Breaking Down the Beat: An Engineering Analysis of a Massage Gun

Topic of Interest: Dissection of the Massage Gun

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Background and Research

Our project was focused on the dissection of a massage gun. This device was selected because it has interesting physical mechanical components and also has medical and therapeutic uses. Plus all group members have used one before and are curious to learn how it works. We would first like to research more on how a massage gun works, and then during the dissection look for different sensors the massage gun uses. We want to characterize the system, including how the user can change the input, what changes in the internal system, and what different output that produces. We will also characterize the system as an open or closed response, and from there create an ODE, block diagram, and transfer function for the system. Finally, we will discover if the system uses active control, and develop a MATLAB model to reflect the system.

The massage gun we were given was a multi-function gun with three different heads and a roller section on the top that was not mechanical (Pictured to the right). The three different heads can rapidly move inwards and outwards creating a vibrating motion that massages muscle tissue. The massage gun also had five different operating settings (1-5). At level 1, the three heads of the gun moved at the slowest speed of 1800 RPM and at level 5, the heads moved at the highest speed of 3600 RPM.

Massage Gun Dissection Analysis

The massage gun incorporated three different output attachments, each tailored to deliver a distinct style of mechanical stimulation based on user preference. The first attachment was a foam ball. The second attachment was a three-pronged textured plastic head, which created a more concentrated and uneven pressure pattern intended for targeting knots. The final attachment was a flat, round metal component that provided a firmer and more uniform contact surface. By offering this range of outputs, the massage gun allowed users to customize the type of mechanical energy delivered to their muscles, which is a key feature for a therapeutic device. These three outputs are shown below. The balls on the top were small rollers that could manually be used to massage out sore muscles.

Top View of Massage Gun, with Three Massaging Heads Visible

The user interface of the massage gun centered around a single multifunction button. Holding this button activated the system by connecting the battery power to the main control board. Pressing and holding the button again increased the operational speed, cycling the device through four distinct vibration settings. Each speed setting corresponded to a different motor frequency, allowing users to control the intensity of the massage. When the gun was opened during the dissection, it was evident that this button was directly wired to a printed circuit board that served as the backbone of the device. The PCB coordinated the battery input, motor output, and user controls, regulating current and distributing power. The PCB is pictured below, the wires coming out of the PCB were attached to the battery, a component not shown in the image.

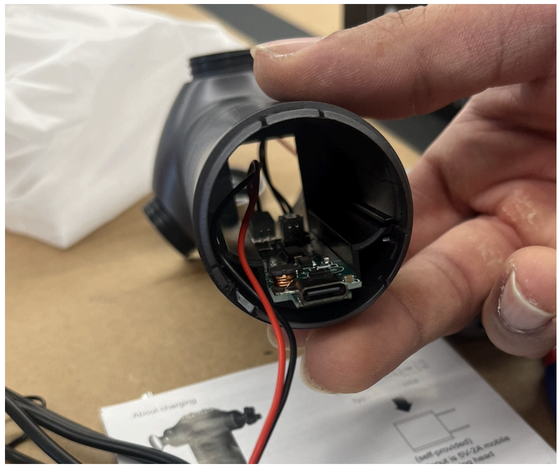
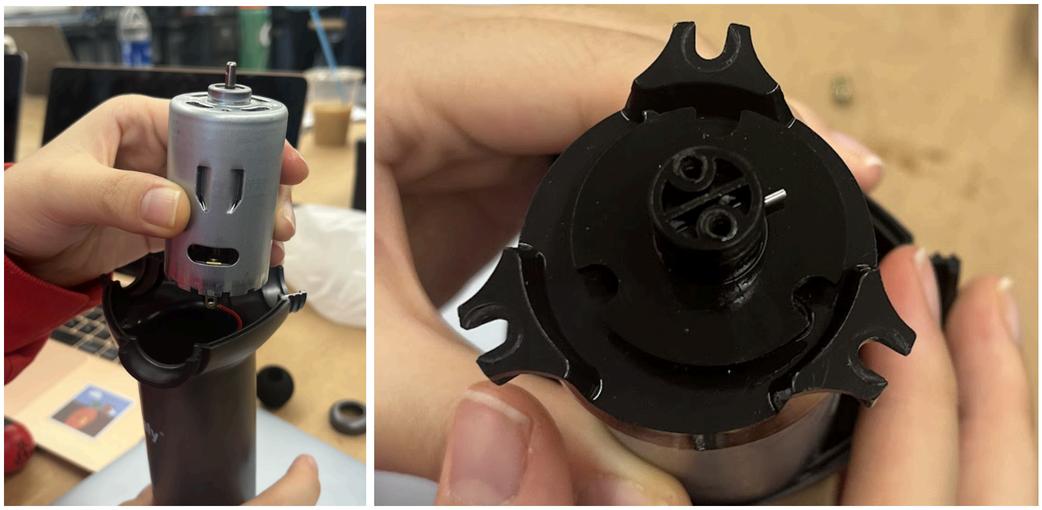


