All four of the cylinders had an m* (oscillating mass divided by displaced fluid mass) less than 1 (the cylinders were less dense than the water). As such, the cylinders are subjected to a component of the buoyance force pushing the cylinder to the highest point in the structure. From the perspective of the underwater camera, located downstream of the cylinders, the cylinders would move to the left of the structure. The control program for the *Oscylator-4* was designed in such a way that the buoyancy force is compensated for regardless of the slope of the riverbed. That is, the energy provided by the cylinder when pushed up by the buoyancy and the energy drawn by the cylinder to be pushed against the buoyancy would be eliminated during the field-test.

The first step is to find the buoyancy force in each direction. The cylinders were moved to the left side of the structure. The variable frequency drive (VFD) was set to manual torque mode. The torque on the cylinder was gradually increased until it started moving to the right. This was repeated 5 times and averaged. The cylinder was then moved to the right side of the structure, and the torque was gradually lowered until the cylinder started moving right. This procedure was again repeated 5 times. This task was completed for the first and third cylinders. The second cylinder had a coupling come loose. The fourth cylinder had flooded. The averaged value of the 5 tests are shown below.

All of the cylinders had color codes associated with them for tracking within the control program. The color code and cylinder position are noted when talking about each of the cylinders.

	1st (Red)	3rd (Green)
Left to Right Average	16.07 N-m	11.97 N-m
Right to Left Average	-6.53 N-m	-0.32 N-m

Table 1 Torque to move the cylinders

The values were converted from torque into N-m. Radius of the pulley was 64mm.

$$\tau = F * r \qquad F = \frac{\tau}{r} \qquad F = \frac{\tau}{0.064}$$

	1st (Red)	3rd (Green)
Left to Right Average	251 N	187 N
Right to Left Average	-102 N	-0.5 N

Table 2 Force to move the cylinders

This is the static Couloumb friction (C2) that was created by the water.

Tests were then run to find what an appropriate dynamic friction (C1) compensation would be. From experience at the MRELab, it was estimated that C1 = 1.5 * C2 would be appropriate. As risk mitigation, smaller values were tested first.

C1 = 0 * C2,
C1 = 0.33 * C2
C1 = 0.66 * C2
C1 = 1.0 * C2
C1 = 1.5 * C2

	1st (Red) L to R	**1st (Red) R to L**	**3rd (Green) L to R**	**3rd (Green) R to L**
C1 = 0 * C2	0.00 N-s/m	0.00 N-s/m	0.00 N-s/m	0.00 N-s/m
C1 = 0.33 * C2	82.83 N-s/m	-33.66 N-s/m	61.71 N-s/m	-0.17 N-s/m
C1 = 0.66 * C2	165.66 N-s/m	-67.32 N-s/m	123.42 N-s/m	-0.33 N-s/m
C1 = 1.0 * C2	251.00 N-s/m	-102.00 N-s/m	187.00 N-s/m	-0.50 N-s/m
C1 = 1.5 * C2	376.50 N-s/m	-153.00 N-s/m	280.5 N-s/m	-0.75 N-s/m

Table 3 – Buoyancy force of the cylinders

The control monitors rotational velocity in rotations / minute rather than meters per second.
The control measures torque in N-m, rather than force in N. Multiply the force by the radius to convert to N-m.

$$N\frac{s}{m} \rightarrow (N*r)\left(\frac{s}{m}*\frac{min}{60s}*\frac{2*\pi*r*m}{Rotation}\right) \rightarrow \left(N-\frac{Min}{Rotation}\right)\left(\frac{2*\pi*r^2}{60}\right) \rightarrow$$

$$\left(N-m-\frac{Min}{Rotation}\right)\left(\frac{2*\pi*0.064^2}{60}\right) \rightarrow 4.29*10^{-4}$$

To convert to the units used by the VFD, multiply by $4.29*10^{-4}$.

