

# Measurements of a Parallel Channel Adjustable Inertance Tube

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**Abstract.** A recent modification to the cylindrical threaded adjustable inertance tube for pulse tube refrigerators links the two helical flow channels existing between the threads of the inner and outer screws in parallel. The phase shifting performance of an earlier design that was limited by fluid leakage occurring between the channels, was thought to be significantly improved by connecting the two channels in parallel. Measurements of the phase shift angle over the entire operating range of the adjustable device are compared with existing models. The models predict a total phase angle shift between pressure and flow waves of  $105^\circ$  with the new parallel flow path configuration. However, the experimental data only achieves a  $28^\circ$  phase shift angle.

## 1. Introduction

After their emergence in the 1960's and significant development in the 1980's, pulse tube cryocoolers have been chosen as the cooling mechanism for numerous applications due to their high reliability and longevity. These traits are attributed to the fact that these devices have few moving parts, and therefore are especially useful for precision measurement devices that are sent to space. One example includes the Atmospheric Infrared Sounder on the Aqua satellite [1].

Pulse tube cryocoolers are operated by a compressor that continually creates pressure and mass flow oscillations that cause the gas to expand and contract inside the device. The performance of the cryocooler is dependent on the phase angle between these two oscillations in the regenerator section of the cryocooler. In 1994, it was discovered that adding an inertance tube with the correct length and diameter to the machine can alter the phase angle between these oscillations to an optimal value [2].

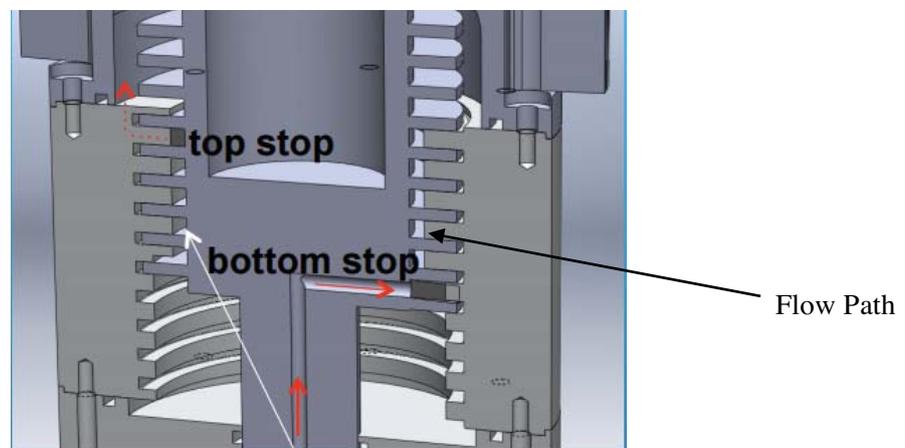
Unfortunately, fixing the correct inertance tube that optimizes the cooling ability of a pulse tube cryocooler can be an iterative, time-intensive, and expensive process. Various models exist defining a required length and diameter for the inertance tube [3a, 3b], but frequently, fabrication or assembly details result in different phase angles than calculated [4]. Furthermore, pulse tube cryocoolers take significant time to cool down to their operating temperature, and depending on how cold the operating temperature is, the warm-up process can be time-consuming, as well. Therefore, a lot of time can be wasted if numerous inertance tubes need to be tested to find the ideal one.

One idea proposed to address these issues is the development of an inertance tube that can shift the phase angle between the pressure and mass flow waves while the cryocooler is operating. This would, theoretically, allow the phase angle to be shifted to the optimal value without having to depressurize



the system or conduct a time-intensive, iterative process to find the correct inertance tube. Furthermore, the optimal phase angle for cooling the cryocooler down the quickest is usually different than the optimal steady-state operation phase angle. Thus, an adjustable inertance tube would have the additional advantage of cooling the pulse tube more efficiently [6].

Theoretical models and experimental studies for various adjustable inertance tube designs have been pursued, and the best predicted phase angle shift results came from a concentric screw configuration. As displayed in Figure 1, the inertance tube is a helical flow path that is formed by the roots of the inner screw and the teeth of the outer screw. Rubber stops are placed at the beginning and end of the inertance tube to dictate the length of the tube. During compression, the fluid at the top of the inertance path reaches the upper rubber stop, which forces the fluid through a hole and into the reservoir. As the outer screw is rotated around the inner screw, the upper stop rotates so that the length and diameter of the path changes; thus, adjusting the size of the inertance tube [6].