Image of the PCB within the Main Housing

The mechanical heart of the device was the motor, which delivered rotational power through its output shaft. This shaft was connected to a circular rotating piece that played a central role in generating the massaging motion. Instead of placing the axle hole at the center of this rotating disk, the manufacturers intentionally offset it. This off-center placement created an eccentric motion that translated rotational energy into a reciprocating and circular path. The design resembled a simplified slider-crank mechanism of the type used in engines and other piston-based systems; with three massaging heads, the device essentially functions as three slider-crank linkages driven from a single off-centered motor-driven disk input. As the motor spun, the eccentric shaft forced the attached massaging heads to follow a small circular trajectory rather than a single linear axis. This combination of rotation and translation is what produced the characteristic oscillating vibration that users feel when operating the device.



Images of the Motor (Left) and Off Axis Rotating Disk (Right)

Image Demonstrating How the Head Pieces Integrate with the Off Axis Disk

Supporting these primary mechanisms was a large cylindrical housing body and an internal framework made of several smaller components which worked to secure the motor, PCB, battery, and attachments in place. These supports ensured proper alignment between moving parts, reduced unwanted vibration, and maintained structural rigidity during high speed operation. Without these stabilizing elements, the eccentric motion would cause excessive electric wobbling or failure at the attachment points. Overall, the internal design demonstrated a well integrated mechanical and electrical system. Although the design was mechanically simple, the massage gun still performed well, and each component contributed to producing reliable and controlled vibrational output that effectively massaged muscle tissue.

Image Demonstrating Full Stack-Up Assembly

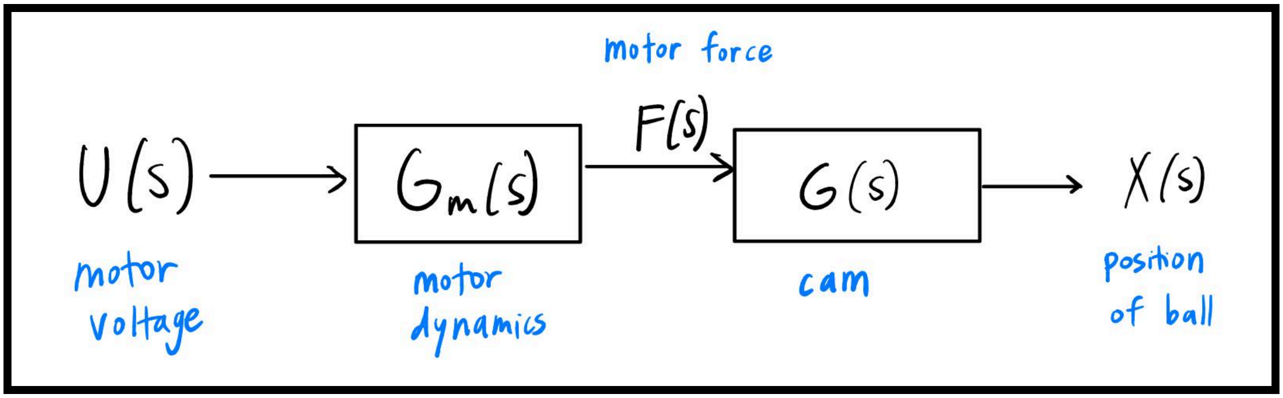
Also, before we began dissecting the massage gun, we had the opportunity to record the motions of the gun under the slow-motion camera that was available. We recorded the massage gun from many different angles, allowing for us to look at the motions and understand what was really going on. The first thing we noticed was that the heads of the gun were not just linearly moving back and forth. Instead, they were moving in a circular motion. Then, we observed how their sinusoidal motions were all shifted from one another. They all peaked at different times, while all having the same period. We later discovered that this was due to all of the heads being connected to one off centered disk, as previously mentioned above. With these videos we were able to confirm the provided measurement on the box and find the amplitude of the heads during the sinusoidal motion. For the rotational speed, we made approximations by counting the number of rotations the rotating disk completed within a period of time much shorter than one minute. From the videos, we counted roughly 15 cycles within a half-second period. Multiplying this with 120 gets an approximate RPM of 1800, confirming the box’s information and resulting in a percent error of 0%. As for the amplitude of the heads during sinusoidal motion, examination of the videos show that amplitude was approximately 4.8 mm, resulting in a percent error of 4%.

$$Amplitude\ Percent\ Error = \frac{|4.8\ mm - 5.0\ mm|}{5.0\ mm} = 0.04 = 4\%$$

Block Diagram, Transfer Function, & the ODE

We first began analyzing the system by creating a block diagram. The input is the voltage provided to the motor, and the output is the position of the end of the massage gun. The output we are focusing on is clearly shown in Figure 1, denoted by the red arrow.