	1st (Red) L to R	**1st (Red) R to L**	**3rd (Green) L to R**	**3rd (Green) R to L**
C1	0.00 N-m-min/Rot	0.00 N-m-min/Rot	0.00 N-m-min/Rot	0.00 N-m-min/Rot
C1	0.0355 N-m-min/Rot	-0.0144 N-m-min/Rot	0.0264 N-m-min/Rot	-0.0000 N-m-min/Rot
C1	0.0711 N-m-min/Rot	-0.0289 N-m-min/Rot	0.0529 N-m-min/Rot	-00001. N-m-min/Rot
C1	0.1077 N-m-min/Rot	-0.0438 N-m-min/Rot	0.0802 N-m-min/Rot	-0.0002 N-m-min/Rot
C1	0.1613 N-m-min/Rot	-0.6564 N-m-min/Rot	0.1203 N-m-min/Rot	-0.0003 N-m-min/Rot

Table 4 – Buoyancy force of the cylinders, rotational units

The tests correcting for the buoyancy forces could be run. The tests were run using the values above. The “normal” damping routine was left enabled. This provided:

- A damping force of: $137*(RPM-60)\ \frac{N-s}{m}$ When the RPM is greater than 60. The torque is in the opposite direction of movement. This is normally used to extract power.
- A “pushing” force of $1665*(RPM-60)\ \frac{N-s}{m}$ When the RPM is less than 60. The torque is in the same direction as movement. This is used to prevent the device from stopping.

The first 10 seconds of each of the test runs are shown on the following pages. The average power needed for these tests is shown in the table below. The sign convention in this table is that negative power is power from the wall driving the cylinder, positive power is power being generated by the cylinder.

Cylinder colors were used in the controls to avoid some numbering confusion.

	1st (Red)	**3rd (Green)**
C1=0.00*C2	-82.87 W	-44.68 W
C1 = 0.22*C2	-141.09 W	-60.90 W
C1 = 0.66*C2	-232.64 W	-105.55 W
C1 = 1.0*C2	-378.69 W	-171.93 W
C1=1.5*C2	-525.10 W	-314.82 W

Table 5 – Measured power from the cylinder without adjusting for the buoyancy force correction power

Test Number:

	1st (Red)	**3rd (Green)**
C1=0.00*C2	0034	0039
C1 = 0.22*C2	0035	0040
C1 = 0.66*C2	0036	0041
C1 = 1.0*C2	0037	0042
C1=1.5*C2	0038	0043

Table 6 – Test number for the cylinder data. Data is in the MHKDR.

