Introduction

The November 10, 2021 tests of the prototype stabilized hydrophone pole on the R/V Paragon provides a useful data set for refining the design and sizing components such as the hydraulic valves, electric HPU, and battery system. The conditions on Nov 10th were moderate, but about twice as active as the initial data collection day for this project. During the test day the system activity and performance changed due to the boat heading relative to the waves, and the ongoing system tuning. For the below results, a subset of the data is used that corresponds to the most demanding direction of travel (into the waves), and the best tuning achieved for the day in terms of pole pitch performance.

At a high level, these results suggest the following:

- A 4GPM pitch control hydraulic valve is appropriate.
- A 1GPM roll control valve is also likely appropriate. This mode was not tested but the tests done can be extended to support this conclusion based on the much smaller inertia of the hydrophones versus the entire pole.
- An accumulator at the hydraulic valve should be advantageous, but may not need to be larger than 1 Gallon.
- An electric motor/battery system for the existing hydraulic pump is plausible, after conservative assumptions of efficiencies, the mean power requirement of the system is about 1500W, so 200A-Hr of 36V batteries (a reasonable amount) will allow about 4.5 hours or operation in the worst-case condition analyzed. Due to the smaller power/energy needs when moving down-swell, the total run time is expected to be higher in practice.
- The total run-time would also be extended if the main engine alternators are available during the testing. The alternators can produce about 500W each at idle speeds, reducing the battery discharge rate to 500W and extending operating times to 12 hours in the worst-case estimate, and perhaps indefinitely in practice.
- For a 36V system, the motor/battery electrical currents are expected to be 42A mean/210A peak, again after conservative efficiency assumptions throughout. These values are not out of reach for LiFePO4 batteries and will require 2/0 or 3/0 electrical cables (.36in and .41in diameter respectively). The peaks may be reduced some by the inclusion of a hydraulic accumulator.

Results

Figure 1a: This shows the Paragon and pole pitch angles while traveling into the swell at 1100RPM on the Paragon engines. The pole angle is held to within 0.75 degrees of vertical for most of the time, with occasional excursions to +/- 1 degree. The pole pitch data has some high-frequency noise that may have been caused by the way it was mounted to the pole, improving this could also help performance.

Figure 1b: This shows the Paragon and pole pitch rates, the noise in the pole angle measurements are evident here in the pole pitch rate, due to the way these rates are calculated as a numerical derivative.

Figure 1c: This is the valve command sent by the control computer to the valve amplifier, and indicates in this arrangement we are using about 40% of the available valve flow, and supports reducing to a 4GPM valve due to availability and improved resolution and bandwidth of the slightly smaller valve.

Figure 1d: Gain Settings for reference, you can see these were being adjusted during the test. Plenty of tuning effort left to go but these get us in the ballpark.

Figure 1e: This is the amount of oil flowing into and out of each end of the hydraulic ram. Each end is different due to the presence of the Rod. These dimensions need to be double-checked.

Figure 2a: This shows the flow rate flowing into the valve (from the HPU), with mean and peak values of .6GPM and 2.8GPM respectively.

Figure 2b: In our testing the hydraulic oil was being supplied at about 1500psi. The product of supply pressure and the flow rates in figure 2a is the total power being supplied to the hydraulic valve, and include losses in the valve and plumbing to the rams. Mean hydraulic supply power is about 370W and peak hydraulic supply power is about 1800W.

Figure 2c: Based on an estimate of the hydraulic pump and plumbing being about 50% efficient (this is a conservative estimate, spec sheet indicates > 80%, but does not include plumbing losses), this plot shows the shaft torque required to drive the hydraulic pump at 2400RPM.

Figure 2d: This plot shows the battery motor currents for a 36V system, assuming a 60% efficient electric motor (again a conservative estimate, the motor spec sheet indicates > 80%). Mean currents of 34A and peak currents of 168A will require 2/0 electrical cables, which are manageable.

