Created in LABVIEW 2021

User’s Guide

Course: Measurements for Automation and Industrial Production

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Abstract

This document is the reference user's guide to the main software application developed within the flow transducer calibration project. This laboratory project takes place during the final lectures of the Measurement for Automation and Industrial Production (MAPI), a first-semester course offered within the Master's Degree in Electronics Engineering for Automation and Sensing, particularly for students in the Automation curriculum. The project aims to develop an automated measurement system for characterizing the Renesas FS-1012-1100-NG analog flow transducer. In this sense, an Automated Measurement System (ATE) was prepared, properly choosing both the hardware and software components needed to solve each task required by the envisioned calibration procedure. The software application developed by us students for the whole calibration procedure uses the LabVIEW development environment exclusively. The Virtual Instrument (VI) described in the following pages is the main VI. This VI comprises a set of menus and tab pages, each meant to address a particular task, guiding the user through the calibration procedure step-by-step. This guide, therefore, offers the reader, who we assume has little to no prior knowledge of how to use a LabVIEW VI or conduct a calibration procedure, a set of instructions that cover both the hardware setup phase and the front panel operations by interacting with the GUI of the main application.

Introduction

The system described in this manual enables precise measurement of gas and liquid flow rates through the use of MEMS sensors based on the principle of heat transfer. This system has been designed to provide a compact, high-performance, and accurate alternative to traditional flow sensors by employing thermal mass flow sensing technology based on the calorimetric effect. The sensors operate on a simple yet highly effective principle: a moving fluid carries heat. Measurement is achieved by comparing the temperatures upstream and downstream of a micro-heater integrated into the sensor. The detected temperature difference is directly proportional to the flow velocity, from which the flow rate is calculated.

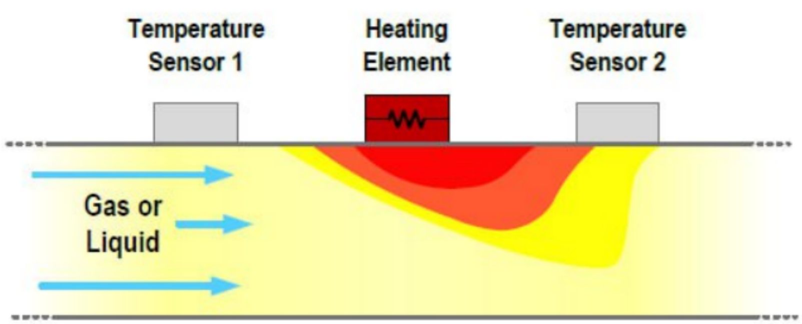


Figure 1: Thermal Mass Flow Sensor Functioning

Thanks to their on-chip integration (MEMS – Micro-Electro-Mechanical Systems), these sensors offer several key advantages, including: miniaturization and low power consumption; high sensitivity and fast response; compatibility with gases and liquids, including corrosive media (due to protective coatings such as silicon carbide); mechanical robustness and reliability; and the ability to be integrated into compact or disposable devices.

The system can be employed across a wide range of applications, including:

- **Medical:** flow measurement in nasal cannulas for oxygen therapy, detection of respiratory disorders, infusion devices.

- **Automation and Industry:** monitoring of gas or liquid flow in machinery, production systems, HVAC systems.
- **Food and Vending:** precise dosing in coffee machines or vending dispensers.
- **Chemical and Environmental:** measurements in corrosive environments or environmental control processes.
- **Research and Development:** laboratories using microfluidics, lab-on-chip systems, or embedded sensors.

The accuracy of thermal mass flow sensors, while generally high, can be influenced by several key factors that require careful consideration during sensor design, calibration, and operation:

- **Fluid Properties Variation:** Thermal mass flow sensors are highly dependent on the thermodynamic properties of the fluid (e.g., specific heat, thermal conductivity, density). Variations in fluid temperature, pressure, or composition from the calibrated conditions can significantly impact measurement accuracy.
- **Flow Profile and Conditions:** The sensor's response can be sensitive to the flow profile (e.g., laminar vs. turbulent, swirl, pulsation) within the conduit. Non-uniform or disturbed flow conditions (often due to upstream piping configurations) can lead to inaccuracies.
- **Contamination and Coating:** The accumulation of dust, moisture, oils, or other contaminants on the heated sensor elements can alter their heat transfer characteristics over time. This can cause sensor drift, reduce sensitivity, and compromise accuracy.
- **Environmental Temperature Fluctuations:** While often compensated, significant variations in ambient temperature can affect the sensor body and associated electronics, potentially introducing errors if not properly managed or compensated for.
- **Sensor Orientation:** For some designs, particularly at very low flow rates, the sensor's orientation relative to gravity can influence natural convection effects, which might interfere with the forced convection measurement.

Chapter I

System requirements

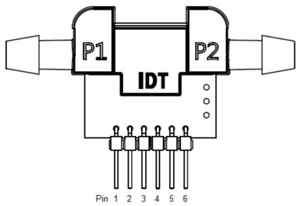
The hardware and software components required to make the whole system work are the following.

Hardware requirements

- **Flow sensors:** Both the flow sensors are designed to measure the amount of gas or liquid that passes through it (in our case we have an air flow). It uses the calorimetric principle (based on heat transfer) to determine the fluid's velocity, and therefore its flow rate. The sensor is based on a simple but effective idea: A moving fluid carries heat with it: the faster it flows, the more heat it can transport. Inside the sensor there are: A micro-heater (a small heating element that generates heat) Two MEMS thermocouples (miniature temperature sensors):One upstream (before the heater, where the fluid enters) and One downstream (after the heater, where the fluid exits). When the fluid is stationary, the heat spreads symmetrically both upstream and downstream of the heater. However, as soon as the fluid begins to flow, it carries the heat downstream. This results in a temperature difference detected by the two thermocouples: the one positioned upstream of the heater measures a lower temperature, while the downstream thermocouple detects a higher temperature. The sensor compares these two readings and calculates the temperature difference, which is directly proportional to the fluid's flow velocity. In simple terms: the greater the temperature difference between the two thermocouples, the faster the fluid is moving and the more heat is being transported. The two flow sensors are similar in their operating principle (both based on the calorimetric principle), but different in the type of signal output. The FS-1012 [1] sensor generates a continuous voltage that varies according to the flow, therefore it generates an analog output. While the FS-2012 [2] sensor sends data already converted into digital numbers, therefore it generates a digital output.

(a) Top View

(b) Rear View



(c) Pin Assignment

Pin Number	Pad Name	Type	Description
1	V_{IN}	Input	Supply voltage
2	SDA	Input/Output	Serial data
3	SCL	Input	Serial clock
4	GND	Ground	Ground
5	MOSI		Do not connect
6	V_{OUT}	Output	Analog output

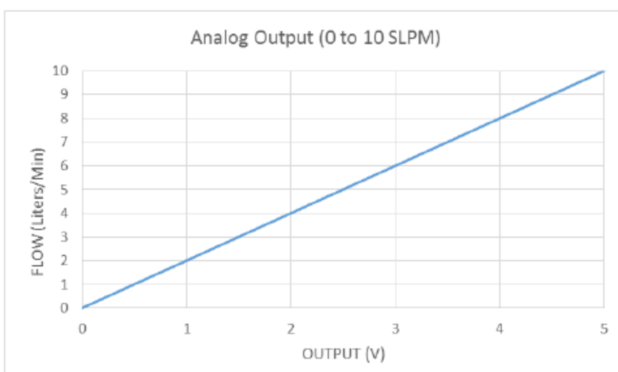
(d) Pin Description

Symbol	Parameter	Conditions	Minimum	Maximum	Units
V_{IN}	Supply Voltage		-0.3	5.5	V
T_{STOR}	Storage Temperature		-50	130	°C
P_{BURST}	Burst Pressure			10	bar

(e) Absolute Maximum Ratings

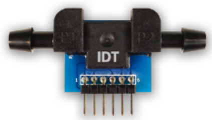
Symbol	Parameter	Conditions	Minimum	Typical	Maximum	Units
I_{VIN}	Current Consumption			30		mA
Gas Flow [a], [c], [d], [d]						
F_{NG}	Gas Flow Range	FS2012-1020-NG	0.015		2 (2000)	SLPM (SCCM)
		FS2012-1100-NG	0.015		10 (10000)	SLPM (SCCM)
E_{NG}	Flow Accuracy	FS2012-1020-NG; 0.2 to 2 SLPM, at 25°C		±2	±5	% Reading
		FS2012-1100-NG; 1 to 10 SLPM, at 25°C				
V_{OUT_ANG}	Analog Voltage Output	Min to Max of Flow Range	0	–	5	V
OFF_{ZERO_NG}	Analog Zero Offset		0.03	0.045	0.05	V
t_{SAMPLE_G}	Gas Sample Rate	Per measurement		0.4096		Sec

(f) Electrical Characteristics

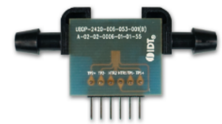


(g) Analog Output: relationship between the analog output voltage of the FS-2012 sensor and the volumetric flow measured in SLPM (Standard Liters per Minute).

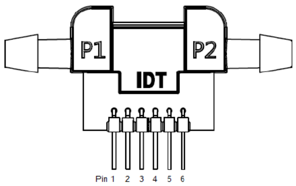
Figure 2: Digital Transducer **Renesas FS-2012-1100-NG** Reference Instrument for the calibration procedure



(a) Top View



(b) Rear View



(c) Pin Assignment

Pin Number	Pad Name	Type	Description
1	TP1+	Output	Thermopile 1 (+)
2	TP1–	Output	Thermopile 1 (–)
3	HTR1	Input	Heater
4	HTR2	Input	Heater
5	TP2–	Output	Thermopile 2 (–)
6	TP2+	Output	Thermopile 2 (+)

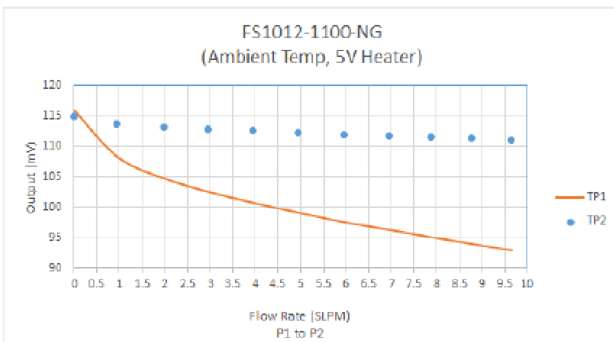
(d) Pin Description

Symbol	Parameter	Conditions	Minimum	Maximum	Units
V_H	Heater Voltage Supply			5.6	V
T_{STOR}	Storage Temperature		-50	130	°C
P_{BURST}	Burst Pressure			10	bar

(e) Absolute Maximum Ratings

Symbol	Parameter	Conditions	Minimum	Typical	Maximum	Units
R_H	Heater Resistor[a]		230	290	400	Ω
$\propto_{\_HTR}$	Heater Temperature Coefficient of Resistance[a]			300		ppm/°C
V_{TP_OUT}	Thermopile Output[a]	3V driving voltage, in air, 20°C, no flow	30	35	60	mV
R_{TP}	Thermopile Resistance[a]	20°C	100	210	300	KΩ
$V_{TP\_OUTDIFF}$	Thermopile Differential Output[a]	3V driving voltage, in air, 20°C, no flow	-1	0	1	mV
t_{RESP}	Response Time			5		ms

(f) Electrical Characteristics



(g) Analog Output: relationship between the analog output voltage of the FS-1012 sensor and the volumetric flow measured in SLPM (Standard Liters per Minute).