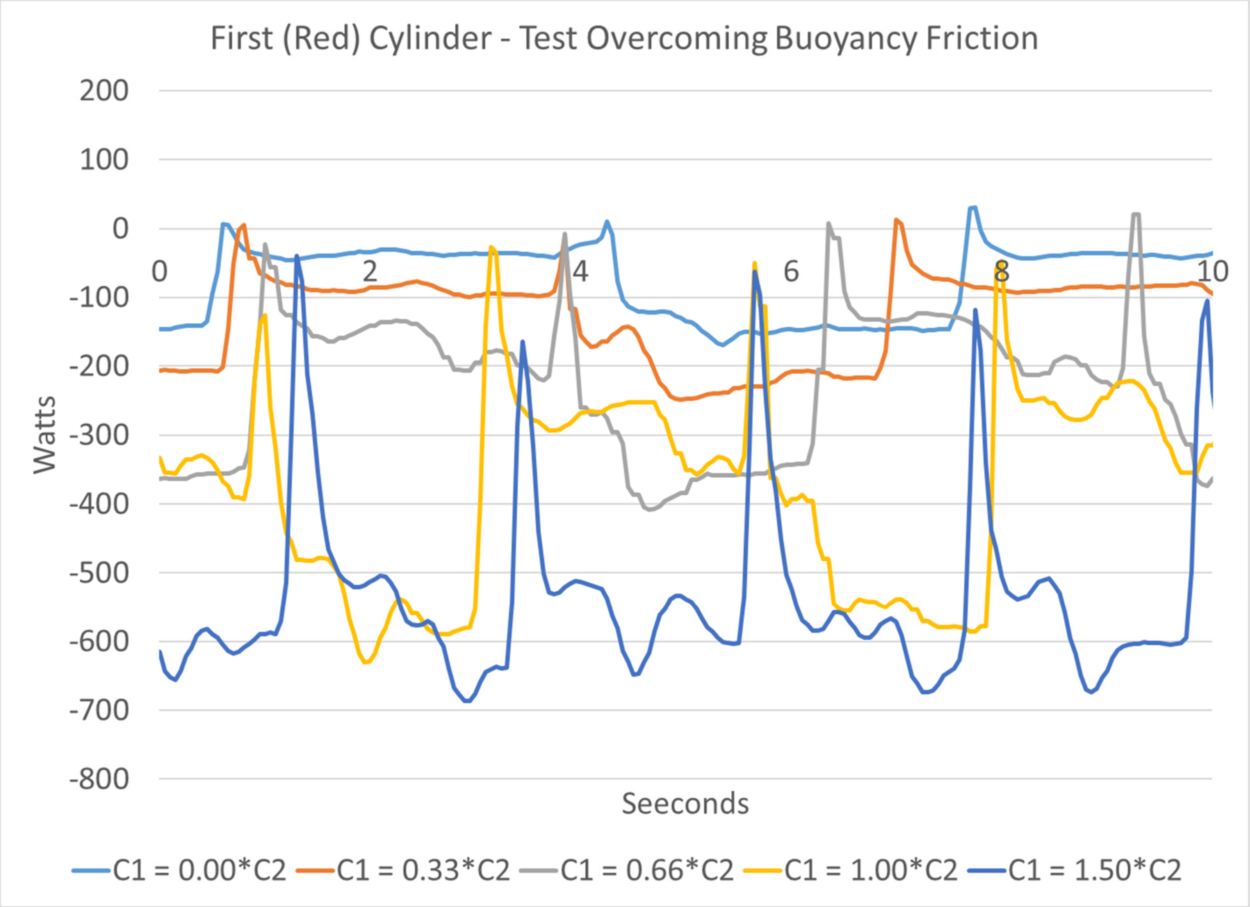

Figure 1 – Power generated by the red cylinder, raw data plotted

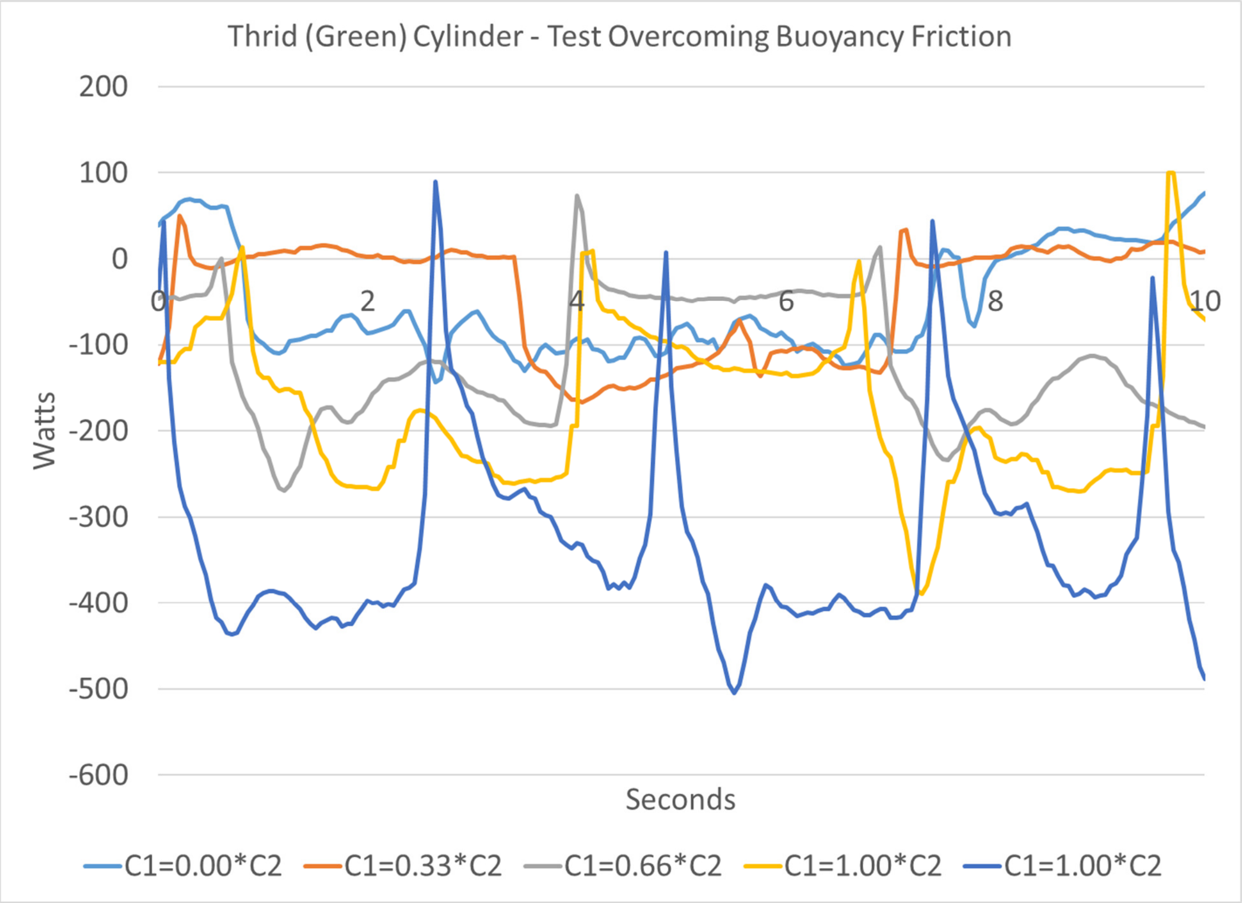

Figure 2 – Power generated by the 3rd (Green) cylinder, raw data plotted

It took 525W for the 1st (Red) cylinder to overcome the buoyancy force.
It took 315W for the 3rd (Green) cylinder to overcome the buoyancy force.
These values will be added to the measured values for power tests that are run.

Now, tests can be run with additional damping. The additional damping was simulated by reducing the value of C1. Various values of a C1 were run, ranging from 0.2 to -0.3 * C2.

	1st (Red) L to R	**1st (Red) R to L**	**3rd (Green) L to R**	**3rd (Green) R to L**
C1 = +0.20 * C2	+3.214 N-s/m	-1.306 N-s/m	+2.394 N-s/m	-0.064 N-s/m
C1 = +0.10 * C2	+1.607 N-s/m	-0.653 N-s/m	+1.197 N-s/m	-0.032 N-s/m
C1 = 0.00 * C2	0.00 N-s/m	0.00 N-s/m	0.00 N-s/m	0.00 N-s/m
C1 = -0.10 * C2	-1.607 N-s/m	+0.653 N-s/m	-1.197 N-s/m	+0.032 N-s/m
C1 = -0.20 * C2	-3.214 N-s/m	+1.306 N-s/m	-2.394 N-s/m	+0.064 N-s/m
C1 = -0.30 * C2	-4.821 N-s/m	+1.959 N-s/m	-3.591 N-s/m	+0.096 N-s/m

Table 7 – Tested damping values, linear motion

Units converted for drive operation

	1st (Red) L to R	**1st (Red) R to L**	**3rd (Green) L to R**	**3rd (Green) R to L**
