SCHOOL OF ENGINEERING
TAYLOR'S UNIVERSITY

MEC60503

Lab Report

Mechanical Vibration Case Study

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Abstract

The experiment was conducted purposefully to investigate a case study to find the potential spring constant for potential use in a race car that complies with the sustainable cost reduction criteria while also requiring to find out if the shock absorbers are required with or without damping constant. The method of the experiment revolves around the concept of analysing 3 variations of coil springs ranging from softest to stiffest while co-analysing varied positions of the lever arm and also the dampening effect. A spring with small spring constant, (k) is soft and a high spring constant, (k) is stiff. The general formula of spring constant is k= F/x, whereby F is force and x is the displacement of spring from an initial position. The spring constant (k) is the ratio of force per unit displacement of spring. The other equations such as the equation of motion, equation of modified deflection of displacement of spring (x) with regards to the torsion and lever arm, equation of mass moment of inertia, equation of natural frequency, equation of periodic time and equation of damping ratio are used to further enhance the credibility and findings of this investigative experiment. Besides that, the damping ratio or damping constant is a measure describing how rapidly an oscillation decays from the initial stage to next. Theoretically, the spring-mass system represents a complex mechanical system while the damper represents the combined effects of the dissipating energy in the system. Based on the experiments conducted one of the key findings is that softer springs have lower spring constants and stiffer springs have higher spring constant. Second finding is that softer springs have small frequency and stiffer springs have high frequency. When coupled with a damper at fully closed, semi closed and fully open settings the fully closed damper has shorter distance for 10 cycles hence shorter time taken to dissipate the vibration. This increases with a semi closed and fully open damper since more time is taken to dissipate the vibration. On the other hand,when the distance of the damper is further from the spring the time taken for damping is longer while the nearer one is shorter. Based on this we can significantly conclude that for a race car setup a stiffer spring operates most efficiently because it prevents the car from lowering or raising much and makes aerodynamics more efficient. Adding a damper that is fully closed dampers the time taken to dissipate any vibration faster and the nearer the damper front the spring the greater the frequency meaning time taken for damping is lower.

1.0 Introduction

Roads aren’t perfectly flat. As such, bumps and cracks are present on daily roads. When going across these imperfections, sudden movement in the chassis can cause ride discomfort.

A suspension system's task is to isolate the vehicle's content from undesirable effects of the road surface. An automotive suspension system consists of tyres, air inside the tyres, springs, dampers, or what is known as shock absorbers and linkages that connect the suspension system to the chassis [1].

A spring is an elastic object that stores mechanical energy. Potential energy is converted from kinetic energy as the spring deforms. Springs are typically made of springs steel, and are used in many different applications. When springs are not stretched beyond their elastic limits, the potential force of the spring can be calculated through the equation of Hooke's Law [2]:

$$F = -kx$$

Where ,
F is the force of the spring,
k is the springs constant of the spring,
x is the displacement or deformation of the spring.

In automotive application, a coil spring is used to absorb bumps and other road inconsistencies. Springs in a suspension system can be configured to be mounted separately to a damper or around a shock absorber.

A damper is a device that influences an oscillating system to reduce or restrict oscillation [3]. A damper is able to dissipate kinetic energy of an oscillating system and convert the kinetic energy into heat energy. The damping force of a damper can be calculated with:

$F_d = -Cv$
Where
$F_d$is the damping force,
C is the damping coefficient and,

The equation of motion for a damped system is:

$$m\ddot{x} + c\dot{x} + kx = 0$$

Where,
$\ddot{x}$is acceleration (a),
M is the mass of the system,
$\dot{x}$ is the velocity(v) of the object attached to the damper.

Damping ratio is used to measure and describe the decay of oscillation in an oscillating system. It is a dimensionless system that is a ratio of the damping coefficient of the system and the theoretical critical damping coefficient of the system. This damping ratio is denoted as ζ, and can describe the system to be undamped (ζ=0), underdamped(ζ<1), critically damped(ζ=1), and overdamped(ζ>1).

In an automotive suspension system, a damper is a device used to absorb and damp shock impulses. A damper is important in a suspension system to reduce the spring oscillation of a stiff spring [4]. This allows for the suspension system to settle down quicker, eliminating any excess vibrations.

To predict the behavior of the vibration system, the equation of motion of the system needs to be determined. The equation of motion for a suspension system can be determined by listing out all the forces in a suspension system, and looking at the system with Newton's 2nd law of motion.

$$\Sigma F = Ma,$$
$$F_{spring} + F_{damper} + F_{weight} = Ma$$

$$m\ddot{x} + kx = 0$$

2.0 Literature Review

Suspension systems are to minimise the vehicle motion when turning, accelerating, braking or going over uneven surfaces and in result gives the rider comfort. Here, the suspension is tested using the CarSim software. Using 5 springs with constant stiffness on 5 different damper values, the car will simulate going over a bump. The results show that the lower the damping constant, the higher the pitch of the vibration will be as shown in the result graphs. This means that the passenger is affected with a lot of vibrations when driving due to no dampers present to absorb any impact. A higher value of damping constant shows that it may provide more comfort to the passenger, however, an optimum value needs to be chosen because too much of a damping effect can also cause discomfort. From the graphs, the amplitudes are also smaller as the damping constant is increased. Based on the data gathered, it can be concluded that the stiffness of the spring and the damping constant will be dependent on the parameters of the vehicle. A higher vehicle mass would need a larger spring and damping constant in order to support the weight of the car after going over an uneven surface. This higher damping constant is able to absorb the shock impact, reducing the amplitude and pitch as well as the oscillations of the vibrations. In short, a softer spring and a damper with higher damping coefficient is preferred when it comes to vehicle comfort.[5]

When it comes to a racing car, comfort is less of a priority. The focus is more on stability and keeping the wheels on the ground preventing it from losing traction and in result loses speed. The driving conditions of a race car is also more critical compared to a normal car. It experiences more vehicle roll motion as it makes a sharp and sudden turn which means more forces are acting on the horizontal axis.[6] This can be difficult to stabilise the car while maintaining optimum performance in racing. The damping effect must also not be too much as it will reduce the grip of the tyres and causes excess wear and tear. Conventional cars have a damping ratio from 0.2 to 0.3 but in a race car, it will require 0.5 to 0.7 for the pitch and roll of the car and 0.3 to 0.5 for the control of the car’s mass. [7]

3.0 Experimental Design

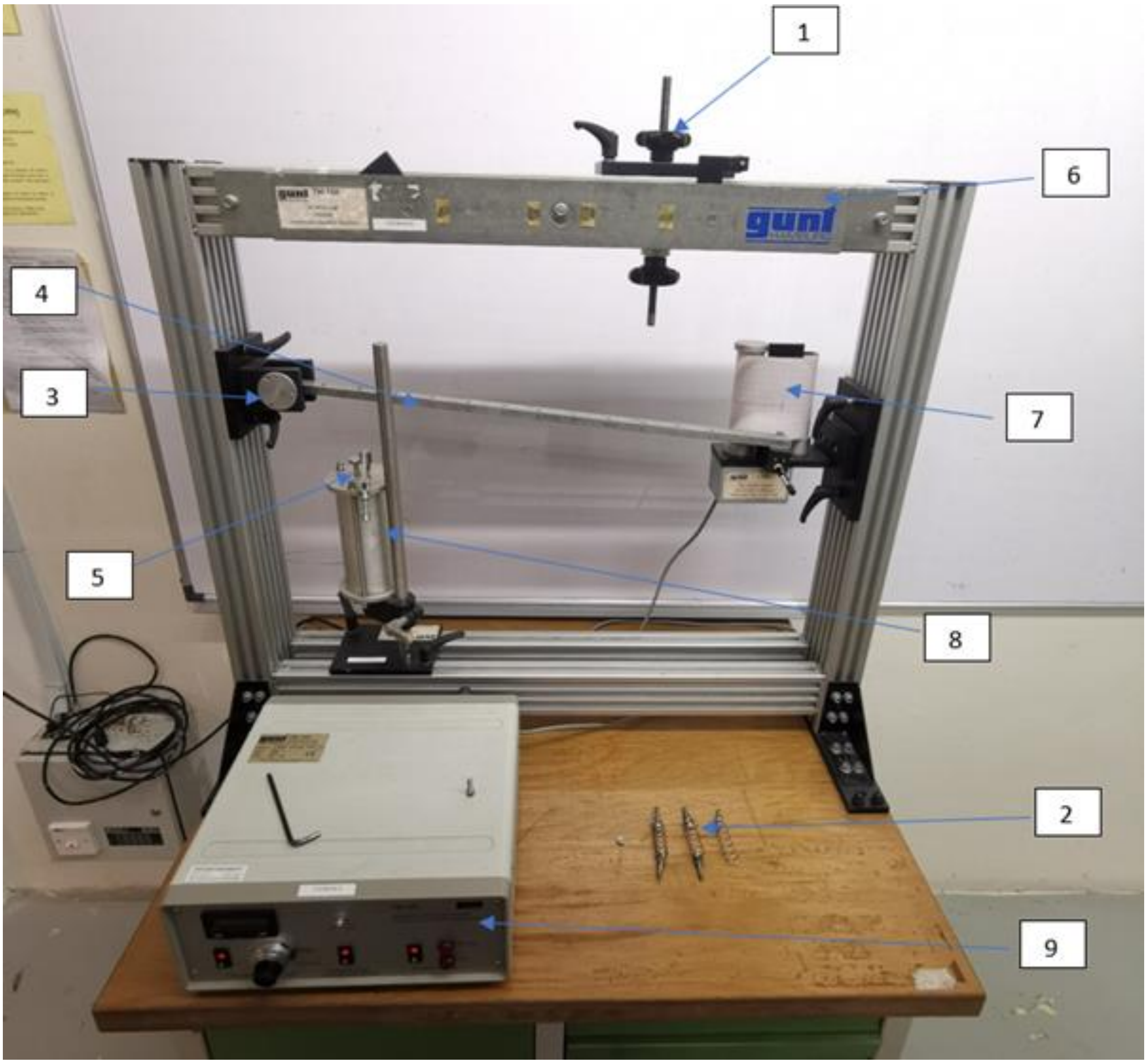


Figure 1 : Universal Vibration System (TM 150)

