

Dynamical Systems Homework 1

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```
[1]: # toc (adds a table of contents)
from typing import Callable, List, Iterable

import matplotlib.pyplot as plt
import numpy as np
import sympy as sp
from scipy.integrate import odeint
from scipy.interpolate import interp1d
import pandas as pd

plt.style.use('../maroon_ipynb.mplstyle') # applies MSU theme to plots
```

Contents

Problem 1	3
Given	3
Find	3
Solution	3
Part A	3
Part B	4
Part C	6
Part D	7
Verification	8
 Problem 2	 9
Given	9
Find	9
Solution	9
Part A	9
Part B	10
Verification	10
 Problem 3	 12
Given	12
Find	12
Solution	12
Verification	13
 Problem 4	 15
Given	15
Find	16
Solution	16
Part A	16
Part B	17
Part C	17
Verification	18
 Problem 5	 20
Given	20
Find	20
Solution	20
Part A	20
Part B	21
Verification	21

Problem 1

Given

$$\frac{d^2x}{dt^2} - \mu(1 - x^2) \frac{dx}{dt} + x - A \sin(\omega t) = 0$$

where $\mu = 1$, $\omega = \frac{2\pi}{10}$, and $A = 10$

Find

From the differential equation above,

- Find the state variable form.
- Use Euler's Explicit method to obtain a numerical solution of the state variable equations from part (a). Assume zero initial conditions and that $t \leq 20$. Find the smallest value of Δt that gives a converged solution (solution doesn't change as time step decreases).
- Repeat part (b) using a fourth order runge kutta solver with a fixed time step.
- The results in parts (b) and (c) should be the same, but the value of Δt chosen for (c) should be greater than that for part (b). If the method used in part (c) requires four times the computational resources per time step, compare the computational resources for each case.

Solution

Part A

```
[2]: mu_, omega_, A_ = 1, 2*np.pi/10, 10 # constants (units not given)

# Defining the ODE
t, mu, omega, A = sp.symbols('t mu omega A')
x0 = sp.Function('x_0')(t)

eq = sp.Eq(x0.diff(t, 2) - mu*(1 - x0**2)*x0.diff(t) + x0 - A*sp.sin(omega*t), 0)
eq
```

[2]:
$$-A \sin(\omega t) - \mu(1 - x_0^2(t)) \frac{d}{dt}x_0(t) + x_0(t) + \frac{d^2}{dt^2}x_0(t) = 0$$

This is a just a single second order ODE, so it only requires one state variable to make a system of first order ODEs.

```
[3]: # Define the new state variable
x1 = sp.Function('x_1')(t)

# Add the new state variable as the second equation
eq2 = sp.Eq(x1, x0.diff(t))

# Substitute the second state variable into the original equation
eq1 = eq.subs(x0.diff(t), x1)
display(eq1, eq2)
```

$$-A \sin(\omega t) - \mu(1 - x_0^2(t))x_1(t) + x_0(t) + \frac{d}{dt}x_1(t) = 0$$

$$x_1(t) = \frac{d}{dt}x_0(t)$$

```
[4]: # Solve the system of equations
sol = sp.solve([eq1, eq2], [x0.diff(), x1.diff()], dict=True)[0]
for key, value in sol.items():
    display(sp.Eq(key, value))
```

$$\frac{d}{dt}x_0(t) = x_1(t)$$

$$\frac{d}{dt}x_1(t) = A \sin(\omega t) - \mu x_0^2(t)x_1(t) + \mu x_1(t) - x_0(t)$$

As seen above, only first order derivatives are on the left hand side, and the instantaneous states are on the right hand side. This is the state variable form, but we can just manually write the python function for numerical use with how simple this is. For more complex problems, you can automate the conversion from `sympy` operations to python or `numpy` operations by using the `lambdify` function.

```
[5]: # Defining state variable function
def state_vars(x, t_):
    return [
        x[1],
        A*np.sin(omega*t_) - mu*x[0]**2*x[1] + mu*x[1] - x[0]
    ]
```

Part B

The below code cell is the routine for Euler's Explicit method and takes into account any number of ODE's.

```
[6]: def euler_explicit(func: Callable, y0: List | Iterable, t_values: List |
↳ Iterable) -> List:
    n = len(func(y0, t_values[0]))
    arrays = [[y0_] for y0_ in y0]

    for i in range(len(t_values) - 1):
        h = t_values[i + 1] - t_values[i]
        current_state = [array[-1] for array in arrays]
        derivatives = func(current_state, t_values[i])
        for j in range(n):
            arrays[j].append(arrays[j][-1] + h*derivatives[j])

    return arrays
```

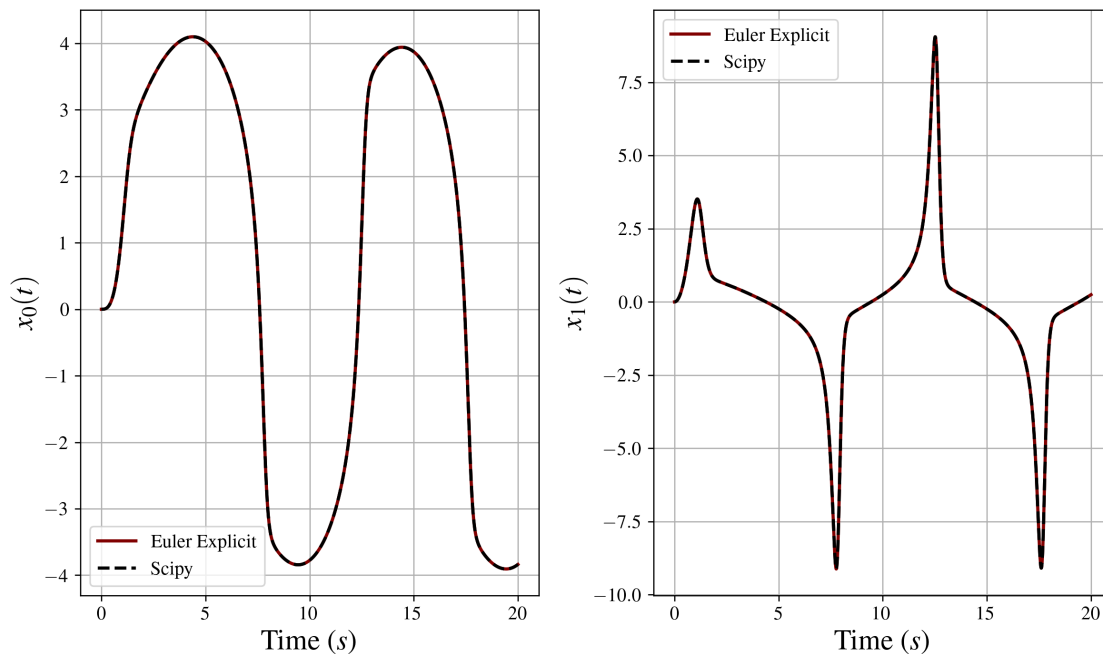
To measure the error of the Euler's Explicit method, we can compare it to the `scipy` solution using the `odeint` function. We can assume that the `scipy` solution is the true solution and the error will be determined by

$$err = \max(|x_{num} - x_{exact}|)$$

We will choose the time step that gives $err < 10^{-3}$.