C1	+0.0014 N-m-min/Rot	-0.0006 N-m-min/Rot	+0.0010 N-m-min/Rot	-0.00 N-m-min/Rot
C1	+0.0007 N-m-min/Rot	-0.0003 N-m-min/Rot	+0.0005 N-m-min/Rot	-0.00 N-m-min/Rot
C1	0.00 N-m-min/Rot	0.00 N-m-min/Rot	0.00 N-s/m	0.00 N-m-min/Rot
C1	-0.0007 N-m-min/Rot	+0.0003 N-m-min/Rot	-0.0005 N-m-min/Rot	+0.00 N-m-min/Rot
C1	-0.0014 N-m-min/Rot	+0.0006 N-m-min/Rot	-0.0010 N-m-min/Rot	+0.00 N-m-min/Rot
C1	-0.0021 N-m-min/Rot	+0.0008 N-m-min/Rot	-0.0015 N-m-min/Rot	+0.00 N-m-min/Rot

Table 8 – Tested damping values, rotary motion

The normal VHE control damping was enabled as well. The parameters were:

- A damping force of: $139 * (RPM - 52)\ \frac{N-s}{m}$ When the RPM is greater than 60. The torque is in the opposite direction of movement. This is normally used to extract power.
- A "pushing" force of $1665 * (RPM - 52)\ \frac{N-s}{m}$ When the RPM is less than 60. The torque is in the same direction as movement. This is used to prevent the device from stopping.

The measured power of the two cylinders for each of the tests was put into the table below. This is the average power for the duration of the test. The correction factors calculated above were factored in. First, each of the two cylinders were run independently, then the two cylinders were run in tandem.