*Figure 1: The adjustable inertance tube helical flow path.*

A recent report [5] discussed the design, theoretical models and experimental results in depth. In summary, early versions of a theoretical model predicted that the concentric screw arrangement could adjust the phase angle between the pressure and flow oscillations from  $-60^\circ$  to  $+60^\circ$ , but the experimental measurement only achieved a  $24^\circ$  shift in the phase angle. The report hypothesized that the discrepancy between the two values was due to gas flow between the inner helical flow path and another one that is formed by the teeth of the inner screw and roots of the outer screw [4]. This outer helical flow path is shown in Figure 2.

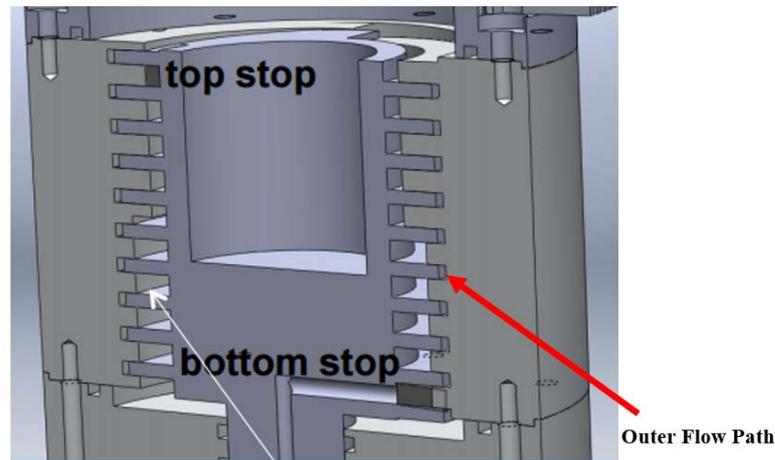


Figure 2: The outer helical flow path that causes gas to leak between paths.

Because the outer helical flow path remains at a constant pressure and the pressure in the inner path oscillates, a large pressure difference between the paths exists. If the leakage can be reduced or eliminated, the experimental phase angle shifts are predicted to mimic those of the theoretical model. One possibility to reduce the leakage is by connecting the second helical flow path in parallel with the original one and operating the two channels in parallel. With such a configuration, the pressure difference between the two paths is significantly decreased.

## 2. Parallel Flow Path Design

Figure 3 presents the calculated pressures in the two parallel flow paths and demonstrates that the pressure differences between the two paths are relatively small throughout the length of the inductance tube.

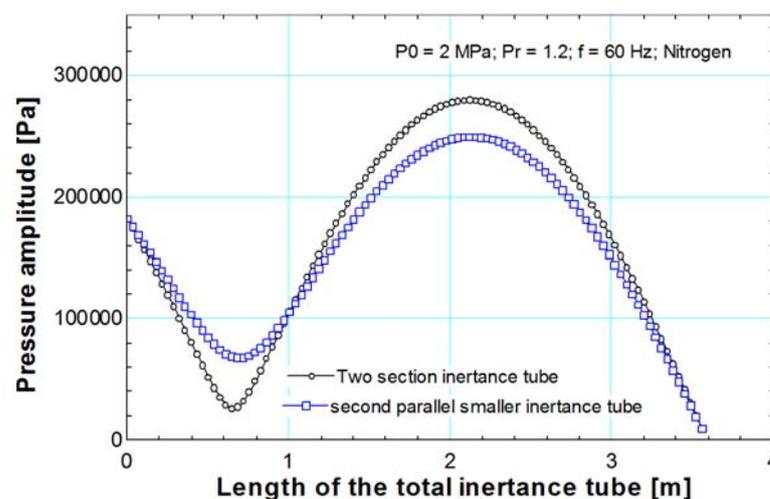


Figure 3: The predicted pressure distribution in each flow path.

A modified version of the model, accounting for the parallel flow paths is also able to predict the range of phase angles that can be produced by the adjustable inductance tube. The best theoretical results occur at 60Hz and are plotted in Figure 4. As the length of the inductance tube is increased, the phase angle is predicted to monotonically increase from  $-65^\circ$  to  $40^\circ$ , leading to an overall shift in the

phase angle of  $105^\circ$ . Based on these calculations, the original concentric screw inertance tube was modified to provide the parallel path configuration.