```
[7]: err = 1
del_t = 0.1
t_array, x0_euler, x1_euler, scipy_sol = None, None, None, None
while err > 1e-3:
    del_t /= 2
    t_array = np.arange(0, 20, del_t)
    sol = euler_explicit(state_vars, [0, 0], t_array)
    scipy_sol = odeint(state_vars, [0, 0], t_array)
    x0_euler, x1_euler = np.array(sol[0]), np.array(sol[1])
    err = np.max(np.abs(x0_euler - scipy_sol[:, 0]))

fig, ax = plt.subplots(nrows=1, ncols=2)
ax[0].plot(t_array, x0_euler, label='Euler Explicit')
ax[0].plot(t_array, scipy_sol[:, 0], label='Scipy', ls='--')
ax[1].plot(t_array, x1_euler, label='Euler Explicit')
ax[1].plot(t_array, scipy_sol[:, 1], label='Scipy', ls='--')
ax[0].set_ylabel('$x_0(t)$')
ax[1].set_ylabel('$x_1(t)$')
ax[0].set_xlabel('Time ($s$)')
ax[1].set_xlabel('Time ($s$)')
ax[0].legend()
ax[1].legend()
plt.show()
```



```
[8]: del_t_euler = del_t
del_t_euler # resulting time step used above
```

```
[8]: 2.44140625e-05
```

Part C

Similarly to Part B, here is the routine for the fourth order Runge-Kutta method.

```
[9]: def runge_kutta(func: Callable, y0: List | Iterable, t_values: List | Iterable) → List:
    n = len(func(y0, t_values[0]))
    arrays = [[y0_] for y0_ in y0]

    for i in range(len(t_values) - 1):
        h = t_values[i + 1] - t_values[i]
        K1 = func([array[i] for array in arrays], t_values[i])
        K2 = func([array[i] + 0.5*h*K for array, K in zip(arrays, K1)],
    t_values[i] + 0.5*h)
        K3 = func([array[i] + 0.5*h*K for array, K in zip(arrays, K2)],
    t_values[i] + 0.5*h)
        K4 = func([array[i] + h*K for array, K in zip(arrays, K3)], t_values[i]
    + h)

        for j in range(n):
            arrays[j].append(arrays[j][i] + h/6*(K1[j] + 2*K2[j] + 2*K3[j] +
    K4[j]))

    return arrays

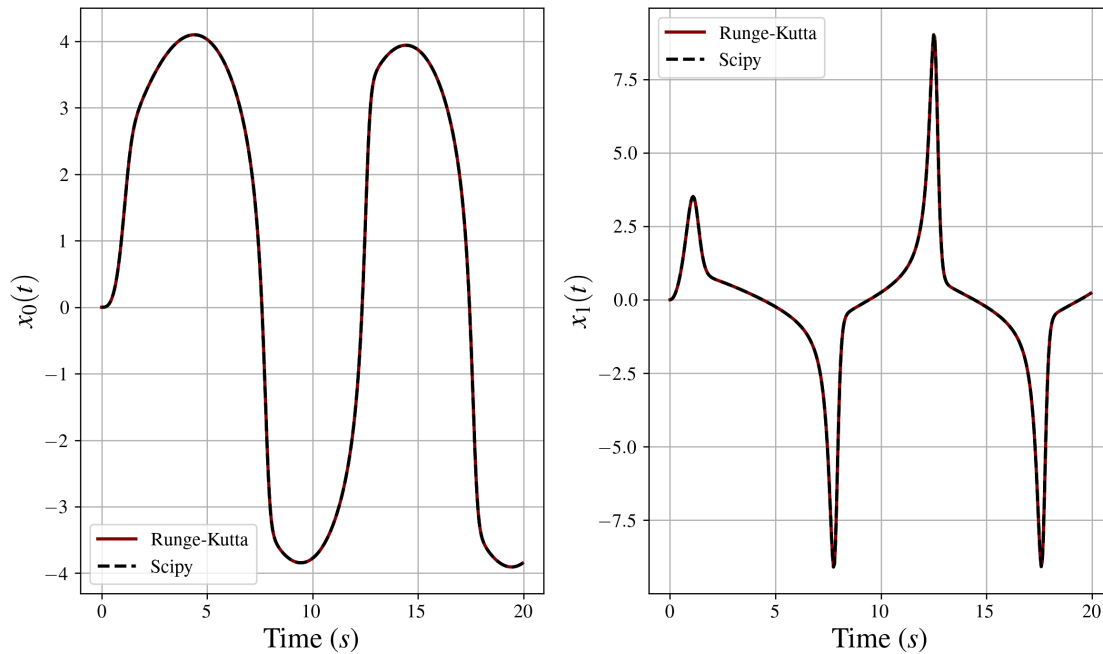
err = 1
del_t = 0.1
t_array, x0_rk, x1_rk = None, None, None
while err > 1e-3:
    del_t /= 2
    t_array = np.arange(0, 20, del_t)
    sol = runge_kutta(state_vars, [0, 0], t_array)
    scipy_sol = odeint(state_vars, [0, 0], t_array)
    x0_rk, x1_rk = np.array(sol[0]), np.array(sol[1])
    err = np.max(np.abs(x0_rk - scipy_sol[:, 0]))

fig, ax = plt.subplots(nrows=1, ncols=2)
ax[0].plot(t_array, x0_rk, label='Runge-Kutta')
ax[0].plot(t_array, scipy_sol[:, 0], label='Scipy', ls='--')
ax[1].plot(t_array, x1_rk, label='Runge-Kutta')
```

```

ax[1].plot(t_array, scipy_sol[:, 1], label='Scipy', ls='--')
ax[0].set_ylabel('$x_0(t)$')
ax[1].set_ylabel('$x_1(t)$')
ax[0].set_xlabel('Time ($s$)')
ax[1].set_xlabel('Time ($s$)')
ax[0].legend()
ax[1].legend()
plt.show()

```



```

[10]: del_t_rk = del_t
      del_t_rk # resulting time step used above

```

[10]: 0.05

Part D

As you can see above, with the convergence criteria, the Euler Explicit method converges at a time step of $2.44140625 \cdot 10^{-5}$, and the Runge-Kutta method converges at a time step of 0.05. The Runge-Kutta method, however, has four times more computations for each time step, but has far fewer time steps to converge.