	Measured		**Corrected**	
	1st (Red)	**3rd (Green)**	**1st (Red)**	**3rd (Green)**
C1=+0.2*1.5*C1	-1.49 W	6.80 W	523.51 W	321.80 W
C1=+0.1*1.5*C1	5.11 W	3.07 W	530.11 W	318.07 W
C1=0.0*1.5*C1	2.43 W	1.58 W	527.43 W	316.57 W
C1=-0.1*1.5*C1	4.32 W	4.98 W	529.32 W	319.98 W
C1=-0.2*1.5*C1	1.49 W	-6.21 W	526.49 W	312.39 W
C1=-0.3*1.5*C1	-5.85 W	-3.61 W	519.15 W	311.40 W

Table 9 – Measured and corrected power of the cylinders run independently

	Measured			**Corrected**		
	1st (Red)	**3rd (Gn)**	**Total**	**1st (Red)**	**3rd (Gn)**	**Average**
C1=+0.2*1.5*C1	1.86 W	-1.28 W	0.29 W	526.86 W	313.72 W	840.58 W
C1=+0.1*1.5*C1	5.85 W	-3.57 W	2.27 W	530.85 W	311.43 W	842.27 W
C1=0.0*1.5*C1	3.61 W	-3.16 W	0.45 W	528.61 W	311.84 W	840.45 W
C1=-0.1*1.5*C1	-7.18 W	-6.81 W	-13.98 W	517.82 W	308.19 W	826.02 W
C1=-0.2*1.5*C1	3.92 W	-3.01 W	0.91 W	528.92 W	311.99 W	840.91 W
C1=-0.3*1.5*C1	2.81 W	-6.24 W	-3.43 W	527.81 W	308.76 W	836.57 W

Table 10 – Measured power of both cylinders run in tandem

The measured power didn’t seem to be impacted by the change in damping, as it only changed by a few Watts. This is within the expected variance within a 5-minute run.

