

AUTOMATING THE TESTING OF INSTRUMENTATION AMPLIFIERS FOR CLINICAL APPLICATIONS

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INTRODUCTION

When evaluating instrumentation amplifiers, it is important to verify the performance of the amplifier over the complete range of frequencies for the application at hand. For many biomedical applications, such as ECG and EMG measurements, the key parameters that are frequency-dependant include differential gain, common-mode rejection ratio (CMRR) and noise performance. Unfortunately, the accurate measurement of these parameters can be very time-consuming, especially if high-resolution data is required over a large frequency range.

In an effort to simplify the testing process, we have designed a system capable of automatically testing instrumentation amplifiers. Using this system the differential gain, common-mode gain and the CMRR can be measured. From these measurements, the bandwidth and GBP can also be deduced, resulting in a system that is capable of quickly determining many key performance parameters of an instrumentation amplifier.

This low-cost system, which relies mainly on off-the-shelf test equipment, is to be used at UNB as an evaluation platform for research into ultra-low noise instrumentation amplifiers for evoked potential monitoring [1]. However it could also find use in verification of commercial amplifier performance as part of a general maintenance program in a clinical engineering department.

CMRR MEASUREMENT

CMRR is the ratio of differential gain (A_d) to common-mode gain (A_{CM}) and is usually expressed in dB:

$$CMRR = 20 \log_{10} \left(\frac{A_d}{A_{CM}} \right) \text{dB} \quad (1)$$

In systems for use with surface electrodes, it is this parameter that is responsible for suppressing the 60 Hz line-borne interference that invariably accompanies such measurements. Determining the CMRR requires

that both A_d and A_{CM} are measured and Equation 1 is applied.

Both A_d and A_{CM} are measured by applying a known differential or common-mode signal to the device under test (DUT) and measuring the corresponding output. The appropriate gain is then defined as the ratio of output to input amplitude. The usual test circuit topology used for this measurement is shown in Figure 1, however in practice, A_d and A_{CM} are determined sequentially.

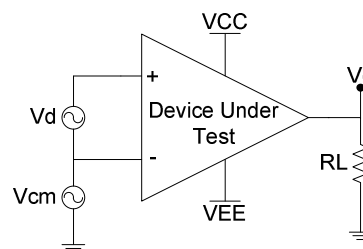


Figure 1 – Ideal test circuit

Measurement of A_{CM} is straightforward to implement. A single-ended signal is applied to both inputs of the DUT and the corresponding output is measured. As the typical value of A_{CM} is in the region of 1 mV/V, an input signal amplitude in the region of 10 V is needed to provide an output signal amplitude of 10 mV. Since most signal generators are fully capable of delivering signals in this voltage range, the output from a signal generator can be used directly.

Measurement of A_d is a bit more involved since it requires that a differential signal be applied across the input terminals of the DUT. Unfortunately, such a signal is not directly available from a standard waveform generator as most of these instruments only generate a single-ended signal. Grounding one of the inputs of the DUT is not an acceptable solution as this creates a common-mode voltage equal to one-half of the differential input voltage.

To derive a differential signal, use of a single-ended to differential signal converter was employed. This is shown in Figure 2 and comprises of an inverting amplifier and a non-inverting amplifier whose input resistances have been matched. An input attenuator ensures that the output voltage is

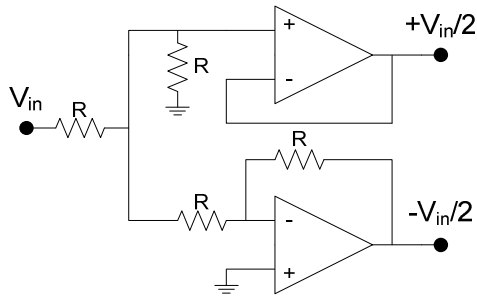


Figure 2 - Single-ended to differential signal converter

$\pm V_{in}/2$. In addition, since A_d can be quite large, the input amplitude needs to be reduced to values smaller than many signal generators can deliver. To accommodate a range of differential gain values, an adjustable attenuator was employed at the input of the single-ended to differential signal converter.

