MAE 3260 Final Group Work:

This Will Blow You Away!

Made by Christopher Miranda Soto and Mathis Vigneau

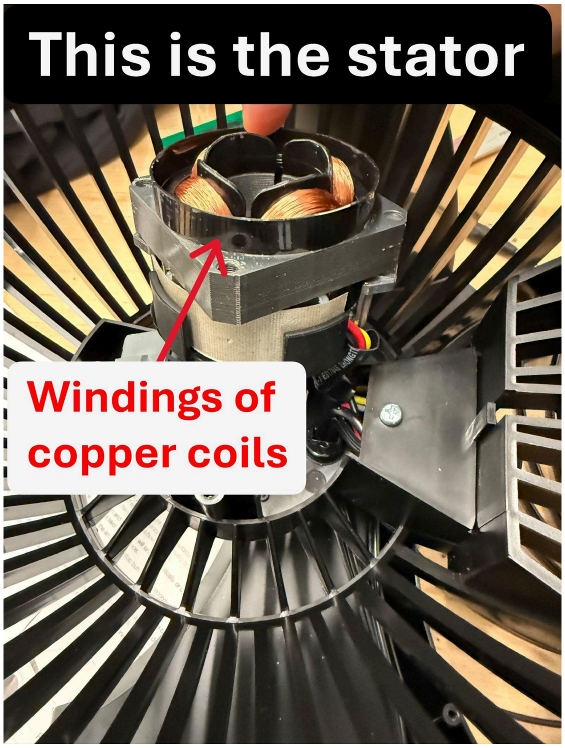
Topic of Interest: Honeywell Room Fan

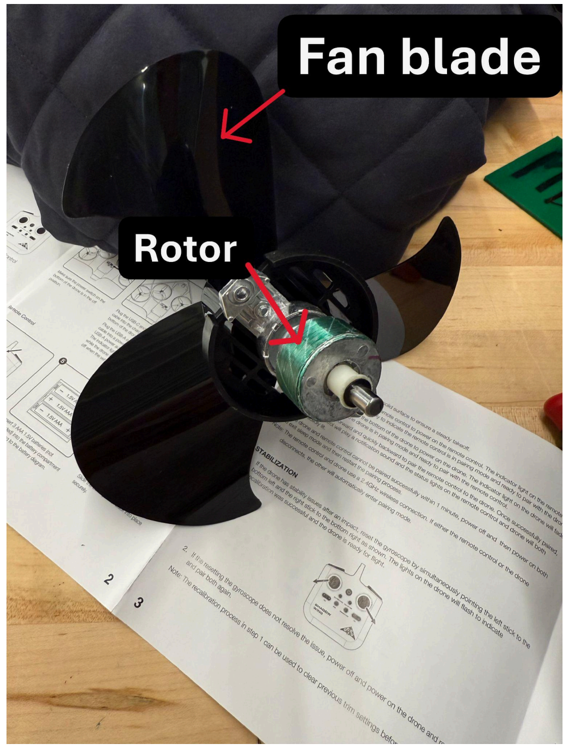
Abstract: We decided to study the Honeywell room fan. The system is an open loop with 4 settings for speed: Off, 1 speed, 2 speed, and 3 speed. The system requires user input. For each speed setting, we will study the settling time, steady state angular velocity, and overshoot (if present), and, based on these parameters, assess whether the design is optimal or if there's room for improvement. We will be modeling and characterizing this system using some of the concepts we've learned in this class, such as ODEs, TFs, Block Diagrams, Parameter Estimation, Steady State analysis, and Step Response.

System Overview

The TurboForce fan system is a fan produced by the company Honeywell. This fan possesses a unique feature in that it is relatively silent when turned on for any of the speed options that the fan presents. The fan has a 90-degree rotation and (LxWxH): 8.94 x 6.3 x 10.9 in. It weighs about 2.9 lbs according to the Honeywell website [1].

When the knob is turned, the fan controller mechanically switches between different electrical configurations that correspond to the different speeds wanted. Each configuration has a different impedance so selecting a higher speed applies a higher effective voltage to the motor windings. Higher effective voltage produces a larger current in the coils, which generates a stronger magnetic field and increases the motor's torque and therefore rotational speed.





Here, we can see the main components of the motor. For our dissection, we separated the two major parts: the stator and the rotor. The stator is the stationary part of the motor and provides a fixed magnetic field. The rotor, which is connected to the fan blades, consists of a metal core with conductive wire coils wrapped around it. When current flows through the rotor coils, it interacts with the magnetic field from the stator, generating torque that causes the rotor and the attached fan blades to rotate.

