TG001: PIEZOELECTRIC DISC PUMP DRIVE GUIDE

1. INTRODUCTION

The Lee Company's piezoelectric disc pumps are high-performance micropumps operating through ultrasonic acoustic resonance driven by a piezoelectric actuator. This document details best practices for driving the pump efficiently and provides guidance to support The Lee Company's customers in their software and electronics design-in processes. The document is set out as follows:

- Section 3: driver communication options
- Section 4: background to disc pump operation
- Section 5: an overview of the resonant characteristics of the pump.
- Section 6: detailed consideration of the drive waveform and control strategies.
- Section 7: algorithm flow diagrams for identifying and tracking the optimum drive frequency.

The key messages are:

- To drive the pump efficiently:
  - adopt the optimised drive waveform shape as per Figure 7;
  - implement frequency optimisation as per Section 7.
- To reduce part-to-part variation, implement power control as per Section 6.6.
- To prevent over-driving of the pump, implement power limiting as per Section 6.7.

Figure 1: A piezoelectric disc pump

2. DISCLAIMER

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3. DRIVER COMMUNICATION

The Lee Company provides options for driving the piezoelectric disc pumps. All designs share a common register-based control interface, which is accessed either via a UART or I2C protocol, depending on the driver. A PCBA is available, or its reference design can be provided to integrate the function into a system PCBA. Alternatively, a module is also available which combines the control function with other features.

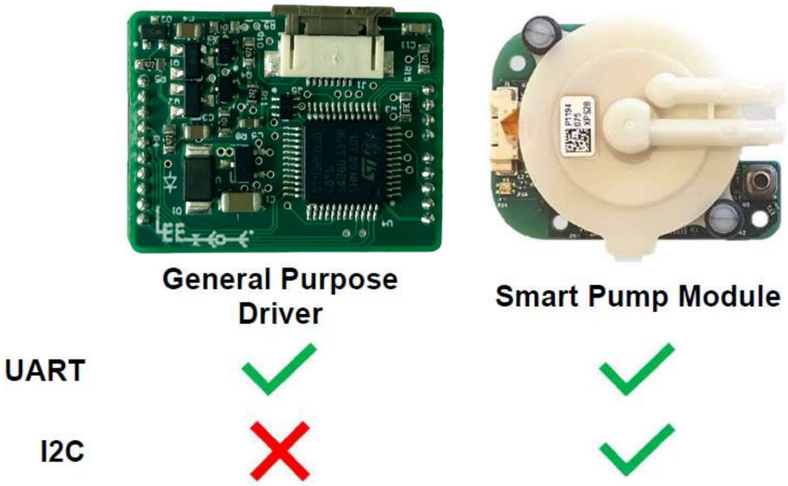


Figure 2. Disc pump drive systems and communication protocol support

4. BACKGROUND

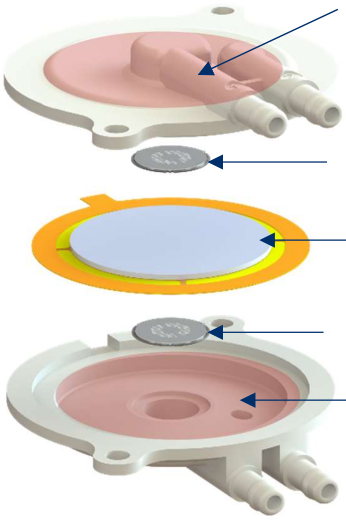
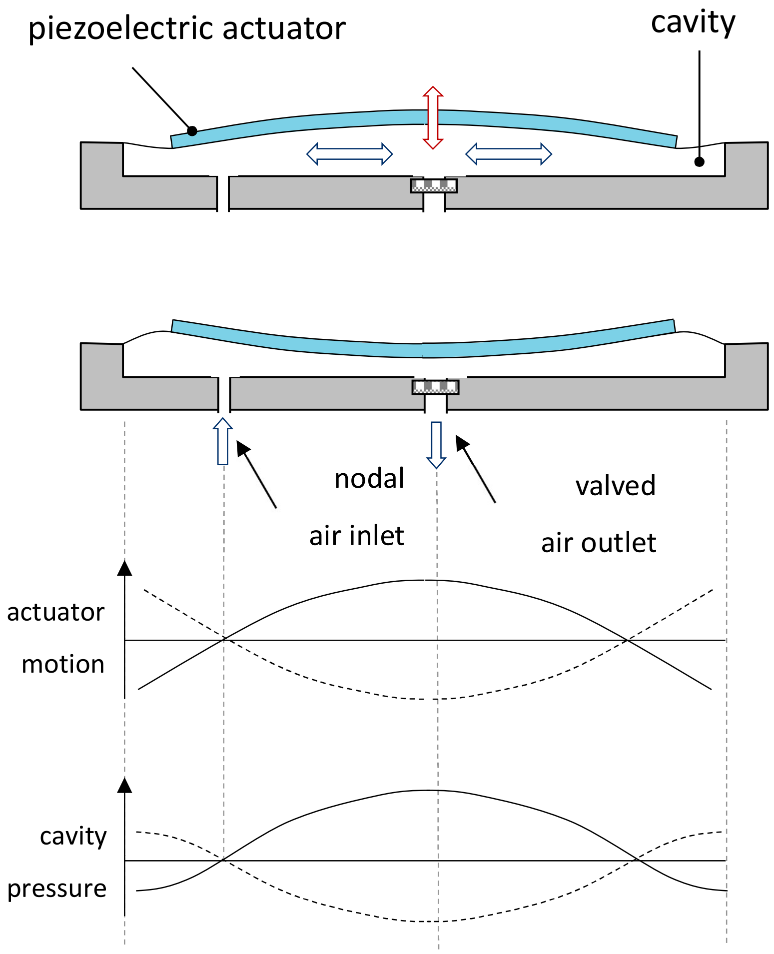


