

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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**DESIGN AND RESEARCH ON
SIGMA-DELTA
DIGITAL-TO-ANALOG CONVERTERS
FOR AUDIO POWER AMPLIFIERS**

SUMMARY OF DOCTORAL DISSERTATION

**TECHNOLOGICAL SCIENCES,
ELECTRICAL AND ELECTRONIC ENGINEERING (01T)**



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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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**SIGMA-DELTA
SKAITMENINIŲ-ANALOGINIŲ KEITIKLIŲ
GARSO GALIOS STIPRINTUVAMS
PROJEKTAVIMAS IR TYRIMAS**

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Introduction

Topicality of the Problem

AB class power amplifiers, applied in audio equipment, have low efficiency ratio, big weight and high price. The operational characteristics of another class of amplifiers – pulse amplifiers – are much better: they are smaller, lighter and function well in the case of complex loads; their efficiency ratio is much higher. One of the subsets – a digital Sigma-Delta ($\Sigma\Delta$) audio power digital-to-analog converter (DAC) – is particularly promising, since they are fully digital to the last stages. Peculiarities of the design of such audio power converters, their structure, properties and characteristics are analysed in the work.

Object of Research

$\Sigma\Delta$ digital audio power digital-to-analog converter: improvement of the structure, calculation of characteristics, evaluation and experimental research.

Aim and Tasks of the Work

The aim of the work is to improve the structure of interpolator of digital $\Sigma\Delta$ audio power digital-to-analog converter and analysis methods of the converter.

The following tasks must be solved in order to attain the objectives:

1. To carry out a comparative analysis of the structures and characteristics of $\Sigma\Delta$ audio power DAC and formulate the issues to be solved in the work.
2. To design an economical (from viewpoint of hardware resources) interpolator for digital $\Sigma\Delta$ audio power DAC and to carry out simulation of characteristics; to verify the economy by an experimental research.
3. To improve a method for interchannel separation (ICS) evaluation of $\Sigma\Delta$ audio power DAC by substantiating it by experimental research of the root mean square (RMS) spectrum and total harmonic distortion (THD). To provide comparison and evaluation of alternative solutions.
4. To propose and analyze a method for testing intermodulation distortions (IMD) of $\Sigma\Delta$ audio power DAC using modified Twin-T filters. To provide simplified alternative options of the test equipment.
5. To carry out simulation of frequency response and an experimental research on Twin-T filter structures with four and two operational amplifiers.

Methods of Research

Digital simulation (Matlab, G, C, Spice, VHDL, Verilog), different optimization methods and experimental research have been applied in the work.

MW Matlab & Simulink, Xilinx ISE, MG ModelSim, HDL Works Ease were used for design and simulation of digital circuits. Spectrum MicroCap, Cadence PSpice, TI Tina & FilterPro, NuHertz Filtre Solution, Tanne Elsie, LT

Filter CAD, Schematica Wiz Pro were used for analog circuits. Experimental studies were carried out in the course of preparation of the dissertation.

Scientific Novelty

1. The economical interpolator of $\Sigma\Delta$ audio power DAC was designed, which ensured stopband attenuation >99 dB of the system instead of 66 dB or 49 dB as in the version of the X. Huang interpolator. The principle of the filter design can serve for creation of new hardware resources optimized filters.

2. The simpler and more informative method for evaluation of interchannel separation and crosstalk of $\Sigma\Delta$ audio power DAC, more suitable for D class audio equipment, was investigated.

3. The modified Twin-T notch filter intended for analysis and evaluation of IMD of $\Sigma\Delta$ audio power DAC was suggested. The filter was developed, designed and experimentally tested. Many aspects of the properties of the filter are better than those of other filters used for the same purpose. The principle of the filter design can serve for creation of new filters with even better characteristics.

Practical Value

The results of the research may be used for design of power digital-to-analog converters, D class ($\Sigma\Delta$, PWM) amplifiers; design, research and optimization of interpolators, design of amplifier measurement equipment, preparation of measurement methodologies and investigation of technical properties of amplifiers. It may also be a stimulus for additional research in order to improve D class amplifiers.

Defended Statements

1. The improved and experimentally analyzed structure of the interpolator of $\Sigma\Delta$ audio power DAC require less hardware resources (compared with X. Huang's variant) and better transfer characteristics (attenuation higher by 17–50 dB at stopband of the system).