Figure 3: Analog Transducer **Renesas FS-1012-1100-NG** Device Under Test (DUT) for the calibration procedure

- **Signal Conditioning Circuit:**

  The conditioning circuit is essential for adapting the analog sensor's voltage output to the appropriate input range of the Data Acquisition (DAQ) device. It comprises a differential amplifier (INA 128) that processes two input signals (derived from the analog sensor's outputs). This amplifier calculates the differential voltage, effectively rejecting common-mode noise, and then amplifies this signal by a precise gain factor. This gain is adjustable via a potentiometer integrated within the circuit, allowing for fine-tuning to optimize signal fidelity and dynamic range for the subsequent DAQ stage.

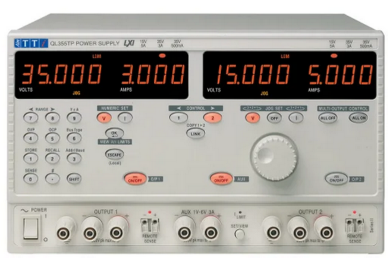
- **National Instruments USB-6008 DAQ Device:**

Figure 4: The National Instruments USB-6008 DAQ Device

This device serves as the critical interface for data exchange between the conditioned analog sensor signals and the host PC running LabVIEW software. Specifically, it is responsible for digitizing the analog signals provided by the conditioning circuit. The NI USB-6008 [5] is a versatile Data Acquisition (DAQ) module from National Instruments, designed for a wide array of measurement and automation tasks. Its operation is streamlined by being entirely powered through a USB 2.0 port (full-speed, 12 Mb/s), eliminating the need for an external power supply. Upon connection to the PC, it is automatically recognized and managed by the NI-DAQmx driver, which facilitates hardware configuration, programming, and real-time data communication.

- **Power Supply Units (PSUs)**:
  - ***Agilent E36436A [3]***: it powers the air pump by providing a costant voltage value and a variable current output.
  - ***TTi QL355TP [7]:*** its purpose is to power the conditioning circuit's differential amplifier and analog flow sensor. Main characteristics
    - Output:
      - Output 1: 0 to 35 V, 0.001 to 3 A;
      - Output 2: 0 to 35 V, 0.1 to 500 mA
      - Output 3: 0 to 15 V, 0.001 to 5 A
    - Accuracy at 25°C ± 5°C:
      - Voltage;
      - Current: 0 to 20 V, 0 to 10 A

(a) Agilent, Type e3634A PSU



(b) TTi QL355TP PSU

Figure 5: Power Supply Units (PSUs) used to power the Automated Measurement System devices

- **Air pump (EAD Neo PP2)**: it produces the air flow that is measured by flow sensor depending on the input current given. The NEO-I [6] pump is a direct current (DC) micro diaphragm pump designed for applications that require vacuum and/or pressure. It operates by using a flexible diaphragm that moves in a reciprocating motion to draw in and expel air. As the diaphragm retracts, it creates suction, pulling air into the pump. When it moves forward, it compresses and pushes the air out, producing a continuous airflow through repeated cycles. This motion is driven by an electric motor, which uses an eccentric connecting rod to convert rotary motion into linear movement. The eccentric connecting rod, attached off-center to the rotating motor shaft, causes the diaphragm to move back and forth as it turns—creating a consistent cycle of suction and discharge. So, the electric motor rotates a shaft; an eccentric connecting rod, mounted off-center on the shaft, converts this rotation into an oscillating motion. This oscillating motion moves the diaphragm in and out, generating airflow through the pump.

Figure 6: The Air pump (EAD Neo PP2)

- **ARDUINO UNO R3**: it samples the digital sensor output and it transfers this value to the PC on which the LABVIEW software is run.

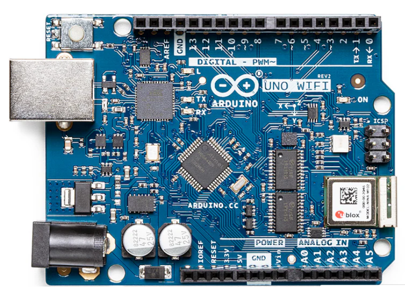


Figure 7: Arduino Uno R3 Board

A typical Arduino board, such as the widely used Arduino Uno, is composed of several essential components. At its core lies the microcontroller unit (MCU), typically an ATmega328P chip in the case of the Uno. This MCU serves as the central processing unit or ”brain” of the board, executing the uploaded program code, also known as **firmware**.

- **Cables and connectors:** used to connect the various devices together. Specifically a **star topology** was chosen for connecting the various measuring instruments. Star topology is a network configuration in which all devices are connected to a central node—typically a switch, hub, or server. This setup allows for centralized management, simplifies maintenance, and enables rapid fault detection. Furthermore, isolating each individual device ensures that a failure on one line does not compromise the entire system

(a) USB Type A – Type B Cable for DAQ board connection

(b) USB Type A – Type B Cable for ARDUINO board connection

(c) USB-GPIB adapter for Power Supply Unit (PSU) connection

(d) USB hub (optional)

Figure 8: Arduino_Serial_FSM.vi Block Diagram.

PC Hardware & Software Requirements

This section outlines the **minimum PC hardware and software requirements** to run LabVIEW 2021 edition, covering both the 32-bit and 64-bit versions.

- **Hardware Requirements**:
  - **Processor (CPU):**
    - **32-bit LabVIEW:** Pentium 4M (or equivalent) or later (e.g., Celeron 866 MHz or later).
    - **64-bit LabVIEW:** Pentium 4 G1 (or equivalent) or later.
    - *Note:* While these are minimums, a faster multi-core processor will significantly improve performance, especially for compilation.
  - **RAM: Development Environment:** 3–4 GB or more are recommended).
  - **Disk Space:**
    - **Development Environment:** 5 GB (includes default drivers).
  - **Screen Resolution:** 1024 x 768 pixels.
- **Software Requirements**:
  - **Operating System (Windows):**
    - Windows 10
    - *Important:* LabVIEW 2021 **does not support** Windows Vista/XP/7/8.x, Windows Server 2003/2008/2012, or any 32-bit Windows operating system for the development environment.
  - **Other Drivers:**
    - **NI DAQmx Drivers:** You must install the NI-DAQmx driver for your DAQ hardware.
    - **NI-488.2 Drivers:** You must install the NI-488.2 driver for your GPIB interface.

Chapter II

Installation and setup

Wiring Instructions

The following is a description of how to interconnect the devices, as illustrated in Figure 9.

It is best advised to interconnect devices before turning on the power supplies or connecting the acquisition devices to the PC or workstation. All wiring interconnections are made using *jumper wires*. Therefore, make sure that each wire is properly attached to each pin of the digital devices, as indicated in the instructions that follow. For analogue devices, a small flathead screw driver is required to connect the jump wire ends to the terminals of the conditioning circuits and the DAQ board's pins. Finally, the air-pump power terminals are attached to the power supply unit (PSU) by inserting the twisted copper wires ($+5V$ *and* GND) into the output lines.

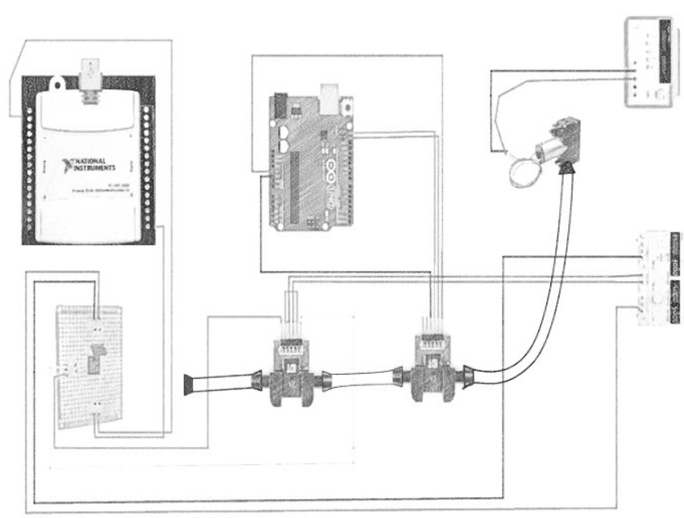


Figure 9: System Setup Connection Overview

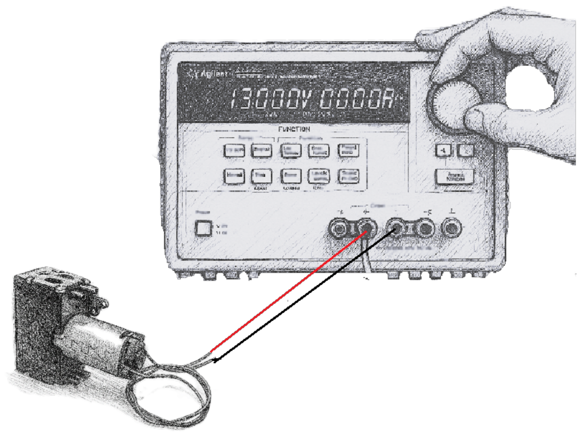


Figure 10: Air Pump – PSU Connection Overview

- **Air Flow Pump (EAD Neo PP2) & Power Supply Unit (Agilent e3634A)**

Connect the positive voltage wire with the positive output terminal of the Agilent E3634A power supply unit (PSU) and the negative wire with the negative terminal, by inserting the twisted copper ends of each wire into the appropriate jack as labeled on the front panel of the PSU, as illustrated in Figure 10.

This connection is crucial for providing the necessary power to the air pump, ensuring its proper operation throughout the experiment. Without a stable and correctly wired power supply, the air pump will not function, impacting any processes that rely on airflow. Note that it is not necessary to operate the PSU from its front panel, as illustrated in Figure 10. The software developed for this project allows you to operate the instrument remotely via the GUI of the main application. The communication with the instrument is established thanks to the **USB-GPIB** cable, shown in Figure 8c that you connect to the rear panel of the PSU.

