Application Note

Design Considerations and Measurement Results for Mechanical Hall-Effect Flow Meters

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Current and Position Sensing

ABSTRACT

Mechanical fluid flow meter systems require significant time for creation of mechanical elements, consequently, making system evaluation challenging. This document details the primary design considerations for creation of Hall-effect mechanical flow meters, and summarizes the results of flow meter evaluation. Also included are PCB Gerber files and 3D design files for creation of the documented flow meter.

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1 Introduction

Mechanical flow meters monitor the rotational speed of an impeller to interpolate the rate of fluid movement. When implemented with a magnet, the rotational speed of the impeller can be measured via changes in magnetic field through the use of Hall-effect sensors. This implementation has primary advantages of retaining the waterproof nature of the mechanical design, while also allowing for accurate measurements for rotational speed. The output of the Hall-effect device can then be connected to a microcontroller for frequency to flow rate conversion.

The flow meter design detailed in this document was created to offer an inexpensive test system capable of evaluating various magnet and Hall sensor configurations. In total, there are three primary configuration options for the 3D printed flow meter. Additionally, each configuration option is capable of evaluating various Hall sensors, including One-Dimensional (1D) and Two-Dimensional (2D) SOT-23 devices. See Section 3.2 for the download link and for instructions for creating the 3D printable mechanical flow meter.

2 Flow Meter Design

2.1 Mechanical Considerations

Mechanical flow meters use fluid movement to drive a rotating assembly with proportional rotational speed to flow rate. It is important to consider mechanical design elements in creation of a flow meter, as these characteristics dictate the performance and accuracy of the meter. The first mechanical characteristic to consider in designing a mechanical flow meter is impeller size. Impeller size influences the minimum and maximum flow rate capable of being measured. Use flow rate simulation software to evaluate the effectiveness of the mechanical system, and the impeller size can be adjusted accordingly to realize the desired sensing range.

Primary sources of inaccuracy originate from losses in the mechanical assembly. Frictional losses in the rotating impeller influence the linearity of sensing across the sensed flow range. Additional losses are attributed to disruptions in fluid flow from the rotating mechanical assembly. Such losses are typically more difficult to evaluate without simulation software, or physical flow meter testing. Ideally, output frequency linearly correlates with flow rate, though losses can force low and high flow rates to deviate from the linear sensing range. Software adjustment can be used in some cases to account for non-linearity in flow rate measurement.

2.2 Magnetic Considerations

2.2.1 Material

Various magnetic material options are suitable for use in flow meters. It is important to evaluate the magnetic field generated at the sensing element to verify the Hall device is capable of sensing the magnet rotation. It is also important to select a suitable magnet material if the magnet will be exposed to fluid.

2.2.2 Geometry

Many magnet options exist for implementation in flow meters. The options can be divided into two distinct categories: multipole and bipolar magnets. Flow meters can rely on a single multipole magnet or the use of multiple bipolar magnets positioned to achieve the desired resolution for the sensor. Magnets can vary in shape and size to meet the Hall sensor requirements. Common bipolar magnet shapes are illustrated in Figure 2-1.

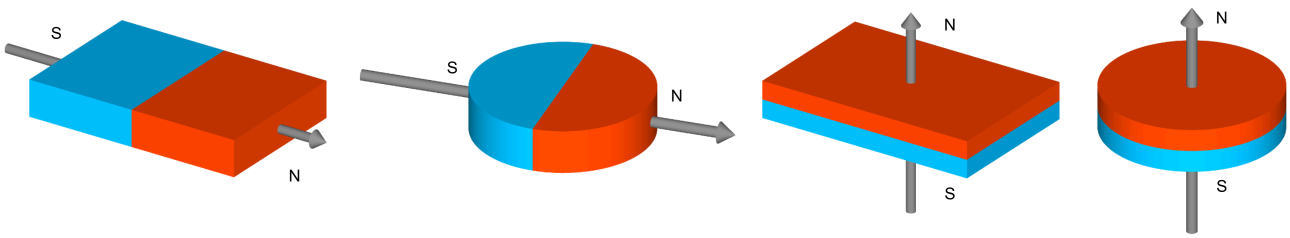

Figure 2-1. Cylinder and Block Magnet

Radially magnetized ring magnets are the most common form of multipole magnet used in flow meters. This type of magnet can be created to have the pole count of many individual magnets, while being retained in a single piece of magnetic material (see Figure 2-2).

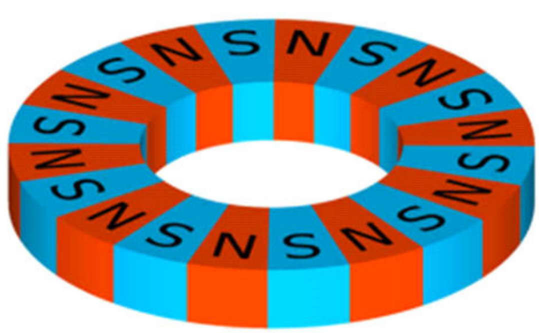

Figure 2-2. Multipole Magnet

Multipole ring magnets enable high resolution in space-constrained designs; however, they typically cost more than other magnet alternatives.

2.2.3 Magnetic Deign Tools

While magnet equations and their non-linear magnetic behavior might look complex, there are tools that greatly reduce calculation time. Such tools include ANSYS and Femm, which leverage Maxwell's equations to solve the B-field while sweeping through different design variables.

2.3 Hall-Effect Sensor Considerations

2.3.1 Device Sensitivity

Select a Hall-effect sensor to have adequate sensitivity for the magnet used in the flow meter. The positioning and size of the magnet can have significant influence on magnetic flux density sensed by the Hall-effect sensor. Hall-effect devices are often available with multiple sensitivity options to suit the specific sensitivity requirements for the application. It is necessary to select a Hall-effect sensor with enough magnetic headroom to reliably trigger on changes in magnetic field.