ODE Modeling and Transfer Functions

We decided to model this system using a first-order, open-loop ODE with respect to the angular rotation, ω, in rads/s. We decided to use two states, ω and i (current, units of Amps), to address both the mechanical and electrical aspects of this system. We assumed that the other relevant variables are rotational inertia (I, units of $\frac{kg}{m^2}$), viscous damping (b, units of $\frac{Nms}{Rads}$), user-controlled motor torque (T_u, units of Nm), disturbance torque (T_d, units of Nm), inductance (L , units of H), resistance (R, units of Ω), and torque gain (K_a, units of $\frac{Nm}{V}$). Since there are four speed settings (including "off") with increasing voltages based on the desired fan speed, we decided to utilize a step function variable that represents the user voltage $u(t)$ that can take four different values $0, U_1, U_2, U_3$, with U_1 representing the input voltage at the lowest speed setting and U_3 representing the input voltage at the highest speed setting. By analyzing the following variables and their relation to the system, the following ODEs and relations were produced.

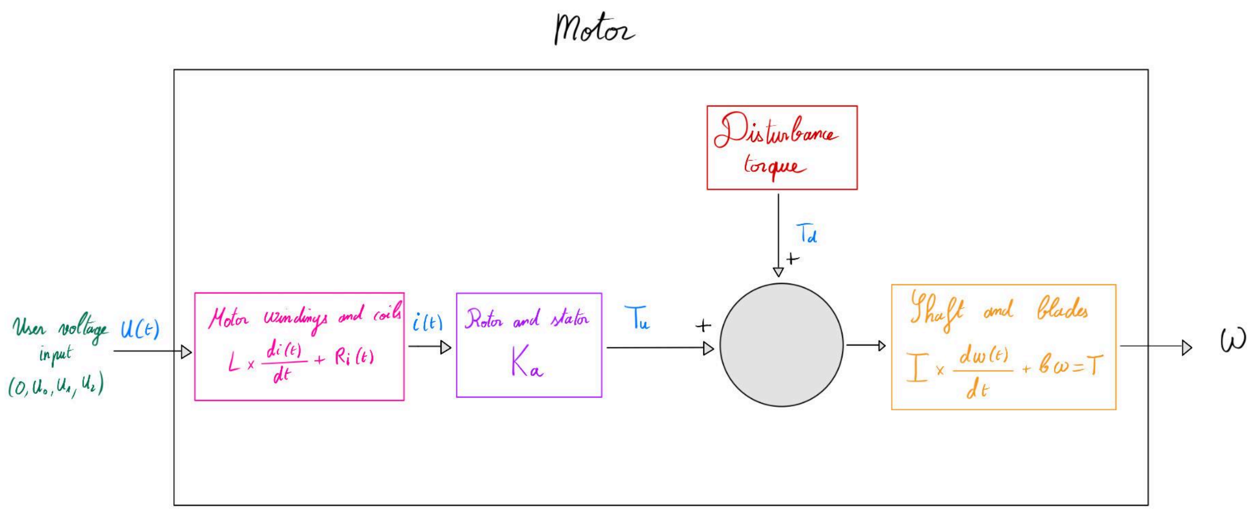
$$I\frac{d\omega(t)}{dt} + b\omega(t) = T$$

$$L\frac{di(t)}{dt} + Ri(t) = u(t)$$

$$T = T_u + T_d$$

$$T_u = K_a i(\mathrm{t})$$

The fan works as an open loop system since the user provides an input to set the speed and the system does not use feedback to adjust the input.



In this model, the disturbance torque T_d represents external disturbance torques such as friction changes and airflow interactions, however, for a typical room fan in a controlled environment, we assume that these disturbances are negligible ($T_d \approx 0$) so it will be omitted from the model going forward and T will be equal to T_u which equals $K_a i(t)$.

Rearranging, we can find the time constant τ for the electrical and mechanical equations:

$$\frac{I}{b}\frac{d\omega(t)}{dt} + \omega(t) = \frac{K_a i(t)}{b}$$

$$\frac{L}{R}\frac{di(t)}{dt} + i(t) = \frac{u(t)}{R}$$

The mechanical time constant is the term in front of the rotational speed derivative, which is $\frac{I}{b}$, hence,

$$\tau_m = \frac{I}{b}$$

Thinking about this physically, this time constant makes sense since higher inertia means more resistance to motion and slower acceleration, and higher damping means faster settling, so smaller settling time.

The electrical time constant is the term in front of the current derivative, which is $\frac{L}{R}$, hence,

$$\tau_e = \frac{L}{R}$$

Thinking about this physically, this time constant makes sense since higher inductance resists changes in current, causing the current to rise more slowly when the input voltage changes, while higher resistance causes the system to stabilize faster.