3.1 Apparatus & Material

Table 1: List of apparatus and materials

Number	**Name**
1	Spring mounting adjustment knob
2	Helical spring
3	Lever position/bearing
4	Lever beam
5	Dampening Adjustment Screw
6	Apparatus Main Frame
7	Rotating plotter
8	Fluid Damper
9	Control switch / Control unit
10	Weights

3.2 Methodology

The Hamburg TM150 Universal Vibration Apparatus was used for this experiment. Three different springs were used in the beginning of the experiment. For the initial experiment, which is an undamped vibration system, the spring constant of the springs was determined by attaching the spring to the spring mounting and securing it in place by tightening the screw. Next a mass of 500g was hung on to the beam and the leveller was used to make sure the beam was fully level by adjusting the top screw at the screw mount, the mass was kept constant throughout the whole experiment. Graph paper roll was inserted into the plotter and a pen was attached to draw the graph. After the plotter was set up, the control unit was switched on to start the plotter at the same time the weight was released on the beam to start the oscillation movement. Three runs was done for each spring to obtain an average reading from the plotter. Once the spring constants of the three springs were obtained, one out of the three springs was chosen to be used for the next experiment.

By using the same apparatus, the next experiment was set up for a damped vibration system by attaching the fluid damper to the lever beam using the screw located on the damper top. The procedure for the damped vibration experiment was similar to the undamped vibration experiment except for the presence of the fluid damper. The fluid damper was set to fully closed for the first oscillation run, this is done by screwing the dampening adjustment screw on top of the damper unit. The second oscillation run was done with the screw half opened and the last run was done with the screw fully opened. Three runs were done for every oscillation run to obtain an average reading of the data.

3.3 Methods & Procedure

Procedure 1 – Experiment 1: Obtaining Spring Constant/ Free Undamped Vibration

1. The fluid damper unit was detached from the lever beam.
2. A mass of 500g was added to the lever beam as the force.
3. The spring was attached to the frame tightly with the distance of 50cm from the lever.
4. A roll of graph paper was inserted into the plotter to record the oscillation data.
5. A pen was attached to the plotter in the pen holder.
6. A water leveller was used to make sure the lever beam was fully balanced horizontally.
7. The control unit was switched on to start the movement of the plotter, the same instance where force was applied to the beam.
8. At the same time plotter starts, the stopwatch was started.
9. The oscillation of the spring was allowed to run for 5 seconds using the stopwatch before the plotter was stopped. The oscillation graph was then cut out to analyse the plot.
10. The data obtained from the plots were recorded.
11. Steps 3-10 was repeated three times to obtain an average data reading.
12. Steps 3-11 was repeated for the next two springs.

Procedure 2 - Experiment 2: Damped Vibration

1. The fluid damper unit was attached to the lever beam at the distance of 10cm from the lever position. The distance was kept constant throughout the test.
2. The selected helical spring was attached to the beam with the distance of 50cm from the lever position.
3. The mass of 500g was applied to the spring by attaching it to the beam.
4. The dampening adjustment screw was set to fully closed position (fully closed valve)
5. A roll of graph paper was inserted into the plotter to record the oscillation data.
6. A pen was attached to the plotter in the pen holder.
7. A water leveller was used to make sure the lever beam was fully balanced horizontally.
8. The control unit was switched on to start the movement of the plotter, the same instance where force was applied to the beam.
9. At the same time plotter starts, the stopwatch was started.
10. The oscillation of the spring was allowed to run for 5 seconds using the stopwatch before the plotter was stopped. The oscillation graph was then cut out to analyse the data.
11. The data obtained from the plots were recorded.
12. Steps 3-11 were repeated three times to obtain an average data reading.
13. Steps 3-12 were repeated with the dampening adjustment screw set to half open.
14. Steps 3-12 were repeated with the dampening adjustment screw set to fully open.

Procedure 3 - Experiment 3: Varying Position of Damper

1. The position of the fluid damper was moved from 10cm to 5cm from the lever position.
2. The selected helical spring was attached to the beam with the distance of 50cm from the lever position.
3. The mass of 500g was applied to the spring by attaching it to the beam.
4. The dampening adjustment screw was set to fully closed position (fully closed valve)
5. A roll of graph paper was inserted into the plotter to record the oscillation data.
6. A pen was attached to the plotter in the pen holder.
7. A water leveller was used to make sure the lever beam was fully balanced horizontally.
8. The control unit was switched on to start the movement of the plotter, the same instance where force was applied to the beam.
9. At the same time plotter starts, the stopwatch was started.

10. The oscillation of the spring was allowed to run for 5 seconds using the stopwatch before the plotter was stopped. The oscillation graph was then cut out to analyse the data.
11. The data obtained from the plots were recorded.
12. Steps 3-11 were repeated three times to obtain an average data reading.
13. Steps 3-12 were repeated with the damper moved to 15cm from the lever position.

4.0 Results and Discussion

4.1 Experimental Results

The first experiment was conducted to investigate the spring constant for three different types of springs available for testing. The springs have varying amounts of stiffness and are around the same length. The beam was adjusted with each spring to ensure that the level was horizontal and each spring will start to oscillate from the same position. The table below tabulates the experimental results obtained from the first experiment.

Table 2: Experimental results to determine free undamped spring constant

	Cycles				Frequency, f	Spring Constant, K (N/m)
	1	2	3	Avg		
Spring 1 (softest)	16.5	16.5	16.5	16.5	3.30	140.44
Spring 2 (medium)	24.5	24.0	23.0	23.8	4.77	293.02
Spring 3 (stiffest)	35.5	33.5	34.5	34.5	6.90	613.99

The second experiment investigates the effect of damping on the springs in addition to the natural vibration of the system. A similar system as the first experiment was used, in addition to a fluid damper unit attached to the beam at 10cm from the origin. The damper unit is tested with three different settings, fully closed, semi closed and open to investigate the effects of each setting on the system.

Table 3: Experimental results to determine damped spring constant

10cm Full Close	Distance (cm)	Time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	10.6	5	0.0212	3.1	1.46	6.84
2	11.2	5	0.0224	2.9	1.29	7.72
3	10.8	5	0.0216	3.0	1.39	7.20
					AVG	7.25

10cm Half/Half	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	10.6	5	0.0212	3.2	1.51	6.63
2	11.3	5	0.0226	3.2	1.42	7.06
3	11.4	5	0.0228	3.3	1.45	6.91
					AVG	6.87

10cm Open	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	11.2	5	0.0224	3.2	1.43	7.00
2	11.4	5	0.0228	3.3	1.45	6.91
3	11.4	5	0.0228	3.4	1.49	5.36
					AVG	6.42

The third experiment investigates the effect of varying the position of the damper along the beam. The position of the damper is moved from 10cm from the origin to 5cm and 15cm for different iterations of the experiment to test the difference in the frequency of the oscillation of the spring.