2.3.2 Unipolar Switch

Unipolar switches are the most simple Hall-effect device available, with sensing capability in one direction, either the North or South pole of a magnet, for B_{OP} and B_{RP}. When using sensors that have a unidirectional sensing direction, proper magnet orientation is required for B-field sensing. Common magnet implementations for Hall-effect switches include alternating North or South orientation magnets, or single orientation magnets spaced far enough apart to allow the B-field to fall below the B_{RP} threshold between magnets. In digital Hall-effect devices, B_{OP} and B_{RP} dictate the switching thresholds for the device. For a Hall-effect switch, this characteristic makes the output duty cycle dependent on the magnetic threshold levels and magnet movement. Generally, more care must be taken to implement Hall-effect switches into a flow meter design compared to latches. However, switches can be used with various magnet implementations, further adding to flexibility in terms of flow meter mechanical design. Figure 2-3 displays the unipolar switch operation.

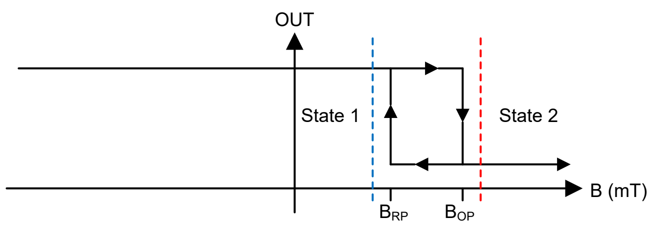

Figure 2-3. Unipolar Switch Operation

2.3.3 Omnipolar Switch

Omnipolar switches act as two opposite polarity unipolar switches connected together. Therefore, the switch still operates using B_{OP} and B_{RP}; however, the polarity of the B-field no longer influences the output of the sensor. This implementation requires the magnets be positioned far enough apart to allow the B-field to fall below the B_{RP} threshold between magnets. Use of the omnipolar switch enables the magnets to be positioned in any orientation (North facing or South facing) with no polarity influence to the sensor operation. Magnets can be positioned in either orientation, simplifying overall mechanical assembly of the flow meter. Omnipolar switch operation is displayed in Figure 2-4.

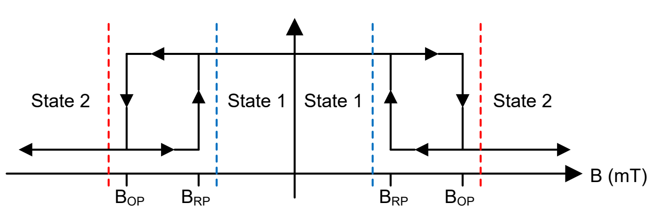

Figure 2-4. Omnipolar Switch Operation

2.3.4 1D Latch

1D Hall-effect latches share similar operational characteristics as switches, but uniquely retain the previous output state until a magnetic pole of the opposite polarity is detected. Therefore, it is necessary that the sensor detect changing magnetic polarities to create corresponding changes on the output. Assuming equal spacing of magnets, the output waveform of a latch is approximately 50% duty cycle regardless of sensing frequency. Figure 2-5 demonstrates the operational characteristics of a Hall-effect latch.

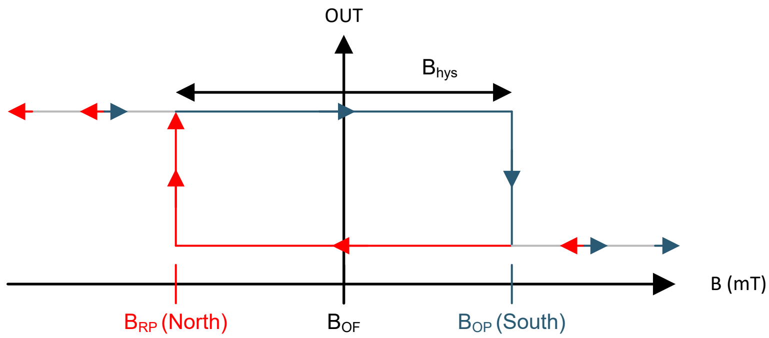

Figure 2-5. Latch Operation

2.3.5 2D Integrated Latch

2D Hall-effect latches operate in a similar fashion to their 1D counterparts, but possess multiple sensing elements integrated into a package. In the case of the TMAG5111 device, this feature allows for rotation sensing as well as direction sensing. With multiple sensing elements, 2D latches can increase the resolution of the sensing system without requiring additional magnetic poles. Furthermore, the inherent quadrature nature of the 2D Hall-effect latch replaces the requirement to alternatively position two 1D Hall-effect latches precisely 90° apart from one another. The quadrature output can allow for more accurate frequency measurement, and backwards flow detection capability in mechanical flow meters.

2.3.6 Bandwidth

Hall-effect sensor bandwidth is specified as a digital characteristic, differing from analog bandwidth in devices like operational amplifiers. Bandwidth determines the maximum frequency capable of being sensed by a Hall-effect sensor. It is necessary to consider the total number of magnetic poles present in the flow meter to verify if the maximum rotational speed of the impeller is less than the bandwidth of the device. For example, a flow meter using a high bandwidth DRV5013 Hall-effect latch (30 kHz) and ring magnet with 32 poles (16 North oriented, 16 South oriented) has a maximum typical theoretical sensing speed of 1875 rotations per second. Using the calculated maximum rotational sensing speed to verify the maximum flow rate does not cause the mechanical assembly to exceed the sensing capability for the Hall-effect device.