```

[11]: euler_array_size = np.arange(0, 20, del_t_euler).size
      rk_array_size = np.arange(0, 20, del_t_rk).size
      euler_array_size, rk_array_size

```

[11]: (819200, 400)

The above output shows that the Euler Explicit array has a size of 819200, while the Runge-Kutta has a size of 400. Even with the four extra computations per time step, the Runge-Kutta method is more computationally efficient because $4 \cdot 400 = 1600 \ll 819200$.

Verification

The above problems show that the `scipy` solver agrees with the Euler Explicit and Runge-Kutta methods. We can further verify that this solution is correct by testing the original differential equation. We can plug each solution into the original equation and see if the error is close to zero.

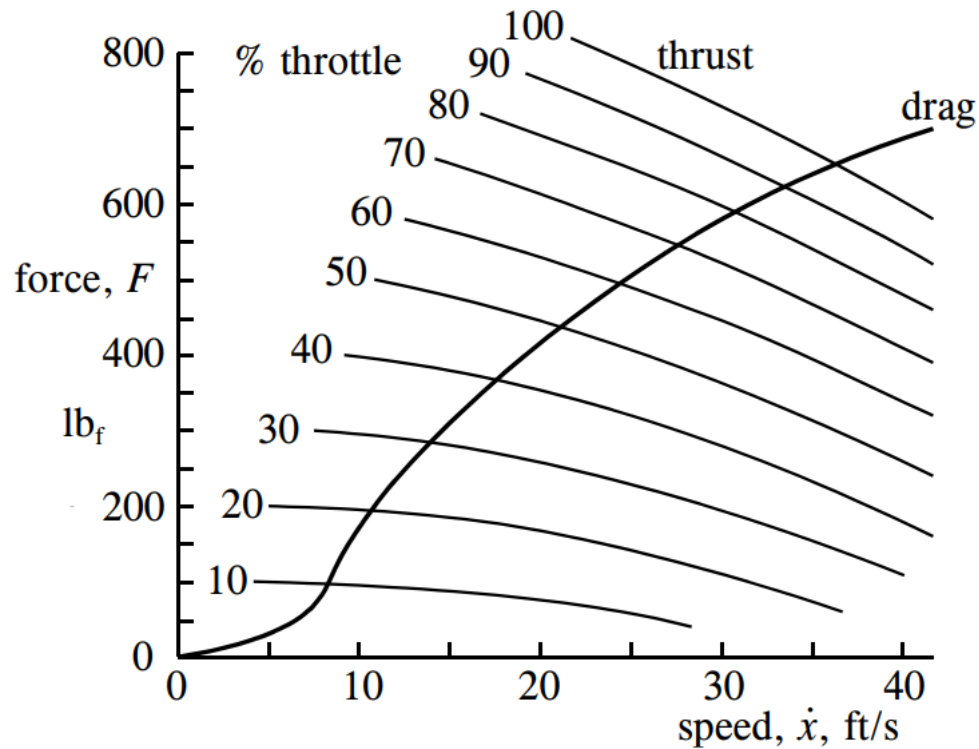
```
[12]: x0, x1 = scipy_sol[:, 0], scipy_sol[:, 1]
      x1_dot = np.gradient(x1, t_array, edge_order=2)
      err = x1_dot - mu_*(1 - x0**2)*x1 + x0 - A_*np.sin(omega_*t_array)
      np.mean(err)
```

```
[12]: -0.0001447673813758238
```

The above cell finds the mean error for each time step and shows that the error is very close to zero. This estimate incurs a non-negligible error when it numerically solves for the second order derivative (\ddot{x}_0).

Problem 2

Given



The above image shows thrust/speed and drag force on a 4000 lbs boat. The thrust is based on the throttle position indicated as a percentage. The boat is traveling at a steady 20 ft/s until the throttle abruptly resets to 80%.

Find

- Find the thrust and drag forces before the velocity has time to change.
- Find the instantaneous acceleration of the boat.

Solution

Part A

The force balance for this system is simply

$$F_{thrust} - F_{drag} = ma$$

```
[13]: m = 4000/32.174 # mass in slugs

# Plotting the curves of interest
drag = pd.read_csv('drag.csv')
thrust_40 = pd.read_csv('thrust40.csv')
```

```
thrust_50 = pd.read_csv('thrust50.csv')
thrust_80 = pd.read_csv('thrust80.csv')
```

If the boat is initially travelling at a constant 20 ft/s, then the thrust and force values must be equal.

```
[14]: # Interpolating the drag force curve and finding force at 20 ft/s
drag_force = interp1d(drag['speed'], drag['force'], kind='linear')
F_drag = np.float64(drag_force(20))
F_drag # lbs
```

```
[14]: 413.98524403963677
```

```
[15]: # Interpolating the thrust force curve at 80% throttle to find the thrust force
      ↪ at 20 ft/s
thrust_force_80 = interp1d(thrust_80['speed'], thrust_80['force'],
      ↪ kind='linear')
F_thrust = np.float64(thrust_force_80(20))
F_thrust # lbs
```

```
[15]: 688.5774442946789
```

Part B

The instant that the throttle is changed to 80%, the force state of on the boat is $F_{thrust} - F_{drag}$, which was determined above. The acceleration is simply that divided by the mass.

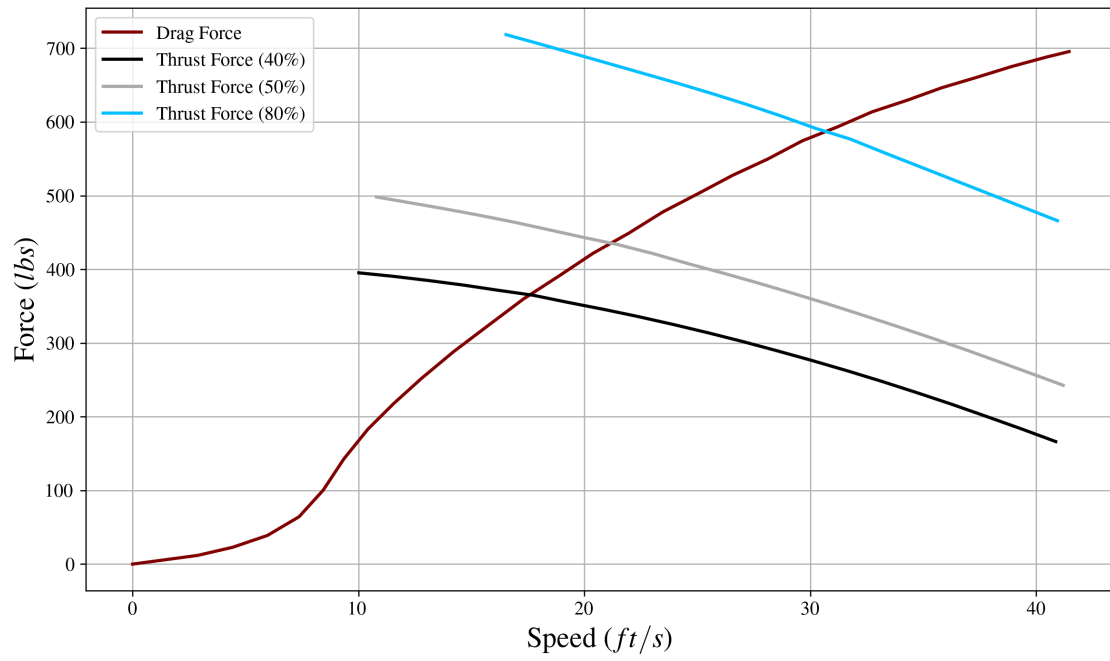
```
[16]: a = (F_thrust - F_drag)/m
      a # ft/s2
```

