Investigating the effects acting upon a rapidly rotating wheel free to rotate around all three dimensions

Rationale

My passion in physics is electronics. Perhaps a passion since young age, perhaps something related to my love for computers - in any case, a love for electronics is present. I sincerely and truly enjoy everything related from the basics of electronics to the complexities of processing signals. Naturally, I decided that I would do my physics internal assessment in the field of electronics. My original idea was to measure the frequency response of a commonly available signal boost pedal, the *MXR Microamp*. However, my original idea was rejected due to being out of syllabus.

I needed a new topic, and since I have a burning passion for engineering in general, as well as electrical engineering, I decided to look into physical phenomena that intrigue me. On one day I was riding a bicycle when I realized what my topic could be - spinning wheels. I always found the motion of wheels to be somewhat unintuitive, so I decided to challenge myself by doing my internal assessment on them.

1 Introduction

Unlike point masses, actual bodies can be rotated, and, as such, these bodies exhibit certain properties that point masses do not posses. A comparison between a point mass and a physical body is shown in figure 1.

Figure 1: A comparison between a point mass and a physical body

Let us consider these objects when equal forces are applied:

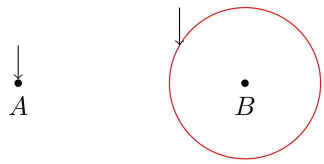


Figure 2: A comparison between a point mass and a physical body when forces are applied

Whenever a linear force is applied to a point mass, it will always create an acceleration proportional to the force and inversely proportional to the inertivity of the object:

$$\vec{a} = \frac{\vec{F}}{m}$$

However, for a real object, whenever a linear force is applied in a line which does not intersect with the centre of mass of the object, the object will rotate. At a given moment, the linear force can be calculated by separating the force vector into two vectors, one which is colinear with the centre of mass and one which is tangential to the object's edge.

The vector which is tangential to the object's edge creates a rotational action upon the object. This rotational action can be measured through torque:

$$\vec{\tau} = \vec{F_t} \times \vec{r}$$

where $\vec{F_t}$ is the tangential force vector

$\vec{r}$ is the radius vector

1.1 Rotational mechanics

Torque is analagous to force. It is a measure of the change of angular momentum, which, for a point mass, is defined analogously to linear momentum $\left(\vec{L} = m\vec{v} \times \vec{r} = mr\vec{\omega} \times \vec{r} = I\vec{\omega}\right)$. I is the moment of inertia, defined as $I = mr^2$ for a point mass revolving around a point with distance r from it. Note that this definition is somewhat limiting in the sense that it is only true for point masses (which is meaningless given that linear momentum only has meaning for non-point objects). The true definition is the sum of all infinitesimally small individual point masses:

$$I = \iiint m(x, y, z)||r||^2 dV$$

Torque is, from these definitions:

$$\begin{aligned} \vec{\tau} &= \frac{d\vec{L}}{dt} \\ &= \frac{d(I\vec{\omega})}{dt} \end{aligned}$$

An inherent property of torque is that, like force, the resulting torque is the total change in angular momentum:

$$\sum_i \vec{\tau_i} = \frac{d\vec{L}}{dt}$$

These basic principles govern the motion of all physical objects in physical space.

1.2 Freewheel mounted on a gimbal

In this section a freewheel mounted on a gimbal as given in figure 3 is presented and the actions it undertakes are mathematically described.

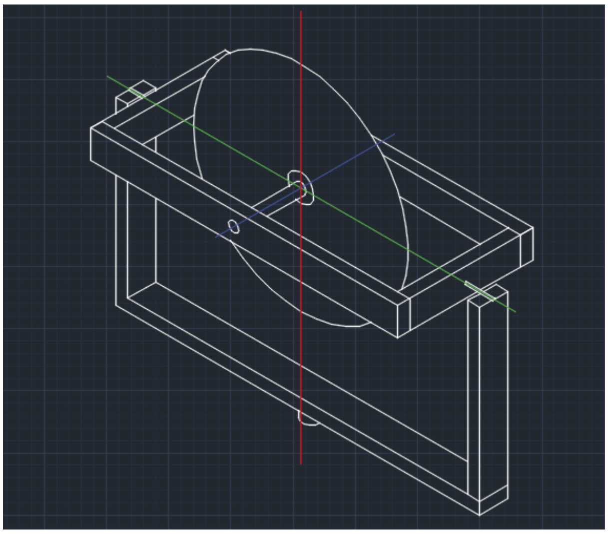


Figure 3: A freewheel mounted on a gimbal

Let us take a moment to define the key elements in this setup. The *freewheel* is a wheel which is rotating around an axis (in figure 3 the blue Z axis) without any friction. The *gimbal* is a single element which allows for free rotation. This setup contains two gimbals - one around the red X axis and the other around the green Y axis.

Let us define the following:

$\vec{r_x}$ - the vector of distance of the X gimbal from the center of to the edge

1.2.1 Freewheel not rotating

To understand the motion of the contraption upon the action of a force tangential to the X gimbal, let us first consider the case when the wheel is not spinning. Consider a pulley of mass m_w added at a position away from the gimbal and connected to its edge with a massless string. For this case, it is supposed that the distance is high enough such that $\sin(\theta) = \theta$. Then:

$$\begin{aligned}\vec{\tau} &= \vec{F} \times \vec{r_x} \\ &= m_w \vec{g} \times \vec{r_x} \\ \vec{\tau} &= I\vec{\alpha} \\ I\vec{\alpha} &= m_w \vec{g} \times \vec{r_x}\end{aligned}$$

Note that I is equal to kmr^2 and that k is an arbitrary coefficient which depends on the body that is rotating. Let m_b the mass of the rotating body. It follows that:

$$\begin{aligned}k \cdot m_b r_x^2 \frac{\vec{a}}{r_x} &= m_w \vec{g} \times \vec{r_x} \\ m_b \vec{a} &= m_w \vec{g} \\ a &= \frac{m_w}{m_b}\vec{g} \\ a &= k\vec{g}\end{aligned}$$

Note how the acceleration is linearly proportional to the acceleration of the pulley (the gravitational acceleration).

1.2.2 Freewheel rotating

Let us now consider the case of the freewheel rotating and having a certain angular velocity.

Let the freewheel be spinning around the Z axis in a direction towards the observer, as shown in figure 4.

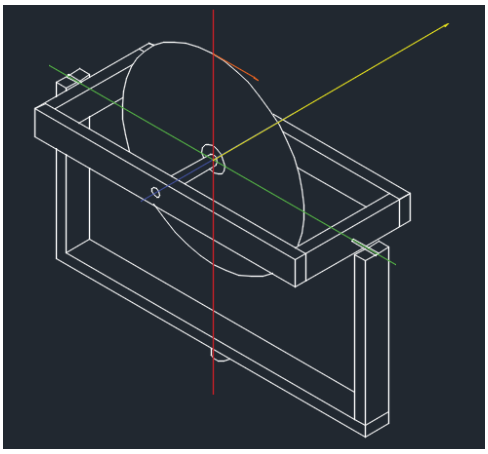


Figure 4: The spinning freewheel gimbal

The vector of angular velocity $\vec{\omega}$ is marked in orange and is pointed away from the observer. The direction of the angular momentum $\vec{L}$ is the same, therefore, and is marked in yellow. Its magnitude is equal to:

$$\vec{L} = I\vec{\omega}$$

When a force $\vec{F_x}$ (marked in purple) is applied to the device, it creates a torque $\vec{\tau}$ (marked in pink) pointed parallel to the Y axis as shown in figure 5.

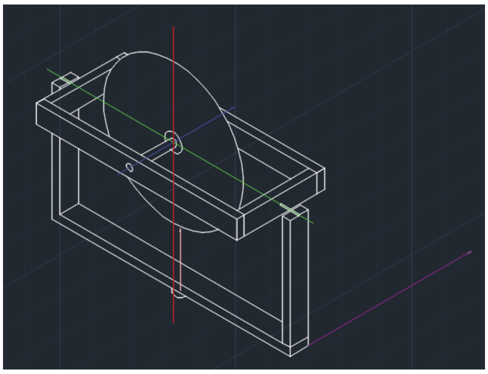


Figure 5: The spinning freewheel gimbal

Note that torque is defined as:

$$\vec{\tau} = \frac{d\vec{L}}{dt}$$

It acts upon the angular momentum. Its action is shown in figure 6.

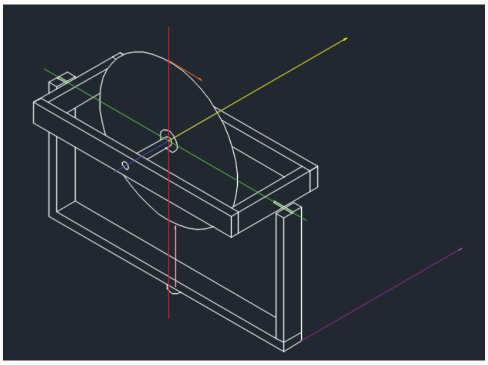


Figure 6: The spinning freewheel gimbal

This action leads to a rotation of the Y gimbal. Let us consider a small change in L, dL. The proportional $d\theta$, according to trigonometry, would be equal to:

$$d\theta = \tan\left(\frac{dL}{L}\right)$$

Since $\theta = \sin\theta = \tan\theta$ at very small angles. We may use this identity since dL is infinetesimally small. The equation then becomes:

$$d\theta = \frac{dL}{L}$$

Let us define a special kind of angular velocity, the *precession*, as the change in the angle of rotation of the Y gimbal:

$$\Phi = \frac{d\theta}{dt}$$

With the previously discussed equations, this value becomes:

$$\begin{aligned}\Phi &= \frac{d\theta}{dt} \\ &= \frac{dL}{L} \cdot \frac{1}{dt} \\ &= \frac{dL}{dt} \cdot \frac{1}{L} \\ &= \frac{1}{L}\vec{\tau}\end{aligned}$$

According to the aforementioned equations, a freewheel which is not spinning behaves intuitively. However, when the freewheel is spinning, and a force is applied to the X gimbal, a motion will emerge in the Y gimbal.

1.3 Research goal

The complexity of rotational mechanics has only been hinted at. The field is yet even more complex than what is hinted at here. To proceed with research, this paper focuses on the relationship between the velocity of the rotating wheel and the inclination of the Y gimbal as described in section 1.2.2.

The goal of this research, therefore is to find the empirical relationship between the angular velocity of the wheel ω and the angle of inclination of the Y gimbal ψ upon a force being applied on the X gimbal.

The *independent variable* is the angular velocity of the freewheel, the *dependent variable* is the angle of inclination of the Y gimbal and the *controlled variables* were the force with which the X gimbal is pulled, the time for which that force acts and the mass of the rotating wheel.