Table 4: Experimental results to determine effect of varying distance (15cm) on damped constant

15cm Full Close	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	11.1	5	0.0222	1.3	0.59	6.83
2	10.7	5	0.0214	1.3	0.61	6.58
3	10.8	5	0.0216	1.3	0.60	6.65
					AVG	6.69

15cm Half/Half	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	10.7	5	0.0214	3.2	1.50	6.69
2	11.1	5	0.0222	3.2	1.44	6.94
3	11.1	5	0.0222	3.3	1.49	6.73
					AVG	6.78

15cm Open	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	10.4	5	0.0208	3.3	1.59	6.30
2	10.7	5	0.0214	3.3	1.54	6.48
3	11.8	5	0.0236	3.3	1.40	7.15
					AVG	6.65

Table 5: Experimental results to determine effect of varying distance (5cm) on damped constant

5cm Full Close	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	11.0	5	0.022	3	1.36	7.33
2	10.5	5	0.021	3.1	1.48	6.77
3	11.3	5	0.0226	3.1	1.37	7.29
					AVG	7.13

5cm Half/Half	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	11.2	5	0.0224	3.1	1.38	7.23
2	11.0	5	0.022	3	1.36	7.33
3	10.8	5	0.0216	3.1	1.44	6.97
					AVG	7.18

5cm Open	Distance (cm)	time (s)	Velocity (m/s)	Distance for 10 Cycles (cm)	Time taken for 10 cycles (s)	Frequency, f
1	10.6	5	0.0212	3.1	1.46	6.84
2	11.3	5	0.0226	3.1	1.37	7.29
3	10.7	5	0.0214	3.1	1.45	6.90
					AVG	7.01

Table 6: Tabulation of the spring constant for each damper position at different settings

Damper Position	Frequency, f	Spring Constant, K (N/m)
5cm Full Close	7.13	656.09
5cm Half/Half	7.18	664.02

5cm Open	7.01	633.86
10cm Full Close	7.25	678.66
10cm Half/Half	6.87	607.87
10cm Open	6.42	532.30
15cm Full Close	6.69	576.70
15cm Half/Half	6.78	593.54
15cm Open	6.65	569.70

4.2 Calculations

Length of the beam, L = 700mm = 0.7m
Distance from the pivot to the spring, a = 500mm = 0.5m
Mass of the force applied = 500g = 0.5kg

Sample calculations

Experiment 1
The data is obtained in the form of an oscillation plot. By calculating the amount of cycles in the period of 5s, the frequency of the spring can be determined.

$$f = \frac{Cycle}{Time} = \frac{16.5}{5} = 3.3\ cycles/s$$

The equation for natural frequency, f is given as:

$$f = \frac{1}{2\pi}\sqrt{\frac{3Ka^2}{mL^2}}$$

By rearranging this, the equation to calculate the spring constant, K can be derived.

$$K = \frac{(2\pi f)^2 mL^2}{3a^2}$$

$$K = \frac{(2\pi(3.3))^2(0.5)(0.7)^2}{3(0.5)^2} = 140.44\ \text{N/m}$$

Experiment 2

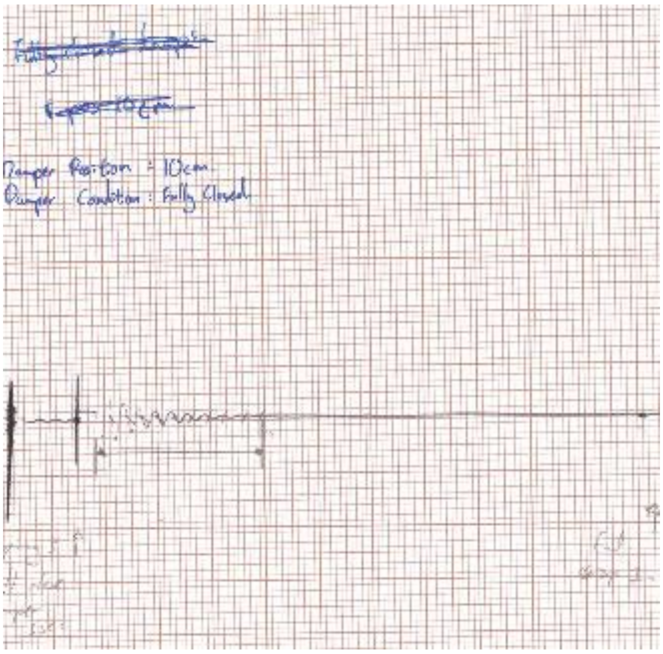


Figure 2: Example of spring oscillation with damper

For the second experiment, the length of the oscillation on the graph is measured until the point where it comes to a complete stop. The length measured is considered as the total distance. By dividing the distance with the period of oscillation measured, 5s, the velocity can be determined.

$$v = \frac{d}{t} = \frac{10.6}{5} = 0.0212\text{m/s}$$

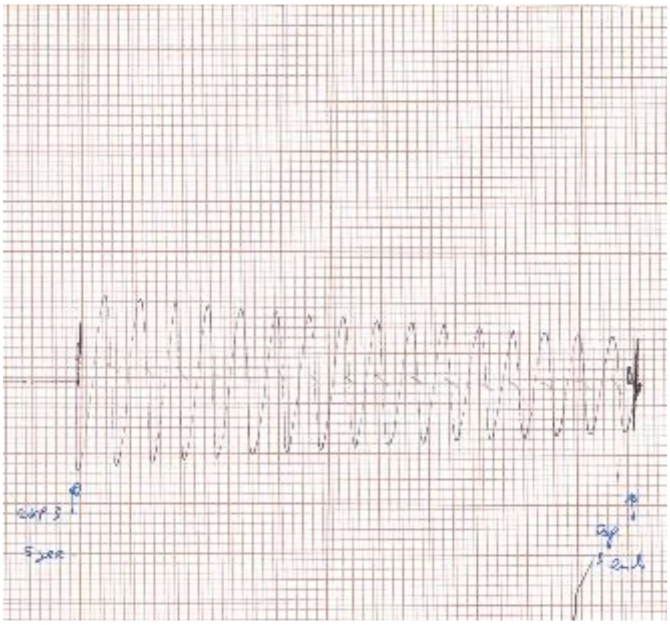
The distance travelled in 10 cycles is also measured and divided by the velocity. This is used to determine the time taken for the spring to oscillate 10 complete cycles.

$$t = \frac{d\ (10cycles)}{v} = \frac{0.031m}{0.0212\ m/s} = 1.46\ s$$

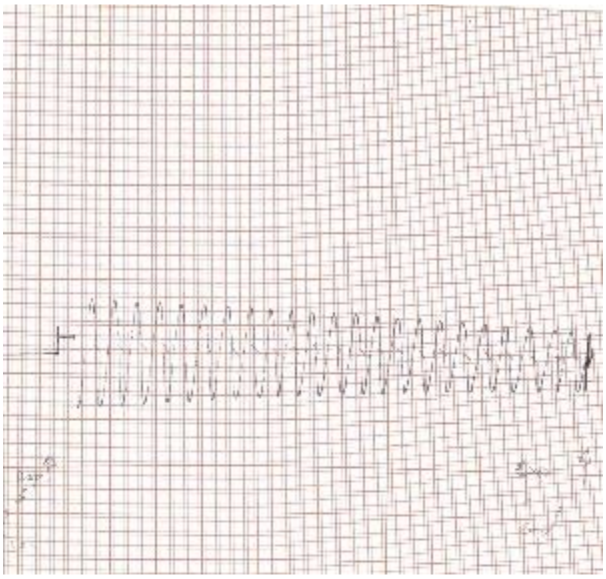
With this, the spring constant can be determined using the same formula as before.

4.3 Discussion

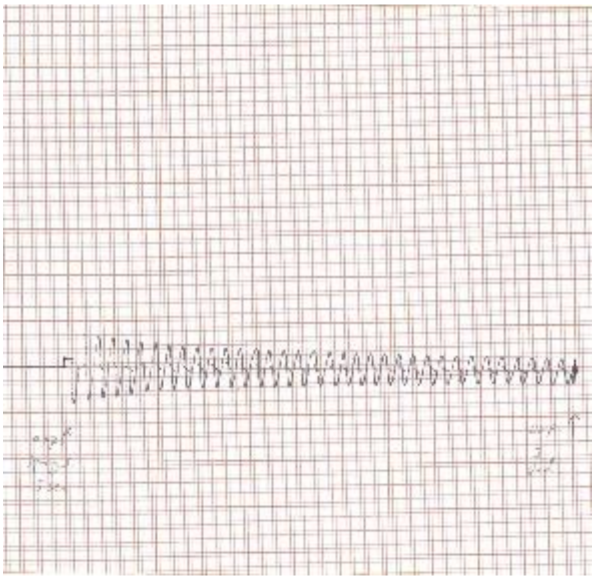
The spring constant determines the displacement of the spring from its equilibrium position and is also a numerical indicator of how stiff the spring is. As shown by the results obtained in Experiment 1, the springs are in an ascending order of stiffness in the order of Spring 1, Spring 2 then Spring 3.



