# EENG307: Semester Project[*]

## Kathryn Johnson[†]

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## Contents

# 1 Key Assignments and Dates

Project Parts 3.1-3.5 will be due on separate dates throughout the semester as designated in Canvas using the submission instructions for each section (see relevant Canvas assignment). For each of these you will receive feedback that you can incorporate into your next steps via one or more of the following:

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[†]Developed and edited by Tyrone Vincent and Kathryn Johnson, Colorado School of Mines, with contributions from Salman Mohagheghi, Chris Coulston, Kevin Moore, CSM and Matt Kupilik, University of Alaska, Anchorage

- your team's Part 3.x report (for Parts 3.1-3.4)
- your team's brief in-class oral status report (for a randomly-selected subset of teams; applies to Parts 3.1-3.5)
- general tips provide to the class as a result of reviewing each team's submissions and oral status reports (Parts 3.1-3.5)

On the dates that Parts 3.2-3.5 are due, you can also re-submit the most recent previous submission to earn up to 50% of any missed points. Resubmission instructions are included near the end of this document.

Part 3.6 will be part of the final submission, which is due on the date designated in Canvas and will summarize all parts of the project. Details will be provided at least a month before the due date.

I may randomly select teams to provide in-class, informal, oral "project status reports" after each submission due date. In the past, this has been an extremely useful tool to help me identify points of confusion and to help all teams – and especially the one giving the report – know what they may need to improve before the next steps. Unfortunately, the class size this semester precludes requiring every team to give such an in-class report as I have done in the past.

# 2   Objectives

The objectives of this design project are

1. to connect the class concepts to the "real world" in a more realistic experience than individual homeworks and exams allow,
2. to develop goal definition skills, make assumptions, and simplify assumptions,
3. to practice the various modeling, analysis, and design techniques from class,
4. to practice using Simulink, and
5. to practice using engineering judgment and build confidence in your own judgment skills, especially for open-ended tasks.

# 3   Project Description

## 3.1   Problem Definition and Goal Setting

Engineers often describe ourselves as problem-solvers, but we often don't think much about who defines the problem we are solving, who might benefit, who might suffer, who might not be able to participate, etc. In this first stage of the project, you will work with your team to identify and articulate (1) a problem that you'd like to solve, and (2) a goal that you would like to achieve using control systems concepts. This is the "why do we care?" motivating portion of the project.

Choose one of the application areas discussed in the Appendix. Articulate your team's goal, which application area will help you to achieve that goal, and why you think control engineering is relevant to that combination.

> *Example of Problem Definition and Goal Setting: As autonomous vehicle technologies continue to develop, it seems inevitable that the number of autonomous vehicles on the road will continue to increase. Depending on the quality of the sensing and control technologies utilized by these vehicles, there can be both positive and negative impacts on people, communities, and the environment. Our team's goal is to improve the speed control capabilities of an autonomous vehicle so that appropriate safety measures can be maintained for given road and traffic conditions. In particular for this project, our goal is to ensure that each vehicle's speed tracking performance is adequate.*

Once you have defined your control goal(s), suggest some *metrics* to measure how well you've achieved these goals. Note that metrics must be quantifiable and measurable for the system your team has selected.

> *Example metrics: We will quantify the performance of our controller in terms of reference speed tracking error for at least two different nonzero reference speed inputs, one of which is constant and one of which is time varying. In other words, we will consider $r_1(t) = Au(t)$, a stepwise constant reference set appropriately for our road condition (e.g., 55 mph for a highway); and $r_2(t) = f(t)$, where $f(t)$ is a time-varying function designed to mimic a stop-and-go traffic situation. In both cases, we will measure*

*and report on the error $e(t) = r(t) - y(t)$ over a 30-second simulation, including both the maximum and the root-mean-square error.*

### 3.1.1 Part 3.1 Submission

Your Part 3.1 submission should include approximately 2 paragraphs inspired by the examples in this section to define the *problem* you want to solve, your *goal*, and the *metric(s)* you will use to measure whether you have achieved your goal. This submission is expected to be no more than 1/2 page long, and *any material beyond the first page will not be read/graded.*

Please see the Part 3.1 rubric in Canvas for grading details.