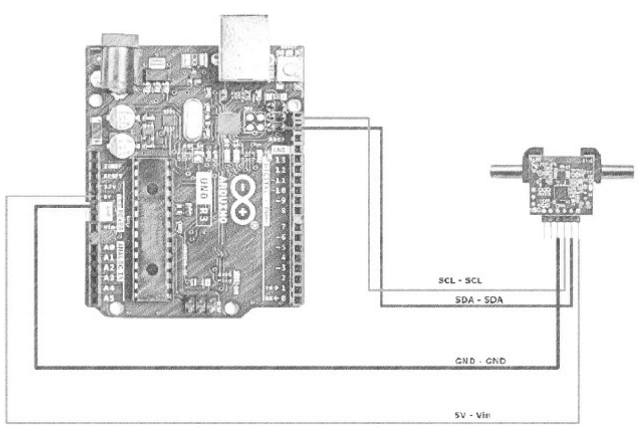


Figure 11: Arduino Board – FS-2012 Connection Overview

- **Digital Signal Acquisition Device (Arduino UNO R3) & (Calibrated Digital Flow Sensor(FS-2012)**

To connect the devices, use *Male-to-Female jumper wires* (male end to Arduino board), connect the *SCL* pin of the Arduino board with the SCL pin of the digital sensor, the *SDA* pin with the SDA pin of the digital sensor, the *5V* pin of the Arduino board with the Vin input pin of the digital sensor, and the *GND1* pin of the Arduino board with the black wire connected to the GND pin of the digital sensor. These connections is illustrated in Figure 11.

Note that the Digital Sensor is powered by the 5V line of the Arduino board, and the latter is powered via a USB Type A – Type B cable, shown in Figure 8b. This cable connects the Arduino board to a PC or workstation. To allow data communication between devices, the I2C protocol is used. This two-wire interface simplifies wiring and allows multiple devices to share the same bus, each identifiable by a unique address. The Digital Sensor address is *0x07*, as reported in the datasheet, and is used in the firmware that you will transfer to the Arduino UNO R3's microprocessor (the firmware is also reported in the programmer's manual).

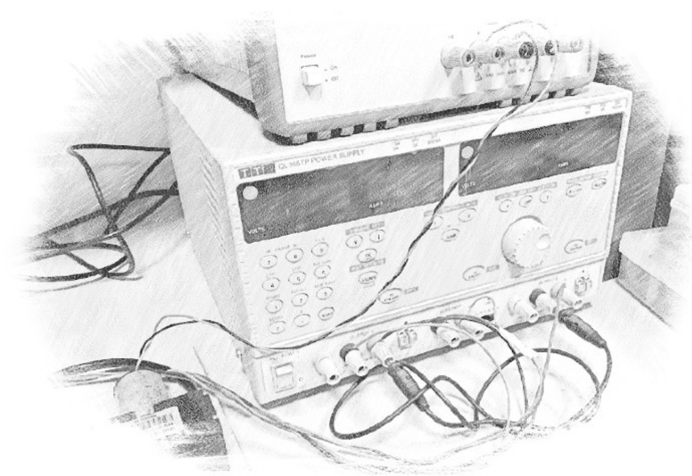


Figure 12: Power Supply Unit (PSU) QL355TP Setup Overview

- **Manual Power Supply Unit (QL355TP): Common Ground Setup:**
  Connect the *PSU OUTPUT1* positive terminal to the *PSU OUTPUT2* negative terminal, as illustrated in Figure 12.

The second power supply unit (PSU) is used to power the differential amplifier installed on the conditioning circuit and the analog flow sensor under test. To ensure that there are no *floating* reference points in the circuit, a copper wire is used to wire the negative terminal of the *PSU OUTPUT1* to the **earth ground terminal** on the *conditioning circuit*, so that it can be used as a reference ground.

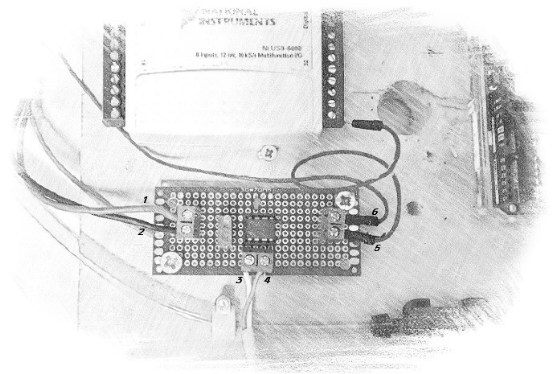


Figure 13: Conditioning Circuit: Left Terminals

- **Conditioning Circuit: Left Terminals Connections**

Looking at the conditioning circuit top side, connect to the *terminal 1* of the conditioning circuit the wire from the positive terminal of the *PSU OUTPUT2 (QL355TP)*, and the *terminal 2* with the wire from the positive terminal of the *PSU OUTPUT1 (QL355TP)*, as illustrated in Figure 13.

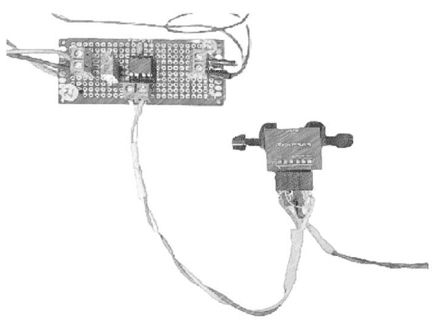


Figure 14: Conditioning Circuit: Bottom Terminals

- **Conditioning Circuit: Bottom Terminals Connections**

Connect to the *terminal 3* the wire connected to the *TP1 terminal* of the analog sensor, and the *terminal 4* to the *TP2 terminal* of the analog sensor under test, as illustrated in Figure 13 and 14.

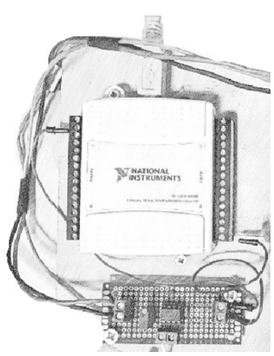


Figure 15: Conditioning Circuit: Right Terminals

- **Conditioning Circuit: Right Terminals Connections**

Connect the *terminal 5* with the GND pin on the DAQ board, and the *terminal 6* to the DAQ pin *AI0+*, as illustrated in Figure 13 and 15.

Remember that the positive terminal of the first output on the manual PSU is connected to the negative terminal of the same PSU second output. The Conditioning Circuit, shown in Figure 13, was specifically engineered to amplify the output signals from the analog sensor under calibration. These signals are inherently low-amplitude, rendering them unsuitable for the precise detection of airflow variations within the sensor.

• **FS-1012 & QL355TP Power Supply**

Connect the HTR1 pin of the analog flow sensor with the negative terminal of the auxiliary output of the power supply, and the HTR2 pin with the positive terminal. The auxiliary output of the PSU must be set to $5V$**.**

• **GPIB connection**

Connect the Agilent E3634A power supply with a GPIB-USB cable to a USB port on your PC or workstation. This connection allows for remote control of the instrument by connecting the GPIB connector to the rear panel.

• **DAQ connection**

Connect the NI DAQ USB-6008 with a Type A - Type B cable to a USB port on your PC or workstation. This connection allows to control the acquisition from the instrument under test (FS-1012) remotely, and also ***powers the DAQ board***.

• **Arduino UNO R3 connection**

Connect the Arduino UNO R3 with a Type A - Type B cable to a USB port on your PC or workstation. This connection allows to control the acquisition from the digital reference instrument (FS-2012) remotely, and also ***powers the Arduino board***.

• **Air Flow Laboratory PVC Tube**

Finally, connect to the air pump air flow pipe (black tube) the ***PVC*** **air tube to the TP1 inlet of the digital sensor. Using another** ***PVC*** **tube, connect the TP2 outlet of the digital sensor to the TP1 inlet of the analog sensor under test. One last** ***PVC*** **tube is connected to the TP2 outlet of the analog sensor and left floating, as illustrated in picture 16**.

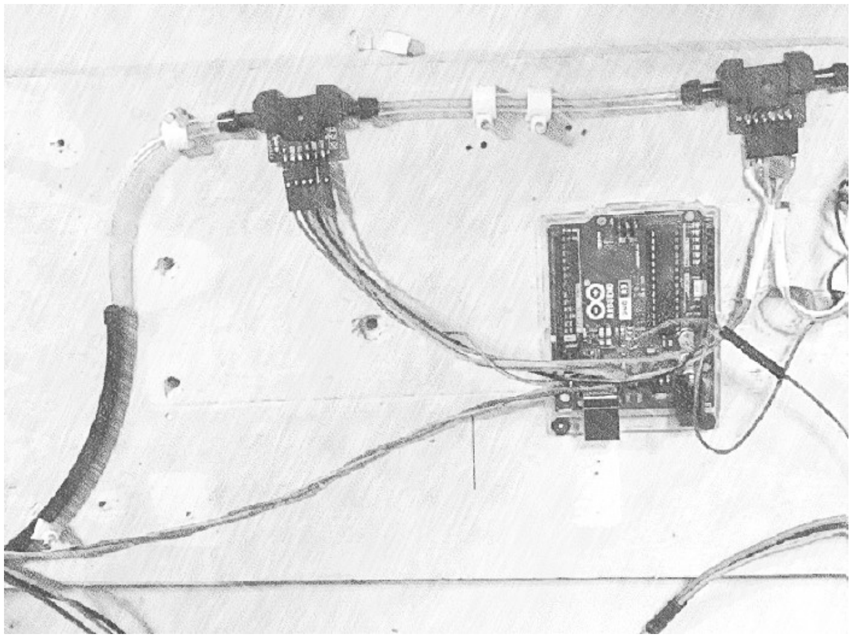


Figure 16: PVC Air Tube used to connect the air flow actuator and the thermal mass flow rate sensors.

The correct installation of the air flow tube is essential foe the success of the calibration procedure. If any tube at any point in the connection is not well fit to an inlet/outlet, then, measurements will not be accurate.

Preliminary Steps

- **PSUs**:
  Connect the power-line cord to each power supply unit (PSU) and turn on each one by pressing the power button on each laboratory instrument and enable both OUTPUT1 and OUTPUT2 channels of the power supply by pressing the **ALL ON** button on the front panel of the instrument.

- **DAQ board**:
  to ensure that the acquisition of the signal is successful, please open the NI MAX software tool and make sure that the signal is acquired properly.

- **GPIB**:
  to ensure that the power supply can be controlled remotely successfully, please check that the instrument receives commands via the GPIB interface by using the NI MAX software tool.

Arduino Firmware Installation

Firmware is a specific type of software that provides low-level control for a device's hardware. Follow these steps carefully to install the firmware onto your Arduino UNO R3 board. Note that these steps must be followed only the first time that you use the project's application files. After that, you will only need to interact with the main application.

- Launch the Arduino IDE [4] software on your computer (download it if you haven't already).
- Select the **sketch_nov15a.ino** file.
- **Select Board:** From **Tools** > **Board** > **Arduino AVR Boards**, select **Arduino Uno**.
- Go to **Tools** > **Port** and choose the appropriate **Serial Port**. If unsure, unplug your Arduino board, check the **Device Manager**.
- Once compilation is successful, click the **"Upload"** button.
- **Serial Monitor:** To verify your firmware sends data to the computer (e.g., flow rate readings), open the Serial Monitor, ensure the **Baud Rate** matches what's set in your code (9600). You should see data streaming in from the digital flow sensor, as shown in Figure 17.