Figure 3. A piezoelectric disc pump – 'exploded' view

Ultrasonic piezoelectric gas pump

Most piezoelectric gas pumps rely on the movement of a piezo actuator to compress the gas in a cavity, thereby increasing its pressure. Such 'displacement' pumps have limited performance because the movement of piezo actuators is very small.

In contrast, our disc pumps do not rely on compression. Instead, it creates a high frequency, high amplitude standing wave and then rectifies that wave with an ultra-fast valve. This principle enables the disc pump to generate much greater flows and pressures than traditional piezo pumps – and because the disc pump operates at an ultrasonic frequency, it is silent.



1. Actuator flexes at its mechanical resonance
2. This drives a standing pressure wave, formed between the centre of the cavity and the side wall
3. Pressure builds up at the centre of the pump once per cycle
4. A central, passive (i.e. undriven) valve allows airflow out of the pump. Air flows into the pump at a nodal hole to replace the air that escapes through the valve.

Figure 4: Principle of operation

5. PUMP CHARACTERISTICS

5.1. Main Resonant Mode

The frequency of the main resonant mode of the pump occurs between 20 and 22 kHz and can be identified as the point of minimum impedance within this frequency range, as per Figure 5.

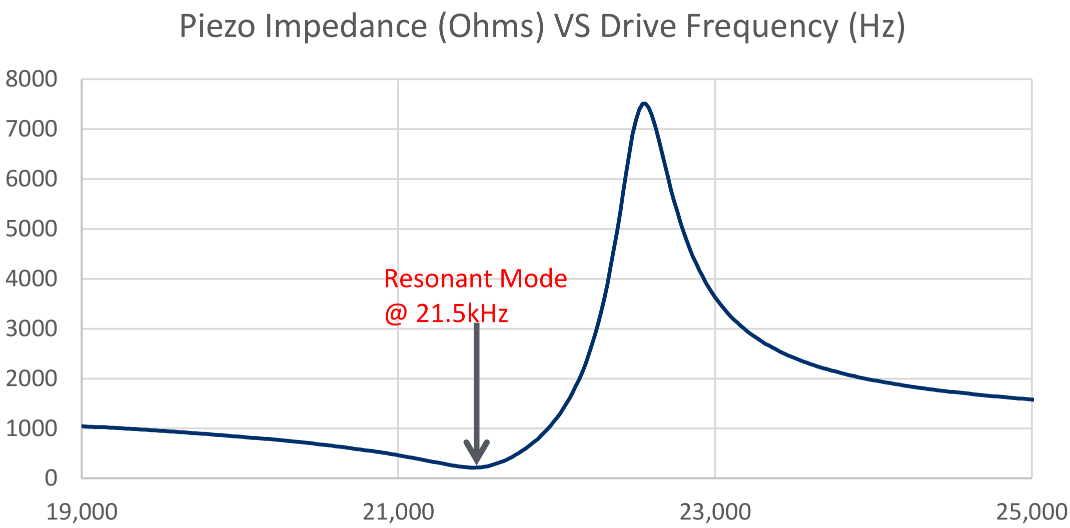


Figure 5: Piezo Impedance VS Drive Frequency

A wider impedance spectrum is presented in Figure 6, in which higher frequency harmonic modes can be seen. Driving power into these harmonic modes may result in excess heating, wear, and will reduce the overall drive efficiency.