## 3.2 Modeling

Once you have defined your problem and selected your plant system from the options in Section 8, you should be able to clearly name the plant's input and output signals. Note that you are working with the *open loop* plant in this Modeling step, as shown in Figure 1.
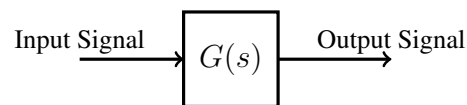


Figure 1: Open loop plant system showing input and output signals as well as plant transfer function $G(s)$

Your open loop plant model should be implemented in Simulink using strategies aligned with Lecture 6: Intro to Simulink. The steps for creating and reporting on this portion of the project include:

1. Find the transfer function $G(s)$ from the input signal to the output signal. You may use differential equation or impedance network techniques to find this transfer function. You are not required to show every step, but should include enough information that it is clear you did not simply find an answer online or via AI.
2. Select plausible numerical values for the parameters in your transfer function. Feel free to use the internet, but be sure to cite your sources, including URLs.
3. Plot the step response – i.e., the output signal vs. time when the input signal is a step function – for this open loop model and show that it conceptually aligns with the relevant step response from Section 8. Comment on any differences you observe according to the control theory we have learned in this class.

### 3.2.1 Part 3.2 Submission

Your Part 3.2 submission should include typeset, easy-to-follow responses to the three items given in this section. This submission is expected to be between 1/2-1 page long (including figure and reference(s)), and *any material beyond the first page will not be read/graded*.

In addition, you can include a revised Part 3.1 submission following the guidelines in Section 5. Your submission of Parts 3.1-3.2 should all be combined into a single PDF file as described in Section 5.

Please see the Part 3.2 rubric in Canvas for grading details.

## 3.3 Open Loop Plant Analysis

In this stage, you will apply theoretical tools learned thus far to analyze your open-loop plant system from Section 3.2 to ensure it is implemented correctly and to set the foundation for the closed-loop control design phase in Section 3.4. To achieve those objectives, please answer the following questions about your open loop plant:

1. Is the plant system BIBO stable according to your team's transfer function derived in Section 3.3?
2. When you simulate the plant's behavior in Matlab or Simulink to a given input (step, impulse, etc.), do the results make sense given the plant's poles? Briefly explain why or why not.

3. Is the plant likely to be disturbed by an outside source (i.e., a disturbance signal)? Why or why not? Will a configuration like the one shown in Figure 2 accurately model the disturbance?
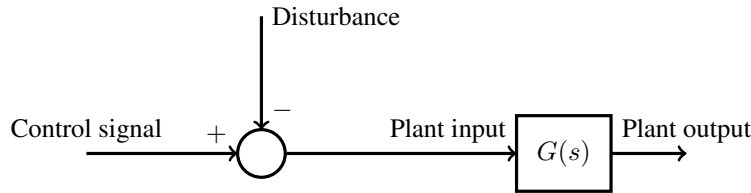4. Are there other questions you think are important to answer about your open loop plant?



Figure 2: Possible configuration for open loop plant with disturbance. Note that the control signal would eventually come from the controller after the feedback loop is created in Section 3.4. It is possible that your disturbance signal might impact your system in a different manner than what is shown here.

### 3.3.1 Part 3.3 Submission

Your Part 3.3 submission should include typeset, easy-to-follow responses to the four items given in this section. This submission is expected to be approximately 1 page long (including figure(s) and reference(s)), and *any material beyond the first two pages will not be read/graded.*

In addition, you can include a revised Part 3.2 submission following the guidelines in Section 5. Your submission of Parts 3.2-3.3 should all be combined into a single PDF file as described in Section 5.

Please see the Part 3.3 rubric in Canvas for grading details.

## 3.4 Closed-Loop Design

In the design phase, you will close the loop (i.e., create a closed loop by using feedback), formulate design specifications to achieve your goal(s), and design your preliminary controller based on control theory.

