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Initial Digital Filtering of Testing Signals of High-speed DAC

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Introduction

High-speed Digital-to-Analog (DAC) and Analog-to-Digital (ADC) converters are widely used in today's engineering [1–2]. Measurement of dynamic parameters of high-speed DAC's and especially measurement of settling times of such converters is a complex problem [3–6]. In the earlier works of the authors it was shown that it is possible to measure settling times of high-speed multi-bit DAC's by using specialized peak-detecting sampling testers with digital processing of measurement signals and digital estimation of settling time [5–6]. Investigation and analysis of such measurement method shown that the internal noise of sampling head has the major influence to the errors of settling time measurement result. A newly developed algorithm for processing of measurement signal and evaluation of settling time [6] allows decreasing influence of such noises to the accuracy of the measurement result. Experimental investigation of the algorithm shown, that it is possible to measure settling times of up to 14-bit high-speed DAC's. Nevertheless measurement with the developed algorithm [6] has number of disadvantages: it is necessary to process number of testing signals (500 and more), increasing number of DAC's bits decreases accuracy of measurement in despite of high number of test signals. Therefore it is necessary to establish further sources of errors and to propose method of initial filtering of test signal to reduce these errors.

Investigation of testing signal processing algorithm

It is shown [7] that major noises in the specialized sampling heads are generated by operational amplifiers and these noises are sum of $1/f$ noise and white noise. During experimental investigations of specialized sampling heads authors have observed similar noise patterns in the output signal of the sampling heads.

Therefore for the investigation of digital processing algorithm a digital array of ideal model of testing signal has been added to the arrays of sinus waves with various frequencies that simulates components of $1/f$ noise. Resultant array has been processed using the developed algorithm.

Experimental investigation shown, that the major inaccuracies are generated by the noises that have frequencies between 0.1 and 80 Hz (Fig. 1).

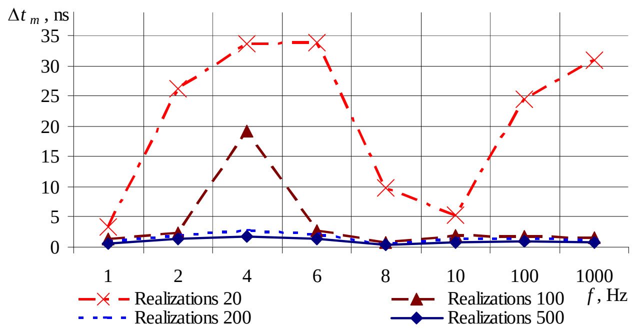


Fig. 1. Dependence of settling time error Δt_m to noise frequency f for different number of realizations

It is seen that prevailing sampling head output noise of type $1/f$ is not eliminated effectively by the proposed algorithm even by increasing number of processed test signals. Nevertheless level compensation and amplitude unification parts of the algorithm are working properly eliminating drift of the test signal realizations. Averaging of signal realizations part of the algorithm is successfully reducing influence of sampling head internal noises of higher frequencies (100 Hz and more).

Therefore in order to reduce influence of low frequency components of $1/f$ noise it was decided to develop algorithm of digital initial filtering for the frequency range from 0 up to 100 Hz.

Algorithm of initial filtering

Magnitude readout levels of DAC under test settling time measurement are set to a very low voltage (tens of microvolts) difference to the settled magnitude level voltage [6]. Therefore the filter to be developed should be capable to eliminate noises in the specified frequency range but at the same time it should not influence the test signal anyhow. This means that the pass band characteristic of the filter should be absolutely flat. Even fractional distortions of test signal would result in non acceptable errors of settling time measurement result.

One realization of digitized real test signal of DAC under test has discrete spectrum that is spread over the frequency axis in steps [7]

$$\omega_s = \frac{2\pi}{N}, \tag{1}$$

where N – number of samples of test signal.

In this case harmonics of the digitized test signal and noises that are digitized in the same device are overlapping and filtering of such signal by using filters is difficult.

Typically testers of DAC dynamic parameters are performing digitalization of n realizations of test signal where major part of the test signal is remaining basically the same but the internal noises of each realization is different due to random nature of noise sources. It is proposed to unify these n realizations into uniform signal of periodic test pulses and to obtain pseudo-periodic test signal.