It was hypothesized for the relationship between the angle of inclination to be proportional to $\ln(\omega I)$, as described in the following set of equations.

$$\begin{aligned}\Phi &= \frac{1}{L}\vec{\tau} \\ &= \frac{1}{\omega I}\frac{dL}{dt} \\ &= \frac{1}{\omega I}\frac{d(\omega I)}{dt}\end{aligned}$$

$$\begin{aligned}\psi &= \int \Phi dt \\ &= \int \frac{1}{\omega I}\frac{d(\omega I)}{dt}dt \\ &= \ln \omega I\end{aligned}$$

2 Method

2.1 Preparation

To measure the aforementioned effect, an object as given in figure 3 was constructed with certain specific modifications to the original design. The X axis was inserted into a bearing. The Z axis also was suspended inside a bearing. On one of the sides of the Y gimbal, a potentiometer was mounted as an axis for the Y gimbal. This allows for electrically measuring the angle of the Y gimbal. A *reed relay*[1] was mounted on the edge of the Y gimbal parallel to the Z axis as shown in figure 7. Small, but powerful, neodymium magnets were mounted on the wheel. These, when in front of the reed relay, trigger it, and allow for electrical sensing of the rotation of the wheel. For higher precission it was decided that 4 magnets would be used.

Electrical connections were established to an *Arduino Uno* (Arduino) as shown in figure 8.

The Arduino Uno was programmed to read these values and the code is given in the appendix. Note how the code utilizes the interrupt service routine to provide accurate measurements of the angular velocity of the wheel as well as the angle of inclination.

The setup is shown in figure 9.

Finally, before measurements were done, the pontentiometer angle of rotation was measured, so as to provide a linear relationship between the resistance of the potentiometer and the angle of the Y gimbal.

A weight was connected to one edge of the X gimbal over a pulley to ensure a constant torque acting on the system. Although the force applied was linear, since the weight was distanced from the contraption, and since $\sin\theta = \theta$ at low angles, it can be assumed that the torque was constant.

[1] A device which connects two electrical terminals internally when a magnet is close to the device

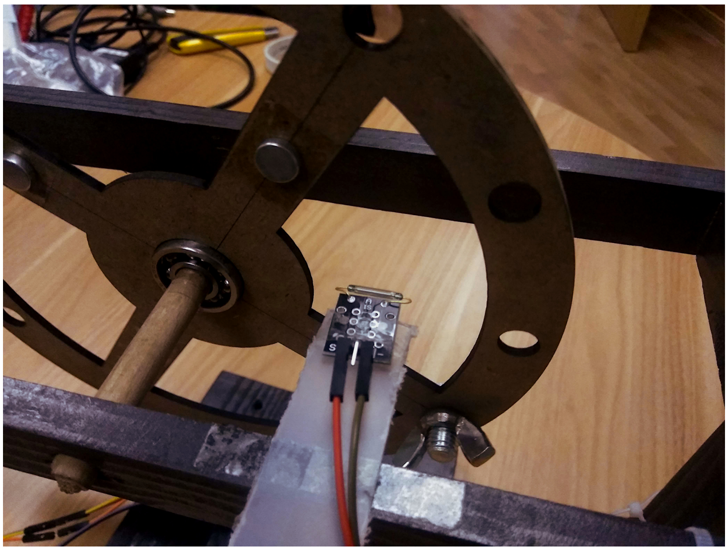


Figure 7: The reed relay

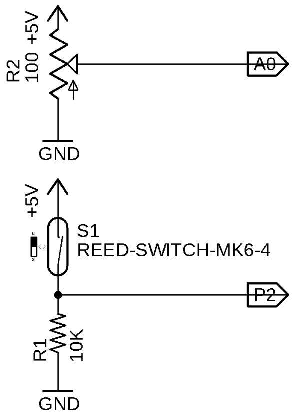


Figure 8: The schematic of the electrical connections

2.2 Environmental remarks

Neither the experiment nor the constructed machinery presented any major environmental impact. The gimbal was constructed from recycled wood to minimize environmental impact.

2.3 Experiment conduction

Upon preparation, the gimbal construction was held in place at an angle of 90° relative to the pulley. The microcontroller was reset and the following command was immediately run on the machine receiving the data:

```
cp /dev/ttyACMx Output.csv
```

where x is the port the microcontroller is connected to.

This command allows for saving the data received from the *Arduino* on a *Linux* machine.

The wheel was spun by hand and the gimbal was released to be pulled by the weight. After the gimbal stopped rotating, the copy operation run on the machine receiving the data was closed by sending an

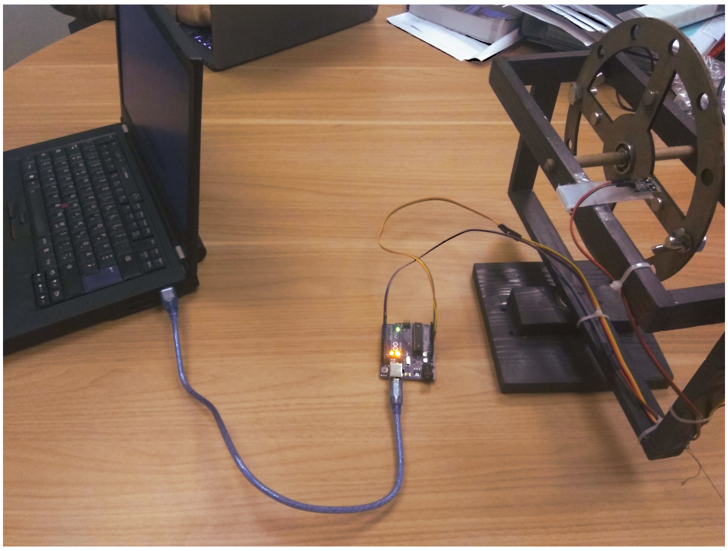


Figure 9: The setup of the experiment

interrupt signal to the running command (pressing the *CTRL-C* key combination).

3 Data

3.1 Raw data

The potentiometer maximal rotation was measured to be:

$$\psi_{pot} = (300 \pm 1)^\circ$$

The mass of the weight was measured to be:

$$m_w = (10 \pm 1)\mathrm{g}$$

Since the raw data was collected electronically, it is highly extensive and is given in the appendix.

3.1.1 Errors

The uncertainty of the measurement by *reed relay* was calculated as follows. Since there are four magnets in a range of $[0, 2\pi]$, then it follows that the range of uncertainty is $\left[0, \frac{\pi}{2}\right]$. The distance of this interval is equal to to $\left[-\frac{\pi}{4}, +\frac{\pi}{4}\right]$, making the uncertainty:

$$\theta_{error} = \pm\frac{\pi}{4}$$

3.2 Data processing

Data processing was done in the *python* programming language (Python Software Foundation). The script used is given in the appendix.

3.2.1 Data cleanup

Due to the naïve implementation of the *Arduino* serial code, all data contained remnants of serial output before the actual data was transmitted. Moreover, due to the nature of *UNIX* and *Windows* line endings, all of the data contained empty *newlines* when copied by the *cp* command.

The extra line endings where removed with a simple *regex*:

```
^\n
```

The remnant data was removed by manually inspecting each individual file and removing the serial output that was left in the buffer before the restart of the *Arduino*.

3.2.2 Graph smoothening

A graph of the relationship between the time and the angular path is given in 10, as well as its numerical derivative, the angular velocity.

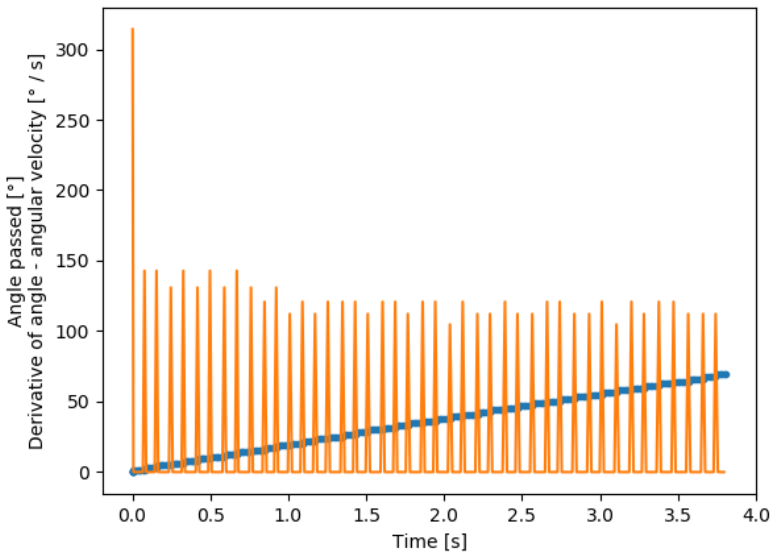


Figure 10: The relationship between the angular path and the time, including the derivative

Note how the velocity graph is incorrect. This can be attributed to the fact that the graph of the angle passed is jagged and is similar to a step function, as shown in figure 11.

To resolve this issue, it was necessary to smoothen the graph of the angle passed. This was achieved by taking the average x coordinate (the time) of each of the individual data points, where the data points are equal, producing a graph as given in figure 12.

This results in a more correct function of angular velocity.

3.2.3 Angular velocity versus the angle of inclination

With the function of the angular velocity calculated, it was possible to calculate the relationship between the initial velocity of the wheel and the angle of inclination.

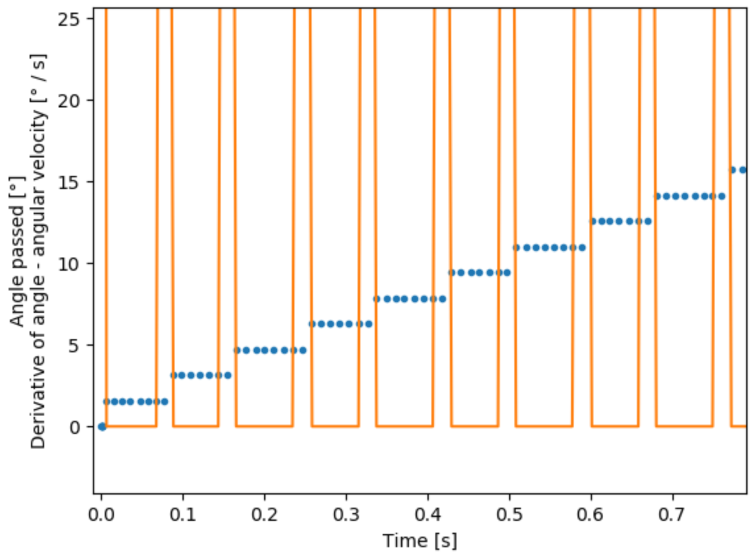


Figure 11: Zoomed view of the function given in 10

Since there was certain error (as shown in figures 13a and 13b) in the calculation of the angular velocity, it was decided that the average of the angular velocity would be taken rather than the initial velocity, since it was more accurate this way. The uncertainty was the standard deviation:

$$\omega_{error} = \sigma(\Omega)$$

The angle of inclination was calculated by subtracting its maximum value from its minimum value:

$$\Delta\psi = (\psi_{max} - \psi_{min}) \pm 2\psi_{error}$$

These calculations were done for all 10 trials. The results of these calculations are given in table 1.