### 3.4.1 Define Specifications for Closed-Loop System

Consider again the goal(s) you wrote in Section 3.1. Translate them into control systems terminology by matching them to control systems concepts such as steady-state error, settling time, and/or phase margin (you are welcome to choose other concepts from this class, as well). Define at least three specifications that make sense toward achieving that goal. Your three specifications must come from *at least two* of these three categories:

1. transient response specifications (e.g., rise time, settling time, percent overshoot)
2. steady state specifications (e.g., final value, steady state error, disturbance rejection, sinusoidal steady state gain/phase)
3. stability margins for robustness (gain margin, phase margin)

Make sure to explain clearly how each of your specifications connect to the control goals. *Hint: many teams appear paralyzed by the idea of quantifying goals at this stage, but go ahead and do so anyway! You will be allowed to revise your specifications in the next part. The important part here is that you can explain, for example, why you might want your vehicle to settle to its final speed within 3 seconds.*

In addition to the specifications you choose, *your closed-loop system must be BIBO stable.*

### 3.4.2 Closing the Loop

Next, use feedback to close the loop, creating a system with a reference input $R(s)$, controller $C(s)$, plant $G(s)$, plant output $Y(s)$, disturbance, and any other required signals or systems.

Your closed-loop system will probably look something like the one in Figure 3, though details may vary depending on your selected system.
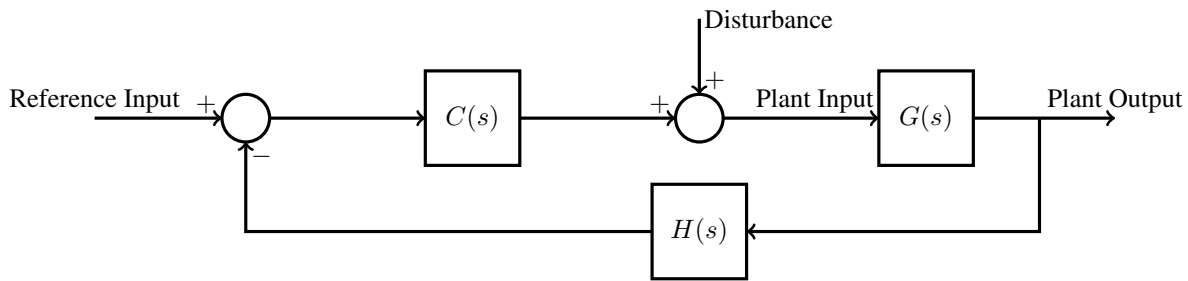
Figure 3: Possible closed-loop configuration including controller $C(s)$, plant $G(s)$, and sensor $H(s)$. Not all projects will have a disturbance or a sensor, but some may.

Now, based on your control goal(s) and specifications, define a reference input signal that you would like your system to track. Common choices include step, ramp, or sinusoid, but you are not required to stick to one of these. In any case, explain why you chose the reference signal.

Then, select a controller structure (e.g., PID or a variation thereof) that seems likely to help you meet your specifications based on what you have learned about control theory (e.g., what type is best for transient specifications? What about steady-state?). Explain why you chose that structure.

Once you have your closed-loop structure and preliminary controller, continue to use theory (for example, direct design of $K_p$, $K_I$, and/or $K_D$ to achieve desired closed-loop pole locations, root locus, or gain/phase margin analysis) to select preliminary gains and/or pole/zero locations for this controller. It is not required that you verify the specifications are met for this stage; the important deliverable is that you are using control tools for the preliminary design.

### 3.4.3   Part 3.4 Submission

Your Part 3.4 submission should include typeset, easy-to-follow responses to the deliverables listed below. This submission is expected to be approximately 1 page long and to include the following deliverables:

1. What type of reference input (or inputs) you chose and why
2. Performance specifications and how they are connected to your control goals. *It's OK if these change at your next submission! But they do need to be quantified and justified here.*
3. Typeset (not hand-drawn) block diagram showing your planned closed-loop system with systems (blocks) and signals labeled according to your selected application (Simulink image OK *only if readable* on a typical monitor at 100% zoom, which is frequently not the case)
4. Preliminary controller structure and gains with theoretical justification. Note that the simulation steps start in Section 3.5 and therefore you are not required to show that controller meets the specifications at this step.
5. Closed loop poles given your preliminary controller, proving that the closed-loop system is stable.

   *Any material beyond the first two pages will not be read/graded.*

   In addition, you can include a revised Part 3.3 submission following the guidelines in Section 5. Your submission of Parts 3.3-3.4 should all be combined into a single PDF file as described in Section 5.

   Please see the Part 3.4 rubric in Canvas for grading details.

## 3.5   Verification and Iteration

In this step, you will simulate the closed-loop design and determine what iterations are necessary.