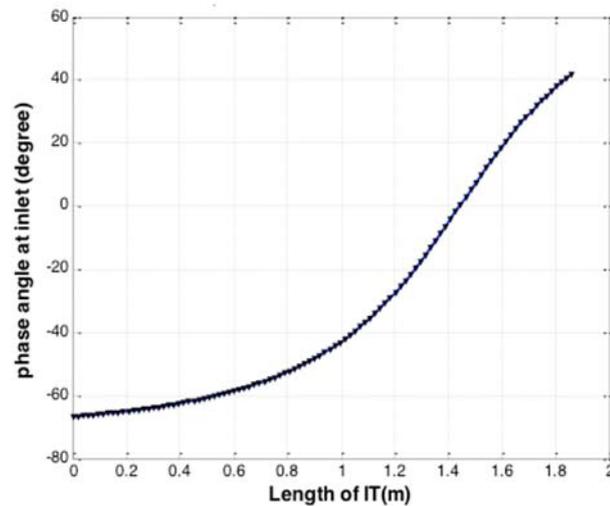


Figure 4: The predicted phase angle shift at 60Hz with both paths connected in parallel.

The modification consists of machining a second channel at the base of the concentric screw arrangement to the outer flow path and placing two stops to dictate the beginning and end of the inertance tube, in the same manner as with the inner helical flow path. Figure 5 displays the modification.

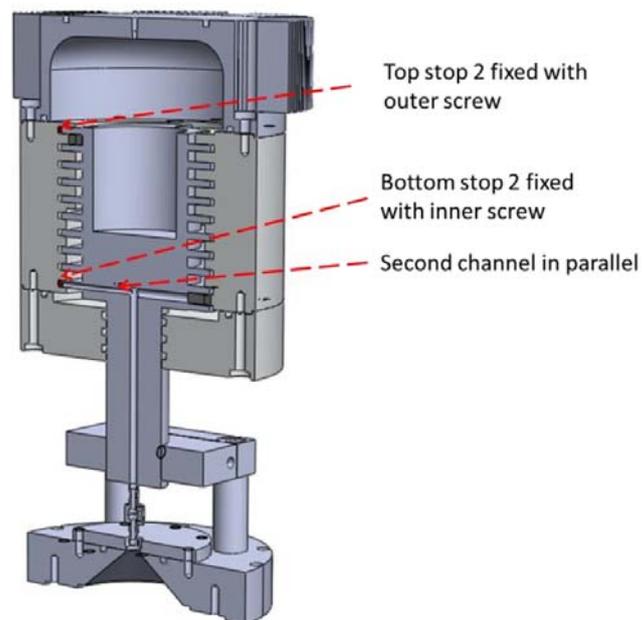
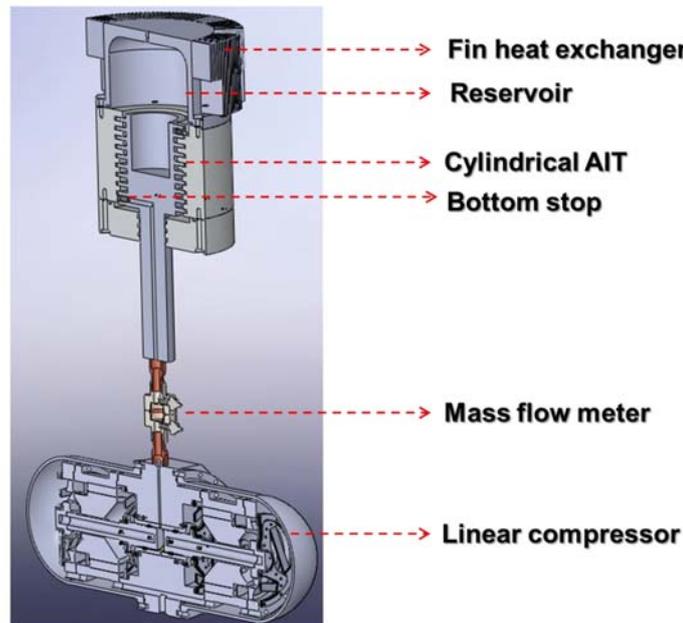


Figure 5: Cut-away view of the machined channel to connect the two paths in parallel.