2.3.7 Package

Package selection can influence the mechanical design of the flow meter, as size of the package and plane of sensitivity dictates Hall-effect sensor location. This is most realized in comparing surface mount packages to a leaded TO-92 package. Figure 2-6 displays the difference in sensing direction of traditional and in-plane Hall-effect sensors in SOT-23 and TO-92 packages. Alternatively, if mechanical constraints limit Hall sensor mounting options, in-plane sensors can be used to sense magnetic fields lateral to the package (see Figure 2-6).

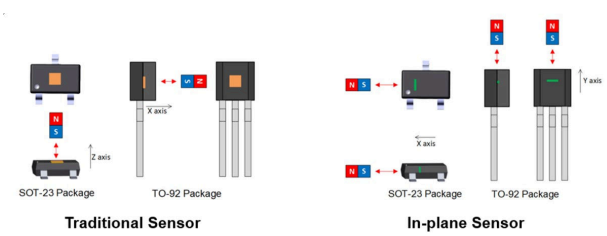

Figure 2-6. Package Sensitivity

2.3.8 Power Consumption

Low-power Hall-effect devices enable longer operating life in battery-reliant systems through reduction of active current consumption. For example, the DRV5032 low power Hall-effect switch has a 5-Hz sample rate device which consumes a typical current of just 0.54 µA at 1.8-V supply. Current consumption generally has an inverse correlation with device bandwidth, so it is necessary to balance the two characteristics for the intended flow monitoring application. If high bandwidth and low power are required, it may be necessary to lower the average current consumption by externally duty-cycling a sleep or enable pin (if the device has one), or by duty-cycling the V_{CC} pin of the device.

3 Flow Meter Development

3.1 3D-Print Recommendations

Print all 3D printed parts with suitable infill to offer adequate structure to the flow meter. Additionally, print all parts with support material to retain the part shape when printing overhangs. Orient all printed components with the largest surface area of the component facing the printer build plate. This orientation promotes adequate bed adhesion, as well as minimizes the support material generated. In the case of the example model, all parts were printed in ABS plastic, with 60% infill, 0.2-mm layer height, and minimal support material setting on a PolyPrinter 229.

The flow meter used for testing was designed to be created on a variety of 3D printers. Due to 3D printers having varying degrees of precision, some parts may require alteration to ensure proper fit. Most interface surfaces require filing or sanding to interlock well with other components. All plastic components are designed to be press fit together. The 3D print files can also be modified to suit specific design requirements.

3.2 Flow Meter Assembly Considerations

Prepare all 3D printed parts by removing any existing support material. Due to printers having varying degrees of precision, some parts may require alteration to ensure proper fit.

Table 3-1 shows the 3D printed files required for flow meter design. All files are available from *Mechanical Flow Meter Design Files*.

Table 3-1. Flow Meter Assembly

Parameter	Vertical Sensor	Alternate Vertical Sensor	Horizontal Sensor
Magnet Compatibility	Phoenix America ring magnet (G8-H-315-50-8)	¼ in × 1/16 in - disc magnets	¼ in × 1/16 in - disc magnets
Flow Meter Body 3D Print File	Flow Body.STL	Flow Body.STL	Flow Body.STL
Flow Meter Impeller 3D Print File	Ring Mag Impeller.STL	Alternate Mag Impeller.STL	Horizontal Mag Impeller.STL
Flow Meter Top 3D Print File	Vertical Top.STL	Vertical Top.STL	Horizontal Top.STL
Flow Meter Cover 3D Print File	Vertical Cover.STL	Vertical Cover.STL	Horizontal Cover.STL

3.3 Flow Meter Assembly Guide

3.3.1 Shaft Installation

Start the assembly by installing the 4-mm diameter stainless steel shaft into the flow meter body. This is a press fit part, though, it is not necessary the fitment require excessive amount of force for assembly. If the shaft does not locate in the recess, sand the internal diameter of the mounting location. Figure 3-1 displays a correctly assembled shaft and flow meter body.

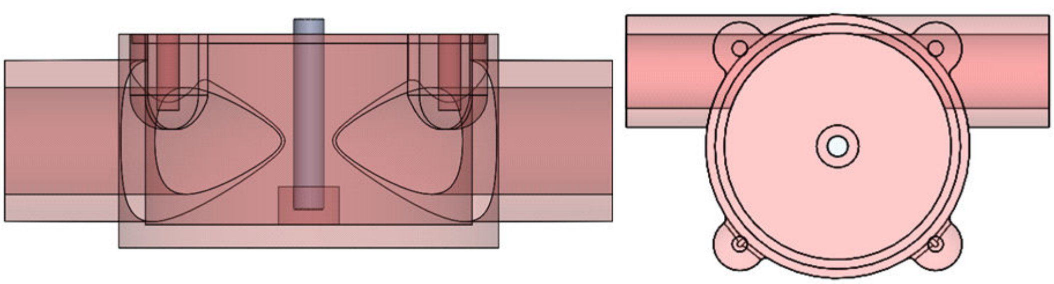

Figure 3-1. Shaft Installation

3.3.2 Bearing Installation

Next, assemble the mechanical components into the flow meter impeller. Assembly of magnets varies depending on the selected variant of the flow meter, but the bearings must be pressed into the plastic housing in all three variants. Two 4- ×10- × 4-mm bearings are pressed into the inside of the impeller with the first bearing seating against the backside of the impeller housing. The next bearing is positioned against the backside of the previous bearing. The location of these two bearings dictates the height of the impeller, and how true the impeller rotates in relation to the shaft. Figure 3-2 shows a correctly assembled impeller.