Once you have a preliminary controller from the previous section, implement it in Simulink and test your results. Are your specifications met? If so, great! In this case, begin reflecting on your success and about how best to explain it to your classmates and professor through your video report. Were you lucky, or meticulous in your design?

Most likely, as in the real world, your specifications won't be met by your first controller design in the initial simulation and there will be some tuning still required. Continue to iterate your control gains and/or controller structure until either (a) both specifications are met, or (b) you prove that they cannot be met as they were originally stated. If you

prove they can't be met, consider whether updated specifications would be necessary or whether a more sophisticated controller might be needed. *Note: you are not required to stay with the PID structure in this step, if for example you find that adding additional controller poles and zeros leads to better performance.*

### 3.5.1 Part 3.5 Submission

Your Part 3.5 submission should include typeset, easy-to-follow responses to the deliverables listed below. This submission is expected to be approximately 1-1.5 pages long and to include the following deliverables:

1. Graphic(s) showing the simulation setup
2. Appropriately-labeled time series plots annotated to verify that your performance specifications are met (or can't be met)
3. Final controller $C(s)$ and gains

*Any material beyond the first two pages will not be read/graded.*

In addition, you can include a revised Part 3.4 submission following the guidelines in Section 5. Your submission of Parts 3.4-3.5 should all be combined into a single PDF file as described in Section 5.

Please see the Part 3.5 rubric in Canvas for grading details.

## 3.6 Robustness Analysis

Finally, compute the gain and phase margins based on your plant system and the final controller. Are the stability margins sufficient to account for the possibility of improperly-modeled dynamics? Based on the margins you have found, determine either (a) how much you can increase or decrease one of your controller gains, or (b) how much time delay your system can tolerate before the closed-loop goes unstable. Verify your theoretical calculation by changing your controller or adding a time delay in Simulink (use `Transport Delay` in the Continuous Library) and observing the time-domain output signal for a gain or delay value just under and over the limit you calculated. *Hint: first consider what type of response you expect to see for a closed-loop unstable system with a given reference signal (step, sinusoid). Also, you may need to decrease your simulation step size within Simulink's options if you choose the time delay option.*

Deliverables for this part of the project include:

1. Gain and phase margin values considering $C(s)$, $G(s)$, and $H(s)$ (if present)
2. Supporting theory and plots for the gain and phase margin calculations
3. Calculation of either new controller gain or time delay that puts the system at the stability margin
4. Time series plot(s) of at least two signals (e.g., just below and just above the calculated margin) verifying your stability margin calculation

### 3.6.1 Part 3.6 Submission

Part 3.6 will be part of the final project submission. Because this is the first semester in which I have had the project submitted in individual parts, I will wait to see how those early submissions are going before providing the details for this final submission.

## 3.7 Tips

Tips to reduce troubleshooting time and effort and to improve your project grade include

- Read the rubric and make sure you have all of the elements included
- Make sure you have your plant model (Section 3.3) implemented correctly in Simulink before adding your controller and feedback loop.
- You can use variables in all Simulink blocks. For example, your transfer function can have `num1` and `den1` written in the relevant numerator and denominator lines, where `num1` and `den1` are initialized in the workspace or within an initialization file and are easier to update without incorporating accidental errors.
- You may find "To Workspace" blocks more useful than Scopes for plotting your output signals.
- Matlab's "plotyy" and "subplot" functions may help to present results in a way that enables easy comparison and enables you to stay within the page limits.

# 4 Reporting

All project part submissions must be typeset and presented in a professional format. It should be generally easy for the graders and I to find the material in each section on which you are being graded – **check the rubrics for each**.

Any material created by others, including use of AI, must be appropriately referenced.

More details on how the reporting format will be graded appear in the rubrics when relevant.

# 5 Resubmissions

My primary goal in allowing you to revise and resubmit is to facilitate your learning. Thus, each resubmission contains two parts: revising according to direct or indirect feedback to improve the quality of your work, and reflecting on where you went wrong and what you learned.

For each resubmission, you must include:

1. A new version of the part you are submitting for regrade *with changes clearly marked*. You can use Track Changes in Word or change the color of the revised text in Overleaf or similar. The revised document should follow the same page limits as the original with the exception of marked deleted text.
2. A brief reflection by each member of the team (with names included) indicating why your original submission went wrong and what you learned from the feedback and/or revision process. These reflections may be approximately 3-5 sentences per person. The reflection does not count against any page limits.