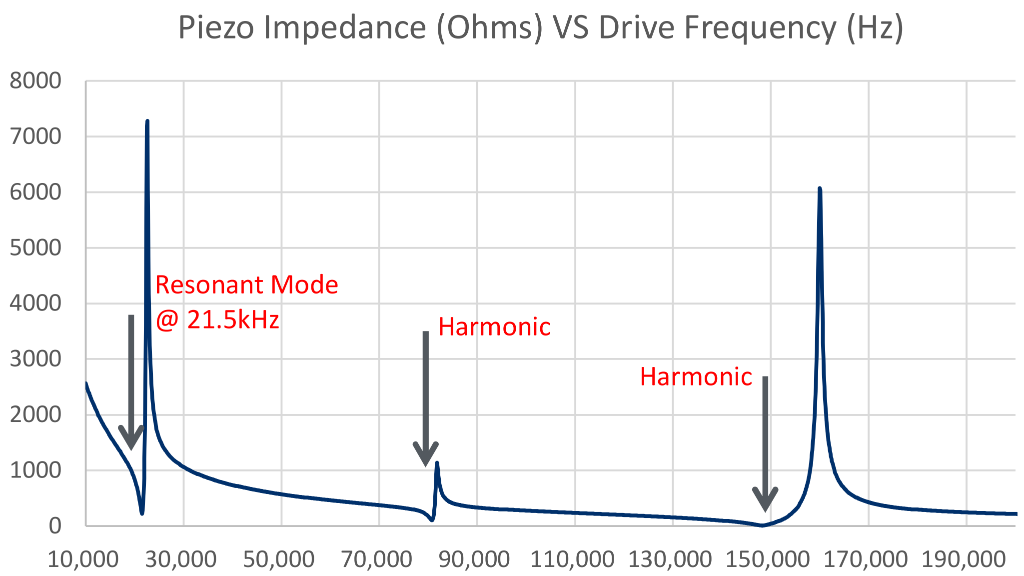


Figure 6: Piezo Impedance VS Drive Frequency showing harmonic modes

6. PUMP DRIVE WAVEFORM

To reduce the complexity of the drive electronics, a square rather than sinusoidal waveform can be used. To avoid driving power into harmonic modes, The Lee Company strongly recommends that customers implement a waveform as specified in Section 6.2, which has been optimised to reduce frequency content around the harmonics.

6.1. Recommended Drive Waveform Parameters

Frequency Range	20 - 22 kHz
Frequency Resolution	≤ 20 Hz
Voltage Range	0 to 48 Vrms
Voltage Resolution	≤ 0.1 Vpp
Waveform Shape	See section 6.2

TABLE 1: Recommended drive waveform parameters

6.2. Waveform shape

Figure 7 shows a comparison between a typical square wave, and an optimised tri-state waveform, which is best for driving the piezoelectric actuator. The pump voltage shown in the picture is the difference between the voltages of the two pump terminals. Note that which pump terminal is which is unimportant due to the symmetry of the system.

The typical square wave has two states HIGH and LOW:

- In the HIGH state the first pump terminal is connected to the drive voltage (VHV) and second pump terminal is connected to ground (GND).
- In the LOW state the voltage is applied in reverse – the first pump terminal is connected to ground (GND) and the second pump terminal is connected to the drive voltage (VHV).

The optimised tri-state waveform has two asymmetric states Mark and Space. At the end of each state, the waveform also contains a short Ground time. During this Ground time, both pump terminals are connected to ground (GND). Ground time makes the waveform more sinusoidal and reduces losses. The output to the pump for the optimised waveform is:

- For majority of the Mark state the first pump terminal is connected to the drive voltage (VHV) and second pump terminal is connected to ground (GND). The end of the Mark state is take up by Ground time during which both pump terminals are connected to ground (GND).
- For majority of the Space state the first pump terminal is connected to ground (GND) and second pump terminal is connected to the drive voltage (VHV). The end of the Mark state is take up by Ground time during which both pump terminals are connected to ground (GND).

