m		Ω
L_m	53.8	mH
ζ	0.7	
ω_n	42.5	rad/s
$k_{p,c}$		V/A
$k_{i,c}$		V/(A.s)

Table 5: PI current control design parameters.

Exercise 5: Current Response with Designed Controller

Exercise 6: Equilibrium Current (I_{eq})

Exercise 7: Current-Torque Thrust Constant (K_t)

Exercise 8: VTOL Natural Frequency (ω_n)

Parameters	***Symbol***	***Value***	***Units***
Measured Period	T_n		s
Number of oscillations	n		
Natural frequency	f_n		Hz
Natural frequency	ω_n		rad/s

Table 6: VTOL Trainer Natural Frequency

Exercise 9: Moment of Inertia (J)

Exercise 10: Stiffness (K)

Exercise 11: Transfer Function Parameters

Exercise 12: Model Validation of Estimated Transfer Function

Exercise 13: Transfer Function found using System Identification

Exercise 14: Model Validation using Identified Transfer Function

Exercise 15: Identified Parameters

Exercise 16: VTOL Trainer Modeling Results Summary

Parameters	***Symbol***	***Value***	***Units***
Equilibrium current	I_{eq}		A
Torque-thrust constant	K_t		N.m/A
Moment of inertia	J		$kg.m^2$
Viscous damping	B	0.0020	N.m.s/rad
Natural frequency	ω_n		rad/s
Stiffness	K		N.m/rad
Sys ID: Torque-thrust constant (optional)	$K_{t,id}$		N.m/A
Sys ID: Viscous damping (optional)	B_{id}		N.m.s/rad
Sys ID: Stiffness (optional)	K_{id}		N.m/rad

Table 7: VTOL Trainer modeling results summary.

Exercise 17: PD Steady-State Error

Exercise 18: Measured VTOL Trainer PD Steady-State Error

Exercise 19: PID Steady-State Error

Exercise 20: Measured VTOL Trainer PID Steady-State Error

Exercise 21: Find Damping Ratio and Natural Frequency

Exercise 22: Find PID Control Gains

Exercise 23: VTOL Trainer Response with Designed PID Gains

Exercise 24: Measure Peak Time and Overshoot

Exercise 25: VTOL Trainer Control Results Summary

Parameters	***Symbol***	***Value***	***Units***
PD steady-state error	$e_{ss,pd}$		deg
Measured PD steady-state error	$e_{ss,meas,pd}$		deg
PID steady-state error	$e_{ss,pid}$		kg.m^2
Measured PID steady-state error	$e_{ss,meas,pid}$		N.m.s/rad
Desired peak time	t_p	1.0	s
Desired percentage overshoot	PO	20.0	%
Desired pole location	p_0	1.0	rad/s

Natural frequency	ω_n		rad/s
Damping ratio	ζ		N.m/rad
Proportional gain	k_p		A/rad
Integral gain	k_i		A/(rad.s)
Derivative gain	k_v		A.s/rad
Measured peak time	t_p		s
Measured percentage overshoot	PO		%

Table 8: VTOL Trainer control results summary.

6. References

[1] QNET Practical Control Guide
[2] QNET User Guide