Figure 3: This plot shows an estimate of the total fluid volume per "stroke" of the hydraulic ram which is an out and back oscillation. The oil volume used during each stroke is plotted versus the peak ram speed achieved during the stroke. This indicates that the fast fluid demands that could be supplied by an accumulator are quite small in volume (a gallon is 241 in^3) and we may benefit from a small 1 Gallon accumulator. The purpose of this accumulator is to provide flow spikes faster than the hydraulic pump can respond and this should help tracking performance and may also reduce the peak currents flowing from the battery to the electric motor. This accumulator could possibly be located in the well with the HPU, but at the small size of a 1 Gallon accumulator, there are performance and safety benefits from mounting the accumulator at the valve. In particular, the valve manifold includes a check valve on the supply line before the accumulator connection so that when the HPU is turned off, oil doesn't flow backwards and spin the hydraulic pump.

Note: The results in these plots are from tests done on the pitch only system. The roll axis will add further flow and power requirements. Because the roll linkage has about ¼ of the throw, it is expected that the roll axis will use about ¼ of the flow and power of the pitch axis. Therefore, a 1GPM hydraulic valve for the roll axis is planned, and the total values highlighted in the Introduction section above are 25% larger than the values found in the figures.

Fig 1a: Paragon and Pole Pitch

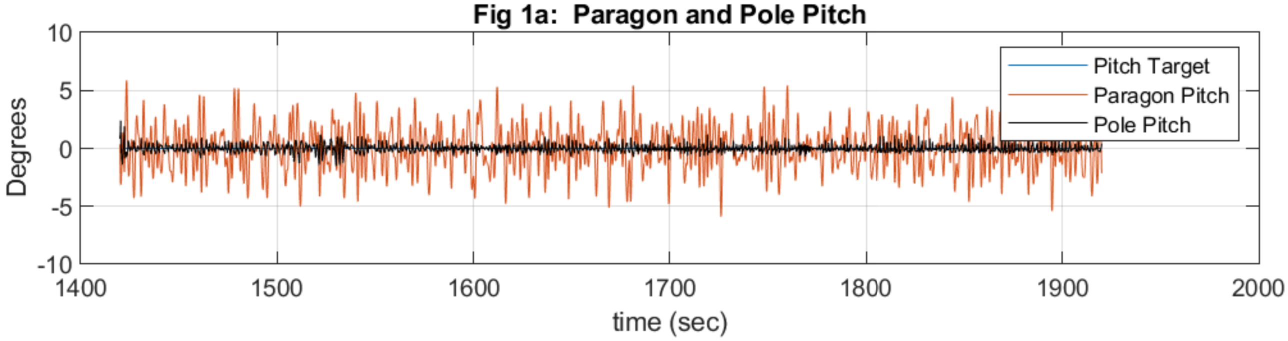


Fig 1b: Paragon and Pole Pitch Rates

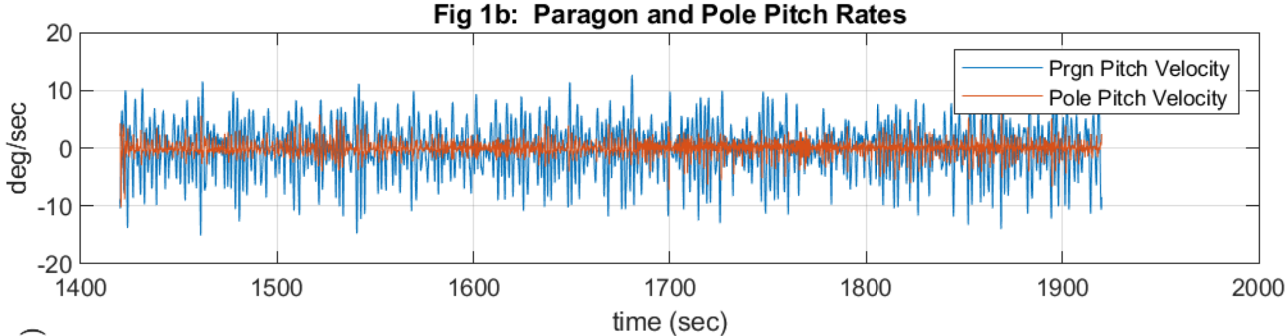


Fig 1c: Valve Command Voltage to 5GPM Valve (+/- 10V max)