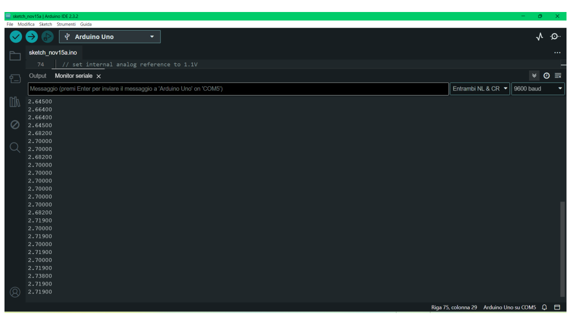


Figure 17: Arduino IDE: Correct firmware installation. Serial Monitor Data

Chapter III

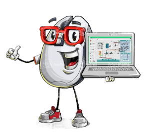
Calibration Software

The following is an overview of the layout and functionalities of the *Virtual Instruments (VIs)* that are used to run calibration procedures. These programs are all found in the **MAPI Project folder**.

MAIN

*The VI **main** implements the calibration procedure for the flow sensors Renesas FS-1012-1100-NG, using the digital flow sensor Renesas FS-2012-1100-NG as a reference instrument.*

To start your program, locate the main.vi file within your project's source code folder. It's the primary file that controls your application's execution in LabVIEW. Double-clicking main.vi will open it in the LabVIEW development environment.



To begin with, the window (**front panel**) that opens at application launch displays the graphical user interface (**GUI**) elements in a silver coloured plain enclosure. The **tabs** on the left of the enclosure allow the user to change the GUI elements which lie on the front panel. Tabs are a convenient way to select a set of GUI elements depending on the task to be executed during the calibration procedure. What follows is a description of each tab that can be selected and what its functionalities are. **Note that** a second window completes the view upon the main application: the **Block Diagram**. The Block Diagram is where the graphical code resides, showing how different functions and sub-VIs are wired together to implement your program's logic. The use of the block diagram of this application is intended only for the users who wish to modify the behavior of the application, as described in the ***Programmer's Manual*** for this application project.

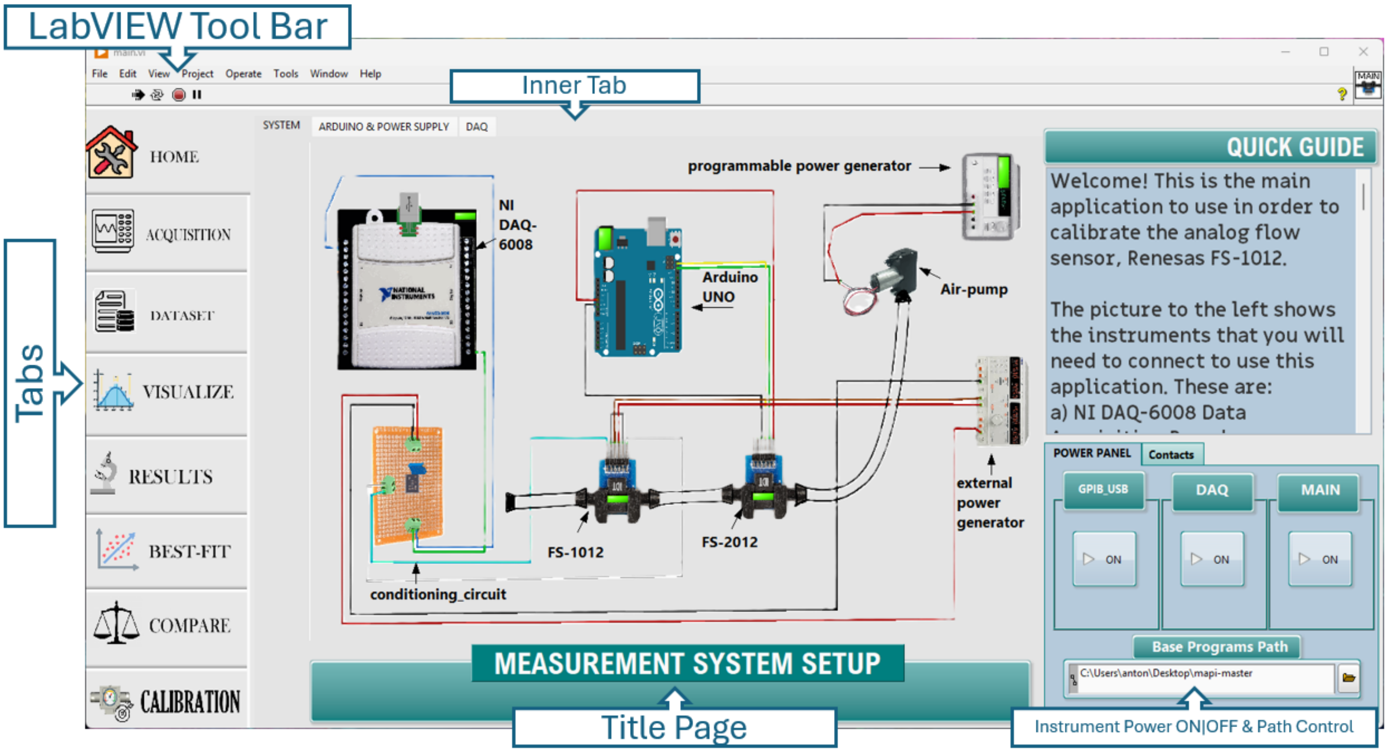


Figure 18: Home Tab

Home

The Home tab is used for the initialization of the application.

When this tab is selected, the front panel shows in the centre a framed picture that indicates how the instruments that compose the **Measurement System Setup** should be arranged. Next to the system interconnection picture, a slim manuscript provides a **quick guide** on how to use the application and tabs that are within, in order to get results as quickly as possible. Below, a set of **power controls** can be turned on and off to start or end the execution of the support application that handles the interconnection between the many instrument interfaces that allow the interconnection of the devices in the Measurement System. Finally, at the bottom of the power controls, lies the **Base Program Path** control. This control is essential, and its correct initialization is required before running the application as explained in the next section, where the Operating Instructions are given.

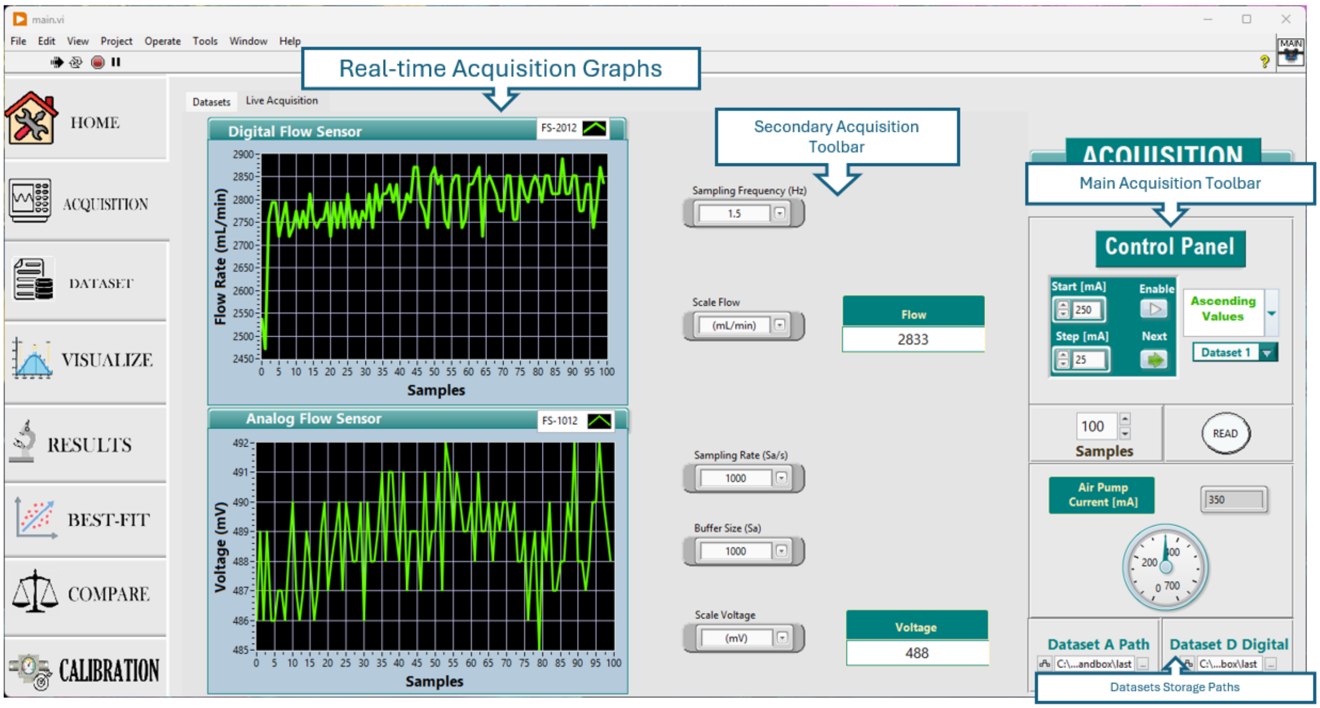


Figure 19: Acquisition Tab: Graphs Page

Acquisition

The calibration procedure followed during this project necessitates the acquisition of a set of samples from the sensor under test, together with the digital sensor output, used as a reference value. The Acquisition tab is used for this aim.

When this tab is selected, the right-hand side of the front panel displays the ***Control Panel***. This panel comprises the controls which make up the main **Acquisition Toolbar**. These controls are used to start and control each acquisition, collecting new data samples from both sensors, saving each acquisition, saving a measurement dataset and forcing a sequence of current input values, increasing or decreasing at the terminal of the air-pump used to generate an air-flow. Further, the Control Panel also displays the **Dataset Paths** that point to the location in the local memory of the folders where each dataset gets stored after creation.

Moreover, the front panel displays the **Output Current** in mA, and the output values sampled, both currently and previously, from both sensors by the DAQ and Arduino UNO, respectively. Finally, the user can choose data acquisition parameters such as the sampling frequency. For the analog signal acquisition (DAQ board) the user can choose how many samples to acquire and at what rate (Sa/s). For digital acquisition, the user can choose the sampling frequency used by the Arduino board to acquire the signal from the digital air flow transducer.