HARDWARE REQUIREMENTS

The control interface for the automated test system was implemented on a standard personal computer (PC) using the Instrument Control Toolbox of Matlab [2]. To keep costs to a minimum, the remainder of the test platform was designed around general purpose equipment that can be found in any electronic tech shop or laboratory. It is required that each instrument have a GPIB (IEEE-488) or USB interface to provide for communication to the control PC. Since most PC's are not equipped with a GPIB interface, a separate GPIB adaptor must be connected if GPIB communication is to be used.

A digital oscilloscope is used for all measurement functions, while a general purpose signal generator is used to provide the necessary test signals. The only additional piece of hardware required is a method of switching between common-mode and differential

measurements. In our system this is via an economical U3-LV Labjack [3] that connects to the host PC via a USB port and is controlled by Matlab.

The topology of the automated test system is illustrated in Figure 3. In our system an Agilent 54621A [5] oscilloscope and an Agilent 33220A [5] signal generator were used. The GPIB adaptor used was an ICS USB 2.0 to GPIB Controller Module [6]. Use was made of the 54621A's averaging feature to reduce the influence of noise.

To maximize the measurement accuracy of the oscilloscope, the measured waveform should occupy as much of the dynamic range of the oscilloscope as possible. To that end, a scaling routine was implemented to ensure that at least 25% of the display is occupied by the measured waveform. The vertical accuracy of the 54621A for dual cursor measurements is specified as 2.4% of full-scale [5]. If the waveform occupies 25% of full scale, measurement of the signal amplitude will be accurate to within 9.6%.

All analogue switches were implemented using MAX4533 [7] devices. These devices provide on-resistance matching to within 10 Ω to minimize any affect that unmatched switches will have on the input to the DUT. These devices are controlled directly by the LabJack digital I/O lines. The OPA2251 [8] precision dual op-amp was used in the single-ended to differential signal converter to minimize errors caused by offset voltages.

USER INTERFACE

The user interface was designed using the Graphical User Interface Development Environment (GUIDE) of the Matlab software package [2]. This interface, as shown in Figure 4, allows the user to specify measurement parameters, monitor the status

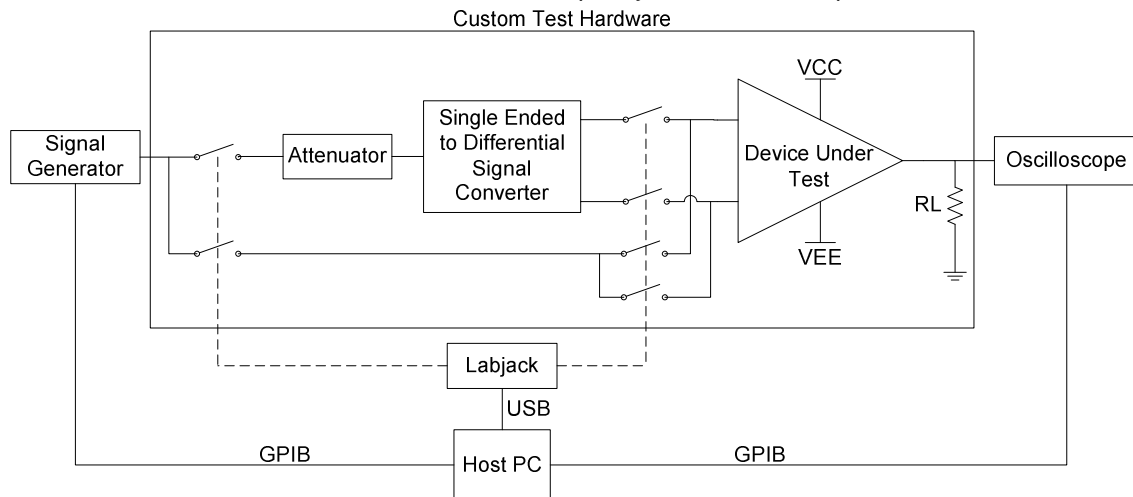


Figure 3 – Automated test system topology

of connected instruments and view measurement results.