To find $\omega(t)$, we first need to find $i(t)$. Converting it to the frequency domain gives us:

(No initial i or change in i so initial conditions equal 0)

$$Ls\, i(s) + R\, i(s) = \frac{U_n}{s}$$

Solving for $i(s)$,

$$i(s) = \frac{U_n}{s(Ls+R)}$$

Now, we have an equation that can be used to find the equation for $i(t)$ using the MAE 3260 Laplace table [2]. This expression best matches #12 in the table, where $\frac{a}{s(s+a)}$ in the frequency domain equals $1 - e^{-at}$ in the time domain. To be able to use the table, we must first transform the equation to be similar to #12.

$$\frac{U_n}{s(Ls+R)} = \frac{U_n}{R} \frac{\frac{R}{L}}{s(s+\frac{R}{L})}$$

In this form, we see that the equation is now in the form of #12 where a is $\frac{R}{L}$ and $\frac{U_n}{R}$ is the gain term. Hence, we can now solve for $\omega(t)$ and we get:

$$i(t) = \frac{U_n}{R}(1 - e^{-\frac{R}{L}t})$$

This equation describes the current with time which ends up leading to a second order system. However, since electric dynamics happen extremely quickly, the system effectively behaves as a first order system and we can make the assumption:

$$i(t) \approx \frac{U_n}{R}$$

Now, we can repeat this process to find $\omega(t)$:

$$I\frac{d\omega(t)}{dt} + b\omega(t) = T = T_u = K_a i(t)$$

Plug in $i(t)$ assuming $i(t) \approx \frac{U_n}{R}$:

$$I\frac{d\omega(t)}{dt} + b\omega(t) = \frac{K_a U_n}{R}$$

Transform to frequency domain with zero initial conditions:

$$Is\omega(s) + b\omega(s) = \frac{K_a U_n}{R}\frac{1}{s}$$

Find $\omega(s)$:

$$\omega(s) = \frac{K_a U_n}{s(RIs+b)}$$

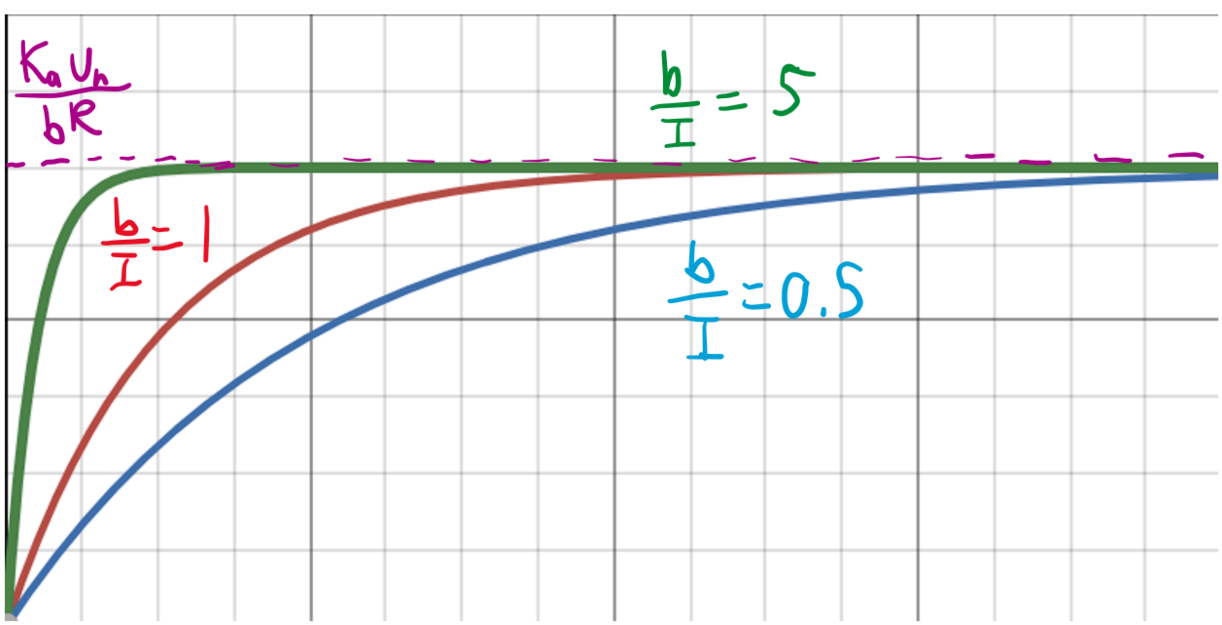
Also similar to #12 so convert:

$$\omega(s) = \frac{K_a U_n}{bR}\frac{\frac{b}{I}}{s(s+\frac{b}{I})}$$

Convert to time domain using table:

$$\omega(t) = \frac{K_a U_n}{bR}\left(1 - e^{-\frac{b}{I}t}\right)$$

And now we have an equation that describes the rotational speed with respect to the parameters defined. From this equation, we can see that the steady state solution is $\frac{K_a U_n}{bR}$, which makes sense according to the parameters included and the fact that the rotational inertia is *not* included since it physically should not affect the final rotational speed value, just the time to steady state. Graphing this system analytically gives us an idea of how the system behaves.