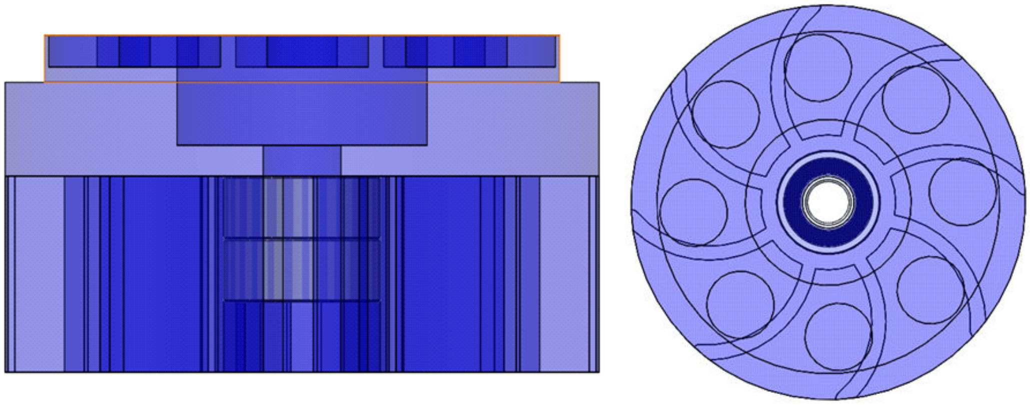

Figure 3-2. Bearing Installation

3.3.3 Magnet Installation

Now install the magnets into the impeller by pressing them in. Note, the direction of the magnetic poles may be important depending on the Hall sensor being used. In the case of the ring magnet, the magnet can be installed either direction. For flow meters using disc magnets, it is most common to utilize alternating N/S oriented poles. Figure 3-3 is an example assembly for the horizontal impeller with four north oriented poles (red) and four south oriented poles (black).

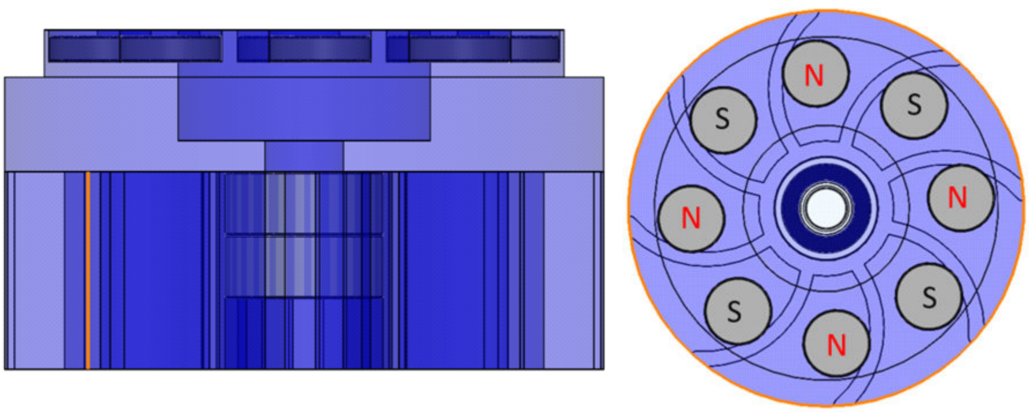

Figure 3-3. Magnet Installation

3.3.4 Impeller Installation

With the impeller and flow meter body assembled, the two components can now be joined together. Install the impeller onto the steel shaft located in the flow meter body. Proper assembly should allow the impeller to now rotate freely. Additionally, the bottom bearing should hold the impeller slightly above the bottom of the flow meter body to reduce friction. If the bearings do not easily assemble onto the shaft, it may be necessary to reduce the outer diameter of the shaft. Reduce the outer diameter of the shaft by cooling the steel shaft in a freezer for enough time to allow the bearing to slide onto the shaft. Figure 3-4 displays the properly assembled components.

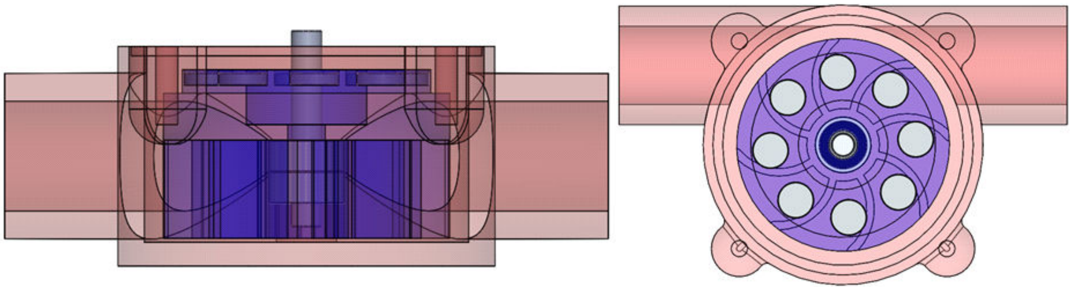

Figure 3-4. Impeller Installation

3.3.5 O-ring Installation

Install the rubber O-ring onto the flow meter top selected for the desired flow meter variant. The O-ring stretches slightly upon installation, and should seat against the bottom edge of the plastic part. Figure 3-5 demonstrates installation of the O-ring.