```
[16]: 2.2086823627514316
```

Verification

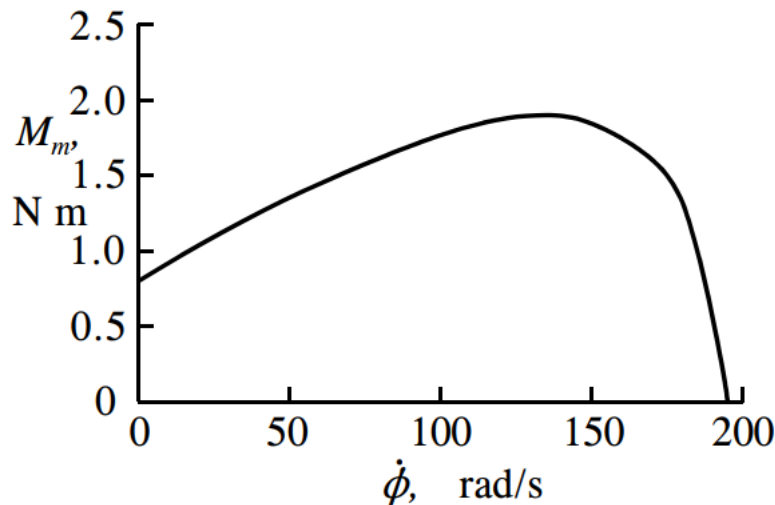
You can see the calculated values more clearly by plotting the dataset. The graph below shows the thrust and drag forces were correctly interpolated at 20 ft/s.

```
[17]: fig, ax = plt.subplots()
ax.plot(drag['speed'], drag['force'], label='Drag Force')
ax.plot(thrust_40['speed'], thrust_40['force'], label=r'Thrust Force (40\%)')
ax.plot(thrust_50['speed'], thrust_50['force'], label=r'Thrust Force (50\%)')
ax.plot(thrust_80['speed'], thrust_80['force'], label=r'Thrust Force (80\%)')
ax.set_xlabel('Speed ($ft/s$)')
ax.set_ylabel('Force ($lbs$)')
ax.legend()
plt.show()
```



Problem 3

Given



The image above shows the moment curve on a shaft with respect to varying angular velocities.

Find

Estimate the maximum power P_{max} the induction motor can deliver, and the associated torque M and angular velocity $\dot{\theta}$. Also, find the ratio of this power to the power P_{maxM} (power at maximum torque) delivered when the torque is maximized.

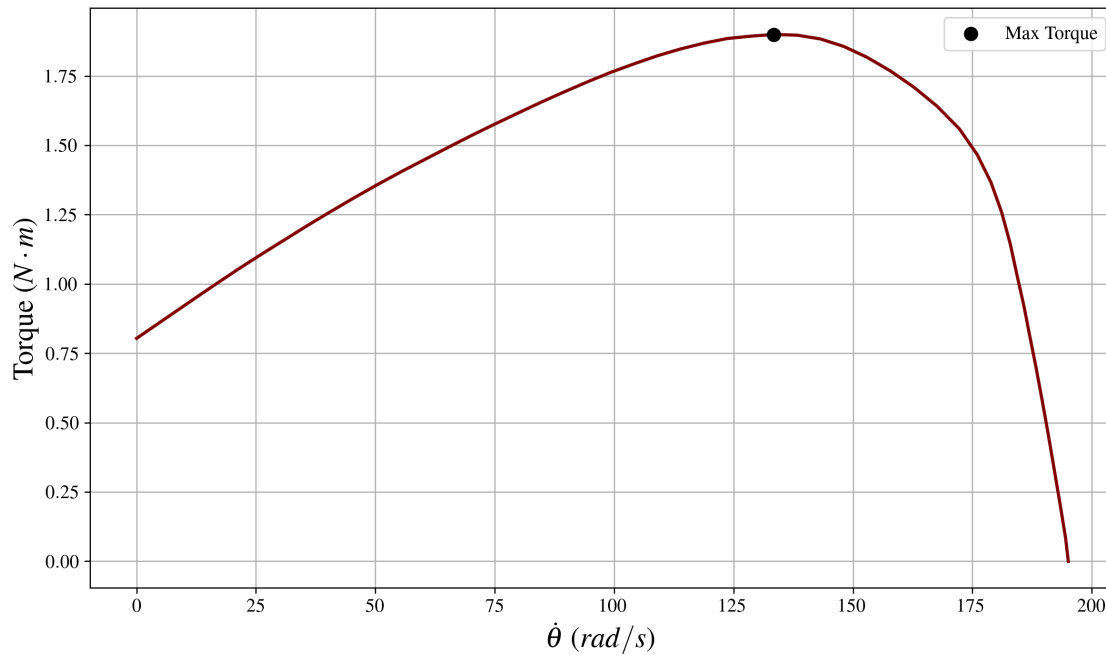
Solution

We first need to convert the torque curve into a dataset.