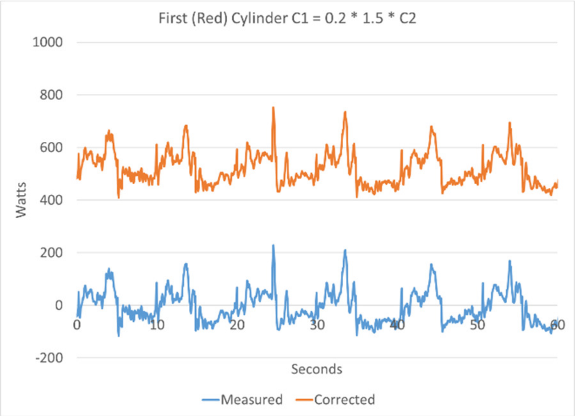

Figure 3 – 1st (Red) cylinder power, first test

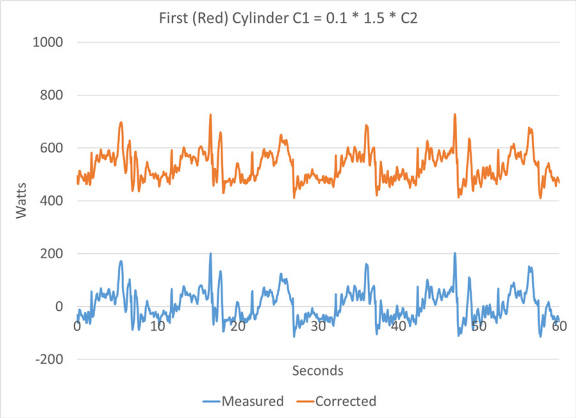

Figure 4 – 1st (Red) cylinder power, second test

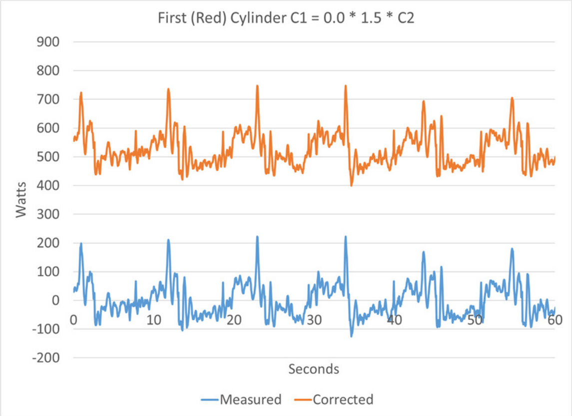

Figure 5 – 1st (Red) cylinder, third test

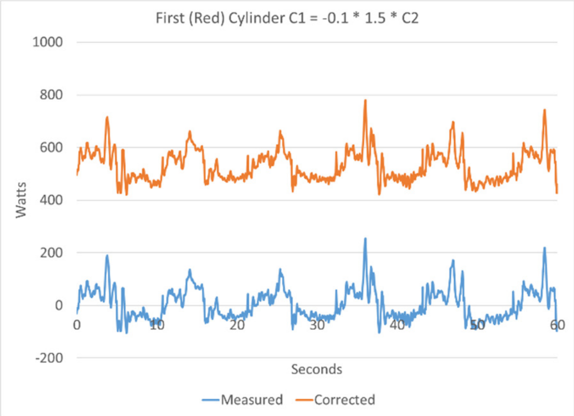

Figure 6 – 1st (Red) cylinder, fourth test

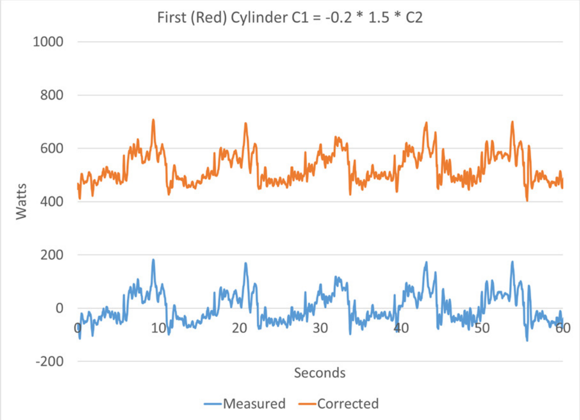

Figure 7 – 1st (Red) cylinder, fifth test

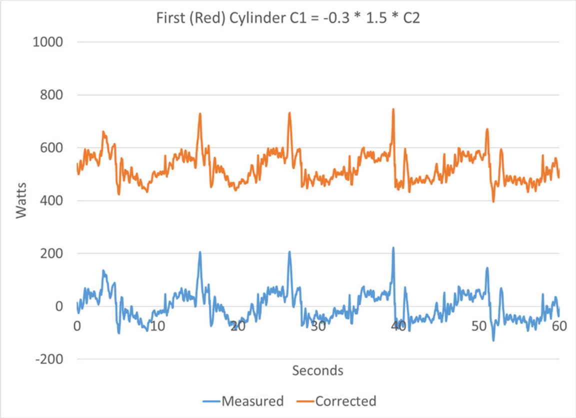

Figure 8 – 1st (Red) cylinder, sixth test

