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Method for estimating effective input noise of mixed-mode measurement systems

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Annotation:
Input noise estimation of mixed-mode measurements systems requires the knowledge of effective noise bandwidth ENBW and noise density of each component. Determining ENBW is not trivial because each component has a different frequency response. However, it is possible to simplify this problem by only considering the components with the lowest cut-off frequencies. In mixed-mode systems that is usually digital filters. Therefore, if the frequency response of these filters is known, it is possible to determine the ENBW of the entire system. It is then trivial to calculate the effects of individual components on input noise using their noise densities. Experimental verification of the calculation was carried out and both calculated and measured noise values are presented.

Anotace:
Estimace vstupního šumu smíšených měřících systémů vyžaduje znalost efektivní šumové šířky pásma ENBW a hustoty šumu jednotlivých komponentů. Určení ENBW není triviální, jelikož každý komponent má rozdílnou frekvenční odezvu. Tento problém je možné zjednodušit pomocí zohlednění pouze prvků s nejmenšími mezními frekvencemi. Ve smíšených systémech se většinou jedná o digitální filtry. Pokud je frekvenční odezva těchto filtrů známá je poté možné určit ENBW celého systému. Poté je triviální určit příspěvky jednotlivých komponent na vstupní šum pomocí jejich šumových hustot. Experimentální ověření metody bylo provedeno a vypočtené a změřené hodnoty jsou prezentovány.

INTRODUCTION

Estimating the value of the input noise of a measurement system is important during the design process of a device to ensure that the requirements demanded by the application are satisfied. Determining the value of input noise in mixed-mode measurement systems can be difficult due to the use of digital signal processing techniques. A method is proposed that can be used to determine the noise of the mixed-mode system.

METHOD

The proposed method consists of two parts. The first step is the calculation of the effective noise bandwidth ENBW of the system, which is subsequently used to estimate the contributions of individual components to the total input noise.

To calculate the ENBW it is important to determine which components, let it be analog filters, digital filters, amplifiers, have dominant effect on the cut-off frequency of the system. These are usually digital filters found in sigma-delta A/D converters or implemented in some other digital circuitry such as microcontrollers, FPGA or DSP.

Next, the frequency response of the dominant filters is combined, and this combined response is determined using the following formula (1)

$$ENBW = \int_0^{f_{\max}} \left(\frac{H(f)}{H_{\mathrm{MAX}}} \right)^2 df \qquad (1)$$

The frequency $f_{\max}$ must be chosen so that it is large enough to cause a minimum error of calculation and also be smaller than the Nyquist frequency of both digital filters.

The exact frequency response of digital filters is often not known. Typically, in sigma-delta A/D converters, manufacturers typically only provide a table of values. Due to this limitation, it is not possible to do an exact analytical integration. But numerical integration is an adequate alternative.

After ENBW is known, the calculation of the effect of individual components is trivial. There are two basic types of noise that need to be considered: 1/f and white noise. For each of them, a different formula is required to correctly calculate the effective value of the noise.

For 1/f noise, this formula is (2)

$$u_{n1/\mathrm{f}} = e_{n1/\mathrm{f}} \sqrt{f_{1/f} \ln \frac{ENBW}{f_1}} \qquad (2)$$

where $e_{\mathrm{n1/f}}$ is the noise density at frequency $f_{\mathrm{n1/f}}$ and f_1 is the lowest frequency of interest. Both of these values must be in the 1/f region. For white noise, the formula for effective value of noise is (3)

$$u_{\mathrm{nBB}} = e_{\mathrm{nBB}} \sqrt{ENBW - f_1} \qquad (3)$$

where $e_{\mathrm{n1/f}}$ is the noise density at frequency $f_{\mathrm{n1/f}}$ and f_1 is again the lowest frequency of interest.