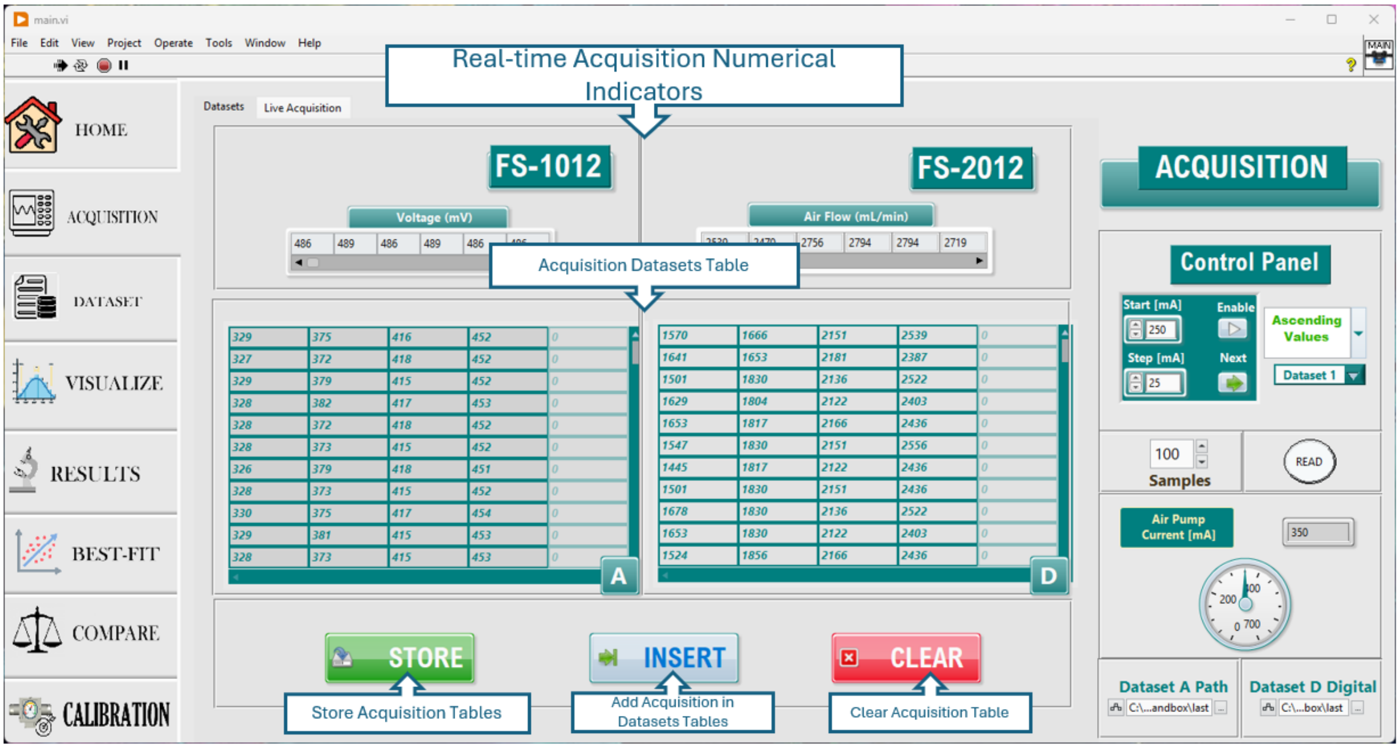


Figure 20: Acquisition Tab: Tables Page

Samples can be visualised in two ways: either by **plotting the samples** during each acquisition on two dedicated waveform graphs, or by listing the present and past acquisitions in the form of **tabulated values**. When visualized in tabulated values, the user can choose to insert the latest acquisition data into the calibration datasets (*A* stands for Analog, and *D* stands for Digital). The user can use the **STORE** button the save the calibration datasets to the folder indicated by the paths at the bottom of the page on the front panel.

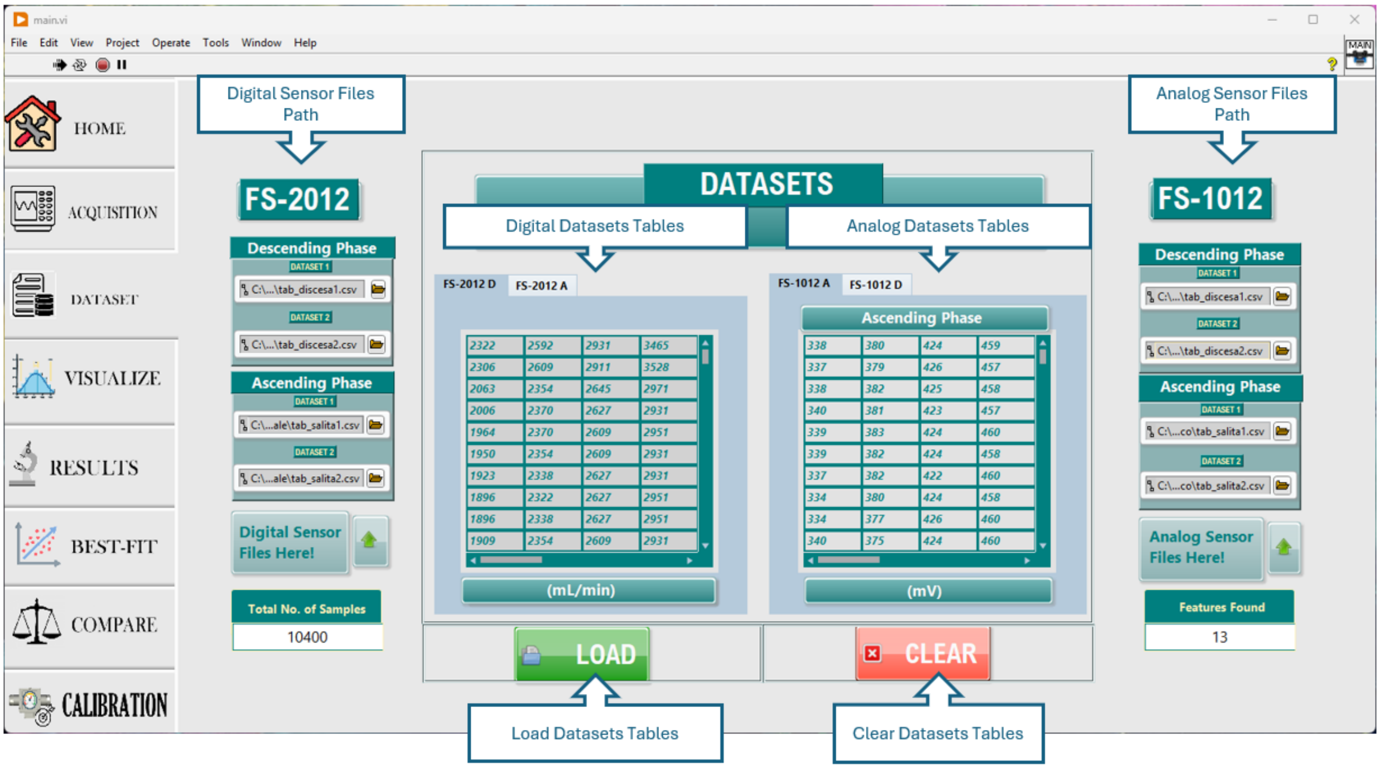


Figure 21: Dataset Tab

Datasets

Having collected a sufficient number of samples during the acquisition procedure, the next step is to assess the statistical distribution of the samples in the datasets. This step is fundamental not only for the evaluation of the analog sensor accuracy, but also to spot spurious values that may come out as a result of noise sources.

The Dataset Tab is used to load all previously stored datasets within the application's accessible memory. During the acquisition step, each dataset should be labeled specifying whether the input sequence is increasing (**Ascending Phase**) or decreasing (**Descending Phase**). Also, it is advised to store each dataset in a dedicated folder, different for each sensor. On this ground basis, when this Tab is selected, the front panel displays to the right and left-hand sides of the screen **four squared boxes**, each containing **two file path controls**. Each file path points at a given dataset of samples acquired from one of the two sensors, as an ascending or descending sequence of input values is forced to the terminals of the air-pump.

The application automatically evaluates the **total number of samples** in each dataset and the **total number of features**, shown in appropriate **numerical indicators**. A feature indicates a current value used to generate different air-flow rates during an acquisition.

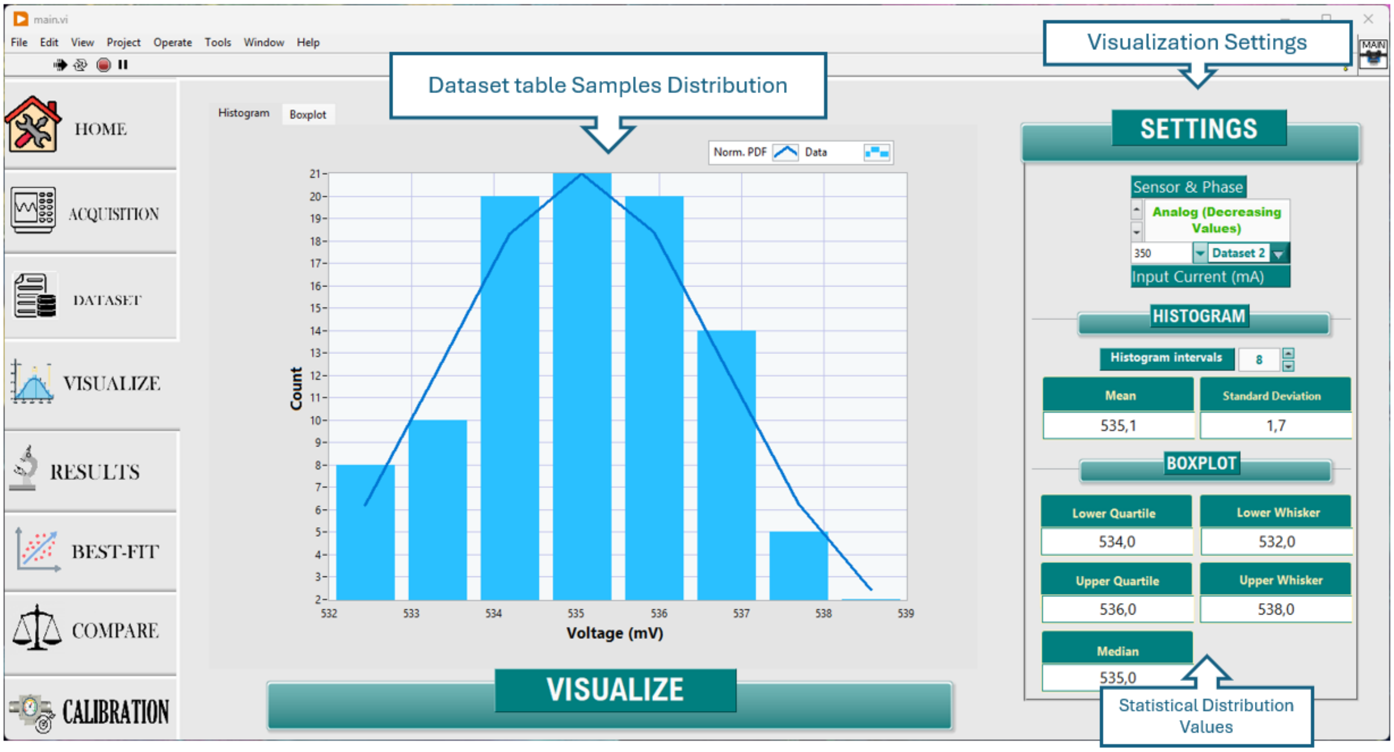


Figure 22: Visualize Tab

Visualize

The next task in the calibration procedure is to have a first look at the sample distribution inside each dataset. This step, although it may seem trivial, is essential. The sample distribution in each dataset should resemble a Gaussian Probability Density Function Curve. This assumption is fundamental when later evaluating the sensor's accuracy.