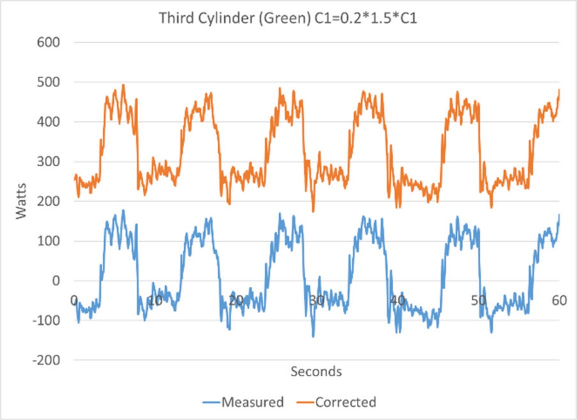

Figure 9 –3rd (Green) cylinder, first test

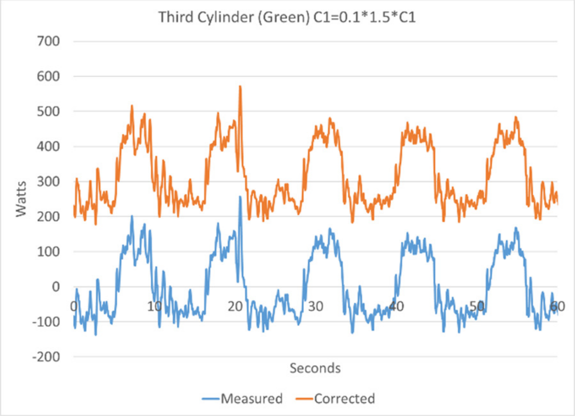

Figure 10 – 3rd (Green) cylinder, second test

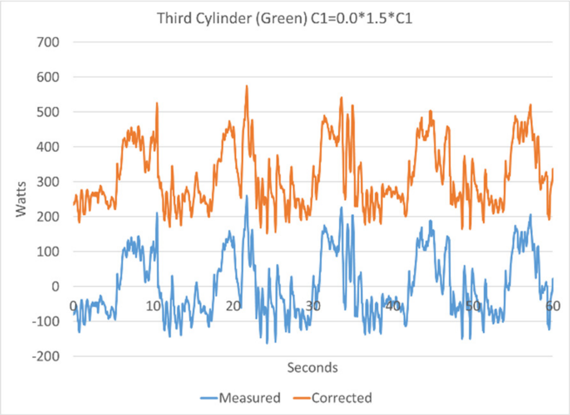

Figure 11 – 3rd (Green) cylinder, third test

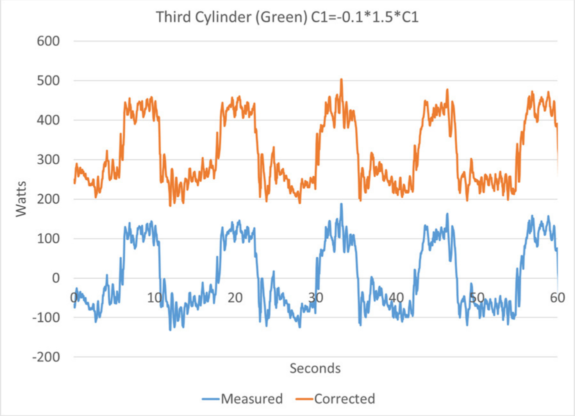

Figure 12 – 3rd (Green) cylinder, fourth test

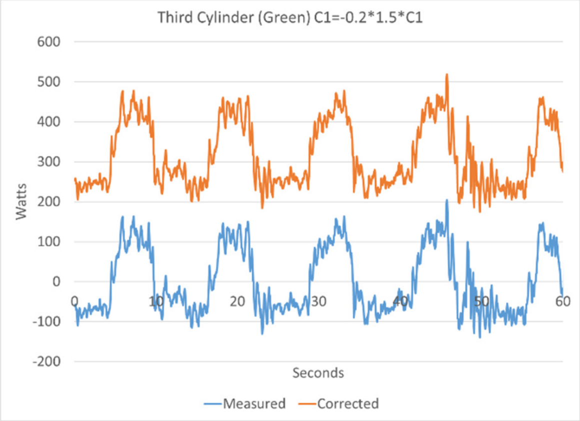

Figure 13 – 3rd (green) cylinder, fifth test

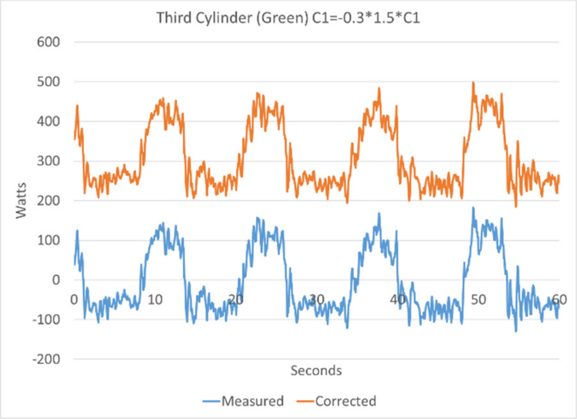

Figure 14 – 3rd (green) cylinder, sixth test