Spring 1



Spring 2



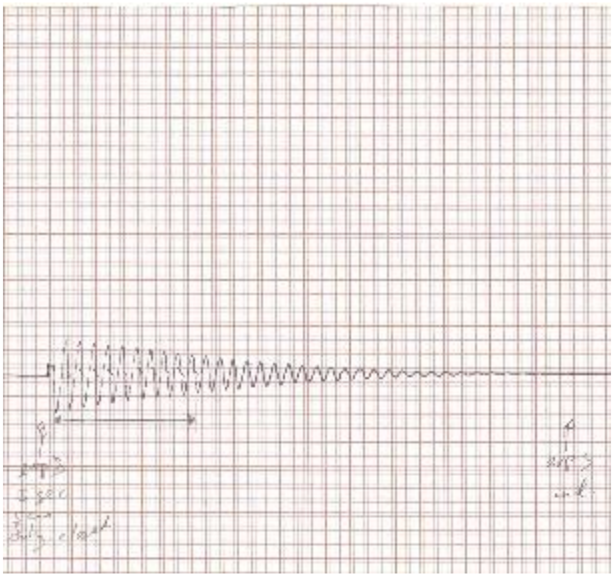
Spring 3

Figure 3: Oscillation graphs without damper for Springs 1,2 and 3

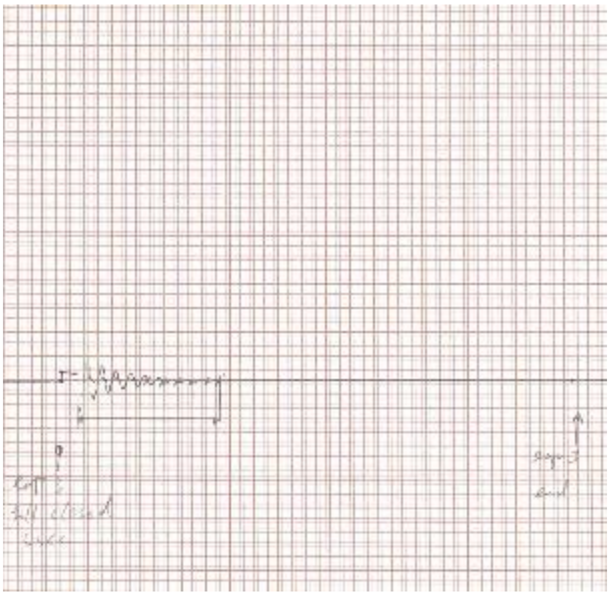
The oscillation plots show that as the stiffness of the spring increases, the amplitude of the vibration also decreases. In real world applications, this means that softer springs will bounce with a greater magnitude compared to stiff springs. At the same time, the plots also show that the vibrational frequency increases with the stiffer springs. This is attributed to the fact that as springs with higher spring constants will take longer to dissipate the force applied as compared to softer springs.

If the amplitude of the vibration is too high, one side of the vehicle will have too much upwards force, leading to the vehicle rolling and losing control. This is why the suspension springs of modern vehicles are stiff to absorb much of the force when driving through bumps or potholes to prevent excessive vibration that may lead to the tyres on one side of the vehicle to lift off the ground. Race cars especially benefit from very stiff springs as it provides better control as the roads are smoother than commercial roads.

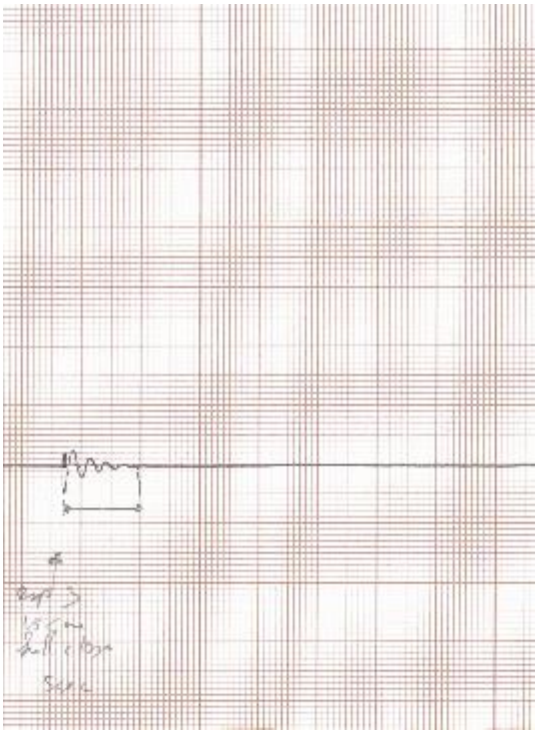
However, if the springs are too stiff, the frequency of the vibration also proportionally increases. This frequency causes the tyres to be vibrating longer and results in an uneven contact area with the road. This is a problem as the tyres cannot maintain a solid grip on the road which causes the car to become unstable with even the slightest bumps or irregularities on the road. Therefore, a damper is needed to maintain stability and grip on the road. Spring 3 was used as a baseline for the subsequent experiments to investigate the effect of a damper unit on the system.



Damper at 5cm



Damper at 10cm



Damper at 15cm

Figure 4: Oscillation graphs with damper for Springs 3 at 15cm distance from the origin

As can be seen in the plots, the damper has the effect of reducing the impact of the vibration, resulting in earlier dissipation of the amplitude of the vibration. According to the data, the damping has the most effective results at 15cm from the pivot of the lever, which means that the damper has the best results closer to the spring. The experiments have shown that the best system for a race car should be a suspension with stiff springs with a damper close to the springs.

5.0 Conclusions and Recommendation

Based on the experiments conducted one of the key findings is that softer springs have lower spring constants and stiffer springs have higher spring constant. Second finding is that softer springs have smaller frequency and stiffer springs have higher frequency. The higher the spring frequency, the more time taken to dissipate the energy/force. Stiffer spring has lower amplitude hence offers a solid grip and control resulting in more force absorption. Although too stiff springs take longer time to dissipate the energy. while coupled with a damper at fully closed, semi closed and fully open settings the fully closed damper has shorter distance for 10 cycles hence shorter time taken to dissipate the vibration. A damper positioned closer to a spring is very efficient in terms of energy dissipation over time because shorter time duration is required such that the force is dissipated from the race car faster. On the other hand,when the distance of the damper is further from the spring the time taken for damping is longer while the nearer one is shorter. Based on this we can signify the data points and conclude that for a race car setup a stiffer spring operates most efficiently because it prevents the car from lowering or raising much and makes aerodynamics more efficient. Adding a damper that is fully closed dampers the time taken to dissipate any vibration faster and the nearer the damper from the spring the shorter the time taken for damping. As a recommendation for a race car we need a stiff spring with high damping constant suspension that is closer to the spring while for a passenger car we can have a softer spring with a moderate damping constant that is placed closer to the spring. As a recommendation to improve the results of the experiments we can have to upgrade to a digital graphing technology for the plotter that produces graphs and results with the aid of a computerised system compared to a manual rotating plotter that requires manual analysis.

For the questions raised by boss:

1) Is my request above do-able or not?
   The request to cut cost for the race car would probably not be made since a stiff spring is more expensive and a fully closed damper is expensive as well. However, for a passenger car the cost can be lowered as we need to use the softer spring and damper with a semi closed setting since roads have bumps and are not like smooth race car tracks.

2) Do we need to have shock absorbers with or without damping? Please provide the most sustainable solution, justifying your analysis based on the three pillars of sustainability.
   3 pillars of sustainability are social, economic and environmental. Based on that we can say that we need a shock absorber with damping in both a race car and a passenger car. However, the stiffness and quality of suspension(damping) differs widely based on the application of the automobile. Economically the passenger car can have a cheaper suspension model while the higher standards are required for a race car to be more efficient and win the race. Higher standards will have more cost.

