FROM 0.5% TO 0.05%: ACHIEVING NEW LEVELS OF SENSOR ACCURACY IN AN AIRBORNE ENVIRONMENT

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ABSTRACT

With recent improvements in data acquisition technology, it is now possible to use an FTI data acquisition system to measure analog signals with a total error from all sources of less than 0.05% - over an extended temperature range - and at high sample rates. This accuracy is better than one count of an old 10-bit system and includes non-linearities, initial errors (in gain, offset and excitation) and drift errors, simplifying the task of interpreting data acquisition system performance specifications.

This paper looks at some practical steps taken to achieve this accuracy, from a hardware design and signal processing perspective. This leads to a discussion of implications for the FTI system designer, including: sensor and wiring specifications, sample rate, filtering specifications, and a discussion of implications for the data processing engineers.

KEYWORDS

Analog accuracy, data acquisition, FTI

INTRODUCTION

At last year's conference ACRA CONTROL gave a paper on specifying the next generation airborne data acquisition systems. This paper suggested a minimum set of specification for analog FTI modules. One of these was specifications was "Total DC error" which should include all gain, offset and non-linearity errors over the full temperature range and including the excitation.

This paper looks at some of the techniques developed at ACRA CONTROL for our next generation calibrated series of analog modules that achieve total errors of better than 0.05% FSR over (and above) the industrial temperature range.

BACKGROUND

To give some idea of the task facing a designer who is aiming for a total error of better than 0.05%, from all sources, over temperature - it is interesting to note that a single device with a 10ppm/°C drift with temperature can drift by ±0.08% ((100° - 25°C) x 10ppm).

In older systems with multiplexers, a specification of 60dB crosstalk can hide a 0.10% dc error, depending on the dc value in other channels.

Another example is as follows: a "good" instrumentation amplifier might have an initial gain error of ±0.05% at 25°C and a gain drift error of ±0.1% (worst case). If this is connected to a bridge, whose excitation has similar errors, than the total error can be as high as ±0.3%.

This error (0.3%) is six times greater than the target (0.05%) and we have yet to include the following factors in the error budget analysis:

- Gain and offset errors in ADC
- Gain and offset errors in gain and offset adjust block
- Offsets in the instrumentation amplifier
- Non-linearities in all the above
- Loading compliance issues on all the above

From the above, it might appear that a total dc error from all sources over temperature of even 0.5% is ambitious enough; without aiming for 0.05% over an extended temperature range of -55°C to +105°C.

The next section outlines five steps taken to achieve just that.

FIVE STEPS TO 0.05% TOTAL ERROR FROM -55 TO +105°C

STEP 1: USE THE MINIMUM AMOUNT OF ANALOG COMPONENTS

All analog components drift with temperature, with time and with loading. To achieve 0.05%, it is essential that as much processing as possible be done digitally. This includes filtering, offset and gain adjust.

An anti-aliasing filter will always be required, but if the digital processing over-samples and decimates then a simple, low-order, fixed filter can be used, with the cut-off frequency set so high that drifts do not affect the bandwidth of interest.

If the ADC range is chosen correctly there is no advantage to analog offset adjust. Digital offset adjust not only saves on components but allows for larger adjustments at larger gains.

Digital gain adjust allows for infinitely more choices of range and saves on components, but is limited to a range of circa 1 decade (a factor of 10 or 20dB), as non-linearities and offset drifts are amplified linearly.

STEP 2: USE A GOOD ARCHITECTURE

The KAM-500 allows for distributed processing on each module. In particular there is one ADC per channel with the ADC close to the filter and this, together with the processing, is all on one PCB.

There are no analog multiplexers. This removes the 60dB crosstalk (0.1%) and associated switching currents form each channel.

Having no analog signals on the back-plane allows a single star point between the analog and digital planes, and allows analog tracks to be kept short and orthogonal to digital tracks. In particular, on KAM-500 modules, analog components and digital components are on opposite sides of the PCB with ground planes in between.

Another advantage of distributed (FPGA) processing is that, if required for exceptional low-noise applications, data processing with respect to the ADC's operation can be strictly controlled to minimise noise.

Not only is the processing distributed, but so is the calibration information - having an EEPROM on each module allows calibration information (see below) to be stored on each module for each channel and each excitation output.

One final trick is to have a temperature sensor on each module so that temperature drifts can be compensated digitally (see steps 4 and 5 below).

STEP 3: USE GOOD ANALOG COMPONENTS

After steps 1 and 2, we are left with excitation, instrumentation amplifier, a simple filter and an ADC. These components must be chosen carefully.

The ADC must be at least 16-bits, especially if processing includes gain. To keep the filter simple and fixed, the ADC must be able to sample at many times the highest sample rate and have excellent linearity (and THD) figures across the full bandwidth. For linearity, Sigma Delta ADCs are an obvious choice, but they have a very low output sample rate and tend to have poor drift and repeatability figures. With the calibration discussed below, the most important specifications for the ADC are low the gain and offset drift with age and temperature.

Instrumentation amplifiers need significant testing as often there are trade-offs such as THD (for good ac accuracy) vs. low bias currents (for good ac accuracy).