$\omega\left[\frac{2\pi}{s}\right]$	$\psi\,[^\circ]$	$\Delta\omega\left[\frac{2\pi}{s}\right]$	$\Delta\psi\,[^\circ]$
7.527	80.93	0.529	0.79
15.46	19.63	4.658	0.79
18.04	117.5	7.062	0.79
18.51	142.1	3.189	0.79
19.75	13.29	6.429	0.79
20.95	131.7	6.451	0.79
22.74	23.83	3.604	0.79
25.97	16.94	2.485	0.79
26.04	91.88	6.600	0.79
32.23	17.29	14.80	0.79

Table 1: The processed data

Finally, a graph of the relationship between the average angular velocity and the angle of inclination was plotted and is given in figure 14.

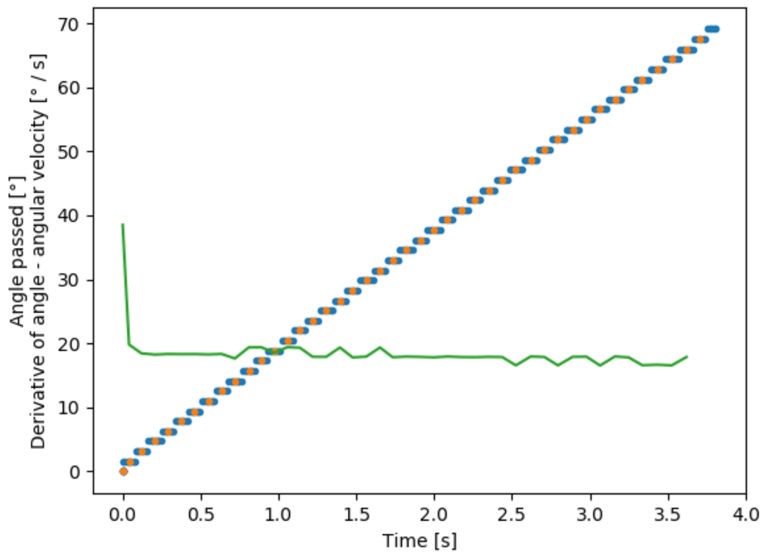
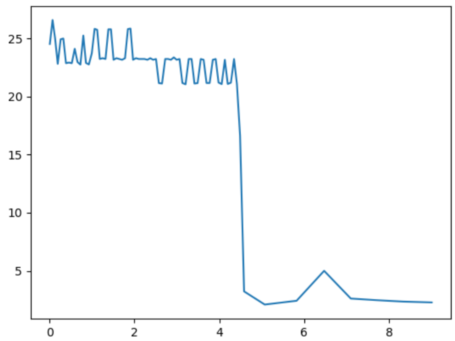
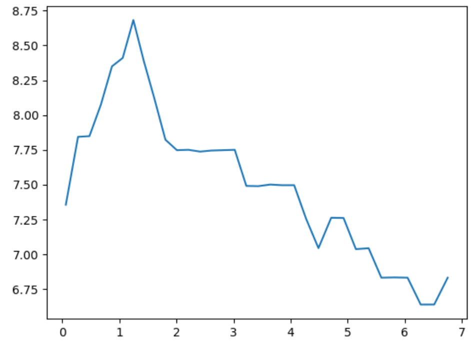


Figure 12: The improved graph of figure 10



(a) The graph of the angular velocity of the fourth trial versus time



(b) The graph of the angular velocity of the second trial versus time

4 Analysis

It is obvious that graph 14 presents no correlation, even though a clear correlation was expected. Moreover, the uncertainties over the x axis are extremely high, showing no useful information.

Qualitative data (observing the mechanism), pointed to the angle of inclination being lower for higher angular velocity, which the quantitative data does not point to.

5 Evaluation

Looking at the original graphs of the relationships between the angle of inclination, the angular velocity and the angular path versus the time, shown in figure 15, the reason behind the lack of correlation becomes obvious.

Note how the graph of the angle of inclination behaves. Strangely, it does not follow a linear trend as was qualitatively observed. This indicates that the resistance of the potentiometer was not in proportion

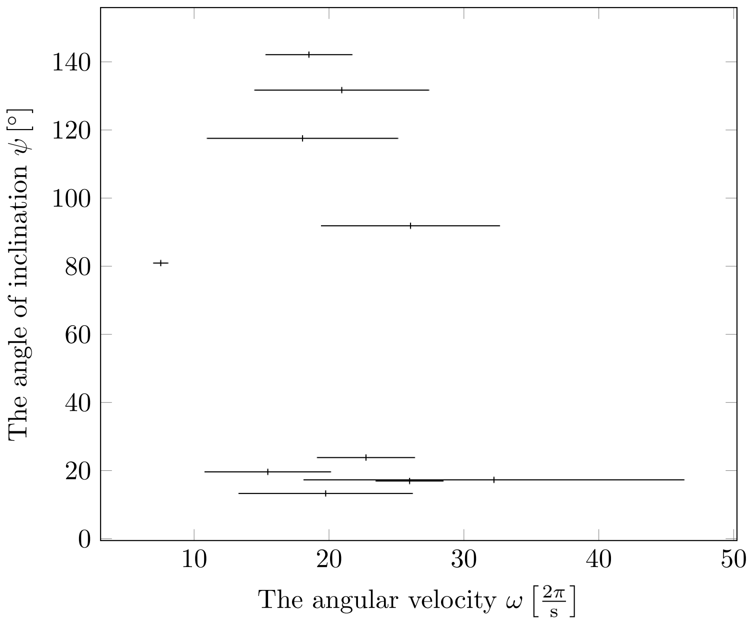


Figure 14: The graph of the relationship between the angular velocity and the angle of inclination

to the yaw of the gimbal.

Since the potentiometer picked was a linear one, this indicates that a possible reason for such inaccuracy could be that the potentiometer employed was broken. Using a multimeter it was tested, and, as expected, it proved to read different values without regard to the position of its axis.

5.1 High uncertainty

The very high x axis uncertainty is most likely a product of the *reed relay* not being fast enough to sense every time a magnet is in front of it. This can be easily resolved by reducing the number of magnets on the wheel, from 4 to 1.

6 Conclusion

The experiment turned out extremely poorly. Due to malfunctioning measuring equipment, the experiment did not shed accurate results. A further revision of this experiment should address the malfunctioning potentiometer and remeasure the data with operative equipment.

The precision of the experiment was equally as poor. Counterintuitivelly, the next revision of this experiment should reduce the number of magnets, so that the *reed relay* triggers with higher accuracy, increasing the precision of the final graph.

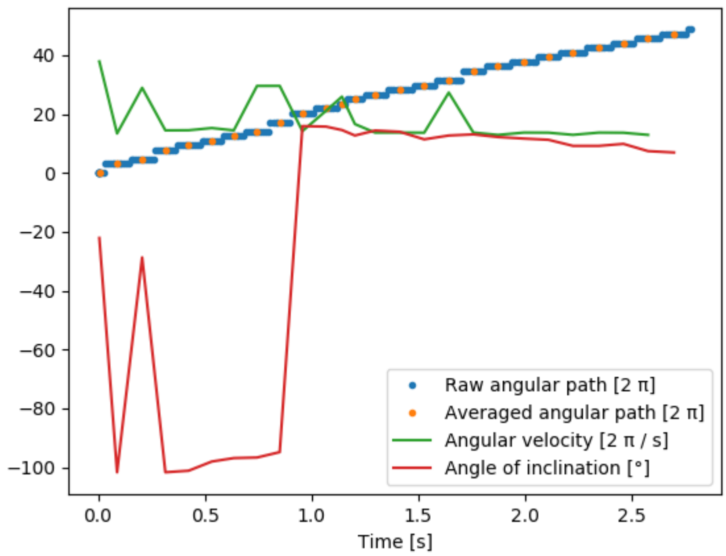


Figure 15: The graph of the angle of inclination, the angular velocity and the angular path versus time

Works Cited

Arduino. *Arduino Uno.* Farnell, 2019, https://www.farnell.com/datasheets/1682209.pdf. Accessed 17 Jan 2019.

LucasVB. *Image:3D_Gyroscope.Png, But Without English Text.* 2006, https://commons.wikimedia.org/wiki/File:3D_Gyroscope-no_text.png. Accessed 16 Jan 2019.

Python Software Foundation. *Python Language Reference.* Version 3.6.

Appendix

Raw data

Measurement 1

T[ms]($\pm$1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	701
0	0	697
1	0	696
1	0	694
2	0	694
2	0	693
2	0	692
7	1	670
16	1	244
26	1	244
36	1	242
48	1	240
58	1	238
68	1	237
78	1	233
89	2	231
99	2	227
109	2	225
121	2	221
133	2	219
144	2	218
155	2	218
166	3	218
178	3	218
190	3	218
201	3	218
212	3	218
224	3	218
235	3	218
247	3	218
259	4	219
270	4	219
281	4	219
292	4	219
304	4	219
316	4	219
327	4	219
338	5	218
350	5	218
361	5	217
372	5	217
385	5	216
396	5	214
407	5	213
418	5	210
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453	6	209
464	6	208
476	6	210
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750	9	209
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1172	14	211
1186	15	211
1200	15	211
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1281	16	218
1294	16	220
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1335	16	223
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1361	17	223
1375	17	223
1389	17	223
1402	17	223
1416	17	223
1429	17	223
1442	18	223
1457	18	223
1470	18	223
1483	18	223
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1524	19	223
1538	19	223
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3417	40	225
3430	40	225
3444	40	225
3458	40	225
3471	40	225
3484	41	225
3497	41	225
3512	41	225
3525	41	225

3538	41	225
3552	41	225
3565	41	225
3579	42	225
3593	42	225
3606	42	225
3619	42	225
3633	42	225
3647	42	225
3660	42	225
3674	43	225
3687	43	225
3700	43	226
3715	43	225
3728	43	225
3741	43	225
3755	44	225
3768	44	225
3782	44	225
3795	44	225
3809	44	225