6.0 References

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7.0 Appendix

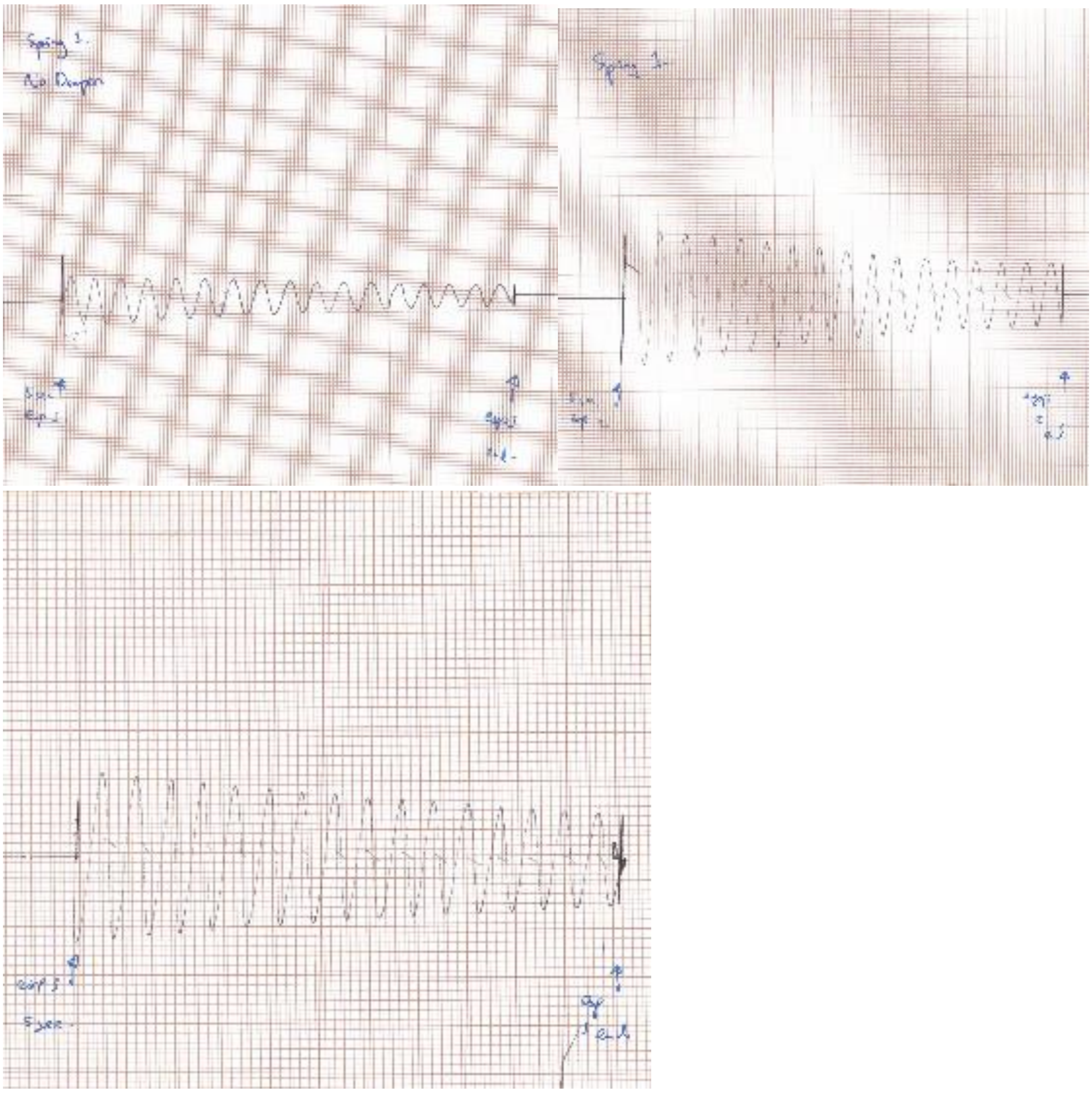
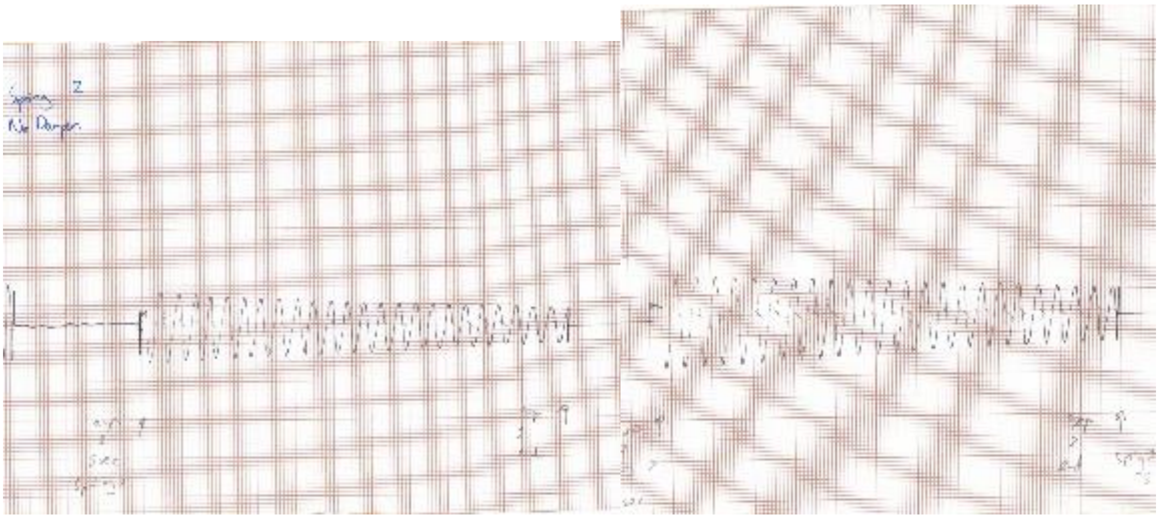


Figure 5: Spring 1, No Damper, 3 Iterations



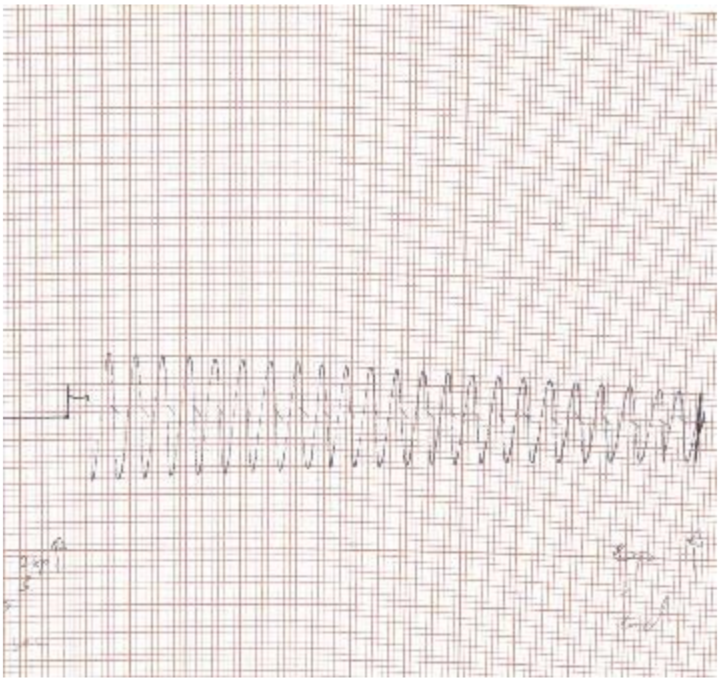
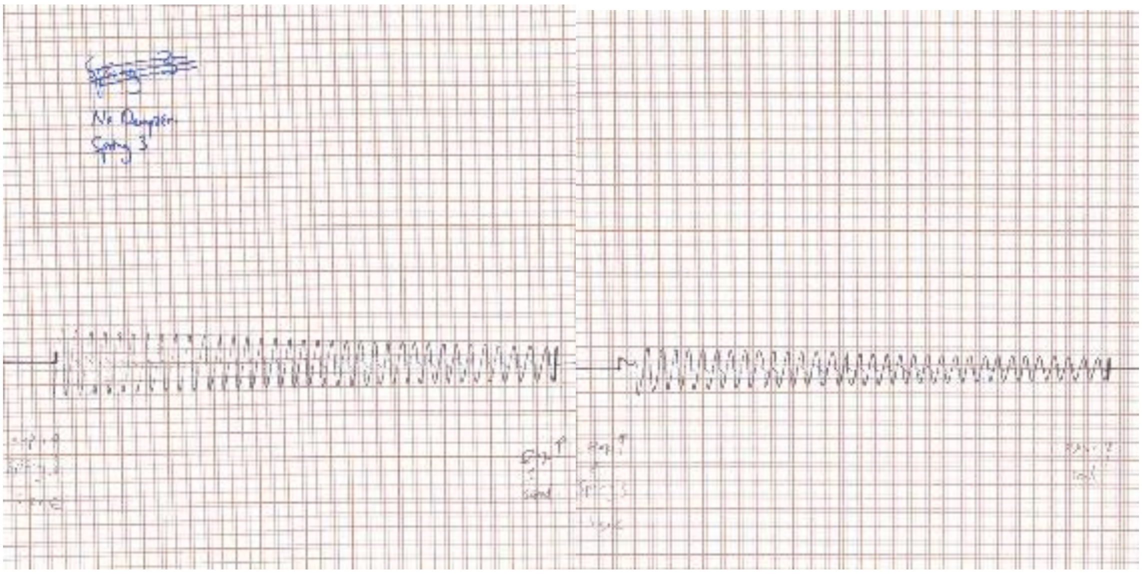