As expected, rotational speed increases rapidly in the beginning from zero to the steady state value and then remains steady. Depending on the values of b and I, the system exhibits different settling times, with $b > I$ showing faster settling times and $b < I$ showing slower settling times. This shows that as engineers, we want to have large damping and small rotational inertia to optimize reaching the ideal rpm the fastest and carefully choose K_a, U_n, b, R to allow the system to produce different steady state rotational speeds that a user might want.

Step Response and Parameter Estimation

The Honeywell turbofan adjusts its speed by modulating the motor current rather than using PWM or direct voltage control. Therefore, the appropriate input for the step response is the commanded speed signal, since this is the control variable that causes a sudden change in motor current. The step response is obtained by applying a step change in the speed command and recording the resulting fan speed over time.

Unfortunately we could not measure the rotating speed of the Honeywell fan nor read the input that the system is trying to achieve since the speeds are only described as “1, 2, 3” and we were not able to find information on the input voltages for these settings nor discern it from the dissection. Nevertheless, we were able to use video recordings to find the settling times by comparing the time from turning the knob to achieving stable fan rotation.

For speed 1: $t_s = 3.0\ seconds$

For speed 2: $t_s = 2.4\ seconds$

For speed 3: $t_s = 1.7\ seconds$

<u>System Assessment + Improvements</u>

Overall, the Honeywell Room Fan is designed very effectively in terms of system design. Having the system open loop is the right decision, as the goal of the fan is very simple and does not need to have a PID/feedback loop for its system. The rise time is very short as it reaches its steady state in a very short amount of time. This is because the fan is designed to have low rotational inertia and sufficent enough damping, as shown in the *ODE and Transfer Functions section*, so the amount of torque necessary to accelerate it is low, and thus each setting has enough voltage to make it move comfortably. Other great decision choices include low weight, which allows the user to place the fan anywhere they want and even on the wall, user-friendly design, as it is very simple to use with a single indicative knob to control the fan, and high rotatability, allowing the fan to rotate up to 90 degrees vertically to meet user needs.

Some improvements that could be made would be to add a feature to make it a closed loop by adding feedback control. If the system could sense the temperature of the room, then it could modify its speed or turn off and on without the user's intervention. To make this possible, it would need to possess high-accuracy sensors that could well assess the environment from the location of the fan. Other practical suggestions include making the fan more accessible for cleaning/lubrication, since dust build up inside the system proves to be a common issue.

References

Honeywell turbofan [1]

MAE 3260 laplace table [2]. MAE3260_Prelim2(Fa25)solns.pdf

(continue 4b here if needed)

Laplace Transform Tables

Table 2.3.2 Properties of the Laplace transform.

	$x(t)$	$X(s) = \int_0^\infty f(t)e^{-st}\,dt$
1.	$af(t) + bg(t)$	$aF(s) + bG(s)$
2.	$\dfrac{dx}{dt}$	$sX(s) - x(0)$
3.	$\dfrac{d^2x}{dt^2}$	$s^2X(s) - sx(0) - \dot{x}(0)$
4.	$\dfrac{d^nx}{dt^n}$	$s^nX(s) - \sum_{k=1}^{n} s^{n-k} g_{k-1}$, $\quad g_{k-1} = \left.\dfrac{d^{k-1}x}{dt^{k-1}}\right\vert_{t=0}$
5.	$\int_0^t x(t)\,dt$	$\dfrac{X(s)}{s} + \dfrac{g(0)}{s}$, $\quad g(0) = \left.\int x(t)\,dt\right\vert_{t=0}$
6.	$x(t) = \begin{cases} 0 & t < D \\ g(t-D) & t \ge D \end{cases} = u_s(t-D)g(t-D)$	$X(s) = e^{-sD}G(s)$
7.	$e^{-at}x(t)$	$X(s+a)$
8.	$tx(t)$	$-\dfrac{dX(s)}{ds}$
9.	$x(\infty) = \lim_{s\to 0} sX(s)$	
10.	$x(0+) = \lim_{s\to\infty} sX(s)$	

For Entries 2, 3, 4, and 5, if $x \neq 0$ for $t < 0$, then replace the initial conditions at $t = 0$ with the pre-initial condtions at $0-$.