Measurement 2

T[ms](±1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	310
1	0	310
1	0	310
2	0	310
2	0	310
2	0	310
7	0	310
16	0	308
26	0	306
36	0	306
48	0	304
58	0	302
68	0	298
78	0	297
89	0	294
99	0	290
109	0	289
121	0	283
133	0	280
144	0	275
155	0	270
166	0	264
178	1	258
190	1	256
201	1	251
212	1	528
224	1	546
235	1	527
247	1	538
259	1	549
270	1	566
281	1	563
292	1	564
304	1	515
316	1	459
327	1	233
338	1	233
350	1	233
361	1	234
372	1	453
385	2	439
396	2	430
407	2	439
418	2	445
430	2	453
441	2	453
453	2	462
464	2	425
476	2	430
487	2	441
498	2	437
509	2	403
522	2	382
533	2	340
544	2	313
556	2	306
567	2	299
578	3	272
590	3	414
602	3	233
613	3	233
624	3	233
635	3	233
648	3	233
659	3	233
670	3	233
681	3	233
693	3	233
704	3	233
716	3	233
728	3	470
739	3	461
750	3	458
761	3	454
773	3	451
785	4	450
796	4	457
807	4	457
819	4	448
830	4	458
841	4	481
854	4	471
865	4	470
876	4	475
887	4	475
899	4	475
910	4	465
922	4	467
933	4	469
945	4	467
956	4	463
967	5	233
979	5	233
991	5	234
1002	5	234
1014	5	234
1027	5	234
1039	5	233
1052	5	234
1064	5	233
1077	5	234
1089	5	234
1101	5	234
1115	5	233
1127	5	234
1139	5	233
1152	5	234
1164	6	234
1176	6	234
1189	6	234
1202	6	234
1214	6	234
1226	6	234
1239	6	235
1252	6	235
1264	6	235
1276	6	235
1289	6	236
1301	6	236
1314	6	236
1327	6	236
1339	7	236
1351	7	236
1363	7	236
1376	7	236
1389	7	236
1401	7	236
1414	7	235
1426	7	236
1438	7	236
1452	7	236
1464	7	236
1476	7	304
1488	7	303
1501	7	303
1514	7	303
1526	8	293
1539	8	236
1551	8	236
1563	8	236
1575	8	292
1589	8	319
1601	8	324
1613	8	307
1626	8	294
1638	8	437
1651	8	469
1664	8	473
1676	8	477

1688	8	485
1700	8	487
1714	9	493
1726	9	501
1738	9	510
1751	9	511
1763	9	514
1775	9	514
1788	9	512
1801	9	518
1813	9	515
1825	9	517
1838	9	517
1851	9	516
1863	9	516
1875	9	508
1888	9	508
1900	9	488
1913	10	479
1927	10	479
1940	10	476
1953	10	479
1967	10	472
1981	10	444
1994	10	417
2008	10	399
2021	10	395
2034	10	412
2049	10	404
2062	10	400
2075	10	394
2088	10	387
2102	10	404
2116	11	407
2129	11	391
2143	11	237
2156	11	382
2169	11	382
2184	11	357
2197	11	359
2210	11	357
2224	11	341
2237	11	372
2251	11	365
2265	11	379
2278	11	398
2291	11	393
2305	11	391
2319	12	375
2332	12	379

2345	12	382
2359	12	387
2372	12	359
2386	12	423
2400	12	405
2413	12	404
2426	12	375
2440	12	384
2454	12	373
2467	12	364
2481	12	350
2494	12	366
2507	12	389
2522	13	377
2535	13	369
2548	13	372
2562	13	369
2575	13	370
2589	13	372
2603	13	393
2616	13	374
2629	13	377
2643	13	398
2657	13	394
2670	13	404
2683	13	409
2697	13	419
2711	13	407
2724	14	416
2738	14	413
2751	14	423
2764	14	432
2779	14	432
2792	14	438
2805	14	442
2819	14	443
2832	14	442
2846	14	444
2860	14	444
2873	14	448
2886	14	449
2899	14	451
2914	14	450
2927	15	452
2940	15	450
2954	15	452
2967	15	451
2981	15	421
2995	15	419
3008	15	403

3021	15	418
3035	15	408
3049	15	408
3062	15	236
3076	15	409
3089	15	428
3102	15	441
3117	15	447
3130	16	447
3143	16	447
3156	16	447
3170	16	447
3184	16	445
3197	16	446
3211	16	447
3224	16	441
3237	16	436
3252	16	395
3265	16	399
3278	16	399
3292	16	398
3305	16	393
3319	16	372
3333	17	396
3346	17	397
3359	17	398
3373	17	390
3387	17	397
3400	17	403
3414	17	401
3427	17	402
3440	17	397
3454	17	398
3468	17	402
3481	17	395
3494	17	423
3509	17	421
3522	17	423
3535	17	407
3549	18	412
3562	18	236
3576	18	237
3590	18	237
3603	18	237
3616	18	237
3630	18	384
3644	18	385
3657	18	383
3671	18	388
3684	18	389

3697	18	395
3712	18	380
3725	18	383
3738	18	236
3751	19	416
3765	19	378
3779	19	422
3792	19	418
3806	19	434
3819	19	433
3832	19	434
3847	19	442
3860	19	439
3873	19	444
3887	19	440
3900	19	444
3914	19	435
3928	19	429
3941	19	425
3954	19	426
3968	20	420
3982	20	425
3995	20	412
4008	20	399
4022	20	395
4035	20	368
4049	20	366
4063	20	379
4076	20	378
4089	20	379
4103	20	382
4117	20	375
4130	20	367
4144	20	390
4157	20	392
4170	21	389
4185	21	388
4198	21	376
4211	21	349
4225	21	369
4238	21	369
4252	21	380
4265	21	382
4279	21	380
4292	21	381
4305	21	405
4320	21	401
4333	21	399
4346	21	402
4360	21	408

4374	21	413
4387	22	411
4401	22	408
4414	22	403
4427	22	402
4442	22	384
4455	22	399
4468	22	400
4482	22	399
4495	22	399
4509	22	388
4523	22	384
4536	22	375
4549	22	384
4562	22	383
4577	22	380
4590	22	386
4603	23	372
4617	23	371
4630	23	370
4644	23	390
4658	23	387
4671	23	366
4684	23	389
4698	23	395
4712	23	392
4725	23	378
4739	23	361
4752	23	384
4765	23	387
4780	23	380
4793	23	388
4806	23	381
4819	23	385
4833	24	399
4847	24	399
4860	24	395
4874	24	395
4887	24	404
4900	24	407
4915	24	391
4928	24	389
4941	24	386
4955	24	393
4968	24	398
4982	24	393
4996	24	394
5009	24	394
5022	24	397
5036	25	396

5050	25	391
5063	25	398
5076	25	404
5090	25	404
5103	25	401
5117	25	407
5131	25	405
5144	25	402
5157	25	362
5171	25	372
5185	25	363
5198	25	382
5212	25	380
5225	25	382
5239	25	384
5253	25	384
5266	26	370
5279	26	372
5293	26	373
5307	26	361
5320	26	363
5334	26	383
5347	26	415
5360	26	411
5374	26	413
5388	26	410
5401	26	408
5414	26	415
5428	26	402
5442	26	413
5455	26	236
5469	26	412
5482	27	379
5495	27	401
5510	27	401
5523	27	403
5536	27	397
5550	27	398
5563	27	400
5577	27	400
5591	27	403
5604	27	401
5617	27	397
5630	27	398
5645	27	396
5658	27	394
5671	27	380
5685	27	386
5698	27	378
5712	28	369

5726	28	371
5739	28	373
5752	28	375
5766	28	377
5780	28	373
5793	28	375
5807	28	374
5820	28	372
5833	28	379
5848	28	374
5861	28	369
5874	28	378
5888	28	363
5901	28	379
5915	28	379
5928	28	380
5942	29	379
5955	29	379
5968	29	374
5983	29	380
5996	29	383
6009	29	383
6023	29	384
6036	29	388
6050	29	390
6064	29	388
6077	29	383
6090	29	384
6105	29	373
6118	29	370
6131	29	368
6145	29	369
6158	29	369
6172	30	362
6185	30	386
6199	30	383
6212	30	382
6225	30	382
6240	30	368
6253	30	387
6266	30	386
6280	30	384
6293	30	374
6307	30	371
6321	30	372
6334	30	373
6347	30	371
6361	30	375
6375	30	376
6388	30	380
6402	31	381
6415	31	362
6428	31	363
6443	31	359
6456	31	374
6469	31	375
6482	31	375
6496	31	371
6510	31	366
6523	31	367
6537	31	363
6550	31	366
6563	31	363
6578	31	363
6591	31	363
6604	31	362
6618	31	367
6631	31	371
6645	32	371
6659	32	372
6672	32	370
6685	32	366
6699	32	369
6713	32	367
6726	32	366
6739	32	367
6753	32	366
6766	32	365
6780	32	368
6794	32	364
6807	32	368
6820	32	369
6834	32	370
6848	32	367
6861	32	375
6875	33	378
6888	33	381
6901	33	236
6916	33	372
6929	33	236
6942	33	236
6956	33	236
6970	33	236
6983	33	236
6996	33	236
7010	33	236
7023	33	236
7037	33	236
7051	33	236
7064	33	236
7077	33	236
7091	33	236
7105	34	236
7118	34	236
7132	34	236
7145	34	236
7158	34	236
7173	34	236
7186	34	236
7199	34	236

Measurement 3

T[ms](±1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	380
1	0	381
1	0	380
2	0	380
2	0	378
2	0	377
7	0	376
16	0	371
26	0	397
36	1	402
48	1	416
58	1	416
68	1	413
78	1	412
89	1	460
99	2	463
109	2	448
121	2	515
133	2	515
144	2	438
155	3	437
166	3	405
178	3	438
190	3	450
201	3	423
212	3	463
224	4	467
235	4	455
247	4	437
259	4	427
270	4	433
281	5	343
292	5	306
304	6	432
316	6	210
327	6	208
338	6	206
350	7	204
361	7	204
372	8	201
385	8	202
396	8	200
407	9	200
418	9	200
430	9	200
441	9	200
453	9	200
464	9	200
476	10	437
488	10	457
500	10	423
514	10	418
526	10	419
538	11	383
550	11	184
563	11	179
575	11	178
588	11	177
601	12	177
613	12	178
625	12	178
637	12	177
651	12	178
663	12	178
675	13	178
688	13	178
700	13	178
713	13	178
726	13	178
738	14	177
750	14	175
762	14	175
775	14	173
788	14	170
800	15	167
813	15	170
825	15	166
837	15	164
850	15	165
863	15	166
875	17	164
887	17	164
900	17	164
913	17	164
925	17	164
937	18	164
950	18	164
962	18	165
974	18	164
988	18	164
1000	19	164
1013	19	164
1027	19	164
1040	19	163
1054	19	164
1068	20	161
1081	20	161
1094	20	163
1107	20	163
1122	20	163
1135	21	164
1148	21	164
1162	21	163
1175	21	163
1189	22	165
1203	22	165
1216	22	166
1229	22	168
1243	22	170
1257	23	170
1270	23	170
1284	23	170
1297	23	170
1310	23	170
1325	24	170
1338	24	170
1351	24	169
1364	24	170
1379	24	170
1392	25	169
1405	25	169
1419	25	170
1432	25	173
1446	26	174
1460	26	176
1473	26	180
1486	26	183
1500	26	187
1514	27	187
1527	27	187
1541	27	188
1554	27	188
1567	27	189
1582	28	189
1595	28	189
1608	28	189
1622	28	189
1635	28	189
1649	29	191
1662	29	191
1676	29	192
1689	29	192
1702	30	194
1717	30	196
1730	30	198
1743	30	201
1757	30	203
1770	31	203
1784	31	203