Capacitors are not so important for dc accuracy, but tend to cause big problems with ac accuracy unless they have very low THD (e.g. NPO types). Today, resistors and references are available with 0.01% accuracy and drifts of less than 10ppm. However, with calibration against temperature (see below) the ageing drift specification is again very important.

After the components are selected, it is vital that extensive non-linearity and repeatability (power on/off, temperature hysteresis and accelerated ageing) tests be carried out. This is important, as calibration will not improve these errors.

STEP 4: CALIBRATE THE SIGNAL CONDITIONING AGAINST TEMPERATURE

Once the board is designed and the components tested for INL, temperature, power on/off hysteresis and repeatability, the next step is to allow for calibration of gain and offset vs. temperature.

Each module is cycled twice over temperature and the gain and offset of each channel is calibrated at each gain setting with multiple readings at the input. These values are then used to tweak the gain and offset as a function of temperature. The calibration values are stored in EEPROM on each board and the gain and offset is then tuned in real-time as a function of the board's temperature.

Care must be taken so that enough temperature points are chosen so that the reading does not appear to "jump". For example, if the gain changes by 0.10% over the temperature range than at least 5 temperature points are required to keep gain jumps within 0.02%. The KAM-500 calibrated series modules use 125 temperature points.

STEP 5: CALIBRATE THE EXCITATION AGAINST TEMPERATURE

Excitation errors are often neglected when doing an error budget. An excitation error of 0.10% in the excitation for a bridge will cause an error of 0.10% in gain.

The strategy used on the KAM-500 calibrated series of ADC modules is to use a low drift high-resolution D/A to set the excitation voltage or current. The D/A setting gives the lowest error at 25°C. Any remaining error or errors with temperature are adjusted as part of the gain compensation with temperature.

IMPLICATIONS OF THIS TYPE OF ACCURACY ON ACCEPTANCE TESTING

HAVE PATIENCE:

One customer, using a highly reputable programmable PT100 simulator that was fine for older FTI equipment, found that when testing for the above low error tolerances, he had to wait 30 minutes for the simulator to warm-up before taking measurements.

USE SENSE LINES

Another test that was fine for older FTI systems had to be modified so that sense lines could be used with the test voltmeters and ohmmeters.

JUST BECAUSE IT CHANGES DOES NOT MEAN IT IS DRIFTING

One customer expressed surprise that error specifications were being met even though the excitation when measured using a voltmeter seemed to be outside the stated accuracy specification at 105°C. It was then explained that the excitation was not adjusted with temperature but its effects were. In other words the gain was adjusted not the excitation.

DO NOT CALIBRATE FOR EXCITATION UNLESS IT IS BEING USED

One user found that a module worked fine with a bridge but was less accurate when a simple differential ended analog signal was applied. The problem here was that the gain was being adjusted to compensate for the excitation that was not being used. Once the module was reprogrammed for voltage input, all was fine.

UNDERSTAND SINAD, THD, SNR AND THE NOISE FROM THE TEST EQUIPMENT

Another problem with high accuracy systems is that noisy test equipment is more obvious. The PT100 simulator mentioned above was fine when the module under test had its filter cut-off frequency set near dc. When it was set for a bandwidth of 100s of Hz, the noise was considerable. The simulator manufactured knew this and correctly argued that temperature changes slowly.

IMPLICATIONS OF THIS TYPE OF ACCURACY FOR USE IN THE FIELD

THINK CAREFULLY ABOUT CALIBRATION IN THE FIELD

Older FTI systems boasted about short insertion or voltage insertion (ZCAL, VCAL etc), which enabled calibration in the field. Both these methods are for calibrating the test equipment (not the sensor!) and are no longer required with instrumentation like the calibrated series. As a matter of fact, introducing the circuitry to do this will cause greater errors then it will correct!

However, the next generation analog module should still support sensor calibration (as opposed to instrument calibration) via pseudo-shunt or similar techniques.

CONSIDER USING 16-BITS AND FORGET ABOUT TWEAKING THE RANGE

For many applications, 0.05% is far more than what is required. For example, it can be argued that a strain gage sensor alone has errors 10 times greater than that even before it is connected to instrumentation.

However, one powerful feature of highly accurate 16-bit FTI systems is that, rather than balancing 1000s of sensors in the hope of getting the optimum range and gain for 12-bit systems, a single range can be chosen for all.

For example, rather than using a gain of 64 and 10-bits, transmit 16-bits and a gain of 1. Not only does this mean that over-shoot and under-shoot data can be observed, but it cuts down considerably on the processing information for each channel that must accompany the archived data. In other words, rather than storing the actual gain and offset used for each channel - simply use the rule that the gain is always one and the offset always zero.

At first glance, it appears that the error for such a scenario would be 64 x 0.05% (3.2%). Typically it would be much less as the excitation and gain errors do not change with gain, only offsets and non-linearities.

CONCLUSION

The next generation analog flight test instrumentation modules, such as the KAM-500 calibrated series will have total dc errors from all sources over all temperatures of better than 0.05%.

To achieve this, the minimum amount of analog components must be used along with a distributed architecture that allows for processing and calibration on the module - not centrally.

Furthermore, some care has to be taken when acceptance-testing modules with this level of accuracy.

However, there are many advantages to having 21^{st} century accuracy: not does it allow greater freedom in terms of range settings but the extra dc and ac accuracies allow the aircraft computer models to be refined.