Table 2.3.1 Table of Laplace transform pairs.

	$X(s)$	$x(t), t \ge 0$
1.	1	$\delta(t)$, unit impulse
2.	$\dfrac{1}{s}$	$u_s(t)$, unit step $\quad \mathbf{u_s(t) = 1(t)}$
3.	$\dfrac{c}{s}$	constant, c
4.	$\dfrac{e^{-sD}}{s}$	$u_s(t-D)$, shifted unit step
5.	$\dfrac{n!}{s^{n+1}}$	t^n
6.	$\dfrac{1}{s+a}$	e^{-at}
7.	$\dfrac{1}{(s+a)^n}$	$\dfrac{1}{(n-1)!}t^{n-1}e^{-at}$
8.	$\dfrac{b}{s^2+b^2}$	$\sin bt$
9.	$\dfrac{s}{s^2+b^2}$	$\cos bt$
10.	$\dfrac{b}{(s+a)^2+b^2}$	$e^{-at}\sin bt$
11.	$\dfrac{s+a}{(s+a)^2+b^2}$	$e^{-at}\cos bt$
12.	$\dfrac{a}{s(s+a)}$	$1 - e^{-at}$
13.	$\dfrac{1}{(s+a)(s+b)}$	$\dfrac{1}{b-a}(e^{-at} - e^{-bt})$
14.	$\dfrac{s+p}{(s+a)(s+b)}$	$\dfrac{1}{b-a}[(p-a)e^{-at} - (p-b)e^{-bt}]$
15.	$\dfrac{1}{(s+a)(s+b)(s+c)}$	$\dfrac{e^{-at}}{(b-a)(c-a)} + \dfrac{e^{-bt}}{(c-b)(a-b)} + \dfrac{e^{-ct}}{(a-c)(b-c)}$
16.	$\dfrac{s+p}{(s+a)(s+b)(s+c)}$	$\dfrac{(p-a)e^{-at}}{(b-a)(c-a)} + \dfrac{(p-b)e^{-bt}}{(c-b)(a-b)} + \dfrac{(p-c)e^{-ct}}{(a-c)(b-c)}$
17.	$\dfrac{b}{s^2-b^2}$	$\sinh bt$

Table 2.3.1 (Continued)

	$X(s)$	$x(t), t \ge 0$
18.	$\dfrac{s}{s^2-b^2}$	$\cosh bt$
19.	$\dfrac{a^2}{s^2(s+a)}$	$at - 1 + e^{-at}$
20.	$\dfrac{a^2}{s(s+a)^2}$	$1 - (at+1)e^{-at}$
21.	$\dfrac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$	$\dfrac{\omega_n}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin \omega_n\sqrt{1-\zeta^2}t$
22.	$\dfrac{s}{s^2+2\zeta\omega_n s+\omega_n^2}$	$-\dfrac{1}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin\left(\omega_n\sqrt{1-\zeta^2}t - \phi\right)$, $\phi = \tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta}$
23.	$\dfrac{\omega_n^2}{s\left(s^2+2\zeta\omega_n s+\omega_n^2\right)}$	$1 - \dfrac{1}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin\left(\omega_n\sqrt{1-\zeta^2}t + \phi\right)$, $\phi = \tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta}$
24.	$\dfrac{1}{s[(s+a)^2+b^2]}$	$\dfrac{1}{a^2+b^2}\left[1 - \left(\frac{a}{b}\sin bt + \cos bt\right)e^{-at}\right]$
25.	$\dfrac{b^2}{s(s^2+b^2)}$	$1 - \cos bt$
26.	$\dfrac{b^3}{s^2(s^2+b^2)}$	$bt - \sin bt$
27.	$\dfrac{2b^3}{(s^2+b^2)^2}$	$\sin bt - bt\cos bt$
28.	$\dfrac{2bs}{(s^2+b^2)^2}$	$t\sin bt$
29.	$\dfrac{s^2-b^2}{(s^2+b^2)^2}$	$t\cos bt$
30.	$\dfrac{s}{\left(s^2+b_1^2\right)\left(s^2+b_2^2\right)}$	$\dfrac{1}{b_2^2-b_1^2}(\cos b_1t - \cos b_2t)$, $\quad (b_1^2 \neq b_2^2)$
31.	$\dfrac{s^2}{(s^2+b^2)^2}$	$\dfrac{1}{2b}(\sin bt + bt\cos bt)$