```
[18]: motor_data = pd.read_csv('motor_data.csv')

max_M = np.max(motor_data['M']) # N*m
max_M_theta = np.array(motor_data['theta_dot'])[motor_data['M'] == max_M][0]

fig, ax = plt.subplots()
ax.plot(motor_data['theta_dot'], motor_data['M'])
ax.scatter(max_M_theta, max_M, color='black', label='Max Torque', zorder=3)
ax.set_xlabel(r'$\dot{\theta}$ ($rad/s$)')
ax.set_ylabel(r'Torque ($N\cdot m$)')
ax.legend()
plt.show()
```



For each point in the dataset, the power is

$$P = M \cdot \dot{\theta}$$

```
[19]: # Getting power
power = np.array(motor_data['M']*motor_data['theta_dot'])
P_max = np.max(power)
max_P_theta = np.array(motor_data['theta_dot'])[power == P_max][0]
P_max # W
```

```
[19]: 279.09391404004356
```

```
[20]: # Getting power at maximum torque
P_maxM = max_M*max_M_theta
P_maxM # W
```

```
[20]: 253.51556550997947
```

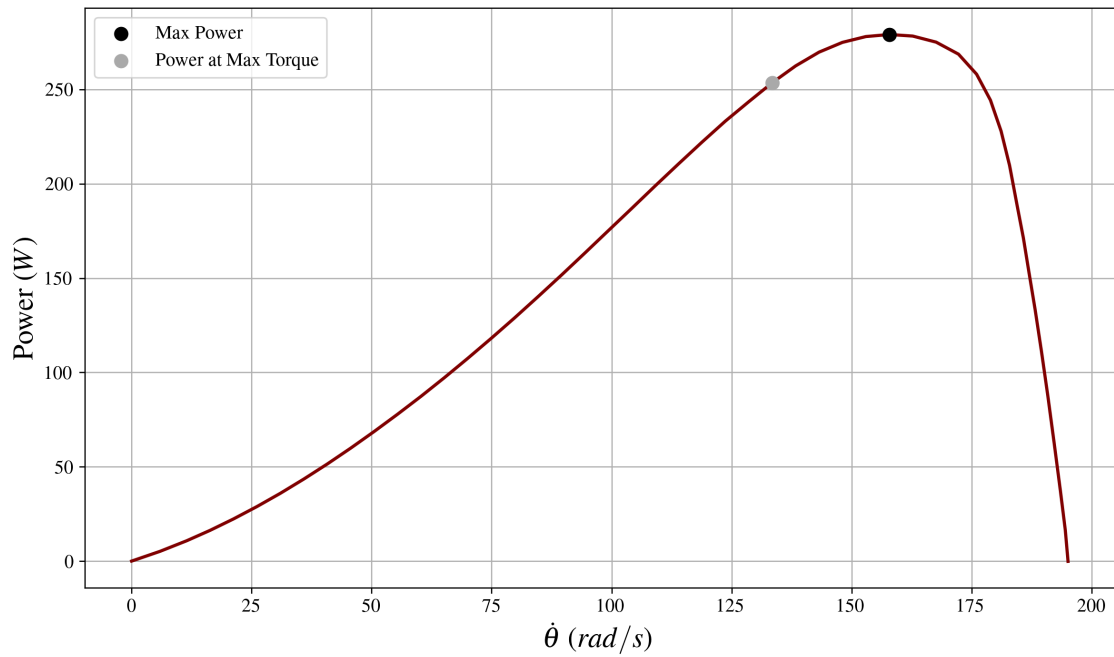
```
[21]: # Getting the ratio of the two
P_max/P_maxM
```

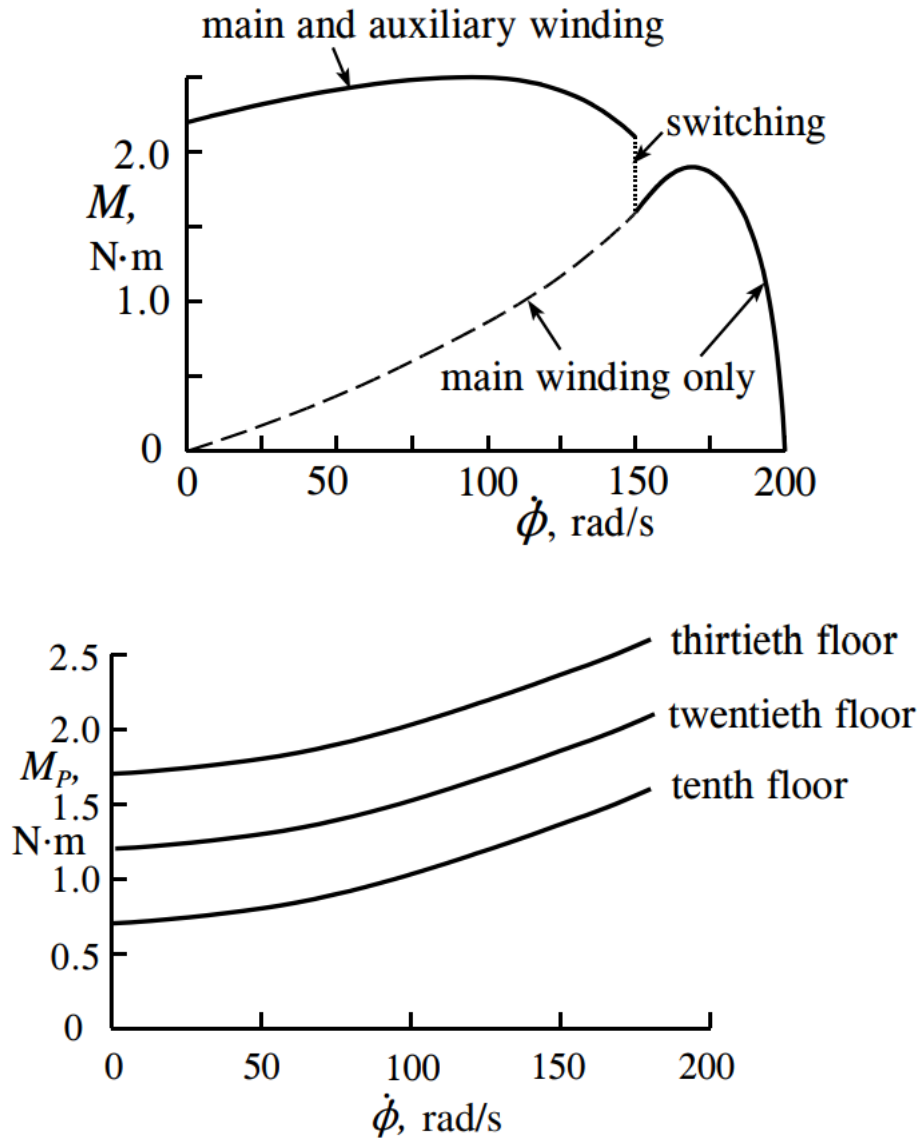
```
[21]: 1.1008945879855934
```

Verification

You can see the results are correct on the graph below.