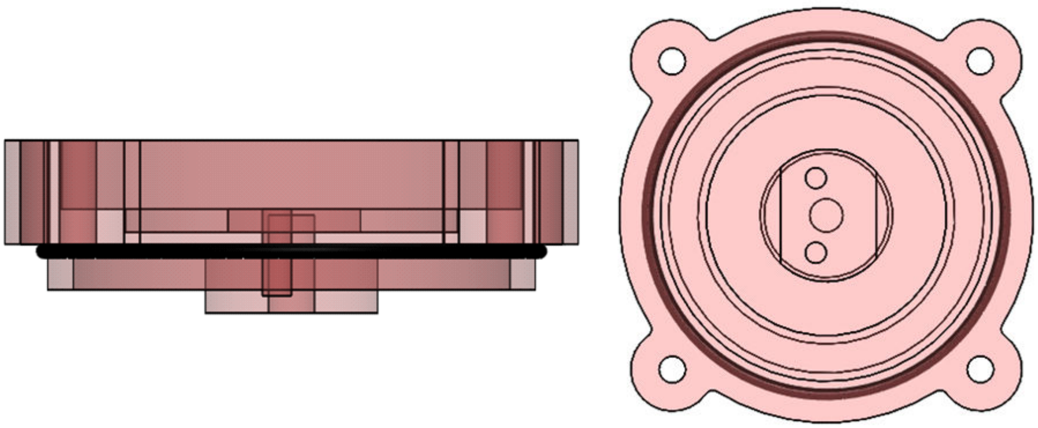

Figure 3-5. O-ring Installation

3.3.6 Flow Meter Top Installation

The two components can now be joined together. Though not pictured in Figure 3-6, add waterproofing PTFE tape between the sealing surface of the flow meter body and flow meter top. Ensure the O-ring forms a tight seal with the retention groove in the flow meter body. The flow meter top should feel relatively tight during the final 2 mm of travel into the flow meter body. Verify proper assembly by ensuring the impeller is capable of rotating without obstruction. Figure 3-6 displays the assembly.

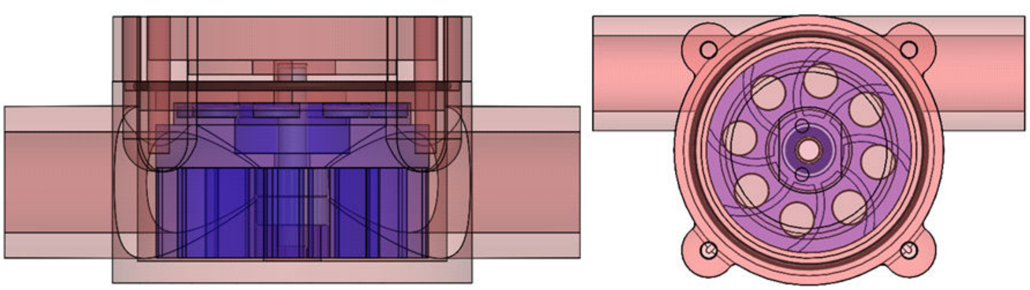

Figure 3-6. Flow Meter Top Installation

3.3.7 PCB Mounting

Install the Hall sensor PCB into the mounting location. Horizontal sensor mounting requires the PCB to be mounted to the 3D printed part denoted "Horizontal Top", whereas vertical sensor options require the PCB to be mounted to the part denoted "Vertical Cover". Both the vertical and horizontal mounting option require the use of 2-56 nylon screws for securing the PCB to the printed mount. Figure 3-7 shows the horizontal mount and Figure 3-8 illustrates the vertical mounting.

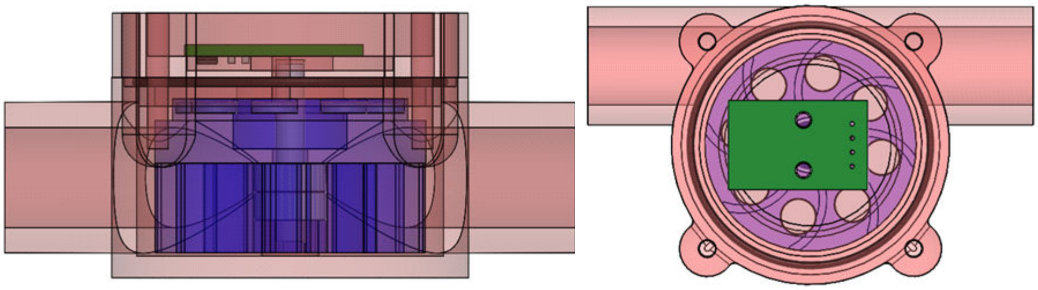

Figure 3-7. Horizontal PCB Mount

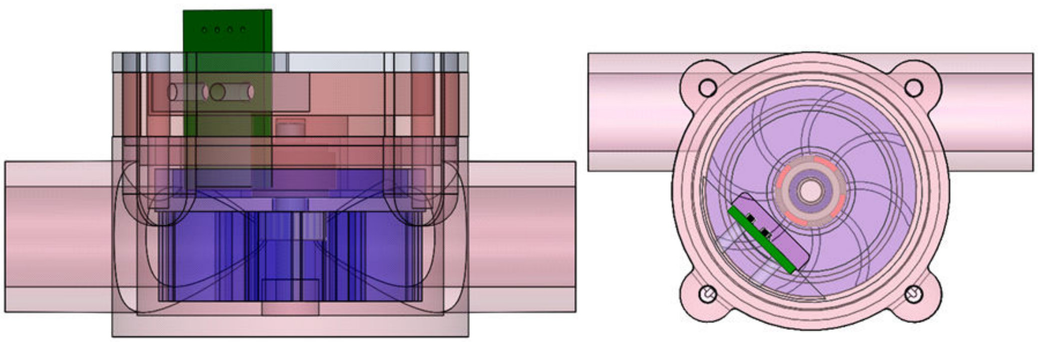

Figure 3-8. Vertical PCB Mount

3.3.8 Cover Installation

Finally, install the cover used in the flow meter design. In the case of the vertical sensing option, this cover also mounts to the PCB. The cover contains a slot for pin headers or wires to be routed to the outside of the flow meter. It is not necessary to waterproof this connection, as this stage of the flow meter is isolated from previous flow meter stages. Final assembly requires installation of four screws into the outer mounting holes. Ensure the four screws create enough clamping pressure to prevent leaking of fluid at assembly joints. Use coarse threaded hardware to thread into the flow meter body. Figure 3-9 shows the final assembly of the horizontal flow meter.