Both parts should be combined into a single PDF along with the new submission in the following order:

(a) Part x submission
(b) Part (x-1) submission
(c) Reflection

Please refer to each section of the Part 3 for the allowable resubmission timing.

Resubmissions can earn up to 50% of points lost in the original submission, which will be added back to the original part's grade on Canvas. For example, if you earned a 6/10 on Part 3.1, you can re-submit it with your Part 3.2 to earn up to 2 additional points (i.e., up to 8/10 on Part 3.1). On the Part 3.3 due date, you can resubmit Part 3.2, but not Part 3.1, and so on.

# 6 Need Help? and Working as a Team

You are always welcome to see me with questions related to this open-ended project. For technical questions, since part of the goal of the project is to enhance your problem-solving confidence separate from an authority figure (by working with your team), I request that as many team members as possible come together with questions. I recognize that schedules do not always allow all team members to attend office hours together and will certainly help partial teams when a good-faith effort is made to involve the entire team in the problem-solving. My goal is to avoid teams dividing the labor and working completely separately on each piece, and I reserve the right to request that more team members attend a meeting if it appears this is happening.

# 7 Grading and Rubrics

See the grading rubrics available in Canvas for each submission.

# 8 Appendix: Strongly Suggested Plant Systems

Here are two suggested plants that I strongly recommend your team choose between. If you have a different "real world" application that your team would like to study instead, you must contact me by Wednesday, Oct. 1 (i.e., 1 week before the model is due in Part 3.2) to get approval. The rationale for this is that modeling of real-world systems can become complicated very quickly and I don't want to see your team struggle hard with this early step and then fail to complete the remaining parts.

## 8.1 Unmanned aerial vehicles (Translational Mechanical System)

Unmanned aerial vehicles (UAVs) have been used in a wide variety of applications, including warfare, natural disaster mapping, and rapid delivery of packages from a major online retailer, to name a few. There are many different types of UAVs; this example concerns a quadcopter, shown in Figure 4.



Figure 4: Quadcopter hovering at a constant height.

To control the height $h(t)$ of the quadcopter, consider the ideal element description below (right), where $F_R$ is the upward force generated by the four rotors and $F_g$ is the downward force due to gravity. Damping due to air resistance is represented with a damping coefficient $b$. This damping is likely small. Note that the gravitational force can be represented as a disturbance (below right).
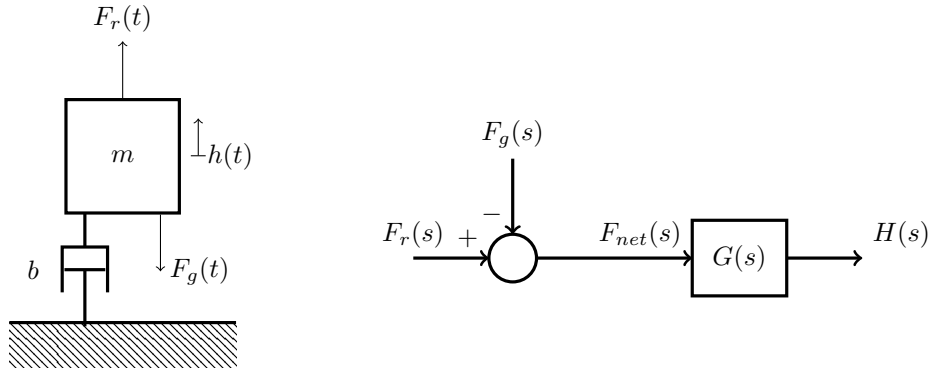


Figure 5: Ideal element diagram and block diagram for quadcopter plant system. Note that the net force $F_{net} = F_r - F_g$ is the input to the plant.

An example step response for the quadcopter is shown in Figure 6.

## 8.2 Wind Turbine With Varying Wind (Rotational Mechanical System)

A wind turbine (Figure 7(a)) is a rotational mechanical system that has a spinning "rotor" (blades plus their connections) with a large rotational inertia $J$. In some portions of its operational region, it can be desired to control the rotational speed $\omega$ of the rotor to maximize the energy conversion efficiency from the wind.