1798	31	203
1811	31	203
1824	31	203
1838	32	203
1852	32	203
1865	32	203
1879	32	203
1892	32	203
1905	33	203
1920	33	204
1933	33	204
1946	33	205
1959	34	205
1973	34	207
1987	34	208
2000	34	210
2014	34	211
2027	35	211
2040	35	211
2055	35	211
2068	35	211
2081	35	211
2095	36	211
2108	36	211
2122	36	211
2136	36	211
2149	36	211
2162	37	211
2176	37	211
2190	37	211
2203	37	212
2216	37	212
2230	38	214
2244	38	215
2257	38	217
2271	38	216
2284	38	216
2297	39	217
2312	39	217
2325	39	216
2338	39	216
2352	39	216
2365	40	216
2379	40	216
2393	40	216
2406	40	216
2419	40	216
2433	41	216
2447	41	216
2460	41	216
2473	41	217
2487	41	218
2500	42	218
2514	42	218
2528	42	218
2541	42	218
2554	42	218
2568	43	218
2582	43	218
2595	43	488
2609	43	496
2622	43	487
2635	44	485
2650	44	217
2663	44	217
2676	44	217
2690	44	217
2703	45	217
2717	45	217
2731	45	217
2744	45	218
2757	46	218
2770	46	218
2785	46	218
2798	46	218
2811	46	218
2825	46	401
2838	47	406
2852	47	384
2866	47	464
2879	47	481
2892	47	440
2906	48	407
2920	48	383
2933	48	295
2947	48	218
2960	48	218
2973	49	218
2988	49	218
3001	49	218
3014	49	219
3027	49	218
3041	50	219
3055	50	219
3068	50	219
3082	50	219
3095	50	219
3109	51	219
3123	51	381
3136	51	450
3149	51	461
3163	51	437
3177	52	452
3190	52	451
3204	52	218
3217	52	218
3230	52	218
3245	53	218
3258	53	218
3271	53	219
3284	53	219
3298	53	219
3312	54	219
3325	54	219
3339	54	219
3352	54	219
3365	54	219
3380	55	218
3393	55	219
3406	55	460
3420	55	457
3433	55	458
3447	56	452
3461	56	443
3474	56	219
3487	56	219
3501	56	219
3515	57	219
3528	57	219
3542	57	219
3555	57	219
3568	57	219
3582	58	219
3596	58	219
3609	58	255
3622	58	219
3636	58	219
3650	58	219
3663	59	219
3677	59	219
3690	59	478
3703	59	454

Measurement 4

T[ms]($\pm$1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	402
1	0	403
1	0	400
2	0	399
2	0	400
2	0	401
7	0	409
16	0	415
26	0	428
36	0	425
48	1	457
58	1	438
68	1	434
78	1	431
89	1	433
99	1	478
109	2	477
121	2	461
133	2	434
144	2	435
155	2	424
166	3	430
178	3	432
190	3	447
201	3	446
212	3	453
224	3	444
235	4	441
247	4	446
259	4	456
270	4	205
281	4	205
292	4	504
304	5	527
316	5	513
327	5	472
338	5	454
350	5	457
361	6	432
372	6	419
385	6	181
396	6	178
407	6	176
418	6	174
430	7	174
441	7	174
453	7	173
464	7	172
476	7	172
487	7	177
498	8	172
509	8	172
522	8	173
533	8	173
544	8	173
556	8	173
567	9	239
578	9	188
590	9	186
602	9	185
613	9	182
624	9	178
635	10	172
649	10	168
661	10	162
673	10	163
686	10	157
698	11	157
710	11	157
723	11	157
736	11	157
748	11	158
760	11	157
773	12	157
786	12	157
798	12	157
811	12	158
823	12	157
835	13	157
848	13	454
861	13	478
873	13	484
885	13	469
898	14	444
910	14	433
923	14	448
935	14	177
948	14	156
960	14	156
972	15	156
986	15	156
998	15	156
1010	15	156
1024	15	156
1037	16	156
1051	16	156
1064	16	156
1078	16	156
1091	16	156
1104	17	156
1119	17	156
1132	17	156
1145	17	157
1159	18	157
1172	18	156
1186	18	156
1200	18	157
1213	18	157
1226	19	158
1240	19	158
1254	19	158
1267	19	159
1281	19	162
1294	20	165
1307	20	168
1321	20	170
1335	20	173
1348	20	175
1361	21	175
1375	21	175
1389	21	176
1402	21	177
1416	21	178
1429	22	178
1442	22	180
1457	22	180
1470	22	179
1483	23	181
1497	23	182
1510	23	183
1524	23	381
1538	23	400
1551	24	376
1564	24	409
1579	24	422
1592	24	425
1605	24	435
1618	25	435
1632	25	443
1646	25	444
1659	25	449
1673	25	455
1686	26	458
1699	26	454
1714	26	459
1727	26	466
1740	26	204
1754	27	453
1767	27	204

1781	27	205
1795	27	205
1808	27	206
1821	28	440
1835	28	454
1849	28	459
1862	28	438
1875	28	440
1889	29	448
1902	29	442
1916	29	433
1930	29	456
1943	30	466
1956	30	468
1970	30	469
1984	30	470
1997	30	466
2011	31	486
2024	31	418
2037	31	209
2052	31	211
2065	31	458
2078	32	463
2092	32	459
2105	32	455
2119	32	426
2132	32	447
2146	33	534
2159	33	524
2172	33	523
2187	33	491
2200	33	497
2213	34	507
2227	34	546
2240	34	553
2254	34	547
2268	34	545
2281	35	564
2294	35	584
2308	35	572
2322	35	217
2335	35	524
2349	36	517
2362	36	514
2375	36	536
2390	36	542
2403	36	491
2416	37	507
2429	37	506
2444	37	500

2457	37	488
2470	37	503
2484	38	494
2497	38	503
2511	38	507
2525	38	483
2538	38	483
2551	39	487
2565	39	494
2579	39	502
2592	39	448
2606	39	442
2619	40	459
2632	40	460
2647	40	460
2660	40	463
2673	40	460
2686	40	441
2700	41	446
2714	41	451
2727	41	432
2741	41	438
2754	41	445
2767	42	434
2782	42	456
2795	42	458
2808	42	442
2822	42	460
2835	43	467
2849	43	465
2863	43	448
2876	43	468
2889	43	474
2903	44	474
2917	44	480
2930	44	480
2944	44	457
2957	44	455
2970	45	479
2984	45	478
2998	45	446
3011	45	483
3024	45	473
3038	46	477
3052	46	435
3065	46	465
3079	46	431
3092	46	455
3105	47	455
3120	47	455

3133	47	431
3146	47	218
3160	47	353
3173	48	359
3187	48	362
3201	48	358
3214	48	219
3227	48	476
3240	48	471
3255	49	485
3268	49	475
3281	49	498
3295	49	506
3309	49	504
3322	50	499
3336	50	479
3349	50	454
3362	50	472
3377	50	461
3390	51	460
3403	51	458
3417	51	434
3430	51	419
3444	51	430
3458	52	441
3471	52	443
3484	52	446
3497	52	447
3512	52	445
3525	52	441
3538	53	439
3552	53	412
3565	53	422
3579	53	443
3593	53	448
3606	54	431
3619	54	440
3633	54	432
3647	54	436
3660	54	432
3674	55	430
3687	55	433
3700	55	434
3715	55	438
3728	55	447
3741	56	437
3755	56	448
3768	56	445
3782	56	446
3795	56	441

3809	56	448
3822	57	446
3835	57	446
3850	57	454
3863	57	448
3876	57	454
3890	58	436
3903	58	435
3917	58	440
3931	58	451
3944	58	450
3957	59	465
3971	59	468
3985	59	447
3998	59	449
4012	59	454
4025	60	467
4038	60	466
4052	60	471
4066	60	475
4079	60	475
4092	60	472
4106	61	458
4120	61	470
4133	61	479
4147	61	475
4160	61	475
4174	62	481
4188	62	480
4201	62	484
4214	62	473
4228	62	471
4242	63	453
4255	63	437
4269	63	390
4282	63	396
4295	63	392
4310	63	430
4323	64	433
4336	64	442
4349	64	452
4363	64	449
4377	64	442
4390	65	448
4404	65	442
4417	65	454
4430	65	461
4445	65	458
4458	66	463
4471	66	452

4485	66	441
4498	66	443
4512	66	439
4526	66	444
4539	67	439
4552	67	427
4566	67	420
4580	67	434
4593	67	446
4606	67	426
4620	67	427
4633	67	441
4647	68	437
4661	68	433
4674	68	423
4687	68	446
4701	68	426
4715	68	429
4728	68	422
4742	68	437
4755	68	426
4768	68	447
4783	68	465
4796	68	453
4809	68	449
4823	68	434
4836	68	424
4850	68	428
4864	68	394
4877	68	402
4890	68	408
4903	68	397
4918	68	400
4931	68	392
4944	68	214
4958	68	214
4971	68	215
4985	68	215
4999	68	413
5012	68	413
5025	68	410
5040	68	405
5053	68	389
5066	68	405
5080	68	393
5093	68	409
5107	68	407
5121	68	410
5134	68	402
5147	68	406

5160	68	408
5175	68	413
5188	68	409
5201	68	412
5215	68	411
5228	68	410
5242	68	409
5256	68	414
5269	68	417
5282	68	419
5296	68	421
5310	68	421
5323	68	422
5337	68	423
5350	68	414
5363	68	409
5378	68	411
5391	68	414
5404	68	400
5417	68	374
5431	68	400
5445	68	398
5458	68	215
5472	68	215
5485	68	216
5498	68	218
5513	69	219
5526	69	394
5539	69	382
5553	69	403
5566	69	412
5580	69	419
5594	69	406
5607	69	411
5620	69	418
5634	69	423
5648	69	424
5661	69	424
5675	69	429
5688	69	438
5701	69	436
5715	69	432
5729	69	431
5742	69	435
5755	69	427
5769	69	433
5783	69	435
5796	69	401
5810	69	407
5823	69	425