The Visualize, when selected, unveils sample variance, mean values and other statistical parameters in each dataset. This information is represented in two ways: either by plotting a histogram of the output values for the same input, or by means of a boxplot. The latter reveals a common flaw which sampling practices are affected by: **outliers**. Indeed, when a sample is taken, different noise sources and the very nature of the components that constitute the sampling device itself could be the cause of **spurious values** read by the sampling device (either the DAQ board or the ARDUINO UNO, for the analog and digital sensor, respectively).

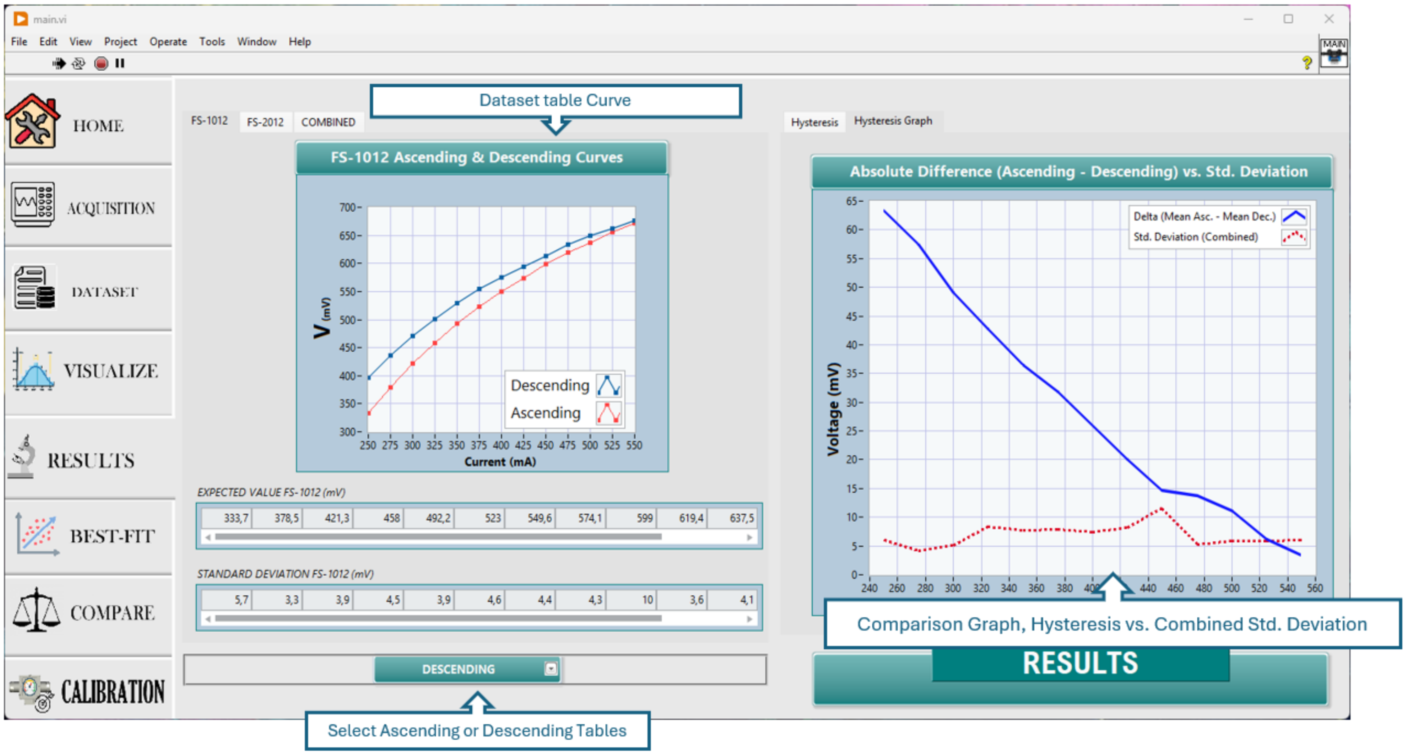


Figure 23: Results Tab

Results

Having validated the samples that were acquired, the critical part is to compute the expected value, hence the statistical mean output value that each sensor produces in response to a given air-flow input, as well as the uncertainties on the expected values (point-by-point). In theory, the value plotted should show a proportional relation between the input current (that affects the air-flow rate) and the sensors' outputs (voltage and flow, respectively). What may happen is that during a sequence of increasing inputs, the sensors' output differs from the response to the same input quantity, but during a decreasing input sequence. This phenomenon is referred to as **Hysteresis**. The Results Tab, consequently, presents the user with the **obtained curves** from both sensors in a dedicated tab. Also, the expected values are reported under each graph. The right half of the front panel, instead, provides the relevant **statistical parameters** found in each dataset, such as the maximum uncertainty associated with each measure (voltage or flow) and maximum deviation between the output values of sensors in response to the same input but during ascending and descending sequences.

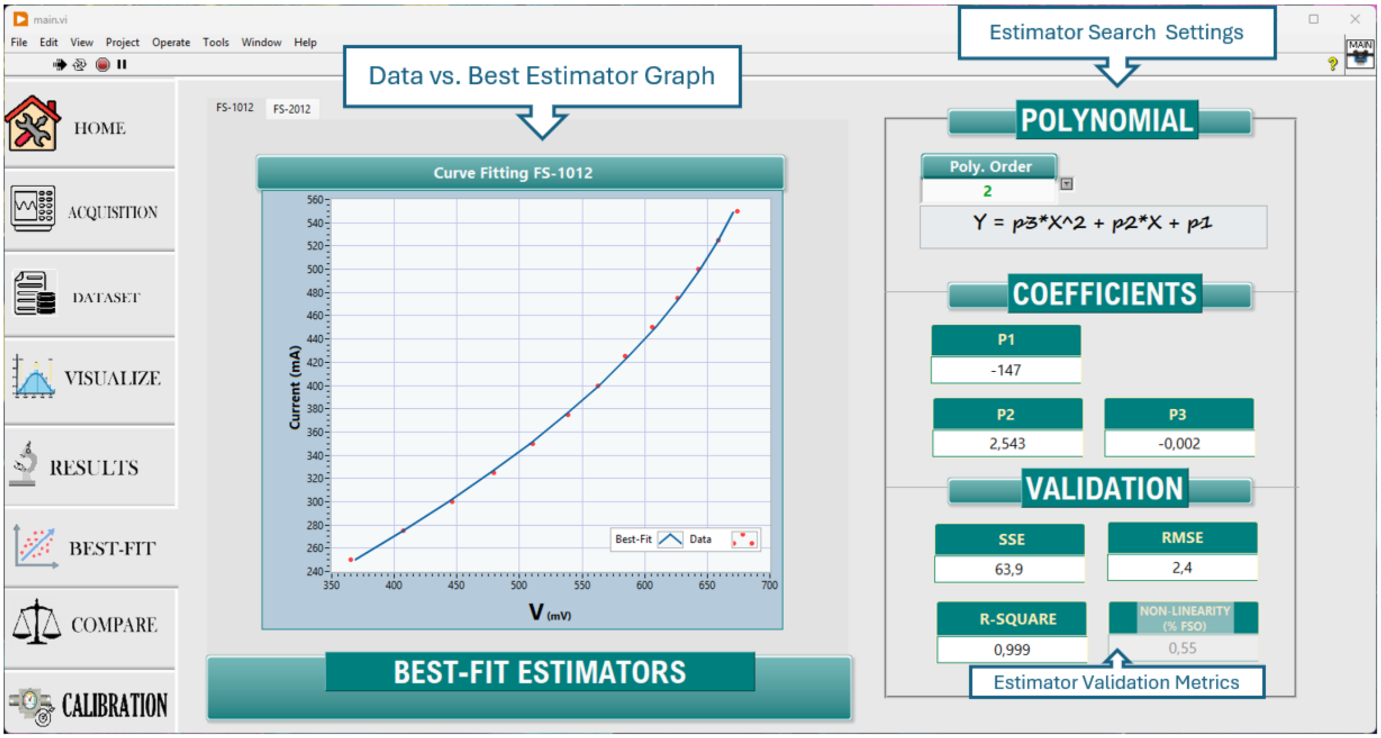


Figure 24: Best-Fit Tab

Best-Fit

When it comes to predicting the output values of both sensors, given a certain current input to the air-pump, best-fit estimators are computed and their coefficients reported in LabVIEW. The order of the polynomial that is used to estimate these output values can be chosen by the user. The metrics that are used to judge on the goodness of the estimators are the **root mean square error** (RMSE), **error sum of square** (SSE), and the **coefficient of determination** (R-SQUARE). These values can help to understand how well the model approximates the data and how well the variance among dataset samples is represented by the model.

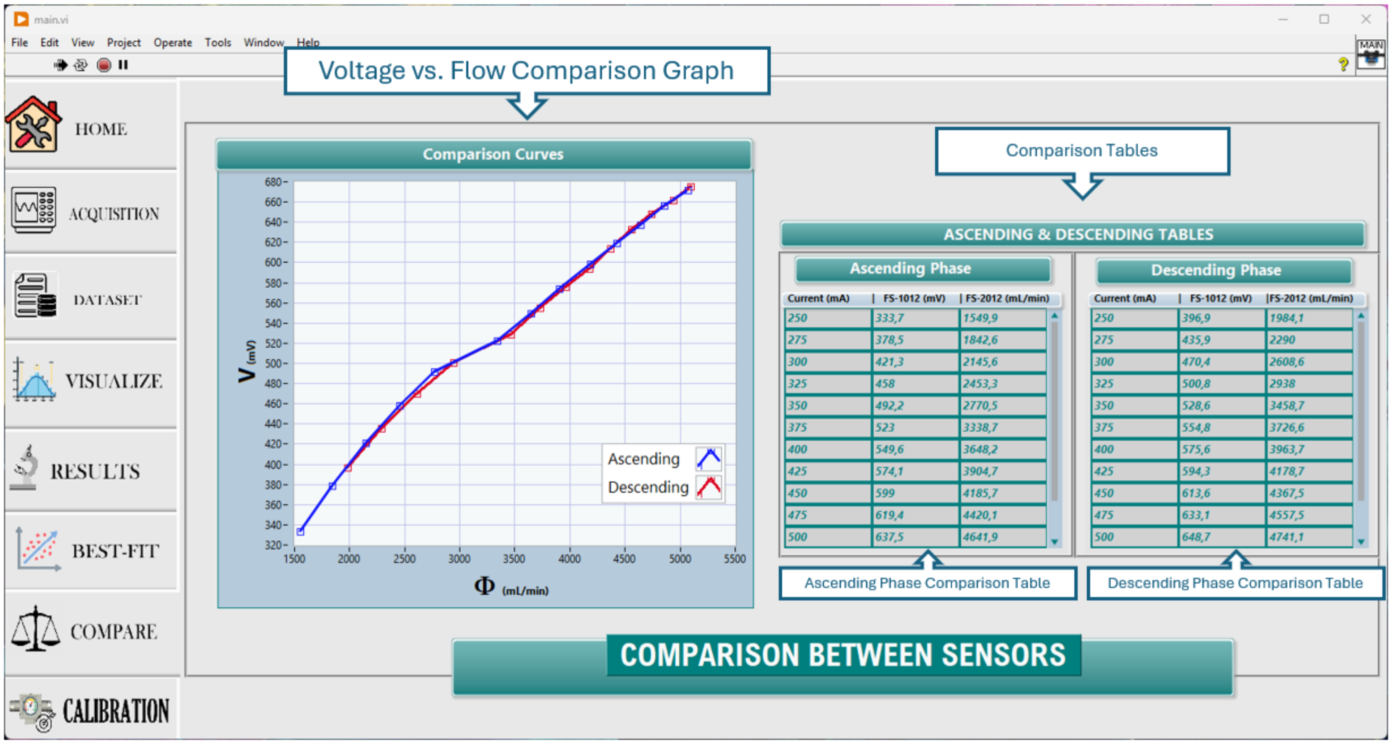


Figure 25: Comparison Tab

Comparison

Ideally, we are interested in proving that there exists a way of relating the output values of the reference sensor to the measures that the analog sensor yields, in response to the same air-flow input. Hence, the Comparison Tab puts in contrast the two sensor curves, both during ascending and descending input sequences, combining them into a **combined plot**, on which the ordinate axis corresponds to the analog sensor output values, while the abscissa represents the digital reference sensor response to the same input. Finally, the UI also shows this comparison in the form of **tabulated values**.