Figure 6: Spring 2, No Damper, 3 Iterations



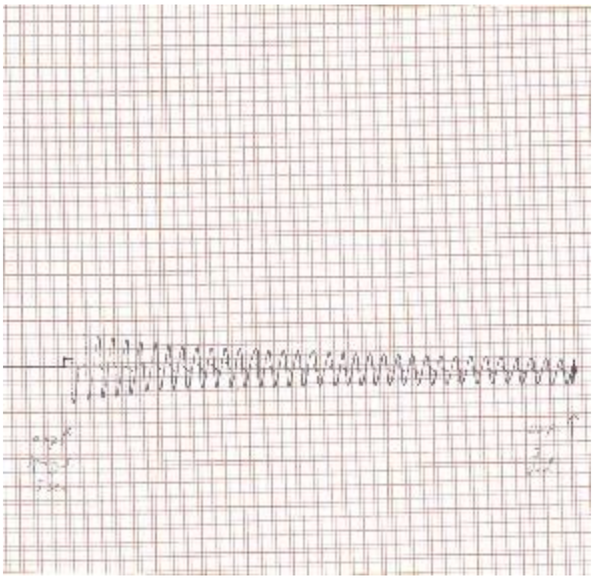


Figure 7: Spring 3, No Damper, 3 Iteration

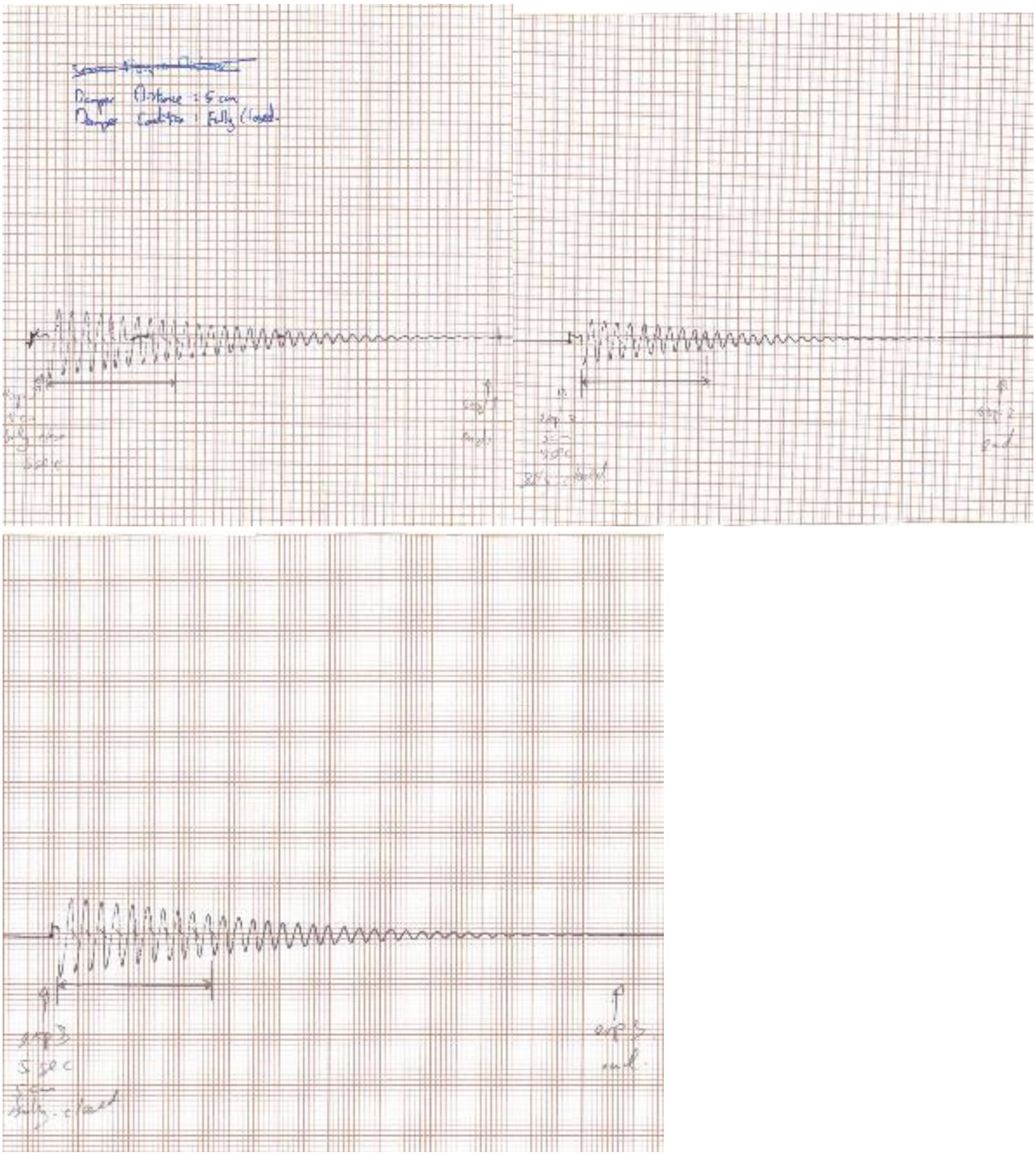


Figure 8: Spring 3, Closed Damper, 5cm Distance, 3 Iterations

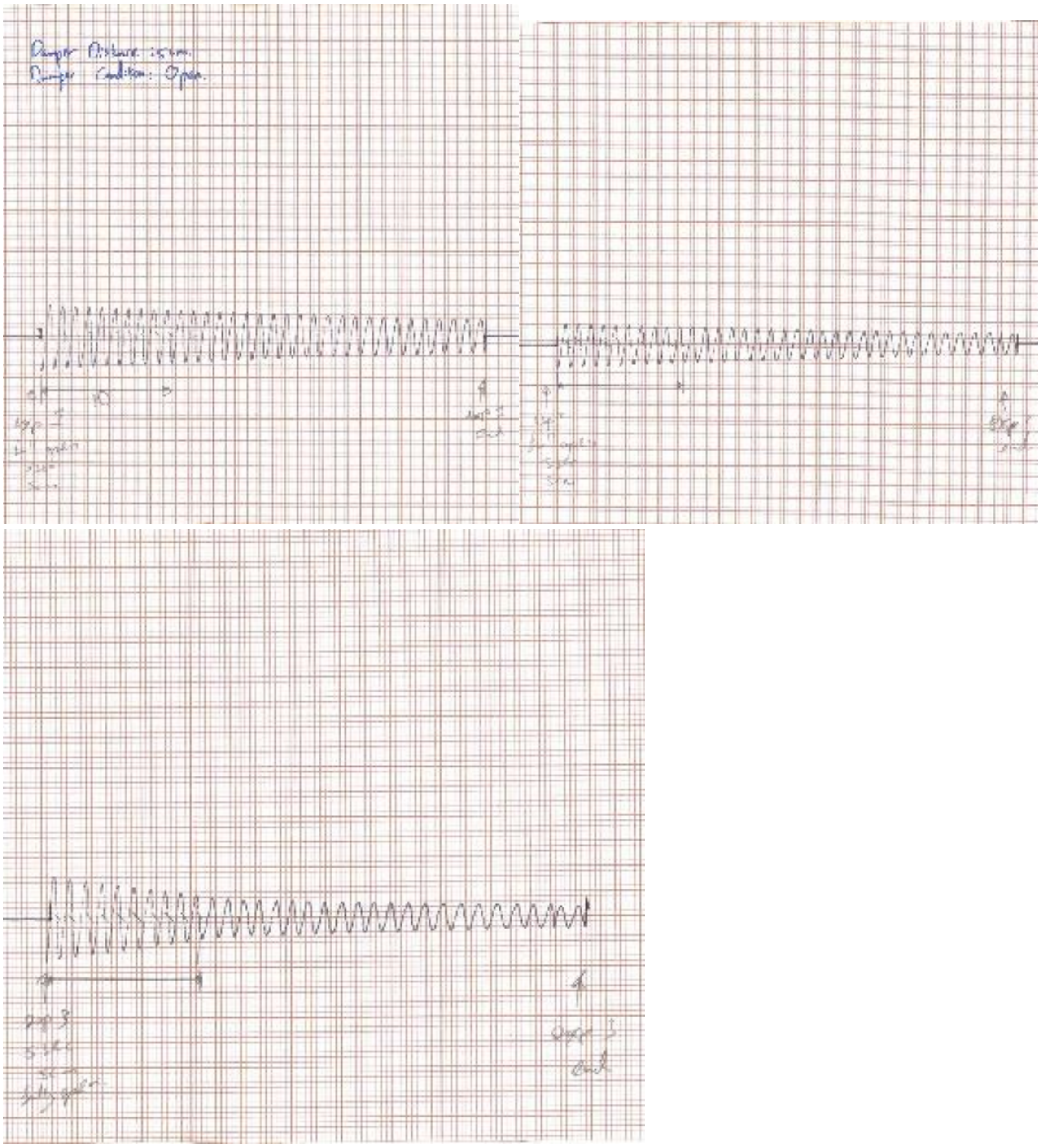


Figure 9: Spring 3, Open Damper, 5cm Distance, 3 Iterations