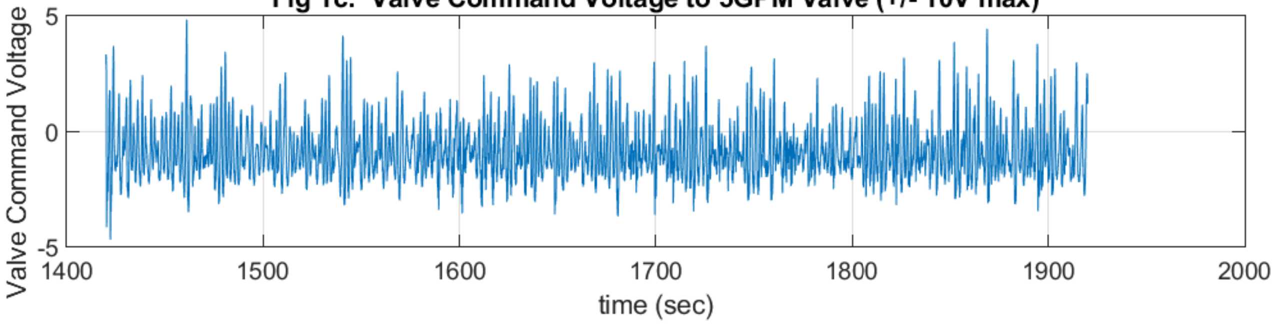


Fig 1d: Pitch Control Gain Settings

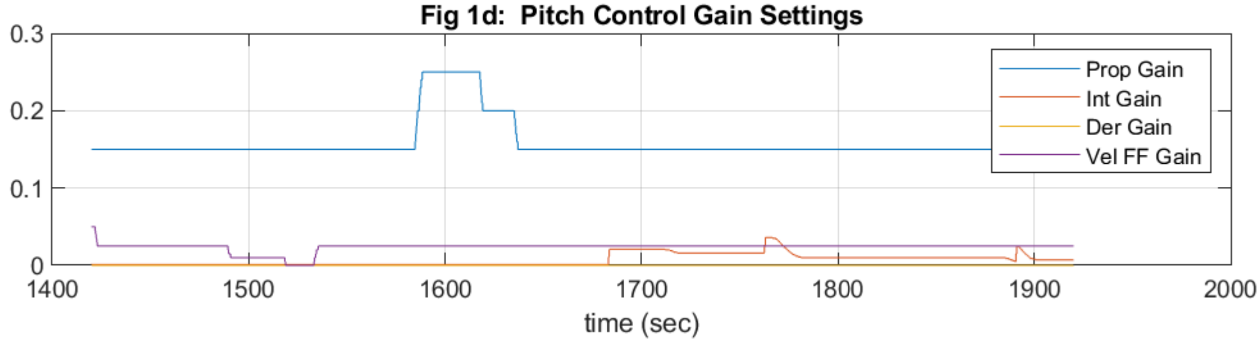


Fig 1e: Flow Rates for Pitch Ram at 20", 1.5" Cyl Diam, .75" Rod Diam)

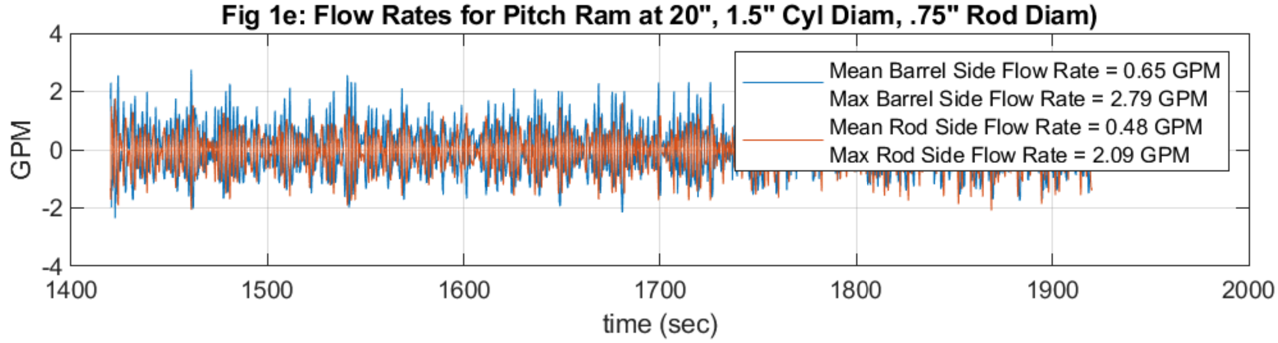


Fig 2a: Supply Flow Rates for Pitch Ram at 20", 1.5" Cyl Diam, .75" Rod Diam)