2. The proposed method for analysis of ICS of $\Sigma\Delta$ audio power DAC is simpler (no need for a tunable a 1/3 octave filter or 1/3 octave filter bank – 31 fixed frequency filters for 20 Hz – 20 kHz span) and more informative (high separation – or low crosstalk – values not only indicate that a direct stimulus signal does not penetrate much, but also it means that harmonious and non-harmonious components, interfering signals and wideband white noise are at or below the measured value).

3. The modified Twin-T notch filter for analysis of IMD of $\Sigma\Delta$ audio power DAC enables extend dynamic range of the analyzer (40–60 dB), empowering to use low dynamic range (8–12 bits) analyzers in the range from –80 dB to –120 dB.

Scope of the Scientific Work

The scientific work consists of the general characteristic of the dissertation, 4 chapters, conclusions, lists of references and publications. The total scope – 116 pages, 80 pictures, 9 tables, 56 formulas and 106 references.

1. Comparative Analysis of the Structure of Sigma-Delta Audio Power Digital-to-Analog Converter

Chapter 1 highlights the main advantages of $\Sigma\Delta$ compared to Nyquist-rate converters. The description of a $\Sigma\Delta$ DAC structure, the analytical description of operation of the 1st order modulator as well as presentation of noise shaping is presented. Moreover, the analysis of stronger noise shaping was given. Some discussion on application of modulators in power DACs accompanied with their own nuances is presented. Several variants on how to increase the signal-to-noise ratio as well as some problems which arise and are not solved in powerful $\Sigma\Delta$ DACs are produced. The objectives and tasks of the work are formulated.

2. Economical Interpolator in Sigma-Delta Audio Power Digital-to-Analog Converter

Chapter 2 is focused on one part of the converter – interpolator, – usually occupying an overwhelming amount of resources, optimization of the structure.

The summarized most common structure of the interpolator is provided in Figure 1. Every stage consists of interpolation lowpass filters. The higher order traditional FIR filters dominate in the first steps where imparity $a \geq b \geq c$ is usually valid. Cascaded integrator-comb (CIC), sample and hold (S/H) and linear interpolation (LI) filters are usually used in the last stage, which are effective from the point of view of equipment resources. Natural numbers k, m, p, r indicate the interpolator factor of every stage. Usually, $k \leq m \leq p \leq r$. The general interpolator factor is usually called the oversampling ratio (OSR) and is equal to the product of interpolation factors of every stage: $OSR = k \cdot m \cdot p \cdot r$.

X. Huang interpolator is one of the possible realizations of interpolation, which consists of 3 stages, with $k = 2, m = 4, r = 8, OSR = 64; a = 47, b = 20$, and the S/H circuit is used in the last stage. There are only 44 non-zero coefficients in FIR filters.

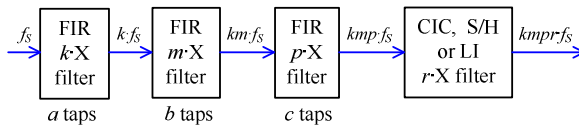


Fig. 1. Predominant structure of the interpolator

In order to reach such a frequency response, by synthesizing the multirate multistage filter in Matlab automatic mode, one will get 95 (IO, intermediate optimization) and 81 (AO, advanced optimization) non-zero coefficients.

There are four stages in the suggested interpolator, where $k = 2$, $m = 2$, $p = 2$, $r = 8$ and $OSR = 64$; $a = 55$, $b = 15$, $c = 9$; the S/H circuit is also used in the last stage. In this case, only 43 non-zero coefficients were needed for gaining frequency response better by 17 dB (> 66 dB vs. 49 dB). Frequency response of the whole system, including the interpolator, the modulator and the analog output filter, is shown in Figure 2. The essence is the used optimized structure, where in Halfband filters almost half of coefficients are equal to zero.