When the turbine is spinning, there is some aerodynamic damping caused by air resistance, so any model of the system should include a damping coefficient $b$. The generator torque $\tau_{gen}$ can be used to partially control the turbine's speed by counteracting the time-varying, uncontrollable aerodynamic torque $\tau_{aero}$ generated by the wind. The block diagram for this looks similar to the quadcopter block diagram and is shown in Figure 7(b). However, there is a key
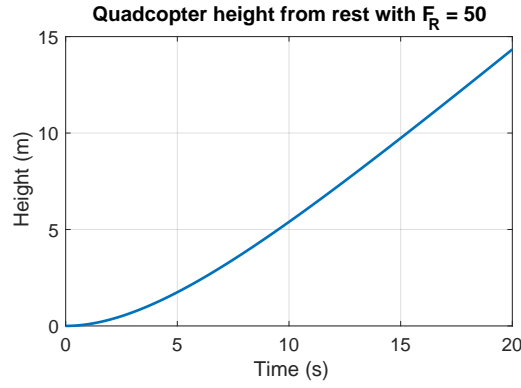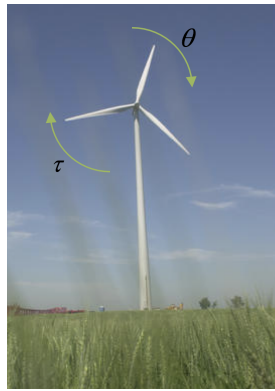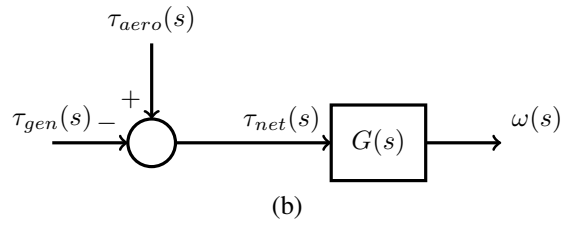
Figure 6: Step response: applied force to quadcopter height.



(a)



(b)

Figure 7: (a) Image of wind turbine with torque $\tau$ and rotational position $\theta$ indicated. (b) Block diagram for wind turbine plant with disturbance torque caused by the wind.

difference in that it is the aerodynamic torque that has a positive sign – driving the turbine to spin with a positive velocity – whereas the generator torque has a negative sign to slow the turbine down while extracting energy.

To get a sense for how this plant system would operate, the step response for a case with a sinusoidal disturbance (torque from the wind) and a step control signal (generator torque) are implemented in Simulink, with results plotted in Figure 8.
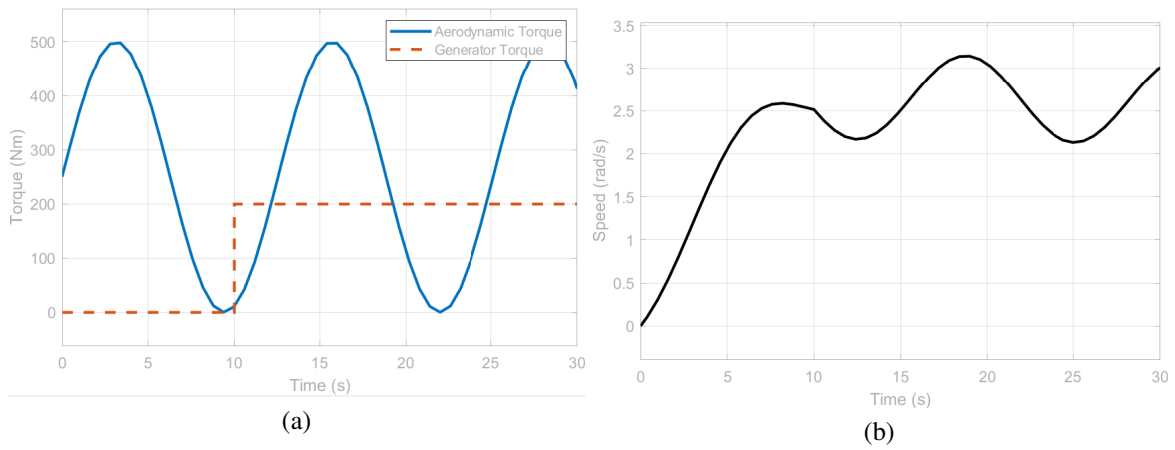
Figure 8: (a) Aerodynamic (disturbance) and generator (control) torque input signals, and (b) resulting rotor speed.