The Ground time and the time ratio between the Mark and Space states is shown in TABLE 2.

Ground time at end of each mark and space	3 µs
Mark-space ratio	44:56

TABLE 2: Optimised drive waveform parameters

Adopting the optimised waveform has been shown to improve drive efficiency by approximately 30% over a typical square wave drive waveform.

Square wave **Optimised drive waveform**

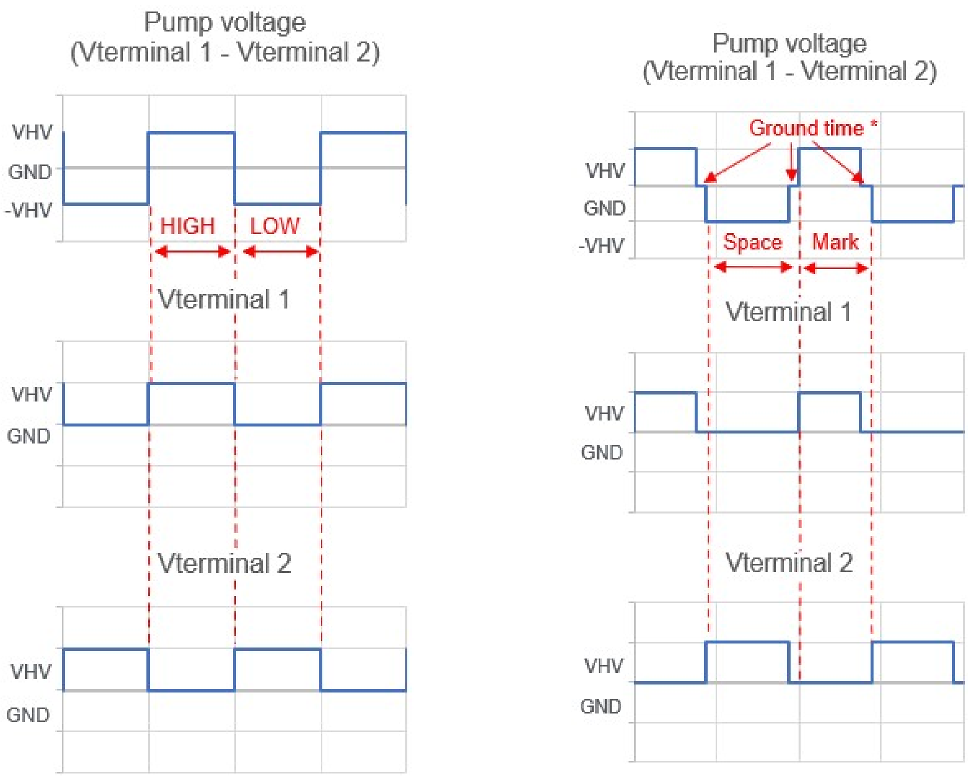


Figure 7: Typical Square Wave (left), Optimised Waveform (right)

** Ground time is a different concept to "dead time", where both FETs on one side of the H-bridge are held open briefly between switching events. Dead time is a common technique to avoid shoot through when driving an H-bridge. Both ground time and dead time are recommended when driving the disc pump.*

6.3. Drive Circuit

The Lee Company provides a General Purpose PCB (UEKA0300000A) and reference schematic design, firmware and bill of materials for the small driver board. The reference circuit includes:

- A microcontroller circuit, for waveform generation and control algorithms.
- A 5 – 50 V DC power supply ("Boost Circuit"), including voltage sensing.

- A DC to AC converter ("H-bridge") output stage, including current sensing.

There is also an option to purchase Smart Pump Modules for most disc pump models which include the drive circuit.

6.4. Waveform Generation

The reference design uses the Output Compare (OC) and Pulse width modulation (PWM) capability of the STM32 family of microprocessors to handle waveform generation in hardware. Each of the four output stage FETs is controlled by and independent OC channel of a single timer; the high-side FETs are controlled via a high-side gate driver. Together, this enables generation of the optimised waveform in Figure 7.

6.5. Voltage Ramping

In applications where the piezoelectric disc pump's silent operation is important – and particularly where it is *critical* – ramping the VHV voltage up/down slowly (e.g. over 100 ms) may help to minimise audible noise associated with pump 'onset' and 'offset'.