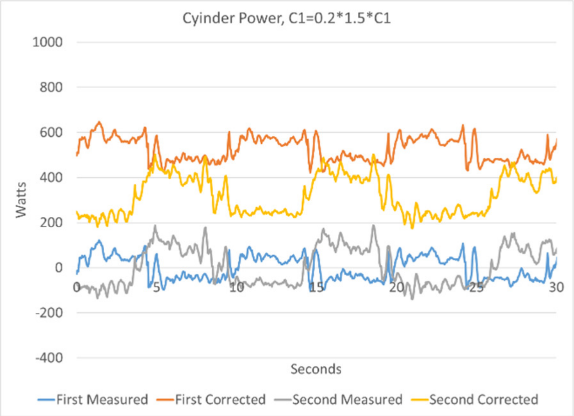

Figure 15 – 1st & 3rd cylinders, first test

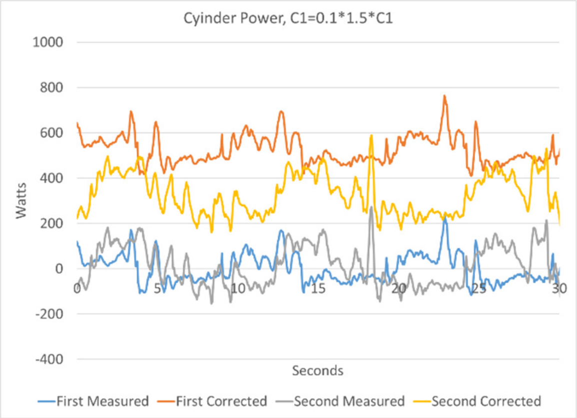

Figure 16 – 1st & 3rd cylinders, second test

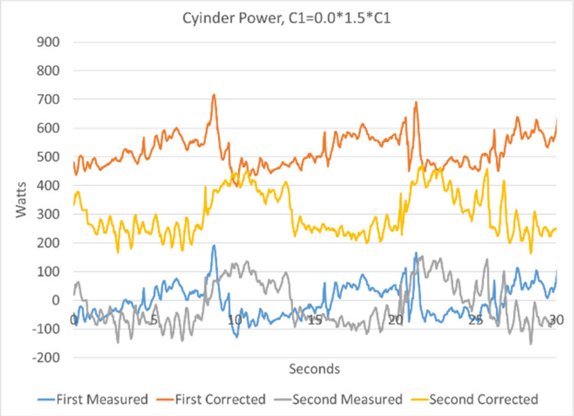

Figure 17 – 1st & 3rd cylinders, third test

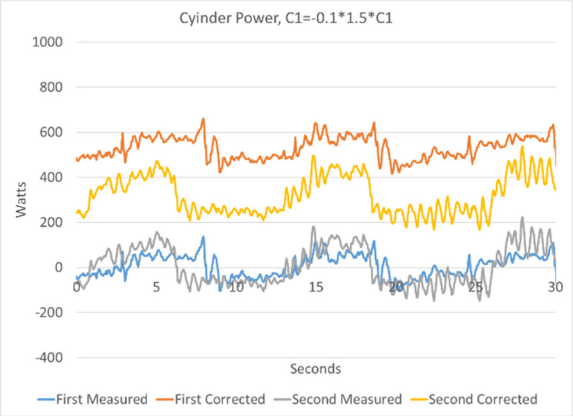

Figure 18 – 1st & 3rd cylinders, fourth test

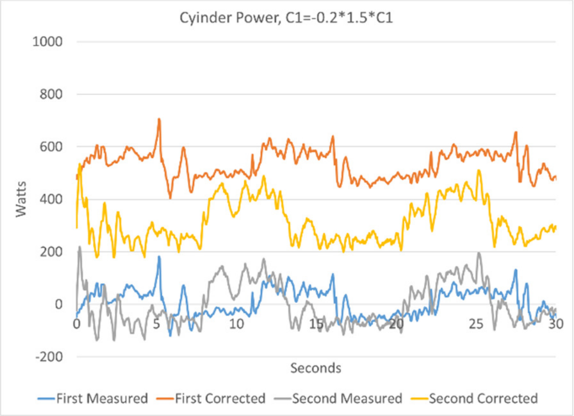

Figure 19 – 1st & 3rd cylinders, fifth test

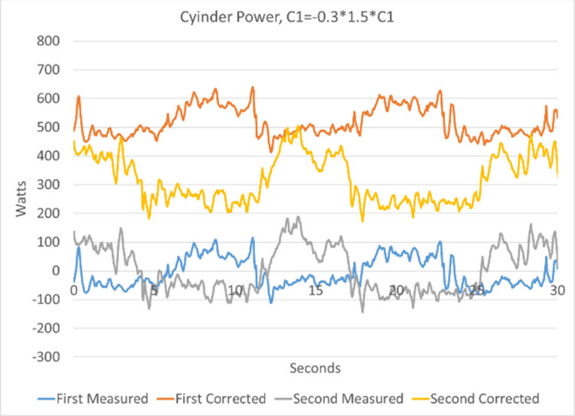

Figure 20 – 1st & 3rd cylinders, sixth test