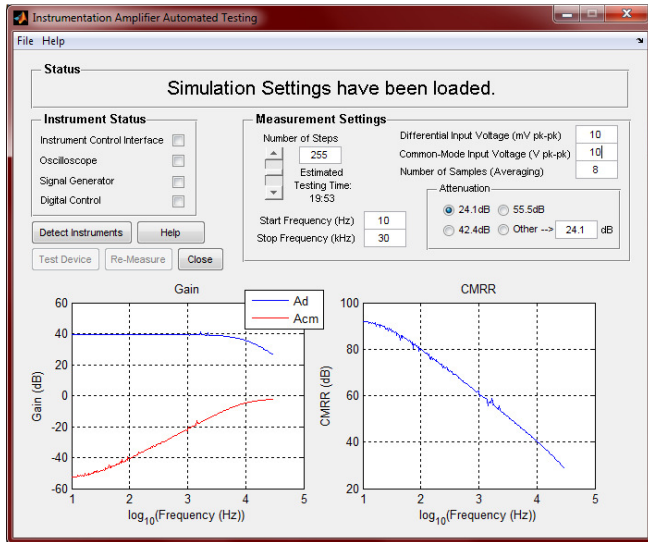


Figure 4 - User interface showing loaded test data for INA2126: A_d (blue) and A_{CM} (red) are displayed on the left plot, CMRR is displayed on the right plot

Parameters which can be specified by the user include the number of measurements (frequency resolution), the frequency range, the number of samples (averaging), the voltage levels applied to the DUT and the attenuation factor of the differential signal. The number of samples refers to the averaging function of the oscilloscope. Individual frequencies can also be re-measured to verify any values which may appear invalid. Settings and measured data can be saved, loaded or exported to a .txt file for use with spreadsheet applications. Since measurement time varies depending on the test parameters, an estimated testing time is also displayed.

PRELIMINARY RESULTS

A prototype of the test platform was implemented using stripboard for the custom test hardware and a breadboard as a fixture for the DUT. While this allowed for rapid prototyping and testing, it also lends itself to increased levels of noise.

To validate the automated test system for CMRR measurements, and therefore differential and common-mode gain measurements, two commercial instrumentation amplifiers were tested using the automated system: an INA2126 [9] and an INA125 [10]. 255 measurements were performed over a frequency range of 10 Hz to 30 kHz with averaging set to 8. These results were then compared with the manufacturers' specifications.

Table 1 – Comparison of measured CMRR to CMRR as shown on datasheets for INA125 and INA2126

Device	Frequency (Hz)	Measured CMRR (dB)	CMRR from Datasheet (dB)[9][10]	Difference (%)
INA2126 (Gain = 100)	10	93.5	97	3.6
	100	80.7	79	2.2
	1k	61	59	3.4
	10k	40.5	40	1.3
	30k	28.7	28	2.5
INA125P (Gain = 10)	10	83	85	2.4
	100	66	65	1.5
	1k	47.2	45	4.9
	10k	26.4	25	5.6
	30k	11.13	11	1.2

Measurements for the INA2126 and the INA125 were both close to values from the device datasheets with the largest difference being 5.6%.

CMRR measurements of an AD620 [11] were also performed. It was found that common-mode gain measurements performed on devices with large values of CMRR (>120 dB at $A_d = 100$) resulted in very small output voltages (<1 mV). Even at the maximum allowable common-mode input voltage of the device and using large amounts of averaging, measurements at the output of the DUT were polluted with noise. This caused the common-mode gain to be overestimated and CMRR to be underestimated. Future improvements to the system include amplifying and filtering the output signal during common-mode measurements to reduce noise.

NOISE PERFORMANCE

In applications where the signal of interest is of a very small magnitude, the noise performance of the amplifier being used is of great value. As such, the ability to measure noise performance is currently being developed and integrated into the existing system.