Once we knew the system input and output, the next step was filling in the steps in-between to map out the full process. The full block diagram is shown below:



After creating the Block Diagram, we found the transfer function. The steps are shown below:

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2 + bs + k}$$

$$G_m(s) = \frac{F(s)}{U(s)} = \frac{k_m}{\tau s + 1}$$

$$X(s) = G(s)F(s) = [\frac{k_m}{\tau s + 1}][\frac{1}{ms^2 + bs + k}]U(s)$$

Here are some of the important variable definitions:

$$Motor\ Force\ Gain\ (k_m)\ [\frac{N}{V}]$$

$$Motor\ Time\ Constant\ (\tau)[s]$$

Moving Mass (m) [kg]

$$Damping\ (b)\ [\frac{N \cdot s}{m}]$$

$$Stiffness\ (k)\ [\frac{N}{m}]$$

Next, we focused on finding the unknown variables. The massage gun box included several important parameters of the system:

$$Rated\ Voltage = 7.4\ V$$

$$Motor\ Power\ (P)\ =\ 25\ W$$

$$Rotation\ Speed\ (\omega)\ =\ 1800\ RPM$$

$$\tau\ =\frac{Power}{\omega}=\frac{7.4}{1800(\frac{2\pi}{60})}=\ 0.133\ N\ \cdot\ m$$

Using a pair of calipers and after taking the top section of the massage gun off we found that the peak-to-peak amplitude of the system was 5mm. We did this by measuring the edge of the off axis disk to an edge of the cylindrical housing when the amplitude was highest. Finally we solved for the rest of the unknowns with the following steps:

$$\Delta r\ =\ 5/2\ =\ 2.5mm$$

$$F\ =\frac{\eta\tau}{r}\text{, assume } \eta = 0.9$$

$$F\ =\frac{0.9*0.133}{0.025}=\ 47.88\ \mathrm{N}$$

$$k_m=\frac{F}{V}=\frac{47.88}{7.4}=\ 6.47\ N/V$$

These values are only rough approximations of the system. We are unable to calculate the real efficiency value, and are unsure if the parameters on the box can be applied to all massage gun settings. The only variables left unknown are m, b, and k, which we will find using a MATLAB script.

ODE

Our massage gun can be modeled as a spring-mass-damper system, and that is the assumption that is made when solving for the transfer functions and the block diagram. Considering other systems modeled in MAE 3260, it would be reasonable to assume that a 2nd order ODE should encode enough information to characterize the system accurately. In order to solve for an ODE for the system, given our transfer function, I used a MATLAB script to run inverse Laplace and give me x(t) from our X(s). The ODE produced is shown below.

```
% Variables
syms s t m b k
% Parameters with values
tau = 0.133;      % s
km  = 6.47;      % N/V
U0  = 7.4;       % step voltage

% Transfer function G(s) = X(s)/F(s)
G = 1 / ((m*(s^2) + (b*s) + k));
% Transfer function G(s) = F(s)/U(s)
Gm = km / ((tau*s)+1)

% Step input: u(t) = U0 * H(t)  ->  U(s) = U0/s (using laplace)
U = U0/s;

% X(s) = G(s) * U(s)
X = Gm * G * U;

% Inverse Laplace transform to get x(t)
x_t = ilaplace(X, s, t);
x_t = simplify(x_t)
```

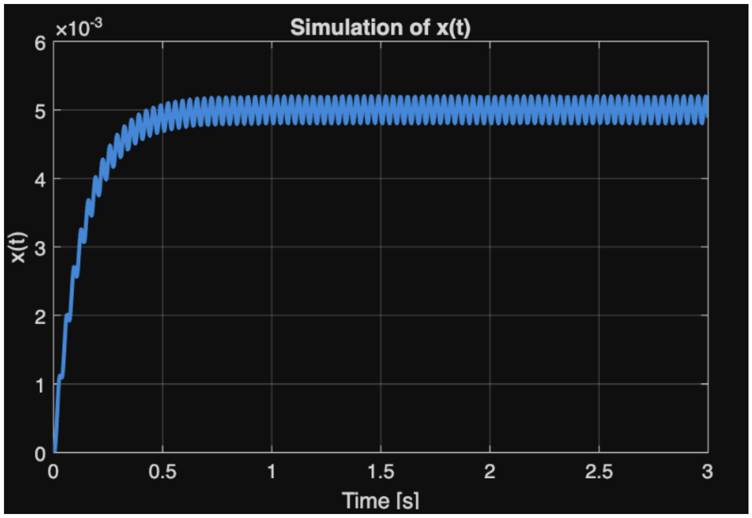
ODE PRODUCED USING INVERSE LAPLACE:

$$x(t) = \frac{23939}{500k} - \frac{423456971\, e^{-\frac{1000t}{133}}}{500(17689k - 133000b + 1000000m)} + \frac{47878\, e^{-\frac{bt}{2m}} \left(\cosh\left(\frac{t\sqrt{b^2-4km}}{2m}\right) - \frac{\sinh\left(\frac{t\sqrt{b^2-4km}}{2m}\right)\left(-133b^2+1000mb+266km\right)}{\sqrt{b^2-4km}(133b-1000m)}\right)(133b - 1000m)}{k(17689k - 133000b + 1000000m)}$$

The function x(t) produced from using inverse Laplace on our X(s), which can be seen above, is the solution of a 3rd-order ODE or higher, which can be seen from the sinh and cosh terms present. Also, from a first impression, the function appears to be much more complicated than one would expect for a system that should have relatively simple motion. Since the massage gun has no built-in control or sensor system besides its speed change setting, which we didn't analyze, I would assume this ODE does not properly represent our physical system. There could be a few reasons for this. The first is that the model we used to solve for our transfer function/block diagram wasn't very accurate to the physical system. This explanation seems to be the most realistic, as performing inverse Laplace on the transfer function should result in an ODE that is indicative of the physical system that the transfer function represents. Another explanation is that the transfer function and ODE are correct, but our understanding of the physical system is flawed and too simplified. This is also a possibility, considering that we used results from a similar but less complex system as a guide when deriving our transfer function. It would have been great to do a physical sanity check on this ODE to assess whether the variable value assumptions and the parameters shown on the box are accurate. However, given the complexity of the ODE solution, this would be difficult to do.

Modelling in MATLAB

The goals in MATLAB were to simulate the ODE and try to find out what m and k are. So, this is split into two pieces of code, the first will calculate m and k, we are assuming b is equal to 0. This is a reasonable assumption because the system likely has very little damping which can be seen as negligible to simplify the system. This is done by inputting the amplitude and period we found. T = 0.0333 s and A = 5mm. You also need the force being inputted, which is found earlier as 47.88 N. This outputted the following values for m and k: m = .2690 kg and k = 9576 N/m. This seems pretty appropriate and it resulted in the following graph of the resulting function.



Here is the code that produced that result:

```
%part 1: calcululating k and m, assuming b = 0.
T = 0.0333;
A = .005;

F0 = 47.88;

k = F0 / A;

m = k * T^2 / (4 * pi^2);

fprintf('Calculated spring constant k = %.2f N/m\n', k);
fprintf('Calculated mass m = %.4f kg\n', m);

b = 0;

% part 2: getting the response graph
t = linspace(0, 3, 1000);

term1 = 23939/(500*k);

term2 = - (423456971*exp(-(1000*t)/133)) ./ (500*(17689*k - 133000*b + 1000000*m));

sqrt_term = sqrt(b^2 - 4*m*k);
cosh_term = cosh((t .* sqrt_term) / (2*m));
sinh_term = sinh((t .* sqrt_term) / (2*m));
factor = (-133*b^2 + 1000*m*b + 266*k*m) ./ (sqrt_term .* (133*b - 1000*m));

term3 = (47878 * exp(-(b*t)/(2*m)) .* (cosh_term - sinh_term .* factor) * (133*b - 1000*m)) ./ ...
        (k * (17689*k - 133000*b + 1000000*m));

x = term1 + term2 + term3;

figure;
plot(t, x, 'LineWidth', 2);
xlabel('Time [s]');
ylabel('x(t)');
title('Simulation of x(t)');
grid on;
```

Conclusion

For this groupwork, we combined dissection, measurement, and system modeling to better understand the mechanical behavior of a massage gun. Slow-motion footage and internal inspection revealed that the device's three massaging heads follow circular, phase-shifted paths, effectively functioning as three slider-crank linkages driven by a single off-centered motor input. Using these observations along with manufacturer specifications, we developed a block diagram, transfer function, and estimated parameters for a spring-mass-damper model. Although the resulting ODE was more complex than expected, likely due to simplifying assumptions such as negligible damping and unmodeled dynamics, the analysis provided meaningful insight into how the device converts electrical input into controlled vibrational output. Overall, the project highlighted both the elegance of the massage gun's slider-crank-based design and the challenges of accurately modeling real-world mechanical systems.

References

Amazon. *High-Frequency Electric Multifunctional Relaxation Massager* [Product page]. Amazon. https://www.amazon.com/high-Frequency-Electric-Multifunctional-Relaxation-Massager/dp/B0F3X9T5GY