Assuming that the test signal is discrete rectangular periodic signal

$$u(m) = \begin{cases} \dfrac{U_A}{2}, \text{when} \quad iM < m < \dfrac{(i+1)M}{2}; \\ -\dfrac{U_A}{2}, \text{when} \quad \dfrac{(i+1)M}{2} < m < (i+1)M; \end{cases} \tag{2}$$

where U_A – peak-to-peak value of the test signal; m – discrete value of signal; M – number of discrete values in one period of signal, $i = -\infty, \ldots, -3, -2, -1, 0, 1, 2, 3, \ldots \infty$.

This signal written down by Fourier series is

$$u(m) = \frac{2U_A}{\pi}\left[\frac{\sin(2\pi m/M)}{1} + \frac{\sin(6\pi m/M)}{3} + \frac{\sin(10\pi m/M)}{5} + \ldots\right]. \tag{3}$$

In case limited number of n periods of test signal are digitized and pseudo-periodic series are generated the sine spectral components will have: first – n periods, third – $3n$ periods, fifth – $5n$ periods and so on and the sine wave with limited length is written

$$u_s(m) = \begin{cases} \sin(2\pi m/M), \text{ when } |m| < \dfrac{n_i}{2}; \\ 0, \quad \text{when} \quad |m| > \dfrac{n_i}{2}; \end{cases} \tag{4}$$

where n_i – number of periods of sine wave, m – discrete value of sine signal.

Spectrum of such sine wave signal containing n_i periods is [8]

$$G_t = \frac{F}{\pi\left(F^2 - f^2\right)} \sin\frac{\pi n_i f}{2F}. \tag{5}$$

Number of periods n_i is increasing for each spectral component of rectangular pseudo-periodic signal: for first it is $1n$ period, third – $3n$ periods, fifth – $5n$ and so on. As it is seen from (5) each harmonic component of higher frequency of rectangular pseudo-periodic signal is narrower than previous. Calculations shown that in case of n = 100 99-th and 101-st spectral lines have only 5 % magnitude level compared to 100-th spectral line. Therefore it was decided to use pseudo-periodic sequence of n = 100 periods of the signal under investigation for the further investigations.

By digitalization and recording to the memory n realizations of test signal forming pseudo-periodic series of test signals, internal noises of sampling head are digitized together. Sum of pseudo-periodic test signal and low frequency sine wave, simulating single component of $1/f$ noise is shown on Fig. 2 (a) and spectrum of such signal on (b). It is seen that spectrum of low frequency internal noise of sampling head can be distinguished from spectrum of test signal.

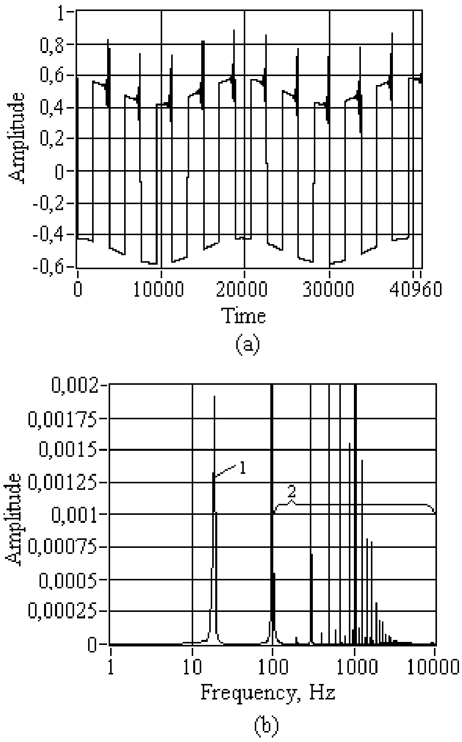


Fig. 2. Digital signal of pseudo-periodic series with internal noises (a) and its spectrum (b). 1 – spectrum line of sine wave, 2 – spectrum of test signal

Therefore as it is seen from Fig. 1 it is necessary to select the period of realizations so that the first harmonic component of this pseudo-periodic signal it is higher than sensitivity limit of signal processing algorithm (80 Hz).