```
[22]: fig, ax = plt.subplots()
ax.plot(motor_data['theta_dot'], power)
ax.scatter(max_P_theta, P_max, color='black', label='Max Power', zorder=3)
ax.scatter(max_M_theta, P_maxM, color='darkgrey', label='Power at Max Torque', zorder=3)
ax.set_xlabel(r'\dot{\theta} ($rad/s$)')
ax.set_ylabel('Power ($W$)')
ax.legend()
plt.show()
```



Problem 4**Given**

The curves above indicate a similar system to the previous problem, but this time, there is a resistive torque acting on the motor shaft. The second image shows the twentieth floor resistive torque. The first image indicates the motor generated motor torque. This motor has a switching component that adds the ability to initiate a faster angular velocity, which adds stability at higher speeds. This can be thought of like a transmission in a car, changing the gear ratio to make certain speeds stable. The shaft has an equivalent inertia of $0.015 \text{ kg} \cdot \text{m}^2$.

Find

- Estimate the average net torque available for acceleration over the speed range $0 < \dot{\phi} < 100 \text{ rad/s}$.
- Repeat (a) for the speed ranges $100 < \dot{\phi} < 130 \text{ rad/s}$ and $130 < \dot{\phi} < 150 \text{ rad/s}$.
- Estimate the time required for the system to accelerate from rest to the switching speed of 150 rad/s .

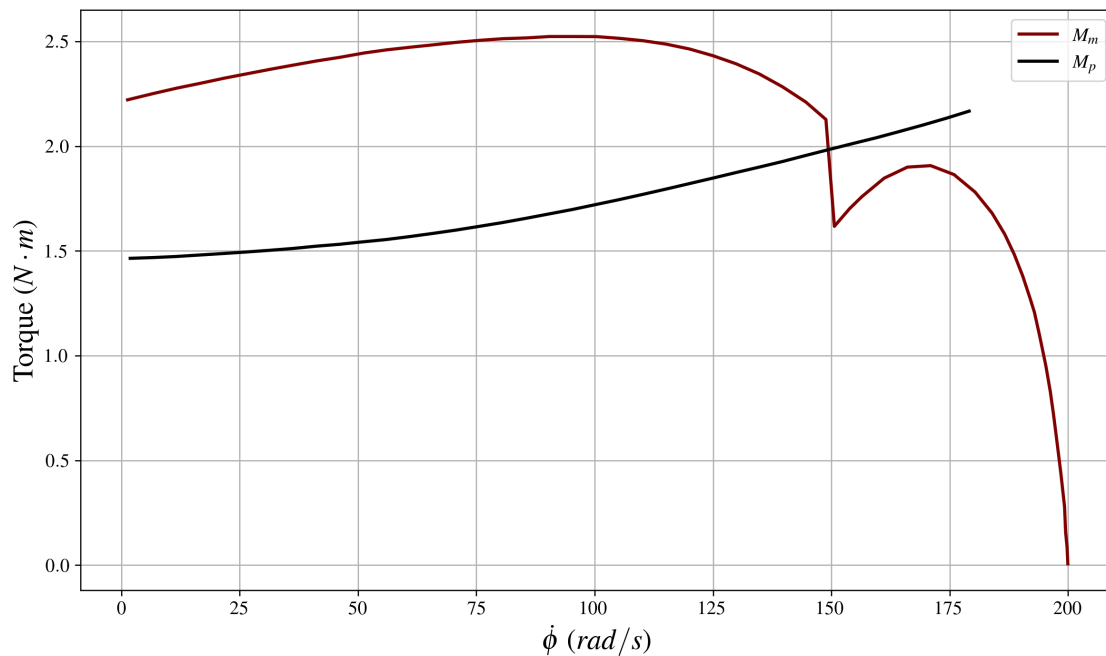
Solution

Part A

We need to superimpose the motor torque curve (M_m) and the resistive fluid torque curve on the twentieth floor (M_p).

```
[23]: switch_motor = pd.read_csv('switching_motor_data.csv')
resistive_data = pd.read_csv('resistive_torque_20.csv')
phi_dot_Mp = np.array(resistive_data['phi_dot'])
Mp = np.array(resistive_data['Mp'])
phi_dot_Mm = np.array(switch_motor['phi_dot'])
Mm = np.array(switch_motor['Mm'])

fig, ax = plt.subplots()
ax.plot(phi_dot_Mm, Mm, label='$M_m$')
ax.plot(phi_dot_Mp, Mp, label='$M_p$')
ax.set_xlabel(r'$\dot{\phi}$ ($\text{rad/s}$)')
ax.set_ylabel(r'Torque ($N \cdot m$)')
ax.legend()
plt.show()
```



We need to determine the average net torque from 0 to 100 rad/s.

```
[24]: # We will perform the operations over the phi_dot_Mm array because the phi_dot_Mp
      ↪ sizes are not the same
      Mp_func = interp1d(phi_dot_Mp, Mp, kind='linear', fill_value='extrapolate')

      zero_to_100 = np.logical_and(phi_dot_Mm > 0, phi_dot_Mm < 100)
      Mm_to_100 = Mm[zero_to_100]
      phi_dot_Mm_to_100 = phi_dot_Mm[zero_to_100]

      # Getting the net torque across this range
      M_to_100 = Mm_to_100 - Mp_func(phi_dot_Mm_to_100)
      M_mean_to_100 = np.mean(M_to_100)
      M_mean_to_100 # N*m
```

```
[24]: 0.85845336699358
```

Part B

We can find the average net torque of 100 to 130 and 130 to 150 using the same procedure.

```
[25]: i2 = np.logical_and(phi_dot_Mm >= 100, phi_dot_Mm < 130)
      Mm_2 = Mm[i2]
      phi_dot_Mm_2 = phi_dot_Mm[i2]

      # Computing the mean net torque from 100 to 130
      M2 = Mm_2 - Mp_func(phi_dot_Mm_2)
      M2_mean = np.mean(M2)
      M2_mean # N*m
```

```
[25]: 0.6775943282803308
```

```
[26]: i3 = np.logical_and(phi_dot_Mm >= 130, phi_dot_Mm < 150)
      Mm_3 = Mm[i3]
      phi_dot_Mm_3 = phi_dot_Mm[i3]

      # Computing the mean net torque from 130 to 150
      M3 = Mm_3 - Mp_func(phi_dot_Mm_3)
      M3_mean = np.mean(M3)
      M3_mean # N*m
```

```
[26]: 0.3008080984842129
```

Part C

The dynamics of this system is expressed by

$$M_{net}(\dot{\phi}) = I \frac{d\dot{\phi}}{dt}$$

This can be re-arranged to be

$$dt = I \left(\frac{1}{M_{net}(\dot{\phi})} \right) d\dot{\phi}$$

$$t = I \int_0^{150} \frac{1}{M_{net}(\dot{\phi})} d\dot{\phi}$$

We don't have the net moment as a function of $\dot{\phi}$, but we do have the discretized dataset. We can just take the reciprocal over the dataset and use the trapezoid rule to estimate the integral.