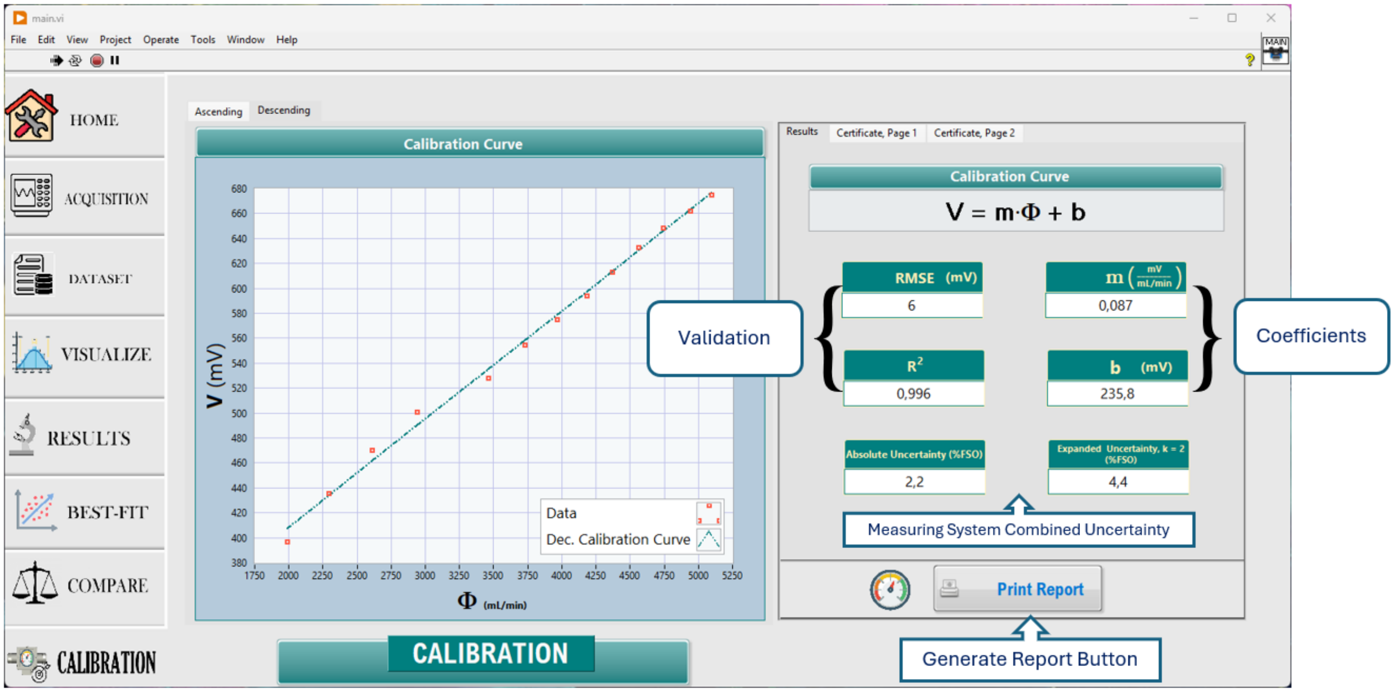


Figure 26: Calibration Tab

Calibration

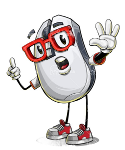
To conclude the calibration procedure, two estimators are computed (one for the ascending and one for the descending phases, respectively) that allow us to use the raw voltage of the analog sensor and convert this quantity into a comparable measurement to the reference transducer flow rate measurement. This conversion is possible by substituting the estimator's coefficient values into the calibration curve equation. The usual metrics of goodness of the estimators are given on the front panel in the Calibration Tab. Moreover, the program computes the ***Measuring System Combined Uncertainty***. This quantity is presented to the user in the form of a ***Absolute Standard Uncertainty***, expressed in percentage of the ***Full Scale Output (FSO***. The user, through the expanded uncertainty, can use the results from this project's work, with a 95% confidence level. Finally, the program allows the user to **print** a **calibration report** document. This happens at the end of the calibration procedure, when the user presses the ***Print Report*** button.

Chapter IV

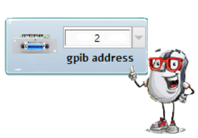
Operating Instructions

Main VI Front Panel Operations: Acquisition Procedure

Starting the VI



Step 0) Before running the VI, the user should use the *Base Path Control* on the front panel to browse to the folder where the programs files are stored on the local workstation. .



Step 1) Once the Programs File Path is set, before running the VI, the user should select the appropriate address for the *GPIB connection* (address of the remote controlled PSU).

To execute the application press the ***Run*** button located in the LabVIEW Toolbar, as shown in Figure 18. **If the VI initialization is successful, a green LED appears on each controlled device, indicating that the connection to these devices is working correctly.**

Before delving into the acquisition procedure, it is essential to set the right properties for each device connection.

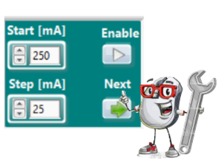
Setting Connection Properties

Step 2) The *serial port* used to communicate to the Arduino UNO board, instead, has to be chosen at this moment, using the menu control located in the *HOME tab*, in the *ARDUINO & POWER SUPPLY page*. The user can navigate to this page by choosing from the inner tab selector on the front panel, as illustrated here.

Similarly, the same procedure must be followed for the **DAQ Channel**, located in the *DAQ* page in the Home tab.

During the acquisition, different flow rate values are generated by modulating the amplitude of the current generated by the PSU, which is fed to the air-pump. This sequence of values is generated automatically by the program, once the **Current Ramp settings are set**.

Current Ramp Settings



Step 3) Select the *ACQUISITION* tab on the front panel. The *Live Acquisition* page is selected by default in the inner tab selector. Locate the *Control Panel* on the front panel, illustrated in Figure 19. Locate the *Start [mA]* control. Select the desired initial value of the current output, in mA units. Press the *Enable button*, which starts the current ramp. Finally, locate the *Step [mA]* control and select the increase/decrease current value change in between steps, in mA units.

As the user gives the start at the current ramp generation procedure, the air-pump is powered on and it starts to pump air-flow in the *PVC* tube connected to the thermal mass flow sensors. The minimum current value which turns on the air-pump is the value set by default, which is *250mA*.

As the user gives the start at the current ramp generation procedure, the air-pump is powered on and it starts to pump air-flow in the *PVC* tube connected to the thermal mass flow sensors. The minimum current value which turns on the air-pump is the value set by default, which is *250mA* Before starting the acquisition procedure, the user should select the number of samples to acquire from each sensor and whether the amplitude of the current values is increased or decreased throughout the acquisition runs.

Starting the Signals Acquisition

Step 4) Locate the *Samples* numerical control. Select the desired number of samples to be acquired in total during the acquisition procecss. Locate the *READ* push button, next to the Samples control. Press the READ button to begin the acquisition.

During the acquisition, the Samples button is **disabled and greyed out**. The user can control other settings, such as the scale used to represent the data point measurement unit on the y-axis scales of the graphs designed on the front panel in the Acquisition tab. Once the number of samples specified by the user is acquired, the acquisition stops, as indicated by the Samples control, which is now **enabled again**.

Step 5) Select the *ACQUISITION* tab on the front panel. Locate the the inner tab selector displayed on the Tab page. Select the *Datasets* page. Locate the *INSERT* button at the bottom of the front panel, illustrated in Figure 20. Press the button to insert the acquired samples in the first available column in the *Acquisition Dataset* tables.

To generate the next input value, the user pushes the "Next Button" push-button to force a new current input to the air-pump, hence a new air-flow output. An ascending input sequence of current amplitude values is generated until the maximum allowed values, set by default to *700mA*. This limit can be changed in the *ARDUINO & POWER SUPPLY* page in the HOME Tab, but it is strongly suggested to avoid increasing these values as it could damage the air-pump. It is also recommended not to lower this limit, as the number of columns (also known as features) in the dataset tables must be sufficiently high to ensure the calibration procedure is successful.

Saving data to .csv files

Before saving the datasets, the user should select the correct file path to the folder where the tables will be stored. The name assigned to each table is generated automatically by the program to specify to which acquisition iteration it belongs. Two distinct acquisition phases (ascending and descending) are required, and the user must generate in total two datasets for each phase and each sensor. Hence, each table is labelled accordingly.

Step 6) Select the *ACQUISITION* tab on the front panel. Locate *Control panel*. Locate the File Path Controls. *Dataset Path A* refers to the folder where the tables belonging to the analog device are stored. Similarly, *Dataset Path D* refers to the digital transducer's datasets folder file path. Select the desired file path to save *Acquisition Dataset* tables.

Step 7) Select the *ACQUISITION* tab on the front panel. Locate the inner tab selector displayed on the Tab page. Select the *Datasets* page. Locate the *STORE* button. Press the button to store persistently the Acquisition Tables. Each file is saved as a comma-separated values file (*.csv* extension).

The acquisition iteration can be considered halfway. Now the user will continue pushing the **Next** button and acquire new measurement samples, this time generating a descending current amplitude sequence. At the end of the second half of the acquisition iteration, the user has generated **four datasets**, two in the ascending phase and two in the descending phase, for each sensor, respectively. The user proceeds to repeat the acquisition iteration once more. As a matter of fact, the program necessitates **two acquisition iterations**. Finally, a total of **eight datasets** will be generated by the program at the end of the acquisition procedure, each containing the same number of samples and the same number of columns (current amplitude values, or features).