5836	69	422
5851	69	418
5864	69	417
5877	69	429
5891	69	411
5905	69	413
5918	69	430
5932	69	431
5945	69	425
5958	69	428
5972	69	430
5986	69	433
5999	69	431
6012	69	432
6026	69	429
6040	69	426
6053	69	426
6067	69	437
6080	69	399
6093	69	417
6108	69	416
6121	69	405
6134	69	225
6148	70	224
6161	70	225
6175	70	225
6189	70	230
6202	70	430
6215	70	450
6228	70	465
6243	70	490
6256	70	476
6269	70	480
6283	70	487
6296	70	459
6310	70	483
6324	70	500
6337	70	499
6350	70	498
6364	70	486
6378	70	485
6391	70	476
6405	70	473
6418	70	475
6431	70	474
6446	70	469
6459	70	471
6472	70	482
6486	70	486
6499	70	481
6513	70	473
6526	70	475
6540	70	469
6553	70	469
6566	70	468
6581	70	481
6594	70	474
6607	70	452
6621	70	452
6634	70	434
6648	70	424
6662	70	408
6675	70	394
6688	70	388
6702	70	394
6716	70	394
6729	70	467
6743	70	504
6756	70	506
6770	70	509
6784	70	508
6797	70	509
6810	72	509
6823	72	505
6838	72	498
6851	72	485
6864	72	486
6878	72	488
6891	72	488
6905	72	487
6919	72	486
6932	72	481
6945	72	476
6959	72	476
6973	72	479
6986	72	481
7000	72	481
7013	72	480
7026	72	480
7041	72	479
7054	72	479
7067	72	479
7080	72	480
7094	72	480
7108	72	479
7121	72	479
7135	72	479
7148	72	478
7161	72	479
7176	72	477
7189	72	471
7202	72	465
7216	72	463
7229	72	462
7243	72	463
7257	72	464
7270	72	467
7283	72	464
7297	72	477
7311	72	479
7324	72	480
7337	72	474
7351	72	476
7364	72	480
7378	72	475
7392	72	464
7405	73	438
7418	73	417
7432	73	430
7446	73	430
7459	73	430
7473	73	431
7486	73	438
7499	73	441
7514	73	438
7527	73	444
7540	73	460
7554	73	460
7567	73	451
7581	73	448
7595	73	446
7608	73	446
7621	73	439
7635	73	435
7649	73	430
7662	73	426
7675	73	427
7689	73	422
7703	73	422
7716	73	421
7730	73	420
7743	73	420
7756	73	394
7771	73	394
7784	73	420
7797	73	418
7811	73	417
7824	73	413
7838	73	413
7852	73	409

7865	73	381
7878	73	382
7891	73	384
7906	73	383
7919	73	385
7932	73	383
7946	73	383
7959	73	383
7973	73	383
7987	73	383
8000	73	384
8013	74	384
8027	74	383
8041	74	384
8054	74	384
8068	74	385
8081	74	386
8094	74	384
8109	74	381
8122	74	381
8135	74	380
8148	74	380
8162	74	380
8176	74	381
8189	74	378
8203	74	381
8216	74	378
8229	74	379
8244	74	379
8257	74	379
8270	74	379
8284	74	381
8297	74	379
8311	74	378
8325	74	381
8338	74	383
8351	74	383
8365	74	383
8379	74	383
8392	74	382
8406	74	382
8419	74	382
8432	74	382
8446	74	382
8460	74	382
8473	74	382
8486	74	383
8501	74	383
8514	74	383
8527	74	383
8541	74	383
8554	74	383
8568	74	382
8582	74	383
8595	74	384
8608	74	384
8622	74	384
8636	74	385
8649	74	385
8663	74	387
8676	75	385
8689	75	386
8704	75	385
8717	75	384
8730	75	384
8743	75	383
8757	75	383
8771	75	383
8784	75	384
8798	75	384
8811	75	384
8824	75	384
8839	75	384
8852	75	382
8865	75	379
8879	75	379
8892	75	378
8906	75	378
8920	75	379
8933	75	379
8946	75	379
8960	75	380
8974	75	380
8987	75	381
9000	75	380
9014	75	379
9027	75	377
9041	75	376
9055	75	376
9068	75	378
9081	75	378
9095	75	378
9109	75	379
9122	75	380
9136	75	375
9149	75	374
9162	75	372
9177	75	373
9190	75	373
9203	75	379
9217	75	378
9230	75	374
9244	75	374
9257	75	374
9271	75	373
9284	75	373
9297	75	373
9312	75	373
9325	75	372
9338	75	373
9352	76	377
9366	76	373
9379	76	381
9393	76	374
9406	76	374
9419	76	374
9434	76	374
9447	76	373
9460	76	373
9474	76	373
9487	76	373
9501	76	373
9515	76	373
9528	76	373
9541	76	373
9554	76	373
9569	76	374
9582	76	374
9595	76	373
9609	76	374
9622	76	374
9636	76	375
9650	76	374
9663	76	374
9676	76	372
9690	76	811
9704	76	824
9717	76	814
9731	76	828
9744	76	829
9757	76	829
9772	76	807
9785	76	818
9798	76	819
9811	76	838
9825	76	837
9839	76	836
9852	76	836
9866	76	832
9879	76	827

9892	76	819
9907	76	810
9920	76	822
9933	76	826
9947	76	821
9960	76	817
9974	76	812
9988	76	812
10001	76	809
10015	76	806
10030	76	803
10045	76	799
10059	77	795

Measurement 5

T[ms]($\pm$1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	538
1	0	537
1	0	534
2	0	536
2	0	540
2	0	546
7	0	550
16	0	191
26	0	191
36	2	191
48	2	191
58	2	191
68	2	191
78	2	191
89	2	191
99	2	191
109	2	191
121	2	191
133	2	191
144	2	191
155	3	191
166	3	191
178	3	537
190	3	561
201	3	572
212	3	572
224	3	553
235	3	531
247	3	501
259	3	191
270	5	191
281	5	191
292	5	191
304	5	191
316	5	191
327	5	191
338	5	191
350	5	191
361	5	191
372	6	191
385	6	191
396	6	191
407	6	192
418	6	192
430	6	193
441	6	193
453	6	194
464	6	195
476	6	196
487	7	198
498	7	198
509	7	201
522	7	203
533	7	205
544	7	205
556	7	207
567	7	207
578	7	207
590	8	208
602	8	207
613	8	207
624	8	207
635	8	207
648	8	207
659	8	208
670	8	208
681	8	208
693	9	208
704	9	208
716	9	208
728	9	208
739	9	208
750	9	208
761	9	208
773	9	208
785	9	208
796	9	209
807	11	209
820	11	211
832	11	212
844	11	212
858	11	213
870	11	217
882	11	218
894	11	223
907	13	573
920	13	591
932	13	593
945	13	593
957	13	599
969	13	597
983	13	597
995	13	595
1007	13	592
1020	14	590
1034	14	589
1048	14	589
1061	14	589
1075	14	595
1088	14	596
1101	14	594
1116	14	591
1129	15	587
1142	15	588
1156	15	588
1169	16	586
1183	16	577
1197	16	585
1210	16	581
1223	16	577
1236	16	582
1251	17	591
1264	17	581
1277	17	584
1291	17	592
1304	17	587
1318	17	592
1332	17	586
1345	17	584
1358	18	584
1372	18	585
1386	18	593
1399	18	588
1413	18	587
1426	18	590
1439	18	585
1454	18	579
1467	18	580
1480	19	578
1494	19	581
1507	19	579
1521	19	580
1534	19	578
1548	19	573
1561	19	576
1574	19	570
1589	20	578
1602	20	578
1615	20	583
1629	20	583
1642	20	586
1656	20	584
1670	20	580
1683	20	583
1696	20	577
1710	22	584
1724	22	582
1737	22	583
1751	22	585

1764	22	584
1778	22	580
1792	22	582
1805	22	581
1818	23	584
1831	23	579
1846	23	581
1859	23	583
1872	23	585
1886	23	574
1899	23	578
1913	23	575
1927	23	577
1940	24	578
1953	24	585
1967	24	576
1981	24	573
1994	24	580
2008	24	575
2021	24	576
2034	24	577
2049	24	580
2062	25	579
2075	25	578
2088	25	574
2102	25	576
2116	25	576
2129	25	577
2143	25	577
2156	25	574
2169	26	575
2184	26	573
2197	26	569
2210	26	569
2224	26	568
2237	26	569
2251	26	568
2265	26	566
2278	26	567
2291	27	568
2305	27	568
2319	27	568
2332	27	567
2345	27	566
2359	27	565
2372	27	579
2386	27	571
2400	27	572
2413	28	570
2426	28	570
2440	28	570
2454	28	573
2467	28	573
2481	28	574
2494	28	572
2507	28	571
2522	29	572
2535	29	565
2548	29	563
2562	29	565
2575	29	566
2589	29	563
2603	29	559
2616	29	558
2629	29	558
2643	30	560
2657	30	559
2670	30	561
2683	30	562
2697	30	561
2711	30	561
2724	30	564
2738	30	563
2751	30	564
2764	31	562
2779	31	565

Measurement 6

T[ms](±1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	161
1	0	161
1	0	161
2	0	161
2	0	161
2	0	161
7	0	161
16	0	161
26	0	161
36	1	160
48	1	158
58	1	157
68	1	155
78	1	155
89	2	154
99	2	155
109	2	154
121	2	154
133	2	154
144	2	154
155	3	155
166	3	155
178	3	155
190	3	155
201	3	155
212	4	155
224	4	155
235	4	155
247	4	155
259	4	155
270	4	155
281	5	155
292	5	155
304	5	155
316	5	154
327	5	154
338	6	154
350	6	154
361	6	155
372	6	155
385	6	155
396	7	155
407	7	155
418	7	155
430	7	155
441	7	155
453	7	155
464	8	155
476	8	155
487	8	156
498	8	158
509	8	159
522	9	159
533	9	160
544	9	160
556	9	161
567	9	162
578	10	162
591	10	162
604	10	162
616	10	162
628	10	163
641	11	163
654	11	163
666	11	164
678	11	165
691	11	167
703	12	170
716	12	170
729	12	173
741	12	174
753	12	175
765	13	175
778	13	176
791	13	176
803	13	177
816	14	177
828	14	178
840	14	178
854	14	179
866	14	179
878	15	180
890	15	181
903	15	183
916	15	184
928	15	186
941	16	188
953	16	191
965	16	193
977	16	195
991	16	196
1003	17	197
1016	17	197
1030	17	197
1043	17	197
1057	18	197
1071	18	197
1084	18	197
1097	18	197
1111	18	198
1125	19	199
1138	19	198
1152	19	198
1165	19	199
1179	20	201
1192	20	204
1206	20	203
1219	20	204
1232	20	204
1247	21	204
1260	21	204
1273	21	204
1287	21	204
1300	22	204
1314	22	204
1328	22	204
1341	22	204
1354	22	204
1368	23	204
1382	23	204
1395	23	205
1409	23	204
1422	24	207
1435	24	207
1449	24	206
1463	24	206
1476	24	206
1489	25	206
1503	25	206
1517	25	206
1530	25	206
1544	25	206
1557	26	206
1570	26	206
1585	26	206
1598	26	206
1611	27	206
1625	27	206
1638	27	207
1652	27	206
1666	27	207
1679	28	208
1692	28	208
1705	28	208
1720	28	208
1733	28	208
1746	29	208
1760	29	208
1773	29	208

1787	29	208
1801	30	208
1814	30	207
1827	30	207
1841	30	207
1855	30	208
1868	31	208
1882	31	208
1895	31	208
1908	31	208
1923	31	209
1936	32	210
1949	32	210
1963	32	210
1976	32	209
1990	33	209
2003	33	209
2017	33	209
2030	33	209
2044	33	209
2058	34	209
2071	34	209
2084	34	209
2098	34	209
2112	34	210
2125	35	210
2139	35	210
2152	35	210
2165	35	211
2180	36	211
2193	36	211
2206	36	212
2220	36	211
2233	36	211
2247	37	211
2260	37	211
2274	37	211
2287	37	211
2300	37	211
2315	38	211
2328	38	211
2341	38	211
2355	38	211
2368	38	211
2382	39	211
2396	39	211
2409	39	211
2422	39	211
2436	40	211
2450	40	213
2463	41	213