As the inertance tube is adjusted from its shortest size to its longest, its length increases from 1.74m to 3.6m and the hydraulic diameter increases from 7mm to 10mm. The outer flow path has the same length dimensions, but the hydraulic diameter of the new path remains constant at 2mm throughout the entire path [6].

### 3. Experimental Setup and Procedure

The equipment in the experiment consists of the adjustable inertance tube, a linear compressor (Q-Drive, model 2S297W), a mass flow meter and three pressure transducers. Notice that the experiment does not require the use of a pulse tube. Rather, the capability of the inertance tube to adjust the phase angle can be measured using only the wave generator, the inertance tube, the reservoir, and the pressure and mass flow transducers. Figure 6 displays the linear compressor directly connected to the mass flow meter and the adjustable inertance tube. Nitrogen gas is used as the working fluid and the system is pressurized to 300psig.



*Figure 6: The experimental equipment consists of a linear compressor, a mass flow meter and the adjustable inertance tube. Two pressure transducers on the mass flow meter are used to measure the mass flow and pressure oscillations.*

Two pressure transducers are placed on the inlet and outlet of the mass flow meter to obtain the pressure data for the phase angle calculations, and an additional pressure transducer is placed on top to measure the reservoir pressure. All measurements are gathered, processed, and stored using LabVIEW.

Measurements of the pressure and mass flow oscillations have been gathered over a frequency range of 40 Hz to 60 Hz in 4 Hz increments. At each frequency the oscillation amplitude was also set at three or four values in order to optimize the signal to noise ratio.

The concentric screw adjustable inertance tube can be rotated a total of 4.5 turns, and measurements at each frequency were gathered at quarter-turn intervals. The Q-drive compressor produces the pressure oscillations and the current amplitudes range from 10A to 40A, depending on the frequency of the compressor. The amplitude of the piston motion in the linear compressor is proportional to the current, and in turn determines the amplitude of the pressure oscillation. The linear compressor has a resonant frequency of around 44Hz, so smaller current amplitudes are required at 40Hz, 44Hz and 48Hz in order to produce large amplitude oscillations.

After steady state conditions are established, three to four seconds worth of data are recorded. The myDAQ reads 15k samples per second, and the LabVIEW program saves exactly one second's worth of voltage measurements into separate text files. Measurements are recorded at each frequency in the same manner, and at quarter-turn increments over the entire 4.5 turns.

#### 4. Data Analysis and Results

The first step in analyzing the data for a specific trial involves extracting multiple pressure cycles from each transducer and averaging them into a single pressure cycle to reduce the effects from noise on the transducers. An Excel macro is utilized to extract 42 raw pressure cycles and produce the averaged pressure cycle curve. Next, the difference between the two pressure curves across the mass flow meter is used to calculate the mass flow wave. The phase angle between the pressure and mass flow waves is calculated, by importing the averaged pressure cycles into EES and utilizing its curve-fit function. A sinusoidal curve is fit to the two waves, and as displayed in Figure 7, those equations include the phase of each wave.