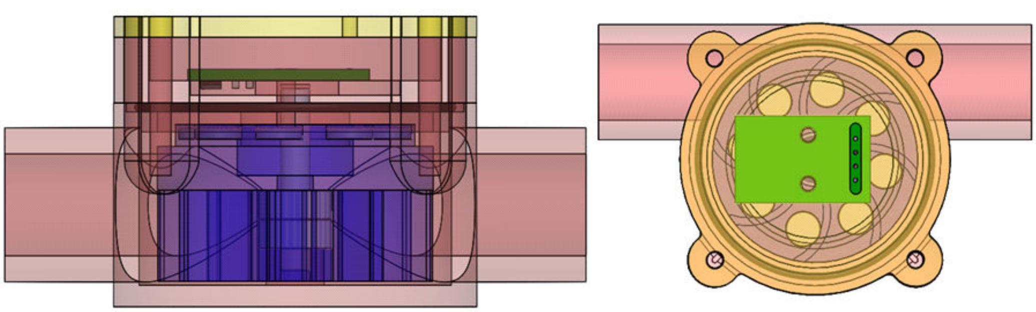

Figure 3-9. Cover Installation

Install ½-in PVC fittings onto the inlet and outlet to suit specific evaluation setups. Use PVC primer and PVC glue if installing fittings onto the flow meter body. Uninstall the sensing PCB for initial waterproof evaluation.

4 Flow Meter Evaluation

4.1 Flow Meter Testing

Due to test system limitations, the maximum controlled flow rate generated in testing was 11.2 liters per minute. The meter under test uses a DRV5013 Hall sensor with four disc magnets, and a horizontally configured flow meter (see Figure 4-1). Reference flow rate was measured using an industrial-grade magnetometer flow meter in series with the mechanical flow meter. Flow rate simulations estimate the 3D-printed flow meter to be capable of accurately sensing in excess of 30 L/min before concerns of non-linearity. Linearity is expected to decrease with flow rates less than 2 L/min. If the desired flow rate exceeds the suggested limits of the 3D-printed design, it may be necessary to re-size the flow meter for more accurate results.

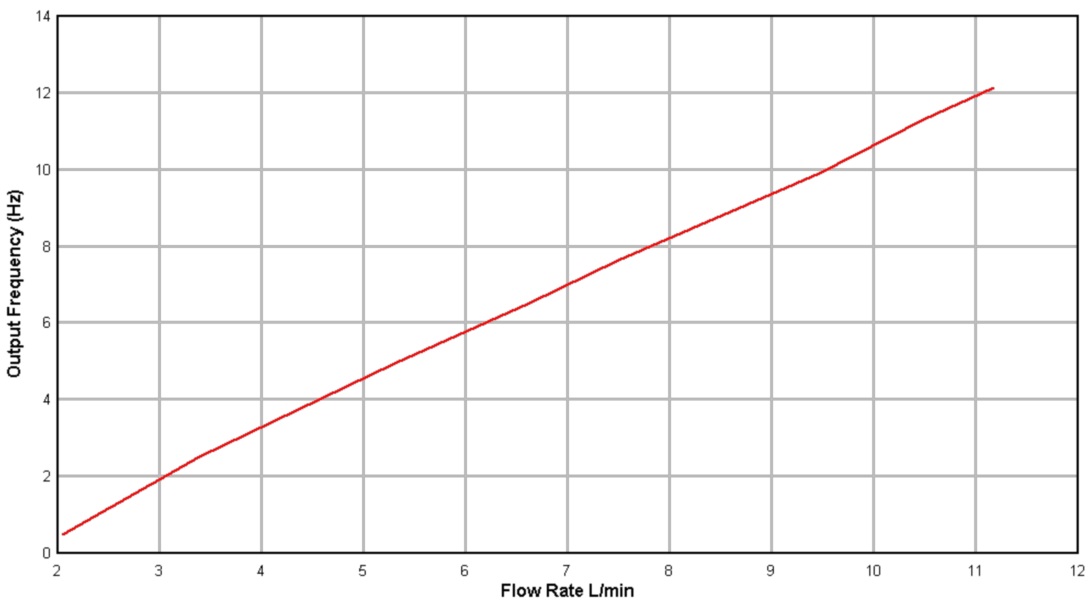

Figure 4-1. Flow Rate Analysis Waveform

5 Error Sources

Many factors can influence the accuracy capability for mechanical flow meters. These error factors can be divided categorically based on source, being: mechanical error, sampling error, and magnetic error.

5.1 Mechanical Error

Mechanical errors can be generalized as physical characteristics of the flow meter which attribute error to the measured flow rate. A common mechanical error associated with rotary flow meters is frictional losses. Frictional losses can in some cases become the dominant source of error depending on the flow rate and meter design. For example, in the case of low flow rates, it is common for the frictional losses in the bearing to influence the ability for the impeller to rotate proportionally to the fluid flow rate. This relatively large frictional force will eventually equal the force of water flowing through the meter, dictating the minimum flow rate.

Additional mechanical errors can originate from inaccuracies in mechanical movement. In the case of a flow meter, it is generally assumed for magnets to be equally spaced and mounted planar to the top of the impeller. Assembly errors; however, can influence the positioning of components, therefore altering the magnetic field sensed by the Hall sensor. An important characteristic of a mechanical flow meter is the trueness in how the impeller rotates with reference to the locating shaft. Misalignment in this movement can be descried as a wobble in the rotating assembly, altering the magnet angle and distance to the Hall sensor.