A major consideration when designing to minimize noise is the expected source impedance. The noise generated by an amplifier is generally expressed as "input equivalent noise," that is, the noise is referred to the input of the amplifier. This input equivalent noise has two components, voltage noise (E_n) and current noise (I_n). If the instrumentation amplifier in question is to be connected to the output of another amplifier, the source impedance is expected to be low and voltage noise will dominate. Conversely, if the instrumentation amplifier is to be connected to a high impedance source, such as a pair of surface electrodes, then current noise will dominate.

The effect of source resistance on the noise power spectral density (PSD) can be seen in Figure 5. Illustrated in this graph are the total noise PSD and

three components of the total PSD: E_n^2 , $I_n^2 R_s^2$ and the thermal noise associated with the source resistance. It is clear that for a given amplifier a source resistance can be selected to minimize the noise contribution of the amplifier; this occurs when the total PSD is nearest to the thermal noise of the source.

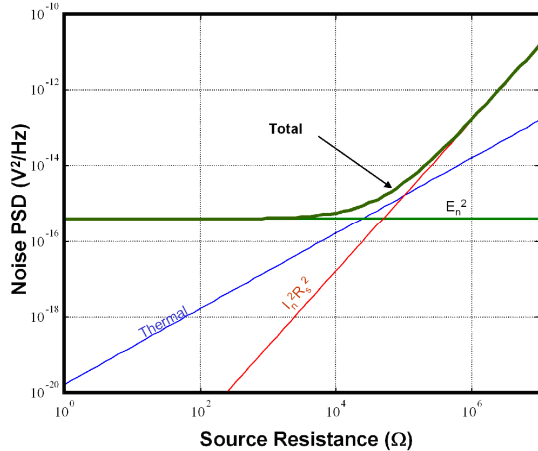


Figure 5 – Noise PSD (dark green) vs. source resistance showing contributions from E_n^2 (light green), $I_n^2 R_s^2$ (red) and thermal noise (blue)

As can be seen from Figure 5, E_n and I_n can be determined by measuring the noise PSD for a series of known source resistances. By repeating this measurement for several frequencies, E_n and I_n can be specified for a given frequency range.

EXTENDING THE TEST PLATFORM

The automated test system is being extended to allow for the automatic measurement of noise performance. This involves the automatic switching of a series of resistors at the input of the DUT and measuring the resulting output noise voltage. Since the noise PSD varies with frequency, it will be required to isolate the noise components at each frequency for which E_n and I_n are to be determined. The proposed implementation of this system is shown in Figure 6.

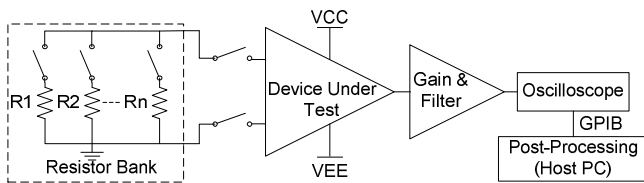


Figure 6 - Proposed automated noise measurement system topology

The automated noise measurement system will be integrated into the existing test system and add a resistor bank, an output amplifier, a low-pass filter and post-processing which will be done on the host PC. The resistor bank will consist of 16 resistors which will

be individually switched using low on-resistance analog switches. The output of the DUT will be amplified and filtered to limit the noise signal bandwidth to 30 kHz before being measured by the oscilloscope. The PSD, and therefore E_n and I_n , of the resulting noise signal can then be determined using the Signal Processing Toolbox of Matlab [2].

We are planning to implement the test platform on a custom PCB encased in a shielded enclosure to limit noise due to external sources. Improvements will also be made to the existing CMRR test system by using the gain & filter stage of the noise measurement system to boost the output signal and reduce noise when performing common-mode measurements.

CONCLUSIONS

A low-cost system has been developed that can automatically measure the differential gain and CMRR of instrumentation amplifiers. This system has been verified to be accurate by testing several commercial devices, although very high values of CMRR currently limit the capability of the system. Future improvements will solve this issue as well as include provisions for measuring the input equivalent noise components of instrumentation amplifiers. Such a system will be admirably suited for use in evaluating custom amplifier designs as well as for verifying the performance of commercial devices.

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