Main VI Front Panel Operations: Data Analysis Procedure

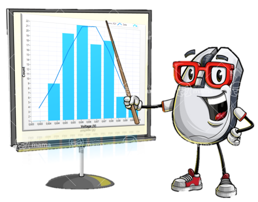
To begin the data analysis procedure, you should enter in the Control Panel on the Acquisition Tab Page the values that were used to generate the current ramp (e.g., "Initial Value[mA]": 250, "Step[mA]": 25).

Dataset Loading

Step 8) Select the *DATASET* tab. Locate the *four squared boxes*, each containing two *file path* controls, as illustrated in Figure 21. As indicated by their label, customize each file path to the location of the acquisition datasets. Then, locate the *LOAD* button. Press to load the dataset into the tables that lie in the centre of the page.

As the files are submitted into the application, they are also analysed by the program to find the total number of samples acquired during the acquisition procedure and the number of columns of each table, also known as **features**. The tables' entries get filled with the measurement samples the user acquired during the acquisition procedure. The datasets are grouped for sensor and ascending or descending phase.
The concern now should be on the statistical distribution of samples in each dataset.

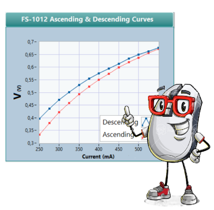
Visualize Samples Distribution



Step 9) Select the *VISUALIZE* tab. Locate the *Sensors & Phase* Menu Ring, illustrated in Figure 22. Select the desired dataset and the feature column used to generate the dataset, by varying the *Input Current mA]* numerical control. Locate the *Histogram Interval* numerical control. Select the desired number of *bins* used to generate the histogram.

The program allows the user to choose which dataset to use and which feature column to analyse in order to generate a histogram and a boxplot. At this moment, the user can appreciate the statistical distribution of feature columns, and compare this distribution with a **Normal Gaussian distribution**.

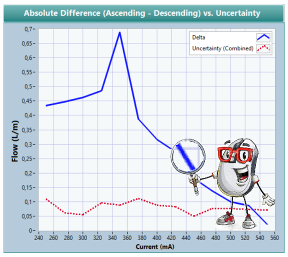
Expected values, Standard Deviation and Measurement Uncertainty Evaluation



Step 10) Select the *RESULTS* tab. Locate the *inner tab page selector* on the left. Select which sensor to analyse (*FS-1012*, *FS-2012*). Locate the *Menu Ring* at the bottom of the page, as illustrated in Figure 23. Select which *Acquisition Phase Dataset* to analyse (ASCENDING or DESCENDING).

The **RESULTS** Tab displays the **Expected Values** and the **Standard Deviation** in each sensor's dataset, **point-by-point**. These values, especially the standard deviation, is used to evaluate the standard uncertainty for each dataset, as the **point-by-point uncertainty**. The **maximum expanded uncertainty** is then computed as the standard uncertainty multiplied by a **coverage factor**. This is a constant value equal to 2, which guarantees to the user that the true values lie within the range of point sample mean value ± the extended uncertainty, with a 95% confidence level. Then, the program verifies whether the sensors' measurements are affected by **Hysteresis**, comparing the maximum deviation between two points with the maximum combined standard uncertainty. This value is obtained by computing the **Root Sum of Squares (RSS)** between the maximum standard uncertainty in the ascending dataset and the maximum standard uncertainty in the descending dataset.

Hysteresis Verification



Step 11) Select the *RESULTS* tab. Locate the *inner tab page selector* on the right. By default, measurement uncertainty is selected. Select the *Hysteresis* page to visualize a comparison between the maximum deviation of the ascending dataset expected values from the descending dataset curve ones, and the maximum uncertainty for each dataset. The combined uncertainty, computed as the Root Sum of Squares (RSS) between the maximum ascending and descending uncertainties, is also shown. Select the *Hysteresis Graph* to visualize a graph that plots the deviation between the ascending and descending curves obtained in the previous step versus the combined standard deviation.

Best-Fit Estimator

Step 12) Select the *BEST-FIT* tab. Locate the *Poly. Order* menu ring displayed on the right, as illustrated in Figure 24. Select the desired *Polynomial Order*. This parameter controls the process that looks for the best estimator of the sensor's output given an input current amplitude.

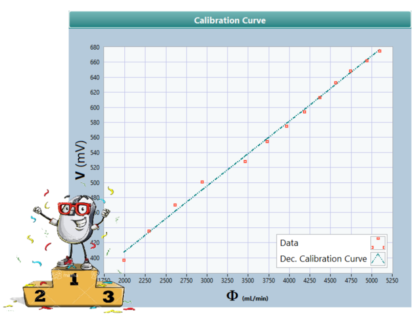
As the user changes the order of the polynomial, the graph that plots data vs. best-fit curve updates. The user should select the best-fit estimator that yields the least error, in terms of SSE, RMSE and R-square.

Calibration fundamentally involves comparing the output of the instrument under test (mass flow rate analog sensor) against the output of an instrument of known, higher accuracy (mass flow rate digital reference sensor) when the same input (airflow) is applied to both. The goal is to determine the analog sensor's unique transfer function (or an accurate approximation), which describes how its electrical output relates to the actual physical quantity (airflow) it is measuring. The goal is to determine the **inverse transfer function**, which allows to infer the input stimulus (airflow) 'F' from the measured output signal 'V' of the analog sensor.

Comparison Between Sensors

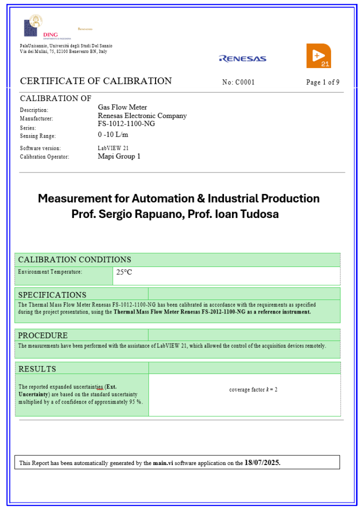
Step 13) Select the *COMPARE* tab. Locate the *ASCENDING AND DESCENDING* Tables on the right. These tables present the user with a comparison between the expected values from each sensor dataset occurring in the same acquisition phase (ascending or descending) in the form of tabulated values. Locate the graph on the left. This plot, illustrated in Figure 25, is the graphical representation of the tables on the right. This is the first example of the comparison between the raw output voltage of the analog sensor under test and the flow rate measured by the reference digital sensor.

Calibration Curves



Step 14) Select the *CALIBRATION* tab. Locate the *Calibration Curve* on the left, as illustrated in Figure 26. Select the desired acquisition phase dataset *(Ascending or Descending)*. Visualize the conversion equation on the right of the calibration curve plot and the calibration curve estimator validation metrics, as for the best-fit estimator case.

Calibration Certificate Preparation


PalaUnisannio, Università degli Studi Del Sannio
Via dei Mulini, 75, 82100 Benevento BN, Italy

CERTIFICATE OF CALIBRATION No: C0001 Page 1 of 9

CALIBRATION OF

Description:	Gas Flow Meter
Manufacturer:	Renesas Electronic Company
Series:	FS-1012-1100-NG
Sensing Range:	0 -10 L/m
Software version:	LabVIEW 21
Calibration Operator:	Mapi Group 1

Measurement for Automation & Industrial Production
Prof. Sergio Rapuano, Prof. Ioan Tudosa

CALIBRATION CONDITIONS	
Environment Temperature:	25°C

SPECIFICATIONS

The Thermal Mass Flow Meter Renesas FS-1012-1100-NG has been calibrated in accordance with the requirements as specified during the project presentation, using the **Thermal Mass Flow Meter Renesas FS-2012-1100-NG as a reference instrument.**

PROCEDURE

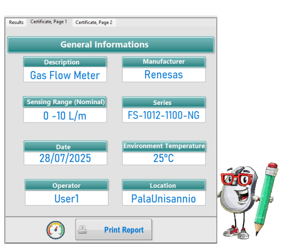
The measurements have been performed with the assistance of LabVIEW 21, which allowed the control of the acquisition devices remotely.

RESULTS	
The reported expanded uncertainties (**Ext. Uncertainty**) are based on the standard uncertainty multiplied by a of confidence of approximately 95 %.	coverage factor *k* = 2

This Report has been automatically generated by the **main.vi** software application on the **18/07/2025.**

Figure 27: Calibration Certificate Template Example

A comprehensive calibration certificate should identify the calibration laboratory, alongside the certificate's unique number, issue date, and total page count. It also provides relevant details about the calibrated instrument, including its manufacturer, type and input scale range (L/m). Information about the calibration procedure includes the measurement date and site, environmental or operational conditions influencing the results, and specifics on site instruments used, such as the reference flow rate instrument and the air flow actuator. The measurement results include the **point-by-point** expanded standard uncertainty of each operating point tested for the DUT. Finally, the calibration report also contains an **uncertainty budget**. An uncertainty budget is a systematic and comprehensive list that identifies and quantifies all known sources of uncertainty in terms of standard uncertainty. Hence, the ***combined absolute standard uncertainty***, visualized also on the front panel of the main.vi, is reported. Finally, the **calibration curve graphs** are also printed in the report.



Step 15) Select the *CALIBRATION* tab. Locate the *Print Report* button on the left-hand side of the front panel, as illustrated in Figure 26. Press the button to generate a calibration report document. The program automatically labels this file as "certificate".

Chapter V

Troubleshooting

Agilent e3634A PSU: Error Codes

It can happen at times that the Agilent e334A PSU **beeps**, indicating that an error occurred. This event is accompanied by a **Error code** that explains the cause that generated the error.

An *LCD* message appears on the instrument front panel. Some errors prevent the user from being able to generate any output at all. Normally, by local operation mode, the user would press the *Store* push button on the front panel of the physical instrument, and continue pressing the same button until the front panel LCD displays the *"NO ERROR"* message.

• **Select the *HOME* tab. Locate the *ARDUINO & POWER SUPPLY* page in the *inner tab control* on the front panel. Locate the *CLR ERROR* button on the front panel of the *subVI*. Press the button as many times as needed until the error alert on the LCD display of the physical PSU disappears.**

Bibliography

[1] FS-1012. *FS-1012-1100-NG Datasheet*. URL: https://www.renesas.com/en/products/fs1012?srsltid=AfmBOoq-YtFJnDtWPIXvf5r-bmM7SfSOkPS-ZZrLn5s--CiSRaY7aP9w.

[2] FS-2012. *FS-2012-1100-NG Datasheet*. URL: https://www.renesas.com/en/products/fs2012?srsltid=AfmBOorzwRwGd3ry-ULoxaDejy4Z_jptth0gBlt7L2kZ6jjbVzHdg2U6.

[3] *Agilent e3634A Datasheet*. URL: https://www.mouser.com/pdfdocs/2sgE3634-90010.pdf?srsltid=AfmBOorRQQ2VP9GIq-5DGQ-Sv8djDk1qZbA8uGPj_DLO6sKE9uAAGN1o.

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[6] EAD pumps. *EAD NEO-PP-2 Datasheet*. URL: https://www.renesas.com/en/products/fs2012?srsltid=AfmBOorzwRwGd3ry-ULoxaDejy4Z_jptth0gBlt7L2kZ6jjbVzHdg2U6.

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