Figure 5-1 represents the horizontal impeller simulated with 0 degree, ±1-degree, ±2.5-degree, and ±5-degree vertical misalignment with the center shaft. The simulation emulates the mechanical positioning of the horizontal impeller used with 8 individual ¼-in diameter N42 disc magnets positioned equally along the impeller with alternating magnetic poles. Position 0° represents the maximum positive misalignment, and 180° represents the maximum negative misalignment. The simulation ranges from 0° to 180°, as it is assumed the maximum negative misalignment is 180 degrees out of phase of the positive misalignment.

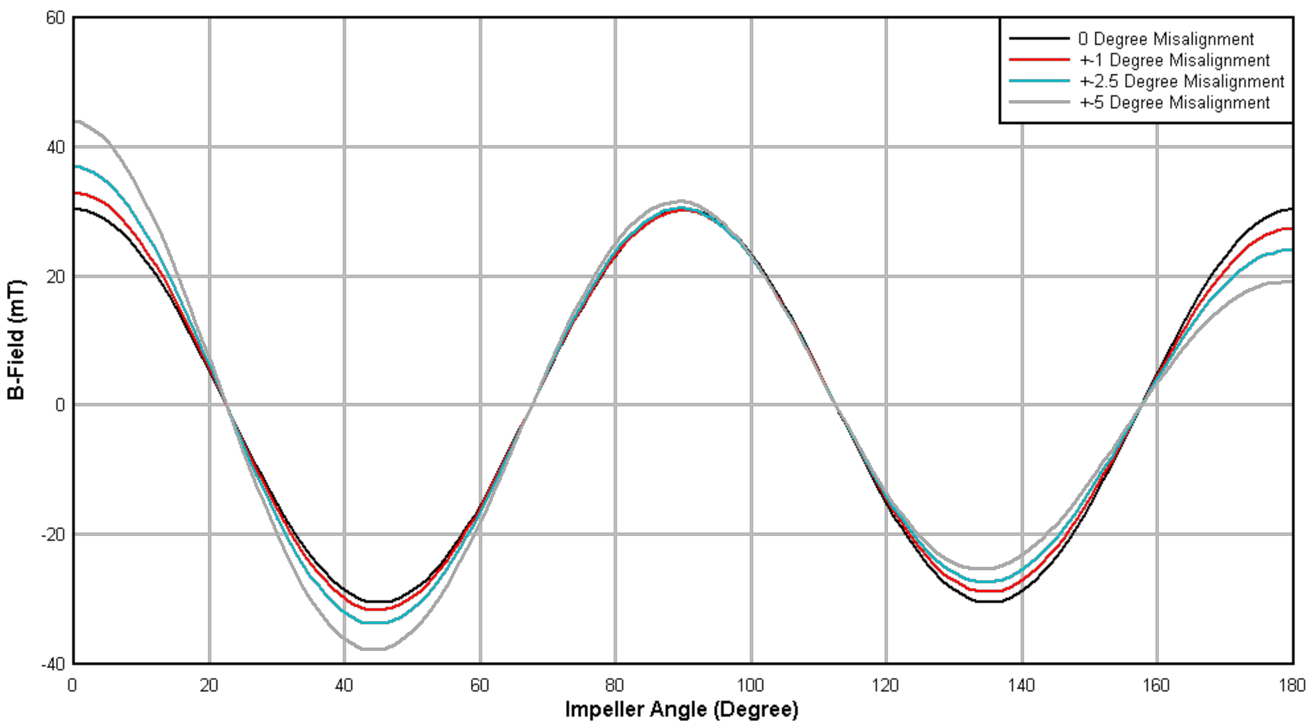

Figure 5-1. Misalignment Simulation

5.2 Sampling Error

Sampling error can be attributed to inadequate sample rate for measuring flow. This error can originate from either the Hall-effect sensor, or the device responsible for data acquisition. In the case of the sensor, ensure the device has adequate bandwidth to support the frequency of changes in magnetic field. Acquisition frequency is similar to sensor sampling frequency, being that a frequency that is too low can compromise accurate frequency measurement. Therefore, at a minimum sample twice the anticipated maximum output frequency.

5.3 Magnetic Error

Magnetic error sources originate from physical and material variation in magnet construction. Such errors are typically specified by the magnet supplier, or otherwise calculated by evaluating maximum tolerance error. Notably, magnetic error has more or less influence over a sensing system depending on the Hall-effect sensor being used. Design tolerance into systems using magnets and Hall-effect sensors.

Another magnetic source for error is in device variation. Manufacturing variance causes characteristics like typical B_{RP} and typical B_{OP} to differ between Hall-effect devices. Hall sensor data sheets include minimum, typical, and maximum values for magnetic characteristics. Consider these values in verifying the suitability of a Hall sensor and magnet.

6 Flow Meter PCB

6.1 PCB Schematic

See Figure 6-1 for the flow meter schematic. C1 is a local supply decoupling capacitor and R1, R2 act as pullup resistors for open drain Hall sensors on OUT1 and OUT2, respectively. The sensor mounting pad is capable of facilitating both 1D and 2D SOT-23 package Hall sensors. Ensure the pin 1 indicator on the PCB (top left) is aligned with pin 1 of the device before use.