Further on the formed test signal pseudo-periodic series should be filtered by digital high-pass filter. As it was mentioned earlier it is necessary to ensure that the pass-band characteristic of the filter is absolutely flat and that the signal is not distorted at the points of settling time measurement. According to these requirements only digital Butterworth high-pass filter is suitable for this purpose.

Algorithm for generating an ideal test signal, internal noises and pseudo-periodic series of test signals with internal noises was developed using LabView®. The generated series were processed using Butterworth high-pass filter and the output signal was compared to the ideal signal model. It was established that the filter is inadmissibly distorting test signal (especially, steady-state part of a signal) even with the cut-off frequency f_p set to 5 Hz and using highest possible (limited by LabView®) order of the filter (Fig. 3). It is seen that the measurement of settling time after using of the Butterworth filter is not possible and standard high-pass filters can not be used for initial filtering of DAC settling time test signals.

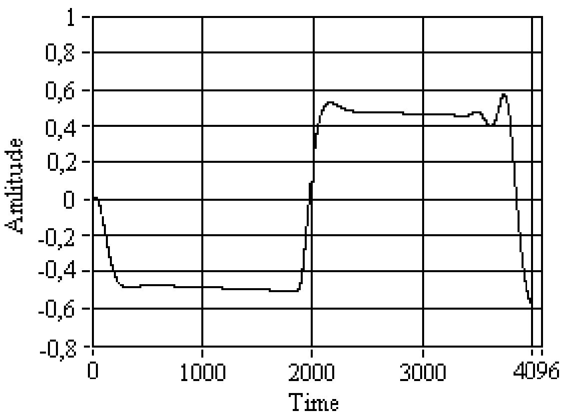
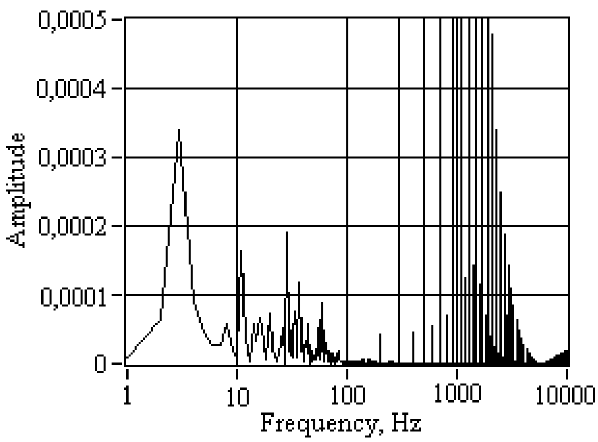
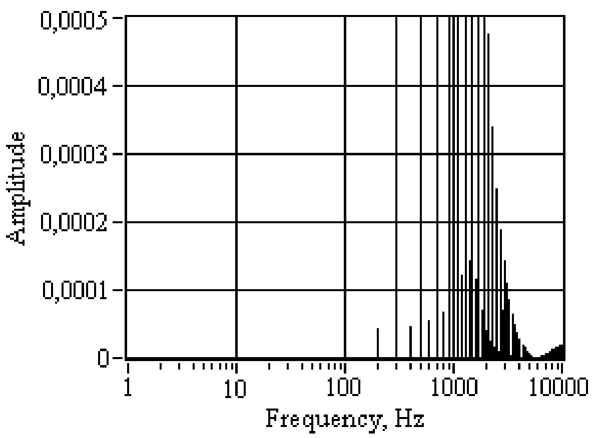


Fig. 3 One realization of test signal after Butterworth high-pass filter with f_p = 5 Hz, k = 30, where f_p, k – parameters of Butterworth filter



(a)



(b)

Fig. 4. Magnitude spectrum of pseudo-periodic test signal and low-frequency internal noise (a) and magnitude spectrum of frequency “fork” digital filter output (b) after blocking 16 spectral blocks

A frequency “fork” digital filter for filtering low frequency internal noises has been developed by authors. For this reason the pseudo-periodic testing signal is converted to frequency domain by using FFT. After that all the spectral components differing from the main test signal spectral components (e.g. 100, 200, 300 …) are blocked (set to $m_i = 0 + 0j$ values). Therefore major spectral components of the noise, those that frequencies are not equal to the frequencies of the test signal, are eliminated from the resulting spectrum. The resulting spectrum is converted back to time domain by using inverse FFT. Filter output is the same pseudo-periodic test signal with significantly lower level of internal noise.