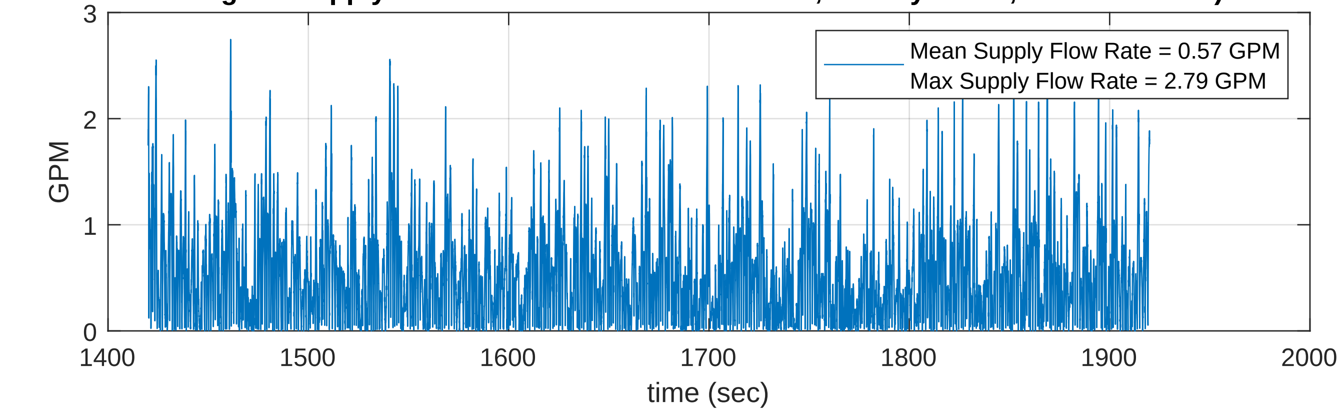


Fig 2b: Hydraulic Power supplied to valve manifold (supply pressure times flow rate)