```
[27]: # Getting the net moment data set from 0 to 150
I = 0.015 # kg*m^2
i4 = np.where(phi_dot_Mm <= 150)
phi_dot_to_150 = phi_dot_Mm[i4]
Mm_to_150 = Mm[i4]

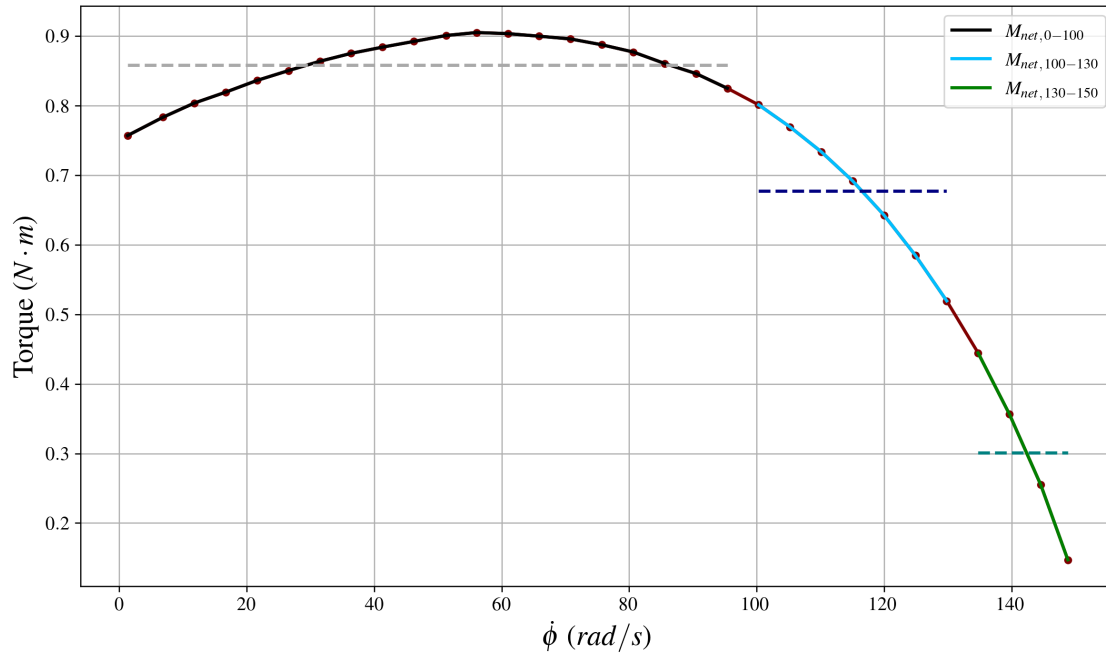
M_net_to_150 = Mm_to_150 - Mp_func(phi_dot_to_150)
area = np.trapz(1/M_net_to_150, phi_dot_to_150)
t_elapsed = I*area
t_elapsed # s
```

[27]: 3.324234091463819

Verification

For parts (a) and (b), we can check the mean net torques by graphing it.

```
[28]: fig, ax = plt.subplots()
ax.plot(phi_dot_to_150, M_net_to_150, marker='.')
ax.plot(phi_dot_Mm_to_100, M_to_100, label=r'$M_{net, \, 0-100}$')
ax.plot([phi_dot_Mm_to_100[0], phi_dot_Mm_to_100[-1]], [M_mean_to_100,
↳ M_mean_to_100], ls='--')
ax.plot(phi_dot_Mm_2, M2, label=r'$M_{net, \, 100-130}$')
ax.plot([phi_dot_Mm_2[0], phi_dot_Mm_2[-1]], [M2_mean, M2_mean], ls='--')
ax.plot(phi_dot_Mm_3, M3, label=r'$M_{net, \, 130-150}$')
ax.plot([phi_dot_Mm_3[0], phi_dot_Mm_3[-1]], [M3_mean, M3_mean], ls='--')
ax.set_xlabel(r'$\dot{\phi}$ ($rad/s$)')
ax.set_ylabel(r'Torque ($N\cdot m$)')
ax.legend()
plt.show()
```



As for verifying the elapsed time calculation, the average net mean should be equivalent to $I \cdot \frac{\Delta \dot{\phi}}{\Delta t}$.

```
[29]: I*(phi_dot_to_150[-1] - phi_dot_to_150[0])/t_elapsed # N*m
```

```
[29]: 0.6657136222702001
```

```
[30]: np.mean(M_net_to_150)
```

```
[30]: 0.7456600010248634
```

The values aren't identical, but this is due to non-uniformity in the dataset. Nevertheless, the answers are in the ballpark.

Problem 5

Given

Consider an impeller pump with the following source curve

$$P_s(Q) = 83 - 0.004901Q - 0.000324Q^2$$

This source drives a load with a load curve of $P_L(Q) = 20 + 0.1Q$. In both the source and load curves pressure has units of psi and Q has units of $\frac{\text{in}^3}{\text{s}}$.

Find

- Estimate the equilibrium pressure and flow.
- Assuming the load can be changed arbitrarily, find the maximum power point on the source curve.

Solution

Part A

The equilibrium pressure and flow occurs when the pressure of the source and load curves are equal.

```
[31]: # Solving for the flow rates
Q = sp.Symbol('Q')
source = 83 - sp.S('0.004901')*Q - sp.S('0.000324')*Q**2
load = 20 + sp.S('0.1')*Q
eq = sp.Eq(source, load)
eq
```

```
[31]: -0.000324Q2 - 0.004901Q + 83 = 0.1Q + 20
```

```
[32]: Q_sol = sp.solve(eq)
Q_eq = Q_sol[1]
display(*Q_sol) # in3/s
```

```
-631.619246076681
```

```
307.850727558163
```

```
[33]: # Getting the pressure
source.subs(Q, Q_sol[0]) # psi
```

```
[33]: -43.1619246076681
```

```
[34]: P_eq = source.subs(Q, Q_sol[1])
P_eq # psi
```

```
[34]: 50.7850727558163
```

In the above calculations, there appears to be an equilibrium point at a negative flow rate. I am going to ignore negative flow rates and assume the fluid is flowing with the pump direction. Therefore, our equilibrium point is $Q = 308 \frac{\text{in}^3}{\text{s}}$, $P = 50.8 \text{ psi}$.

Part B

Power is

$$P = P_s \cdot Q$$