Functioning of developed frequency „fork” digital filter has been tested using LabView®. Internal noises were simulated by using sine wave of f_{t1} frequency, and initial phase of which for each test signal realization is set randomly by using continuous uniform distribution from 0 to 360^o. This noise signal is added to the ideal test signal realization. Pseudo-periodic test signal array was formed using 100 signal realizations. Spectrum of the pseudo-periodic test signal is shown on Fig. 4(a). Spectrum of internal noise for each realization of the signal consists of random harmonic components, majority of which are concentrated in the up to 100 Hz frequency range. Analysis of digital pseudo-periodic test signal and internal noise shown that spectral components of pseudo-periodic test signal are absent or appears only because of non ideal periodic manner of the signal in the low-frequency range (up to 80 Hz) where internal noise spectral components are most intensive (Fig. 4). 4, 8 and 16 spectral blocks were removed from the signal spectrum (Fig. 4(b)) during experiments. Inverse FFT was performed on the resulting spectrum to get result test signal after filtering in time domain. Filter input test signal (unfiltered) and filter output (filtered) signal was subtracted from ideal signal to get filtering error (Fig. 5).

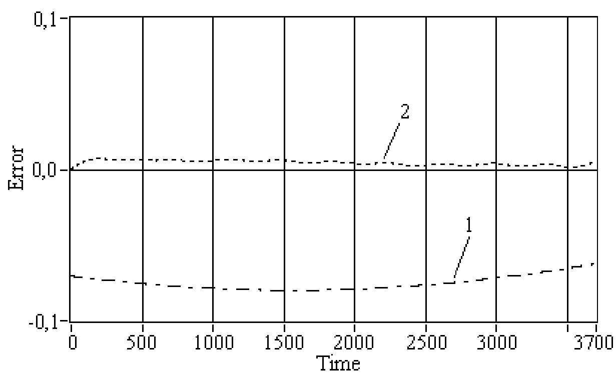


Fig. 5. Error of unfiltered (1) test signal array and filtered test signal array with 8 spectral blocks removed (2) compared to the ideal test signal

It is seen that the developed frequency „fork” digital filter has not influenced testing signal and the error generated by the internal noise has reduced significantly.

Further investigations shown that the filtered signal is not distorted for different number of spectral blocks removed (4, 8, 12 or 16). Therefore 100 realizations of test signal is enough to form pseudo-periodic test signal and the resulting harmonic components are narrow enough to prevent distortion of output signal when applying frequency filter.

Conclusions

1. Spectrum components of one period of DAC test signal and internal noises of sampling head are overlapping. Therefore it is not possible to filter noises and remove errors generated by internal noise from settling time measurement result.

2. Combining *n* realizations of the test signal with random internal noises and setting periodization parameters right it is possible to get pseudo-periodic test signal where test signal spectral components are separated from the random internal noise. This makes partial filtering of the test signal feasible.

3. It was established that very tough requirements are set to the distortions of the test signal. Therefore standard filters can not be applied for filtering of the test signal.

4. Frequency „fork" digital filter has been developed for filtering of low-frequency internal noise while keeping the test signal not distorted. Modeling of the process has shown that the filter developed is effectively reducing low-frequency internal noises of the sampling head. Further investigations are planned to establish how many spectral blocks should be removed and what number of periods is necessary for pseudo-periodic test series in order to make settling time measurement method most effective.

5. Frequency „fork" digital filter developed can be used to filter other digital signals. It can be used when it is possible to get number of comparably equal test signal realizations influenced by noises and when it is possible to build pseudo-random digitalized test signal series with right parameters to separate spectral components of test signal and noise.