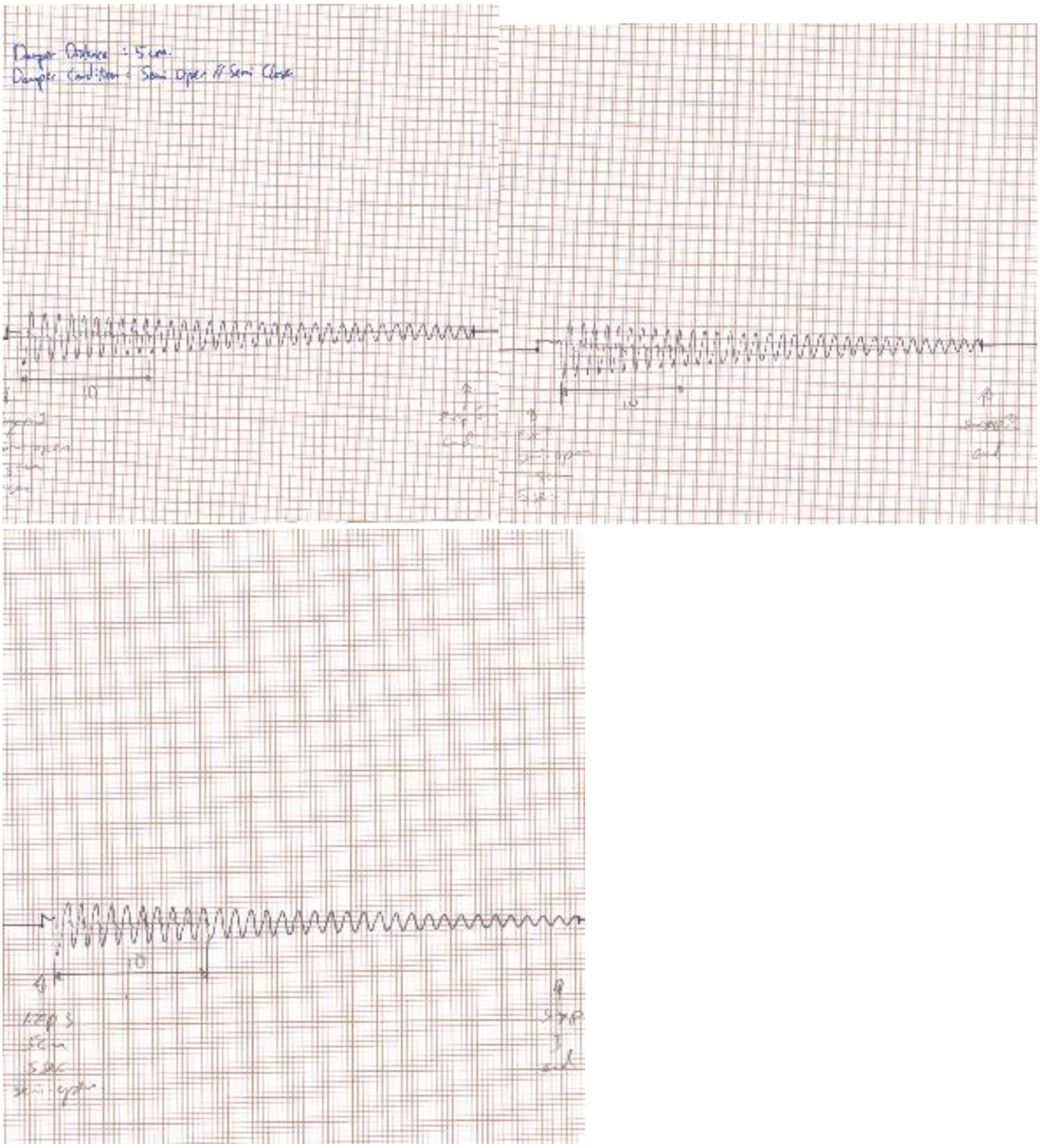


Figure 10: Spring 3, Semi-Closed Damper, 5cm Distance, 3 Iterations

Figure 11: Spring 3, Closed Damper, 10cm Distance, 3 Iterations

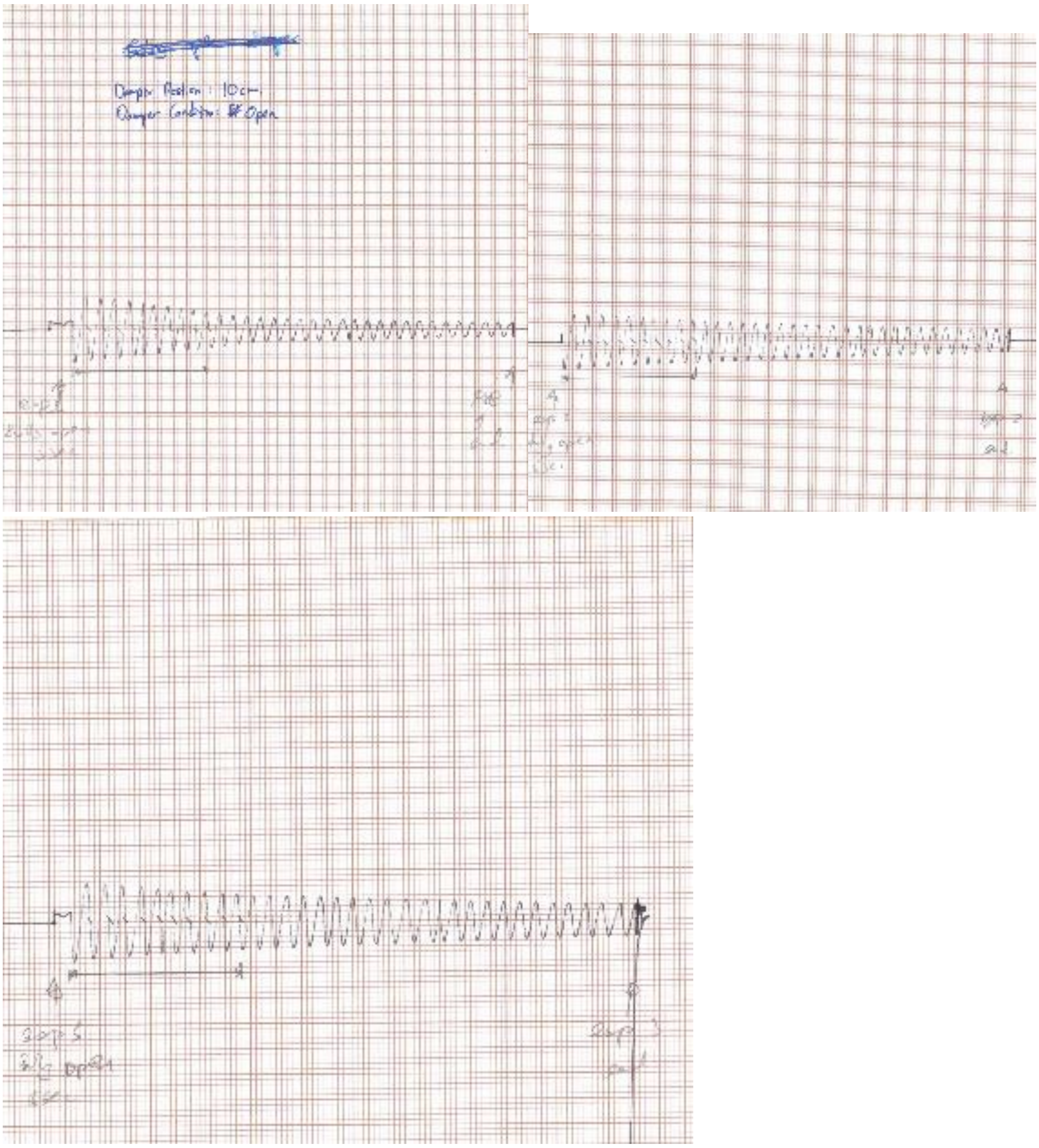


Figure 12: Spring 3, Open Damper, 10cm Distance, 3 Iterations

Figure 13: Spring 3, Semi-closed Damper, 10cm Distance, 3 Iterations