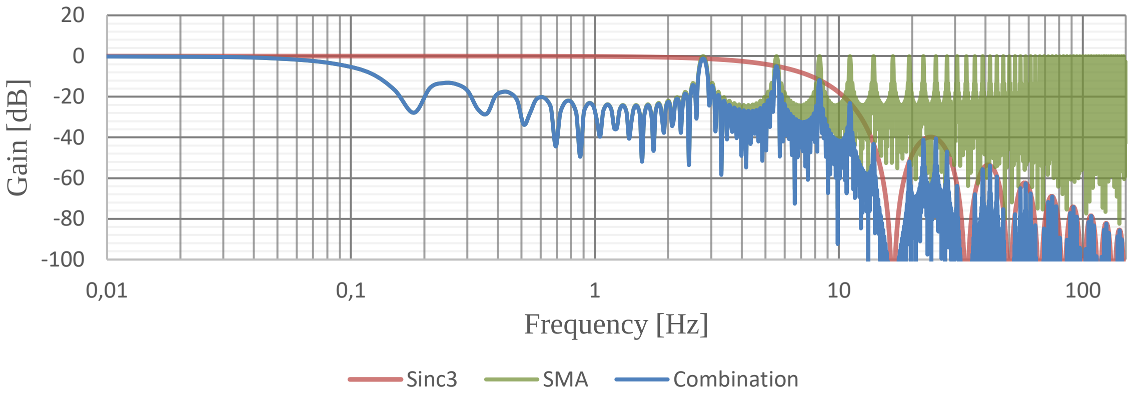

Fig. 1: Frequency response of Sinc3 and SMA digital filters and their combination

CALCULATION

The designed system consists of an AD7177 sigma-delta A/D converter, voltage reference module based on LM399 buried Zener reference and an amplifier with switchable gain. The value measured by the A/D converter is read by a microcontroller. The simplified schematic of the system is shown in figure 2.

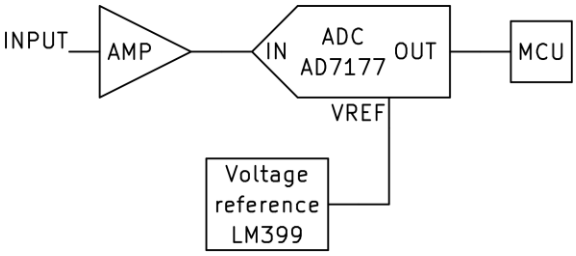

Fig. 2: Simplified schematic of the experimental system

The frequency response of the entire system is dominated by two digital filters. The first one is a Sinc3 filter with 5,6 Hz output data rate in the A/D converter. The second filter is a simple moving average filter of 16 samples and is implemented in the microcontroller. The frequency response of both filters and their combination is in figure 1.

ENBW of the system was calculated using the formula (1), which after substitution is (4)

$$ENBW = \int_0^{150} \left(\frac{H(f)}{1}\right)^2 df \approx 0{,}29\ Hz \qquad (4)$$

The frequency f_{max} was chosen to be 150 Hz, because the attenuation of the filter is large enough at these frequencies that any noise with frequency larger than 150 Hz will have negligible effect on the ENBW.

The calculation of effective noise is based on knowledge of the noise density spectrum. Specifically, it is critical to correctly decide whether the frequency range of interest lies in the 1/f or white noise region. Or if it lies across both regions. For most active parts (A/D converter, voltage reference, op-amp), the noise density spectrum is specified in the datasheet, and the decision is trivial. For passive parts, specifically resistors, the spectrum is rarely presented, and one needs to measure the spectrum themselves.

Due to the low ENBW, basically all components were in the 1/f region. The calculation of the reference noise value for is (5)

$$u_{\mathrm{nREF}} = 170 \cdot 10^{-9} \sqrt{10 \cdot \ln \frac{0{,}29}{\frac{1}{3600}}} = 1{,}42\ \mu V \qquad (5)$$

The parameters $e_{\mathrm{n1/f}}$ and $f_{\mathrm{n1/f}}$ are specified by the manufacturer of the LM399 reference in its datasheet. The lowest frequency of interest was to correspond to the period of one hour. This was also determined to be the duration of the verification measurement.