6.6. Power Control

The impedance of the piezoelectric disc pump at its fundamental resonant mode (Figure 5) will vary pump-to-pump, and under changes in temperature, pressure and loading. As impedance changes, so too will the power consumed and the pressure/flow generated by the pump, assuming that the drive voltage (VHV) is kept constant.

To minimise performance variation with changes in impedance, we strongly recommend implementing closed-loop control of the power consumed by the pump. This involves adjusting the drive voltage (VHV) until a certain power set point is reached, as calculated from the values measured by the voltage and current sense circuitry (See reference circuit). We find that a simple Proportional-Integral (PI) controller is effective for this purpose.

6.7. Power Limit

In addition to closed-loop power control, we strongly recommend that customers implement a power limit; that is to say, an algorithm to prevent the pump being driven at power levels greater than a certain limit. As a guide, we recommend that 1 W electrical power is used as this limit.

6.8. Current Sample Timing

When switching the H-bridge FETs, brief spikes are typically observed in the measured current supplied to the H-bridge as the bulk capacitance of the piezoelectric actuator charges. It is strongly recommended:

- to time the sampling of the current sense measurements to avoid these spikes; and,
- to sample at a consistent phase of the drive waveform cycle.

One way of achieving this is to trigger the Analogue to Digital converter (ADC) capture from the Pulse width modulation (PWM) module itself (Figure 8).

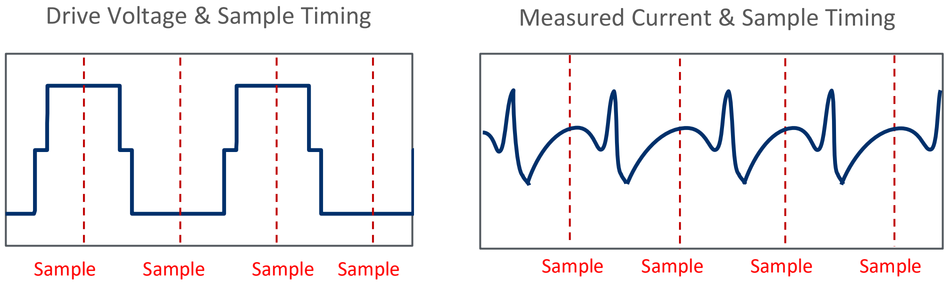


Figure 8: Current sense sample to avoid spike in measured current

7. FREQUENCY OPTIMISATION

7.1. Frequency Sweep Algorithm

Before running our disc pumps in normal operation, a drive frequency sweep should be performed to find the drive frequency which corresponds to the piezoelectric actuator's lowest input impedance (maximum current). This is done by stepping through a range of drive frequencies at a constant drive voltage and finding the frequency which results in the highest current draw. Figure 9 shows the necessary steps to performance a frequency sweep.