```
[35]: P = source*Q

# Finding the peak
dP_dQ = P.diff()
Q_sol_power = sp.solve(dP_dQ)
Q_peak = Q_sol_power[1]
display(*Q_sol_power) # in^3/s
```

−297.30297230272

287.218610162803

```
[36]: # Only use the positive value
P.subs(Q, Q_sol_power[1]) # lbf*in/s
```

```
[36]: 15757.9945317928
```

```
[37]: P_peak = P.subs(Q, Q_sol_power[1])/6600
P_peak # hp (peak source power)
```

```
[37]: 2.38757492905951
```

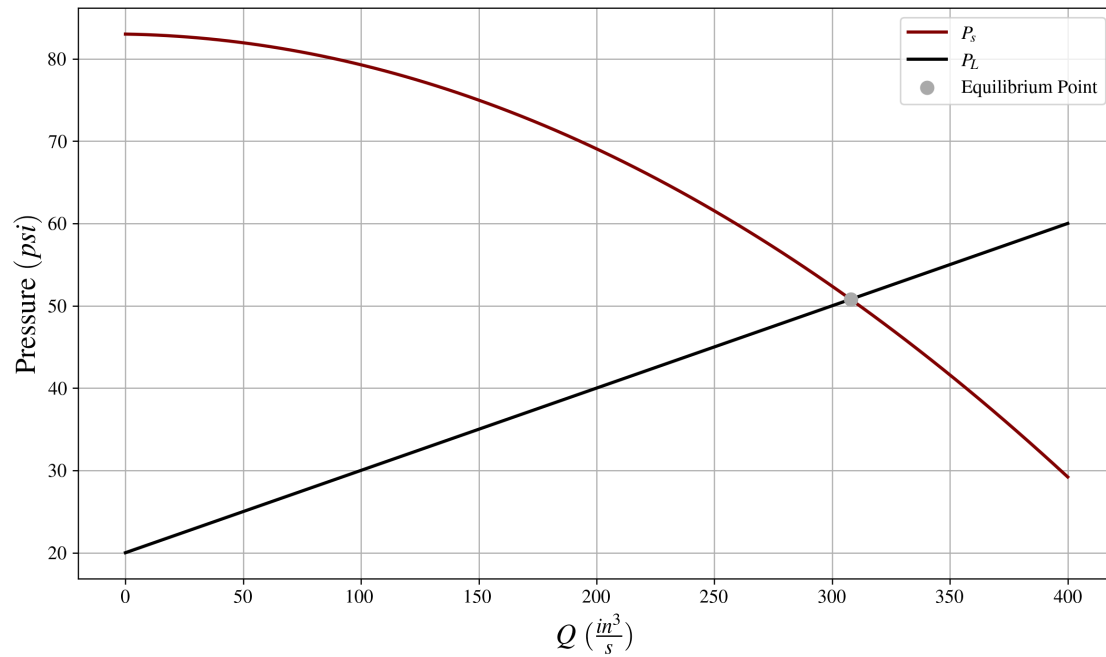
As seen above, the peak power is 2.39 hp at $287 \frac{\text{in}^3}{\text{s}}$.

Verification

Here are the plots.

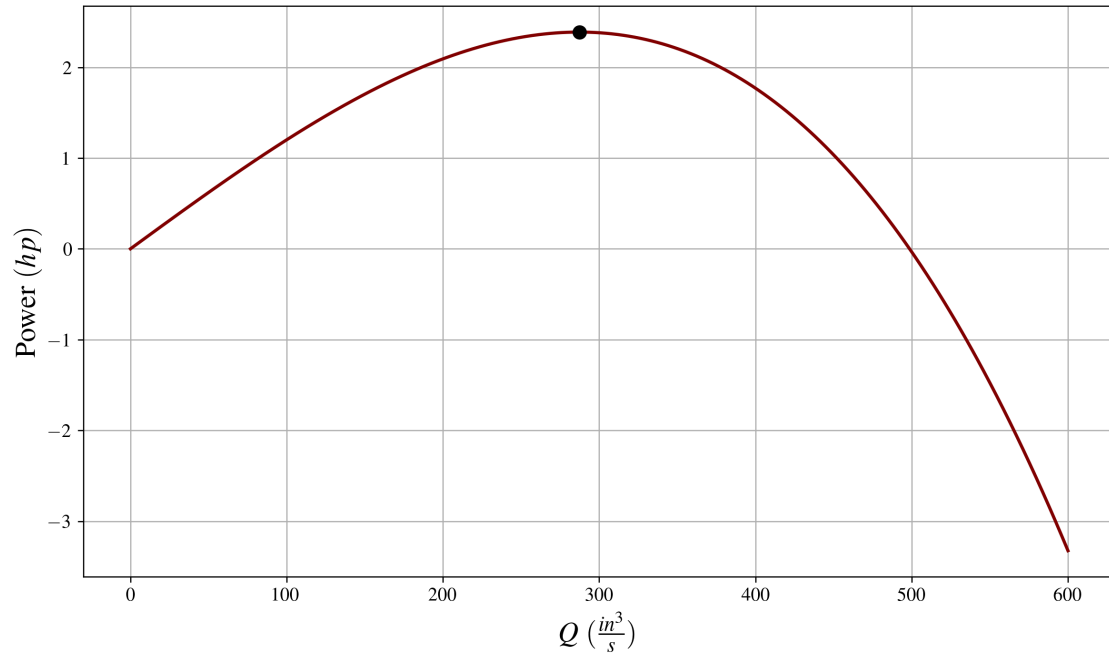
```
[38]: Ps = sp.lambdify(Q, source, modules='numpy')
PL = sp.lambdify(Q, load, modules='numpy')
Q_array = np.linspace(0, 400, 1000)

plt.plot(Q_array, Ps(Q_array), label='$P_s$')
plt.plot(Q_array, PL(Q_array), label='$P_L$')
plt.scatter(float(Q_eq), float(P_eq), zorder=3, color='darkgrey',
            label="Equilibrium Point")
plt.xlabel(r'$Q\ (\frac{\text{in}^3}{\text{s}})$')
plt.ylabel('Pressure $(\text{psi})$')
plt.legend()
plt.show()
```



```
[39]: P_lamb = sp.lambdify(Q, P, modules='numpy')
      Q_power = np.linspace(0, 600, 1000)

      plt.plot(Q_power, P_lamb(Q_power)/6600)
      plt.scatter(float(Q_peak), float(P_peak), zorder=3, color='black')
      plt.xlabel(r'$Q\ (\frac{\text{in}^3}{\text{s}})$')
      plt.ylabel(r'Power $(\text{hp})$')
      plt.show()
```



The peak power and equilibrium points align with the calculated values.