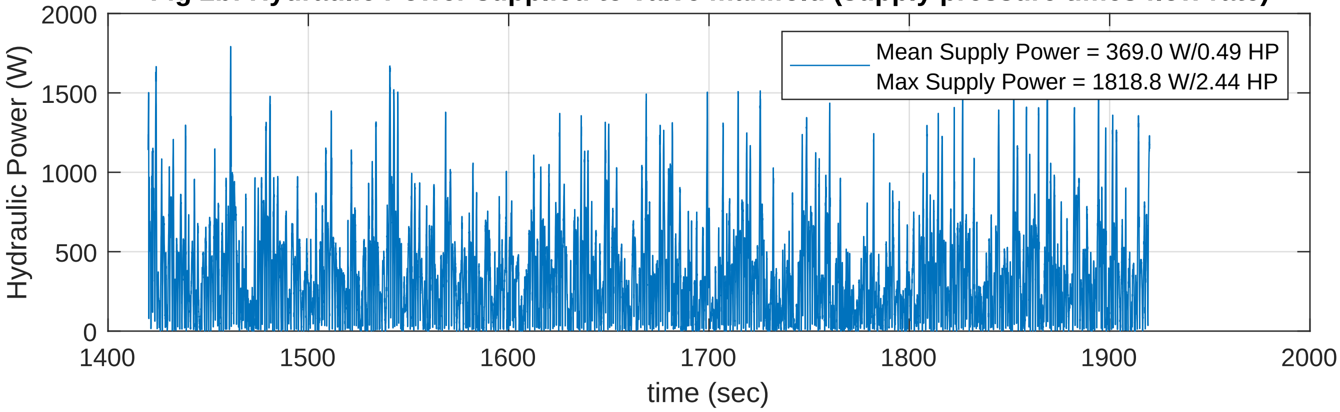


Fig 2c: Shaft Torque required of electric motor at 2400RPM and 50% eff Hyd Pump

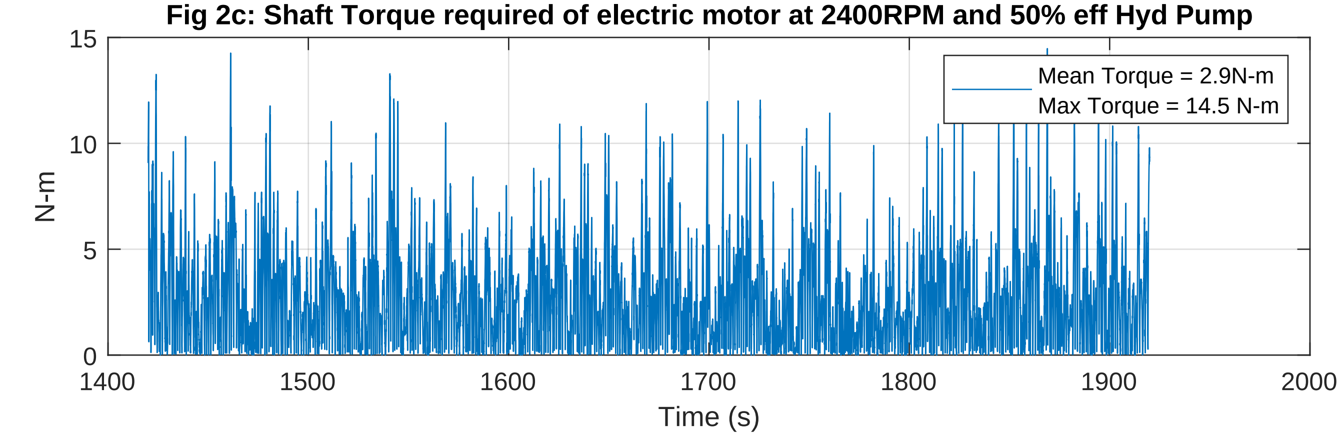
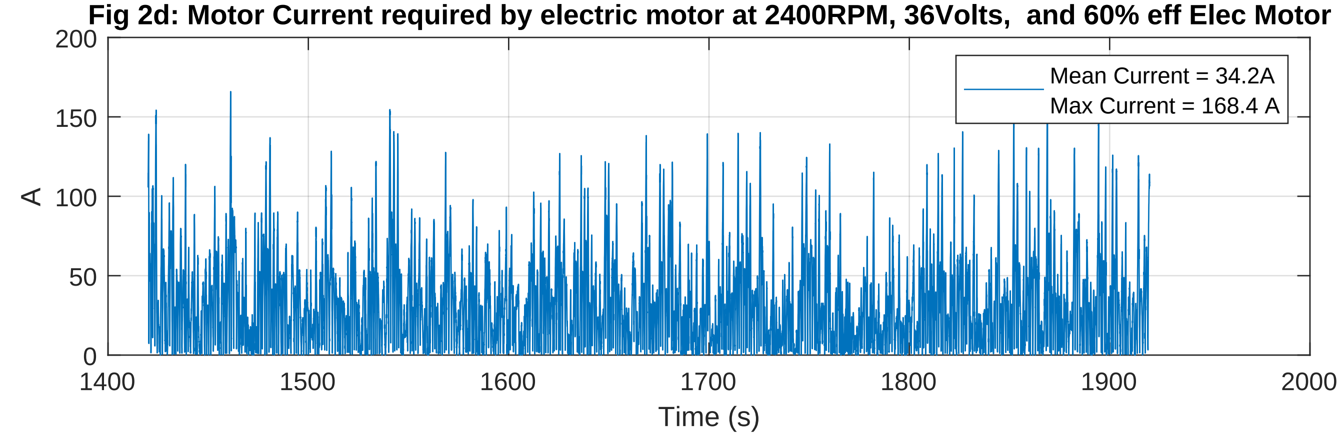


Fig 2d: Motor Current required by electric motor at 2400RPM, 36Volts, and 60% eff Elec Motor