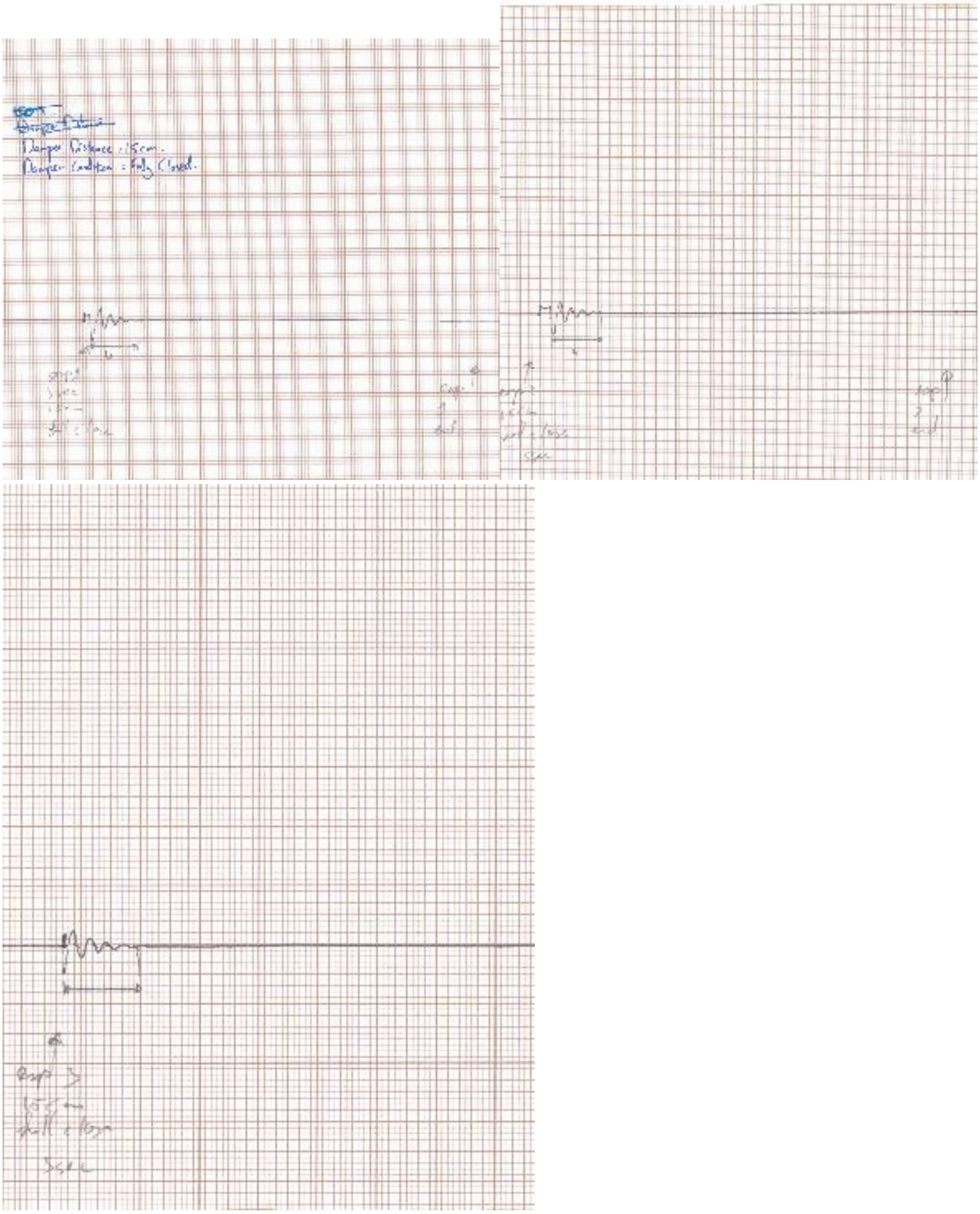


Figure 14: Spring 3, Closed Damper, 15cm Distance, 3 Iterations

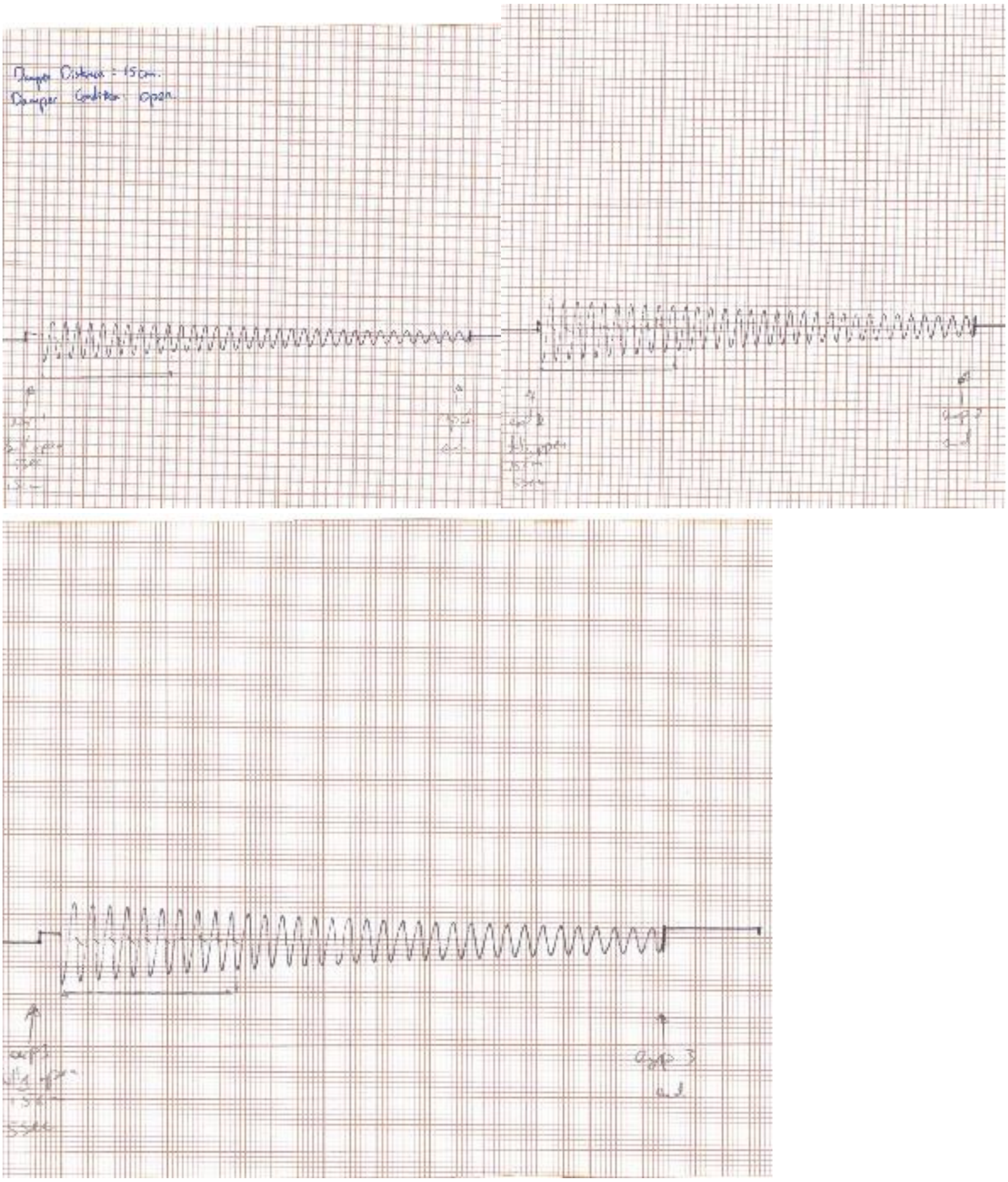


Figure 15: Spring 3, Open Damper, 15cm Distance, 3 Iterations

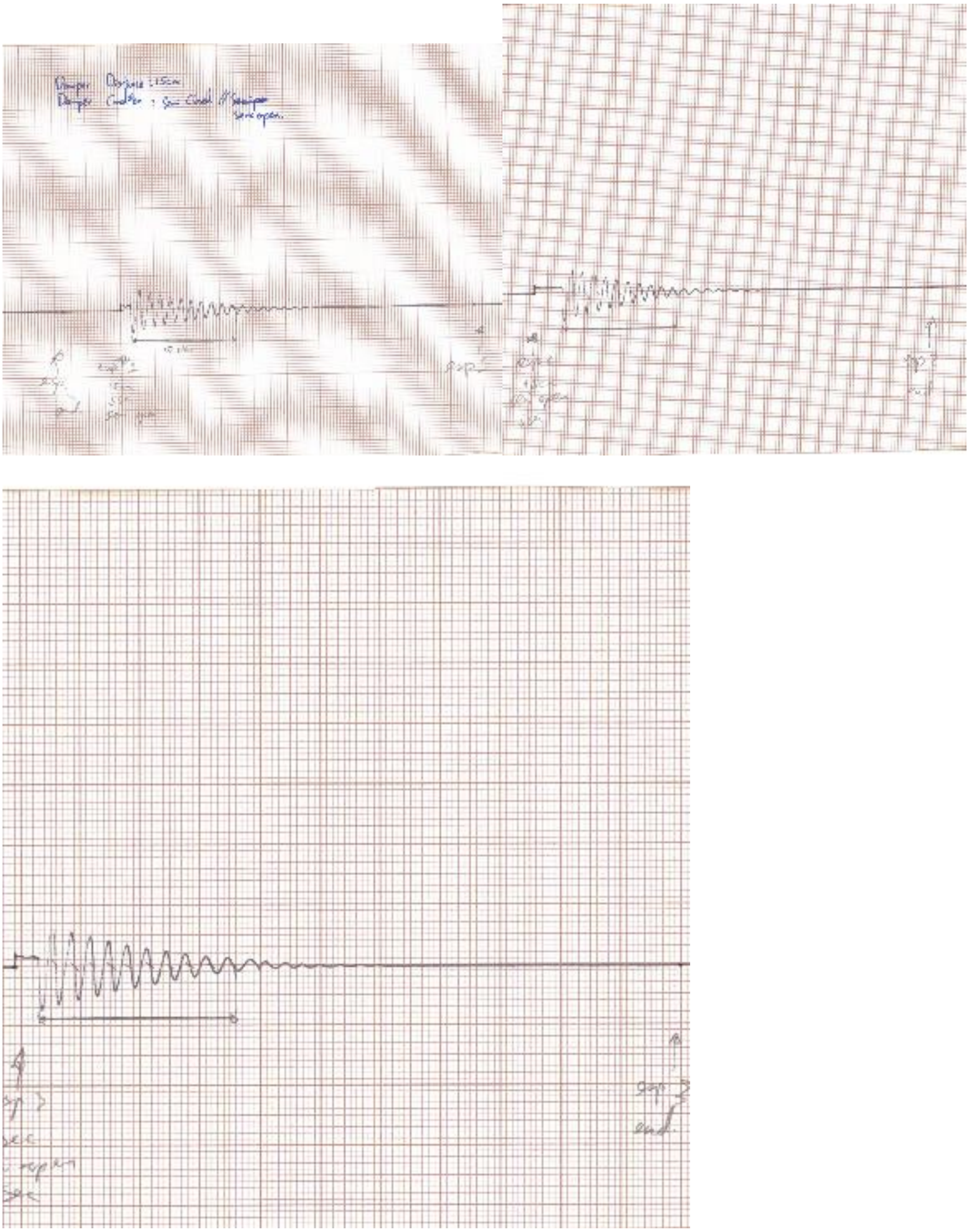


Figure 16: Spring 3, Semi-Closed Damper, 15cm Distance, 3 Iterations