Measurement 7

T[ms](±1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	161
1	0	161
1	0	161
2	0	161
2	0	161
2	0	161
7	1	160
16	1	159
26	1	159
36	1	159
48	1	159
58	1	159
68	1	158
78	2	157
89	2	157
99	2	157
109	2	157
121	2	157
133	2	157
144	3	157
155	3	157
166	4	157
178	4	158
190	4	158
201	4	158
212	5	158
224	5	158
235	5	158
247	5	158
259	5	158
270	5	158
281	5	158
292	6	158
304	7	158
316	7	158
327	7	158
338	7	158
350	8	158
361	8	158
372	8	158
385	8	158
396	8	158
407	8	158
418	9	159
430	9	159
441	9	159
453	9	160
464	9	162
476	9	164
487	10	165
499	10	169
512	10	170
525	10	172
537	10	174
549	10	175
562	11	175
574	11	176
587	11	177
600	11	177
612	11	177
624	12	178
636	12	179
650	12	179
662	12	179
674	12	180
687	13	181
699	13	181
711	13	182
724	13	184
737	13	186
749	13	188
761	14	191
774	14	194
787	14	196
799	14	199
812	14	202
824	15	202
836	15	203
849	15	204
862	15	203
874	15	203
886	15	203
899	16	203
911	16	203
924	16	203
936	16	204
949	16	203
961	17	204
973	17	204
987	17	205
999	17	205
1011	17	206
1025	18	206
1038	18	206
1052	18	208
1065	18	209
1079	18	209
1092	18	209
1105	19	209
1120	21	209
1133	21	209
1146	21	209
1160	21	209
1173	22	209
1187	23	209
1201	23	209
1214	23	209
1227	23	209
1241	24	209
1255	24	210
1268	24	210
1282	24	212
1295	24	213
1308	25	215
1323	25	213
1336	25	215
1349	25	216
1362	25	215
1376	26	215
1390	26	215
1403	27	215
1417	27	215
1430	27	215
1443	28	214
1458	28	214
1471	28	214
1484	28	214
1498	28	214
1512	28	214
1525	29	214
1539	29	214
1552	29	214
1565	29	216
1580	29	216
1593	30	216
1606	30	216
1619	30	216
1633	30	216
1647	30	216
1660	31	216
1674	31	216
1687	32	216
1700	32	213
1715	32	213
1728	33	213
1741	33	213
1755	33	213
1768	33	213
1782	33	213

1796	33	213
1809	34	213
1822	34	213
1836	34	213
1850	34	214
1863	34	214
1876	35	214
1890	35	214
1903	35	214
1917	35	214
1931	35	214

Measurement 8

T[ms](±1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	172
0	0	172
1	0	172
1	0	173
2	0	172
2	0	172
2	0	172
7	0	173
16	0	173
26	0	174
36	0	174
48	0	174
58	1	174
68	1	174
78	1	174
89	1	174
99	1	174
109	1	174
121	1	174
133	1	174
144	2	174
155	2	174
166	2	174
178	2	174
190	2	174
201	2	174
212	2	174
224	2	174
235	2	174
247	3	174
259	3	174
270	3	174
281	3	174
292	3	174
304	3	174
316	3	174
327	3	174
338	4	174
350	4	174
361	4	174
372	4	174
385	4	174
396	4	174
407	4	174
418	4	174
430	5	174
441	5	174
453	5	174
464	5	174
476	5	174
487	5	174
498	5	174
509	6	174
522	6	174
533	6	175
544	6	177
556	6	181
567	6	182
578	6	184
590	6	185
602	6	186
613	7	186
624	7	187
635	8	187
648	8	187
659	8	188
670	8	187
681	8	187
693	9	188
704	9	187
716	9	187
728	9	187
739	9	187
750	9	187
761	9	187
773	9	188
785	10	189
797	10	190
809	10	190
822	10	191
834	10	192
847	10	194
860	10	196
872	11	197
884	11	202
897	11	204
909	11	206
922	11	209
934	11	211
947	11	213
959	11	212
971	12	213
985	12	213
997	13	213
1009	13	213
1022	13	213
1036	13	213
1050	14	213
1063	14	213
1077	14	213
1090	14	213
1103	14	213
1118	14	213
1131	14	213
1144	15	213
1158	15	214
1171	15	215
1185	15	215
1199	15	216
1212	15	216
1225	15	216
1239	16	217
1253	16	218
1266	16	218
1280	16	218
1293	16	218
1306	16	218
1320	16	218
1334	17	218
1347	17	218
1360	17	218
1374	17	218
1388	17	218
1401	17	217
1415	17	217
1428	18	217
1441	18	217
1456	19	217
1469	19	218
1482	19	218
1496	19	218
1509	19	218
1523	20	218
1537	20	218
1550	20	218
1563	20	218
1576	20	218
1591	20	218
1604	20	218
1617	21	218
1631	21	218
1645	21	218
1658	21	218
1672	21	218
1685	21	218
1698	21	218
1713	22	218
1726	22	217
1739	22	218

1753	22	217
1766	22	217
1780	22	217
1794	22	218
1807	23	217
1820	23	217
1833	23	217
1848	23	218
1861	23	218
1874	23	218
1888	23	218
1901	24	218
1915	24	218
1929	24	218
1942	24	218
1955	24	218
1969	24	218
1983	24	218
1996	25	218
2010	25	218
2023	25	218
2036	25	219
2051	25	218
2064	25	218
2077	25	218
2091	25	218
2104	26	218
2118	26	218
2131	26	218
2145	26	218
2158	26	218
2171	26	218
2186	26	218
2199	27	218
2212	27	218
2226	28	218
2239	28	218
2253	28	218
2267	28	218
2280	28	218
2293	29	217
2307	29	218
2321	29	218
2334	29	218
2348	29	218
2361	29	218
2374	29	218
2388	30	218
2402	30	218
2415	30	218
2428	30	218
2442	30	218
2456	30	219
2469	30	218
2483	30	218
2496	31	218
2510	31	218
2524	31	218
2537	31	218
2550	31	218
2564	31	218
2578	31	218
2591	32	218
2605	32	218
2618	32	218
2631	32	218
2646	32	218
2659	32	218
2672	32	218
2685	33	218
2699	33	218
2713	33	218
2726	33	218
2740	33	218
2753	33	218
2766	33	218
2781	34	218
2794	34	218
2807	34	218
2821	34	218
2834	34	218
2848	34	218
2862	34	218
2875	34	218
2888	35	218
2902	35	218
2916	35	218
2929	35	218
2942	35	218
2956	35	218
2969	35	218
2983	36	218
2997	36	218
3010	36	218
3023	36	218
3037	36	216
3051	36	218
3064	36	218
3078	37	218
3091	37	218
3104	37	218
3119	37	218
3132	37	218
3145	37	218
3159	37	218
3172	38	218
3186	38	218
3200	38	218
3213	38	218
3226	38	218
3239	38	218
3254	38	218
3267	38	218
3280	39	218
3294	39	218
3307	39	218
3321	39	218
3335	39	218
3348	39	218
3361	39	218
3376	40	218
3389	40	218
3402	40	218
3416	40	218
3429	40	218
3443	40	218
3457	40	218
3470	40	218
3483	41	218
3496	41	218
3511	41	218
3524	41	218
3537	41	218

Measurement 9

T[ms](±1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	161
1	0	161
1	0	161
2	0	161
2	0	161
2	0	161
7	1	161
16	1	161
26	1	162
36	1	161
48	1	162
58	1	162
68	1	162
78	2	161
89	2	161
99	2	159
109	2	159
121	2	158
133	2	157
144	2	156
155	3	154
166	3	155
178	3	155
190	3	155
201	3	157
212	3	158
224	4	157
235	4	158
247	4	158
259	4	158
270	4	158
281	4	159
292	5	159
304	5	160
316	5	160
327	5	162
338	5	162
350	5	162
361	6	162
372	6	162
385	6	162
396	6	162
407	6	162
418	6	162
430	7	162
441	7	162
453	7	163
464	7	162
476	7	163
487	7	163
498	8	164
509	8	164
522	8	164
533	8	166
544	8	167
556	8	169
567	9	172
578	9	173
590	9	176
602	9	180
613	9	183
624	9	185
635	10	185
649	10	187
661	10	190
673	10	191
686	10	191
698	10	192
710	11	193
723	11	193
736	11	194
748	11	194
760	11	196
773	12	195
786	12	196
798	12	199
811	12	202
823	12	203
835	13	205
848	13	206
861	13	210
873	13	213
885	13	217
898	13	218
910	14	219
923	14	220
935	14	220
948	14	221
960	14	221
972	14	221
986	15	222
998	15	221
1010	15	221
1024	15	221
1037	15	222
1051	16	223
1064	16	223
1078	16	223
1091	16	221
1104	16	223
1119	17	225
1132	17	225
1145	17	227
1159	17	228
1172	17	228
1186	18	228
1200	18	228
1213	18	228
1226	18	228
1240	18	228
1254	19	228
1267	19	228
1281	19	229
1294	19	229
1307	19	229
1321	20	229
1335	20	229
1348	20	229
1361	20	229
1375	20	230
1389	20	232
1402	21	234
1416	21	235
1429	21	236
1442	21	236
1457	21	236
1470	22	236
1483	22	236
1497	22	236
1510	22	236
1524	22	236
1538	23	236
1551	23	236
1564	23	236
1579	23	236
1592	23	236
1605	24	236
1618	24	236
1632	24	236
1646	24	237
1659	24	237
1673	24	237
1686	25	237
1699	25	237
1714	25	237
1727	25	237
1740	25	237
1754	26	237
1767	26	237

1781	26	237
1795	26	236
1808	26	236
1821	27	235
1835	27	235
1849	27	235
1862	27	235
1875	27	235
1889	27	236
1902	28	236
1916	28	236
1930	28	236
1943	28	236
1956	28	236
1970	29	236
1984	29	236
1997	29	236
2011	29	236
2024	29	236
2037	30	236
2052	30	236
2065	30	235
2078	30	234
2092	30	234
2105	30	234
2119	31	234
2132	31	234
2146	31	235
2159	31	235
2172	31	235
2187	32	235
2200	32	235
2213	32	235
2227	32	235
2240	32	235
2254	33	235
2268	33	235
2281	33	235
2294	33	235
2308	33	235
2322	33	235
2335	34	235
2349	34	235
2362	34	235
2375	34	234
2390	34	234
2403	35	234
2416	35	234
2429	35	234
2444	35	234