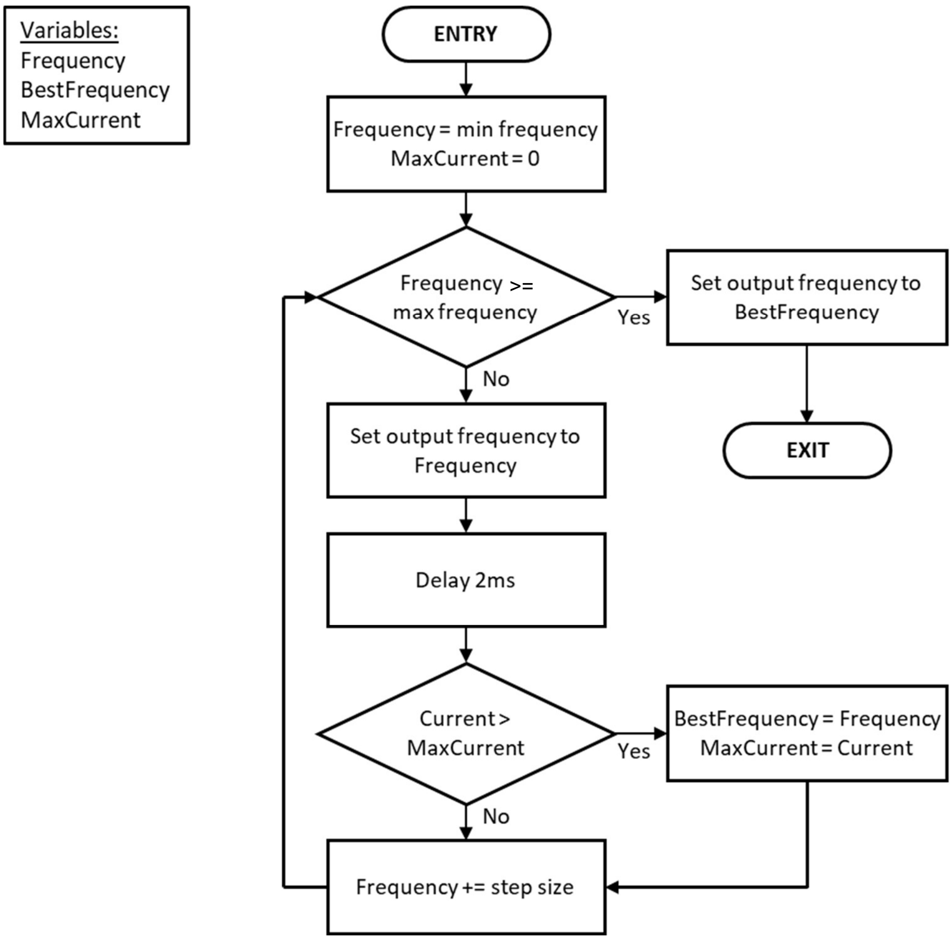


Figure 9: Frequency Sweep Flow Chart

7.2. Frequency Tracking Algorithm

During operation the main resonant mode of the piezoelectric actuator may drift, due to changes in temperature and loading. Therefore, it is necessary to continuously track the resonant mode. This is performed in a very similar way to the initial frequency sweep, but only for frequencies in a small range around the current drive frequency. Figure 10 shows the steps for one iteration of the frequency tracking algorithm.

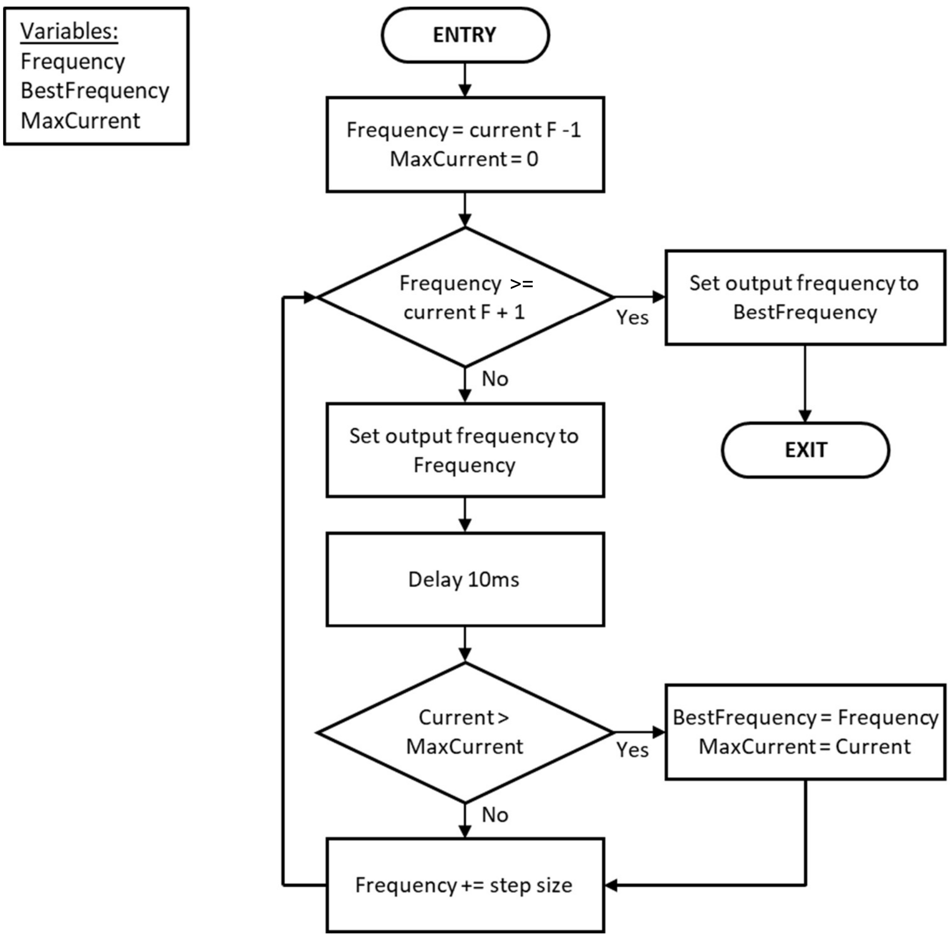


Figure 10: Frequency Tracking Flow Chart

8. ERROR DETECTION

The Lee Company recommends implementing in firmware tests for the following error conditions.