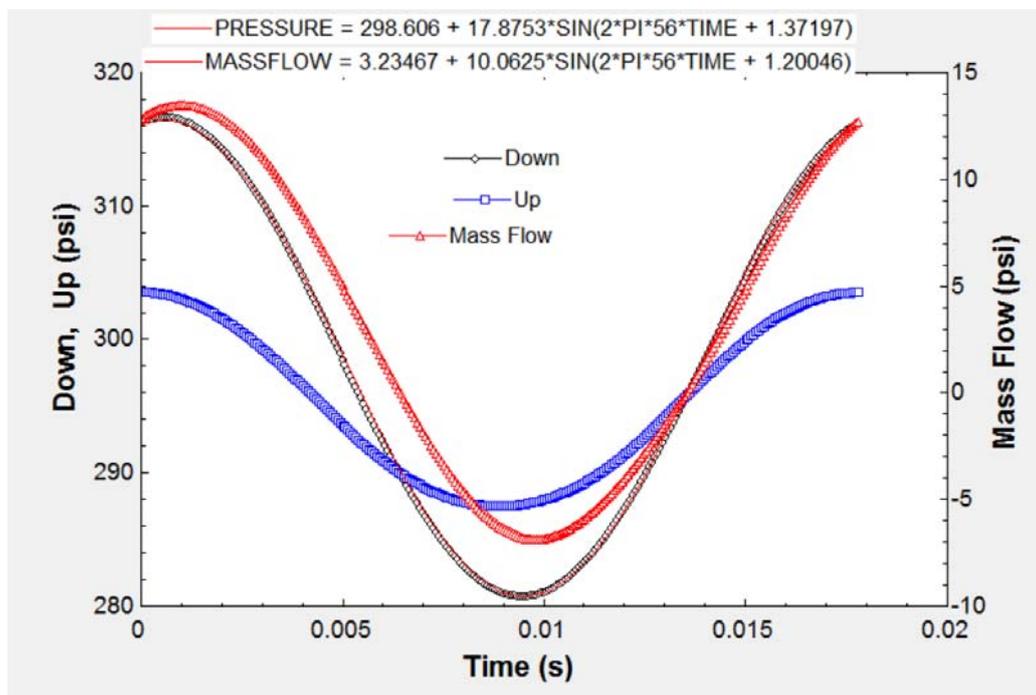


Figure 7: An example of the averaged pressure data in EES with curve-fit equations.

The phase angle between the two waves is calculated by subtracting the pressure phase from the mass flow phase. This procedure is repeated for each measured frequency and at each quarter-turn interval.

The final phase angle data is summarized in Figure 8. The maximum change in the phase angle as the inertance tube is adjusted is  $28^\circ$  occurring at 60Hz. The next largest change in the phase angle ( $19^\circ$ ) occurred at a frequency of 56Hz while frequencies of 44Hz, 48Hz, and 52Hz all produced a phase shift of only  $9^\circ$ . Surprisingly, the phase angle shift increased to  $16^\circ$  at 40Hz. The smoothest curves in Figure 8 correspond to conditions near the compressor's resonance when the oscillation amplitude was largest, and the corresponding signal to noise ratio was maximum.

The noise associated with the off-resonance conditions can be observed by comparing a composite of the 42 raw pressure cycles, which were used to generate the average pressure cycle, from a 40Hz trial with those of a 60Hz trial. Figures 9 & 10 display the raw pressure cycles at 40Hz and 60Hz for the same setting of the adjustable inertance screw.

The experimental phase angle shift data shown in Figure 8 does not display a similar behavior to the predicted curve. While the theoretical model predicts a steady increase in phase angle as the length of the flow path increases, the experimental phase angle increases at first, and then decreases. Furthermore, the  $105^\circ$  calculated change of the phase angle is  $77^\circ$  larger than the largest experimentally observed phase angle shift of  $28^\circ$ .

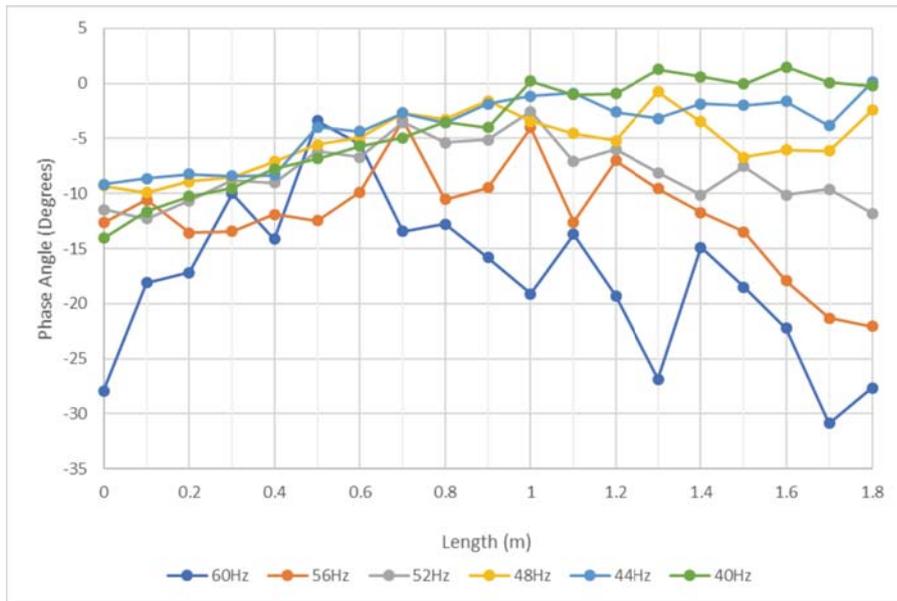


Figure 8: The experimental phase angle shift results as the inertance tube length increases. 60Hz had the largest phase angle shift of 28°.