2457	35	235
2470	35	235
2484	36	235
2497	36	235
2511	36	235
2525	36	235
2538	36	235
2551	37	235
2565	37	236
2579	37	235
2592	37	235
2606	37	235
2619	37	235
2632	38	235
2647	38	235
2660	38	235
2673	38	234
2686	38	234
2700	39	235
2714	39	236
2727	39	235
2741	39	235
2754	39	235
2767	39	235
2782	40	235
2795	40	235
2808	40	235
2822	40	235
2835	40	235

Measurement 10

T[ms](±1ms)	N_{reed}[ ]	Val_{pot}[ ]
0	0	168
1	0	168
1	0	168
2	0	168
2	0	168
2	0	168
7	1	168
16	1	168
26	1	169
36	1	169
48	1	169
58	1	169
68	1	169
78	1	169
89	1	169
99	2	169
109	2	169
121	2	169
133	2	169
144	2	168
155	2	169
166	2	168
178	2	169
190	3	169
201	3	169
212	3	169
224	3	169
235	3	169
247	3	169
259	3	169
270	3	170
281	4	170
292	4	172
304	4	172
316	4	172
327	4	173
338	4	174
350	4	175
361	5	177
372	5	180
385	5	183
396	5	186
407	5	189
418	5	190
430	5	192
441	5	193
453	6	194
464	6	196
476	6	196
487	6	196
498	6	198
509	6	198
522	6	199
533	6	199
544	7	202
556	7	202
567	7	202
578	7	202
590	7	202
602	7	202
613	7	202
624	8	202
635	8	203
648	8	204
659	8	206
670	8	206
681	8	207
693	8	208
704	8	211
716	9	213
728	9	217
739	9	220
750	9	223
761	9	224
773	9	228
785	9	227
796	9	229
807	10	229
820	10	229
832	10	229
844	10	230
858	10	230
870	10	230
882	10	230
894	11	230
907	11	230
920	11	230
932	11	230
945	11	230
957	11	230
969	11	230
983	12	230
995	12	230
1007	12	229
1020	12	231
1034	12	232
1048	12	232
1061	12	232
1075	13	234
1088	13	234
1101	13	234
1116	13	234
1129	13	234
1142	13	235
1156	13	235
1169	14	235
1183	14	235
1197	14	235
1210	14	235
1223	14	235
1236	14	235
1251	14	235
1264	15	235
1277	15	234
1291	15	235
1304	15	235
1318	15	235
1332	15	235
1345	16	235
1358	16	235
1372	16	235
1386	16	235
1399	16	235
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1426	16	235
1439	17	235
1454	17	235
1467	17	235
1480	17	235
1494	17	235
1507	17	235
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1561	18	234
1574	18	234
1589	18	234
1602	18	234
1615	18	234
1629	19	234
1642	19	234
1656	19	234
1670	19	234
1683	19	234
1696	19	234
1710	19	234
1724	20	234
1737	20	234
1751	20	234

1764	20	234
1778	20	235
1792	20	234
1805	20	234
1818	21	234
1831	21	234
1846	21	234
1859	21	234
1872	21	234
1886	21	234
1899	21	234
1913	22	235
1927	22	234
1940	22	234
1953	22	234
1967	22	234
1981	22	234
1994	22	234
2008	23	234
2021	23	234
2034	23	234
2049	23	234
2062	23	234
2075	23	234
2088	23	234
2102	24	234
2116	24	234
2129	24	234
2143	24	234
2156	24	234
2169	24	235
2184	24	235
2197	25	235
2210	25	234
2224	25	234
2237	25	234
2251	25	234
2265	25	234
2278	25	234
2291	26	234
2305	26	234
2319	26	234
2332	26	234
2345	26	234
2359	26	234
2372	26	234
2386	27	234
2400	27	234
2413	27	234
2426	27	235

2440	27	234
2454	27	234
2467	27	234
2481	28	234
2494	28	235
2507	28	235
2522	28	235
2535	28	235
2548	28	235
2562	28	235
2575	29	235
2589	29	235
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2629	29	235
2643	29	234
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2670	29	234
2683	30	234
2697	30	234
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2724	30	234
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2751	30	234
2764	30	234
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2792	31	234
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2832	31	234
2846	31	235
2860	31	234
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2954	32	234
2967	33	234
2981	33	234
2995	33	234
3008	33	234
3021	33	234
3035	33	234
3049	33	234
3062	33	234
3076	34	235
3089	34	234
3102	34	234

3117	34	234
3130	34	234
3143	34	234
3156	34	234
3170	35	234
3184	35	234
3197	35	234
3211	35	235
3224	35	235
3237	35	235
3252	35	235
3265	35	235
3278	35	235
3292	36	235
3305	36	235
3319	36	234
3333	36	234
3346	36	234
3359	36	234
3373	36	234
3387	36	234
3400	37	234
3414	37	234
3427	37	234
3440	37	234
3454	37	234
3468	37	235
3481	37	234
3494	37	234
3509	37	234
3522	37	234
3535	38	234
3549	38	234
3562	38	234
3576	38	234
3590	38	235
3603	38	234
3616	38	234
3630	38	234
3644	38	234
3657	38	234
3671	39	234
3684	39	234
3697	39	235
3712	39	235
3725	39	235
3738	39	235
3751	39	235
3765	39	235
3779	39	235

3792	39	235
3806	39	235
3819	39	234
3832	40	235
3847	40	235
3860	40	235
3873	40	235
3887	40	235
3900	40	235
3914	40	235
3928	40	235
3941	40	235
3954	40	235
3968	40	235
3982	40	235
3995	40	235
4008	41	234
4022	41	235
4035	41	235
4049	41	235
4063	41	235
4076	41	236
4089	41	235
4103	41	235
4117	41	235
4130	41	235
4144	41	235
4157	41	235
4170	41	235
4185	41	235
4198	41	235
4211	41	235
4225	42	235
4238	42	235
4252	42	235
4265	42	235
4279	42	235
4292	42	235
4305	42	235
4320	42	235
4333	42	235
4346	42	235
4360	42	235
4374	42	235
4387	42	235
4401	42	235
4414	42	235
4427	42	235
4442	42	234
4455	42	234

4468	42	234
4482	43	235
4495	43	235
4509	43	235
4523	43	235
4536	43	235
4549	43	235
4562	43	235
4577	43	235
4590	43	235
4603	43	235
4617	43	235
4630	43	235
4644	43	235
4658	43	235
4671	43	235
4684	43	235
4698	43	235
4712	43	235
4725	43	235
4739	43	235
4752	43	235
4765	43	235
4780	43	235
4793	44	235
4806	44	235
4819	44	235
4833	44	235
4847	44	235
4860	44	235
4874	44	235
4887	44	235
4900	44	235
4915	44	234
4928	44	235
4941	44	235
4955	44	235
4968	44	235
4982	44	235
4996	44	235
5009	44	235
5022	44	235
5036	44	235
5050	44	235
5063	44	235
5076	44	235
5090	45	235
5103	45	235
5117	45	235
5131	45	235

5144	45	235
5157	45	235
5171	45	235
5185	45	235
5198	45	235
5212	45	235
5225	45	235
5239	45	235
5253	45	235
5266	45	235
5279	45	235
5293	45	235
5307	45	235
5320	45	235
5334	45	235
5347	45	235
5360	45	235
5374	45	235
5388	45	235
5401	45	235
5414	46	235
5428	46	235
5442	46	235
5455	46	235
5469	46	235
5482	46	235
5495	46	235
5510	46	235
5523	46	235
5536	46	235
5550	46	235
5563	46	235
5577	46	235
5591	46	235
5604	46	235

Arduino Uno code

```
volatile int count;
int theta;

void isr() {
  count++;
}

void setup() {
  pinMode(2, INPUT_PULLUP);
  attachInterrupt(digitalPinToInterrupt(2), isr, FALLING);
  Serial.begin(9600);
}

void printAllValues() {
  long t = millis();
  theta = analogRead(A0);

  Serial.print(t);
  Serial.print(",");
  Serial.print(count);
  Serial.print(",");
  Serial.println(theta);
}

void loop() {
  printAllValues();
}
```

Data Processing code

```
#!/usr/bin/env python

import matplotlib.pyplot as plt
import numpy as np
import csv
import sys

t = []
rev = []
theta = []

drev_dt = []

t_avg = []
rev_avg = []
theta_avg = []

drev_avg_dt = []

v_final = 0
theta_final = 0

def read(path):
        global t
        global rev
```

```
        global theta

        with open(path, 'r') as f:
                reader = csv.reader(f)

                is_first = True
                for row in reader:
                        if is_first:
                                is_first = False
                                continue
                        t.append(float(row[0]) / 1000)
                        rev.append(np.pi * 2 * float(row[1]) / 4)
                        theta.append(300 / 1024 * float(row[2]))

        theta_new = []
        for v in theta:
                theta_new.append(v - theta[0])
        theta = theta_new

def calculate_avg():
        global t_avg
        global rev_avg
        global theta_avg

        i = 0
        last_rev = 0
        n = 0
        time_sum = 0
        theta_sum = 0
        while i < len(rev):
                if rev[i] == last_rev:
                        time_sum += t[i]
                        theta_sum += theta[i]
                        n += 1
                else:
                        t_avg.append(time_sum / n)
                        rev_avg.append(last_rev)
                        theta_avg.append(theta_sum / n)

                        last_rev = rev[i]
                        time_sum = t[i]
                        theta_sum = theta[i]
                        n = 1
                i += 1

def diff():
        global drev_dt
        global drev_avg_dt

        drev_dt = np.diff(rev) / np.diff(t)
        drev_avg_dt = np.diff(rev_avg) / np.diff(t_avg)

def plot_v_over_t():
        plt.plot(t, rev, '.')
        plt.plot(t_avg, rev_avg, '.')

        plt.plot(t_avg[0:-1], drev_avg_dt)
```

```
    plt.xlabel("Time [s]")
    plt.ylabel(u"Angular path [2 \u03C0]\n " +
               u"Derivative of angle - angular velocity [\u00B0 / s]")

def plot_theta_over_v():
    plt.plot(t_avg, theta_avg)

def plot_all():
    plt.plot(t, rev, '.',
             label=u'Raw angular path [2 \u03C0]')
    plt.plot(t_avg, rev_avg, '.',
             label=u'Averaged angular path [2 \u03C0]')

    plt.plot(t_avg[0:-1], drev_avg_dt,
             label=u'Angular velocity [2 \u03C0 / s]')

    plt.plot(t_avg, theta_avg,
             label=u'Angle of inclination [\u00B0]')

    plt.xlabel('Time [s]')

    plt.legend()

def calculate_final(plot=False):
    global v_final
    global theta_final

    v_final = np.mean(np.array(drev_avg_dt))
    theta_final = max(theta_avg) - min(theta_avg)

    if plot:
        plt.plot(v_final, 0, 'yo')

    print(str(v_final) + ',' + \
          str(theta_final) + ',' + \
          str(np.std(np.array(drev_avg_dt))) + ',' + \
          str(np.pi / 4))

if __name__ == '__main__':
    read(sys.argv[-1])
    calculate_avg()
    diff()

    calculate_final()

    plot_all()

    plt.show()
```