8.1. Short Circuit

The most likely cause of a short circuit condition is where a conductive foreign object bridges certain parts of the circuit board or the pump terminals / electrodes on the flexi tail. A short circuit condition may also arise in the unlikely event of a circuit board or pump failure. The symptom of this failure mode is a significant apparent reduction in load impedance, and a significant increase in measured drive current. The disc pump impedance typically varies between a few hundred Ohms to greater than 1 kOhm. Therefore, we recommend calculating the approximate load impedance using the measured drive voltage and current values, and then setting a threshold below which the short circuit error condition is triggered – for guidance a value of 100 Ohms or less should be sufficient. In the event the short circuit error condition is triggered, we recommend disabling the pump drive signal immediately.

8.2. Open Circuit

The most likely cause of an open circuit condition is where the pump flexi tail becomes disconnected (or not properly mated with) the FPC connector on the PCB. An open circuit condition may also arise in the unlikely event of a circuit board or pump failure. The symptom of this failure mode will be a significant apparent increase in load impedance, and a significant reduction in measured drive current. The disc pump impedance typically varies between a few hundred Ohms to greater than 1 kOhm. Therefore, we recommend calculating the approximate load impedance using the measured drive voltage and current values, and then setting a threshold above which the open circuit error condition is triggered – for guidance a value of 5 kOhms or more should be sufficient. In the event an open circuit error condition is triggered, we recommend disabling the pump drive signal immediately.

8.3. Frequency Outside Range

The most likely cause of a 'frequency outside range' error condition is pump or circuit board failure. A frequency outside range condition may also arise in the event of an open or short circuit error condition. The symptom of this failure mode is that the frequency optimisation algorithms defined in Section 5 identify a drive frequency at/outside the specified range for the pump (typically 20-22 kHz). In the event a frequency outside range condition is triggered, we recommend disabling the pump drive signal immediately.

9. SUPPORT

9.1. Code Snippet Library

The Lee Company code snippet library, hosted on GitHub (The Lee Company · GitHub), provides serial communication and control examples in Python for common functions, including turning the pump on and off, setting drive power, closed loop control of pressure and reading back and plotting data. The code snippet library implements the aspects of the communication protocol set out in our 'TG003: PCB Serial Communications Guide' and is intended to support customers after their initial evaluation of our pump technology, as they move on to developing prototypes and products.

9.2. Additional Support

The Lee Company website provides advice on:

- Getting started
- Application examples
- Development process
- Downloads (including datasheets, application notes, case studies and 3D models)

https://www.theleeco.com/disc-pumps/

Resources related to this application note:

- 'TG003: PCB Serial Communications Guide': a communications guide for controlling the pump without the GUI/PC App via the Development or Evaluation kit, drive PCB or Smart Pump Module or with users' own hardware.
- 'Disc Pump Electronics Reference Design Package': a pack of reference designs for the drive electronics and firmware. This can be downloaded from the website via the Resources tab.

9.3. Demonstrations

For more information and demonstrations, please visit The Lee Company website for videos of various application examples — visit: https://www.theleeco.com/disc-pumps/

10. REVISION HISTORY

Date	Version	Change
20th March 2024	240320	Formatting only, referencing the Development Kit
June 2023	06/23	Rebranded document
5th Jan 2023	220321	Add images for background to pump operation and clarify ground time in more detail
18th May 2022	220321	Refine sampling diagrams
3rd February 2022	220302	Add §7. Added drive voltages differences for model families in §4.1. Differentiated ground time and dead time in §4.2.
05 August 2021	210805a	Corrected voltage range in §4.1.
17 June 2021	210617a	Change to TN001 and updated document template.
26 November 2020	201126a	Corrected cross-references and updated Figure 5 to show rectified current.
4 May 2020	200504a	Added §4.8.
1 March 2019	190301a	Revised to refer to Ventus Pump Driver 59017-200-0002-01 schematic.
26 November 2018	181126a	XP draft schematics added.
6 November 2017	171106a	Initial release.