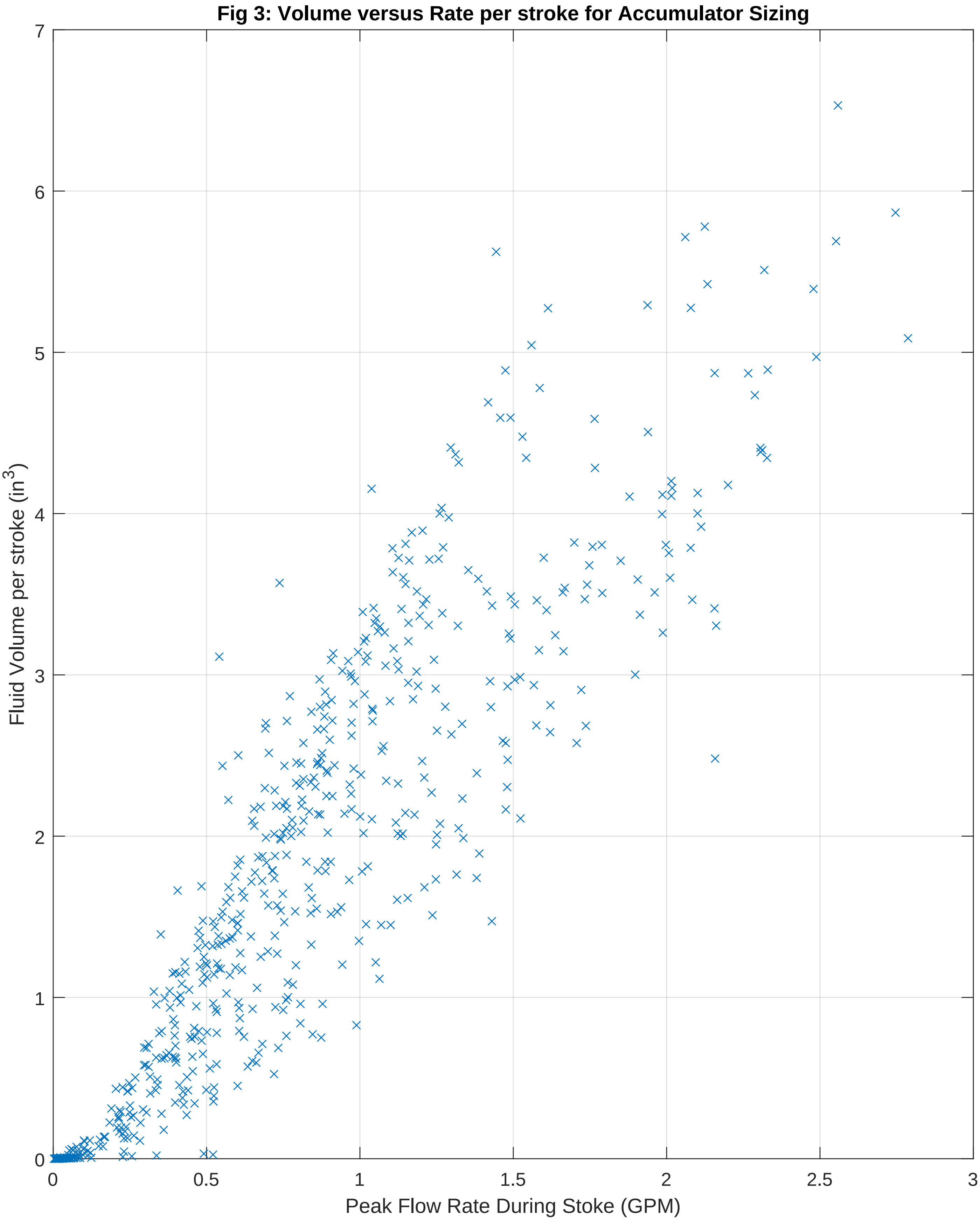


Fig 3: Volume versus Rate per stroke for Accumulator Sizing
Fluid Volume per stroke (in^3)
Peak Flow Rate During Stoke (GPM)
0
1
2
3
4
5
6
7
0
0.5
1
1.5
2
2.5
3