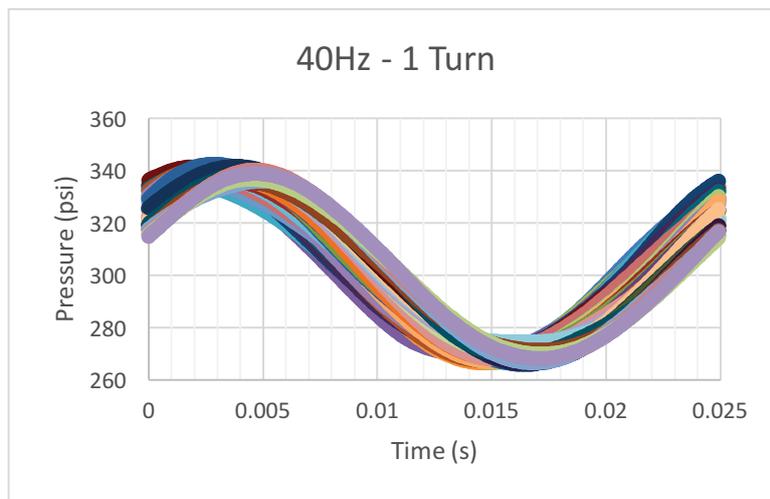


Figure 9: The raw pressure cycles of a 40Hz trial.

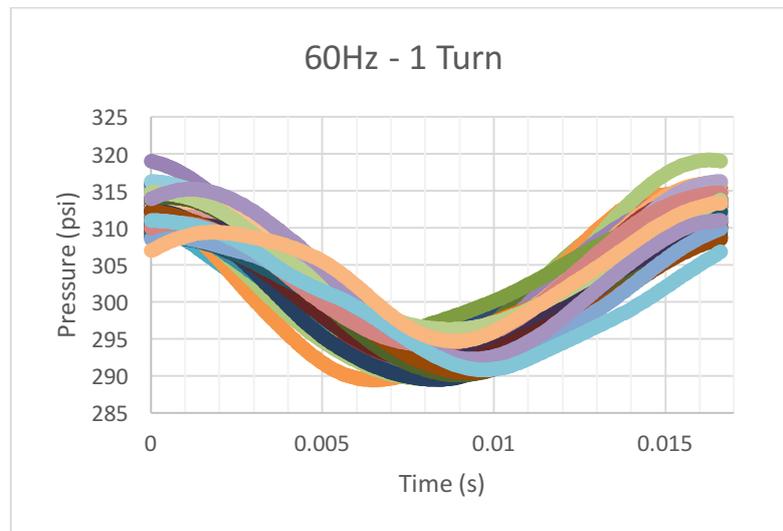


Figure 10: The raw pressure cycles from a 60Hz trial.

## 5. Conclusions

Neither the curve trends nor the phase angle shifts of the experimental data confirm the theoretical predictions for the phase shifting capability of the concentric screw adjustable inertance tube. While the theoretical model predicts a continuous increase from  $-65^\circ$  to  $+40^\circ$  at 60Hz, the experimental data increases from  $-31^\circ$  up to  $-3^\circ$ , and then back down to  $-28^\circ$ . It is still unclear why such a large discrepancy exists between the two data sets. One possibility that may yet be explored regards the geometry of the flow path. The models used to date assume a smooth tube, whereas the actual flow path in this case is rectangular in cross section and helically wound rather than straight.

In addition to the significant differences between the theoretical and experimental data, the smoothness of the phase shift curves depends on the oscillation amplitude. By looking at the raw pressure cycles, it can be concluded that there is more variation in the 60Hz cycles compared to the 40Hz cycles. The large amplitude oscillations at near resonance conditions produce the smallest signal to noise ratio and consequently the smoothest data set. Additional investigations regarding the phase shifting capability of the parallel adjustable inertance tubes are envisioned to explore other factors that may be influencing the realized phase angles.

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