References

1. **Marcinkevičius A., Jasonis V.** Analoginės informacijos keitiklių išrinkimo ir saugojimo schemos dinaminių charakteristikų skaičiavimas // Elektronika ir elektrotechnika – Kaunas: Technologija, 2004. – Nr. 5(54). – P. 23–26.
2. **Barzdenas E., Navickas R.** Two chips digital diagnostics systems for mammography and dentography // Electronics and Electrical Engineering. – Kaunas: Technologija, 2006. – No. 2. – P. 36–40.
3. **Williams J.** Measuring 16-bit settling times: the art of timely accuracy // EDN. – Nov 19, 1998. – P. 159.
4. **Balestrieri E.** Some critical Notes on DAC Time Domain Specifications // Proceedings of Instrumentation and Measurement Technology Conference IMTC 2006. – Sorrento, Italy. – 24–27 April 2006.
5. **Kvedaras V., Kvedaras R.** Tester for investigation of dynamic parameters of ICs // Electronics and Electrical Engineering. – Kaunas: Technologija, 2003. – No. 7(49) (in Lithuanian).
6. **Kvedaras R., Kvedaras V.** The measurements of dynamic parameters of high-speed multi-bit DACs // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 3(83). – P. 11–14.
7. **Intersil Corporation.** Operational Amplifier Noise Prediction (All Op Amps). – Application Notes AN 519.1. – 1996. – 4 p.
8. **Харкевич А. А.** Спектры и анализ. – Москва: Гос. издательство технико-теоретической литературы. – 1957. –236 с.

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Results of investigation of the digital processing algorithm for processing test signal of DAC settling time measurement are presented. It is shown that the highest influence to the measurement errors is generated by the internal noises of sampling head. Initial filtering of test signal is proposed. Spectrum components of test signal and noises are separated by generating digital pseudo-periodic test signal out of *n* test signal realizations and internal noise signal realizations. It is shown that standard high-pass filters are not feasible for filtering test signals because of tough requirements set to distortions of test signal. Algorithm for digital filter has been developed. It is shown by experiments that the frequency „fork" digital filter is effectively reducing low-frequency internal noises of the sampling head in the test signal. Ill. 5, bibl. 8 (in English; summaries in English, Russian and Lithuanian).

Т. Устинавичюс, Р. Квядарас, В. Квядарас, З. Янкаускас. Предварительная цифровая фильтрация исследуемых сигналов быстродействующих ЦАП // Электроника и электротехника. – Каунас: Технология, 2009. – № 7(95). – С. 63–66.

Приводятся результаты исследования разработанного алгоритма цифровой обработки исследуемых сигналов и определения времени установления быстродействующих ЦАП. Установлено, что наибольшее влияние на погрешности определения времен установления имеет низкочастотные шумы преобразователя. Предложено проводить предварительную фильтрацию исследуемых сигналов. Спектры исследуемых сигналов и шумов разделены периодизируя массив из *n* реализаций исследуемого сигнала и внутренних шумов. Показано, что стандартные фидьтры нижних частот не пригодны из-за предъявляемых высоких требовании к передаче формы сигнала. Предложена структура частотного «гребенчатого» цифрового фильтра. Экспериментально установлено, что такой фильтр эффективно подавляет внутренние шумы низких частот. Ил. 5, библ. 8 (на английском языке, рефераты на английском, русском и литовском яз.).

T. Ustinavičius, R. Kvedaras, V. Kvedaras, Z. Jankauskas. Sparčiųjų SAK tiriamųjų signalų pradinis skaitmeninis filtravimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 7(95). – P. 63–66.

Pateikiami sparčiųjų SAK tiriamųjų signalų skaitmeninio apdorojimo ir nusistovėjimo trukmės nustatymo algoritmo tyrimo rezultatai. Nustatyta, kad didžiausią įtaką nusistovėjimo trukmės nustatymo nuokrypiams turi žemųjų dažnių savieji triukšmai. Pasiūlyta atlikti pradinį tiriamojo skaitmeninio signalo filtravimą. Tiriamųjų signalų ir savųjų triukšmų spektrai išskiriami periodizuojant masyvą iš *n* tiriamųjų signalų ir savųjų triukšmų realizacijų. Parodyta, kad standartiniai aukštųjų dažnių filtrai dėl labai aukštų tiriamojo signalo perdavimo kokybei keliamų reikalavimų yra netinkami. Pasiūlyta dažninio „šakučių" skaitmeninio filtro struktūra. Eksperimentais nustatyta, kad toks filtras efektyviai slopina žemųjų dažnių savuosius triukšmus. Il. 5, bibl. 8 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).