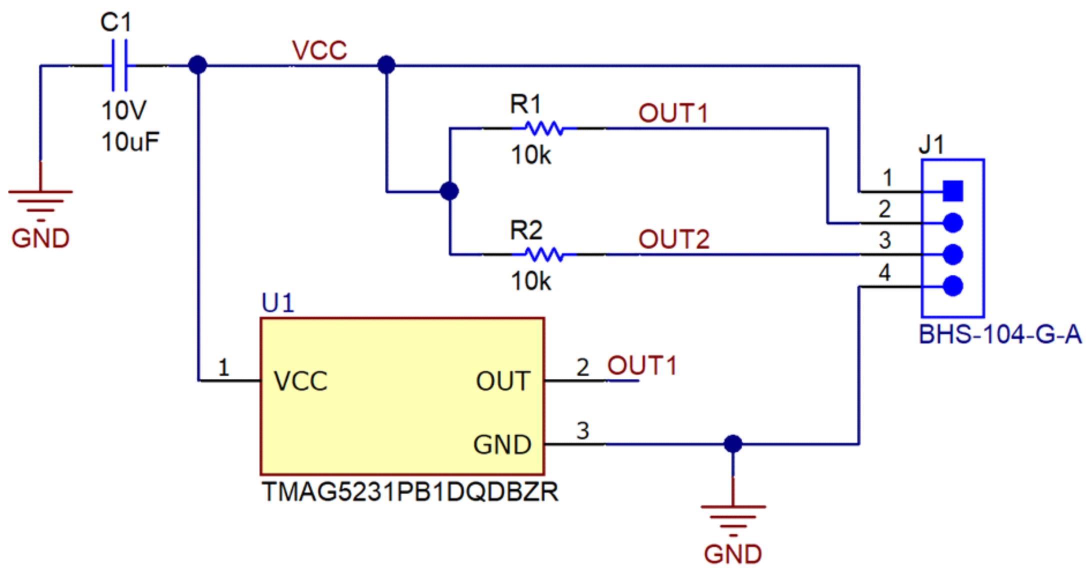

Figure 6-1. PCB Schematic

6.2 PCB Layout

Gerber files are available in the download file in Section 3.2 of the document.

Figure 6-2 and Figure 6-3 show renderings of the top and bottom of the PCB, respectively.

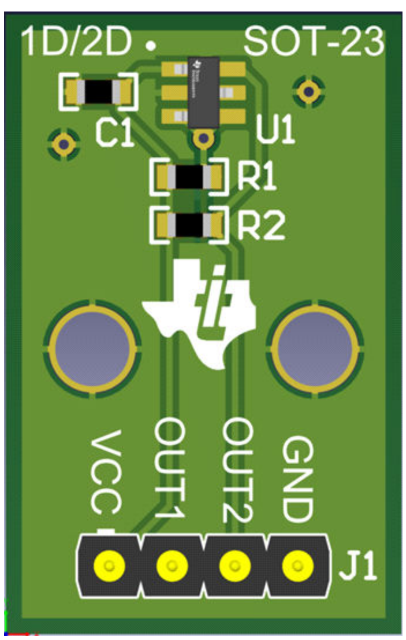

Figure 6-2. PCB Top Rendering

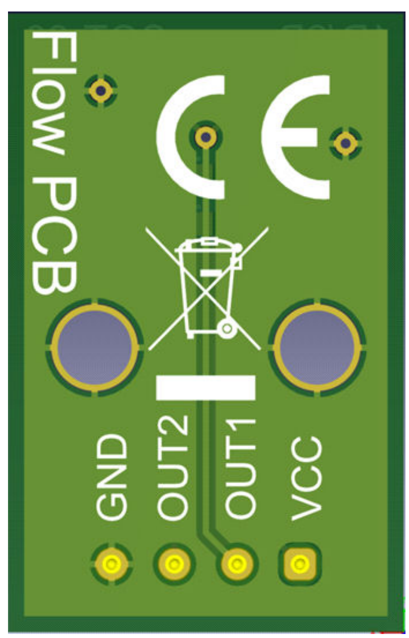

Figure 6-3. PCB Bottom Rendering

7 Bill of Materials (BOM)

Table 7-1 shows the BOM.

Table 7-1. Bill of Materials

Designator	Quantity	Value	Description	Package	Part Number	Manufacturer
PCB	1		Flow Meter PCB, 2 Layer board			
C1	1	10 µF	10 µF Capacitor, 20%, 10 V, 0603	0603	LMK107BC6106MA-T	Taiyo Yuden
R1, R2	2	10 kΩ	10-k Resistor, 5%, 0.1 W, 0603	0603	RC0603JR-0710KL	YAGEO
J1	1		Header, 2.54 mm, 4 × 1, Gold, TH	2.54 mm, 4 × 1	BHS-104-G-A	Samtec
U1	1		DRV5013, SOT-23	SOT-23	DRV5013FAQDBZR	Texas Instruments
O-Ring	1		Nitrile Rubber 1.5-mm width O-Ring 40-mm ID, 43-mm OD			
Shaft	1		4-mm dia. x 25-mm Stainless Steel Rod			
Bearing	2		Sealed Bearing: 4-mm ID, 10-mm OD, 4-mm Thickness		MR104-2RS	Bearings Direct
Ring Magnet	1		8 Pole Radial Multipole Magnet, 8 mm Bore, 1/2in OD		G8-H-315-50-8	Phoenix America
Disc Magnet	8		1/4in dia. × 1/16in Thick N52 Axially Magnetized Disc Magnet		D41-N52	K&J Magnetics
PTFE Tape	1		PTFE Tape, ½ in width		21TF19	Grainger
Screw	4		Coarse Screw, ¾ in length #6		32MT17	Grainger
Nylon Screw	2		2-56 Nylon Screw, 1/8” length, Pan Head Philips		94735A705	McMaster-Carr
Flow Top	1		Flow Meter Top, 3D-Printed, 2 Versions: Vertical and Horizontal			
Flow Body	1		Flow Meter Body, 3D-Printed ABS, 1 Version			
Impeller	1		Impeller, 3D-Printed, 3 Versions: Horizontal, Alternate, Ring Mag			
Flow Cover	1		Flow Cover, 3D-Printed, 2 Versions: Horizontal, Vertical			

8 References

- Texas Instruments, *Mechanical Flow Meter Design Files*