All noise values are then transformed to the input of the system in such a way that the relative values of noise match e.g., if 1,42 µV is 0,2 ppm of the reference voltage, then 0,2 ppm is also the value of relative noise of the input range. That is equal to 600 nV effective input noise for ±1,5 V range. Of course, this is only from a single source of noise. All noise voltages are added using the following formula (5)

$$u_{\mathrm{nTOT}} = \sqrt{{u_{\mathrm{nREF}}}^2 + {u_{\mathrm{nADC}}}^2 + {u_{\mathrm{nAMP}}}^2 + \cdots} \qquad (5)$$

The number of noise sources is not limited. For the addition, it is necessary that all noises are in absolute value and calculated with the same ENBW.

The calculated values of noise of the system are shown in table 1. In the table, it can be seen that the dominant noise source of the system is the voltage reference. To increase the performance of the system, it would be necessary to decrease its noise. This can be done by filtering with cut-off frequency well below ENBW or by changing the reference for a better one.

Tab. 1: Calculated values of noise in the system

Gain of amplifier	Input range	u_{nAMP} [ppm]	u_{nADC} [ppm]	u_{nREF} [ppm]	u_{nTOT} [ppm]	u_{nTOT}
0,1	±15 V	0,0007	0,03	0,2	0,2	6 μV
1	±1,5 V	0,001	0,03	0,2	0,2	600 nV
10	±150 mV	0,014	0,03	0,2	0,2	60 nV
100	±15 mV	0,14	0,03	0,2	0,25	7,5 nV

MEASUREMENT

One of the main obstacles to measuring small voltages is the variation of temperature during the measurement. This causes errors that cannot be calibrated and affect the measurement in the same way as noise. To combat this, the system was placed in a sealed box, which prevented airflow around the system it. Temperature was also recorded and if its variation was too large during the one-hour measurement, the measurement was repeated. The system can be seen in a figure 3.

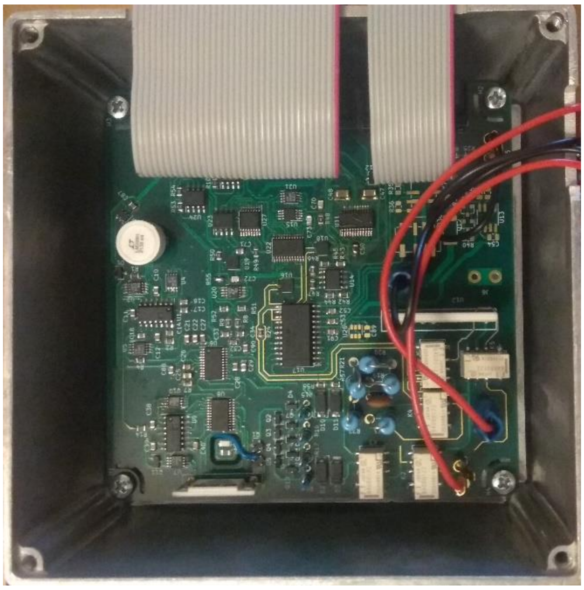

Fig. 3: Photo of the experimental system

Measurement was performed with input terminals shorted to remove any noise that could be could by the voltage source.

During the one-hour measurements, the inputs were samples with a frequency of 2 Hz and the data was sent to PC and saved for further analysis.

The measured effective input noise is in table 2. The results show that the calculated and measured values match each other with a small error. This error is probably caused by the noise specification tolerance. On the smallest range, the measurement was influenced by the temperature variation, which increased the apparent noise.

Tab. 2: Comparison of calculated and measured values of input noise of the system

Input range	$u_{nTOTCalculated}$	$u_{nTOTMeasured}$
±15 V	6 μV	5,5 μV
±1,5 V	600 nV	540 nV
±150 mV	60 nV	58 nV
±15 mV	7,5 nV	10 nV

The small error also shows that the usage of the method is possible for the estimation of the noise. For a more precise calculation, it would be necessary to calculate the noise using the frequency response of the system directly without using ENBW.

CONCLUSION

The method for estimating the value of input noise of a mixed-mode system was proposed and experimentally verified. The error between the calculated and measured values of input noise is smaller than the specified manufacturing limit for the noise of individual components. The error is therefore caused by the components and the uncertainty of their noise. One of the main advantages of the proposed method is the simplicity of the calculation after the ENBW is determined. The noise contribution from individual components can then be quickly calculated using a hand calculation without complicated simulations. This allows fast screening of available components and determining the on best suited for the role.

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