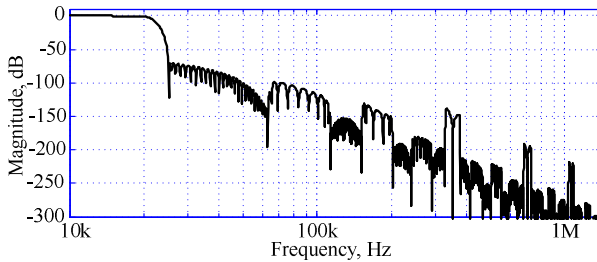


Fig. 2. Frequency response of the whole system

Finally, knowing which circuit follows the interpolator, it is possible to choose a very economic interpolator suiting only a certain system (fitted interpolator). One of the possible solutions for the mentioned system could be an interpolator with three stages, where $k = 2$, $m = 2$, $r = 16$ and $OSR = 64$; $a = 87$, $b = 15$ and the CIC filter in the last stage (differential delay = 1, number of sections = 2). Only 52 non-zero coefficients are present in the FIR filters. In this case, stopband attenuation reaches > 99 dB (Fig. 3).

A brief comparison of the interpolators is provided in Table 1.

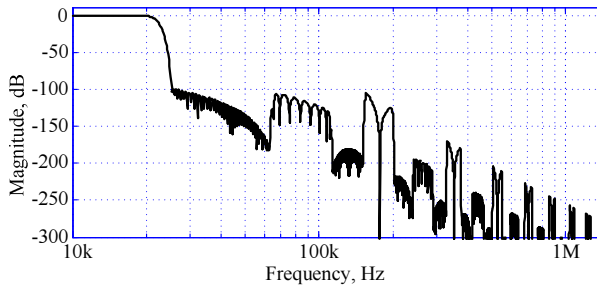


Fig. 3. Frequency response of the whole system with a fitted interpolator

Table 1. A brief comparison of the interpolators

Parameter	Interpolator				
	Matlab IO	Matlab AO	X. Huang	Suggested	Fitted
Non-zero coefficients	95	81	44	43	52
Upper band edge frequency, kHz	19.4	19.4	19.4	19.4	19.4
Passband ripple, dB	<0.1	<0.1	<0.1	<0.1	<0.15
Stopband attenuation of the whole system, dB	49	49	49	66	99

Simulated results concerning the occupied chip resources are also confirmed by the experiment – implementing it in Xilinx Spartan-3 FPGA.

Despite the fact that the filter attenuation has increased and total number of non-zero coefficients has reached 52, it occupies even less resources in FPGA (Table 2) than the previous filter thanks to the altered structure of the interpolator.

Table 2. Occupied resources in FPGA by interpolators

Parameter	Interpolator		
	X. Huang	Suggested	Fitted
Channels	1 or 2 (no data)	2	2
Slides	2763	777	761
Slice Flip Flops	1644	1312	1296
4-input LUTs	3983	894	969
Input/Output Blocks	no data	72	72
Conditional requirements	100%	14.1% or 28.2%	13.8% or 27.5%

Most probably the only drawback of the last interpolator is that the pass band suppression at 19.4 kHz already reaches -0.15 dB instead of the previous -0.1 dB. However keeping in mind that the analogue output filter also impairs everything at 0.5 dB, it is a worth compromise for stopband attenuation > 99 dB instead of the previous 66 dB (or 49 dB in the reference version of interpolator).

It was shown, that modelling PSD of the full system, it is possible to identify places of the interpolator, where hardware resources could be saved, herewith reducing occupied chip area by converter, what is not always obviously analysing nodes separately.

3. Analysis of Interchannel Separation Evaluation Methods of Sigma-Delta Audio Power Digital-to-Analog Converter

Chapter 3 is focused on methods for evaluation of interchannel separation (ICS) of a Sigma-Delta audio power DAC, which are more suitable for equipment of this class.

The standard method of interchannel crosstalk and separation is intended for measuring linear penetration of interference from one channel to another. The simplified flow diagram of the measurement when there are only two channels in the equipment under test (EUT) is presented in Figure 4.

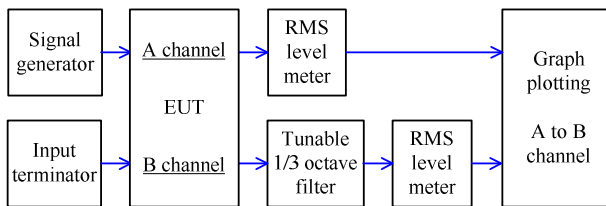


Fig. 4. The common evaluation method of interchannel separation

Practically, only the fundamental tone is filtered-out and any information of other related components is lost, after the application of the 1/3 octave filter. In the case of AB class amplifiers, it is reasonable. However, sometimes it leads to an inadequate result when the common method is used to $\Sigma\Delta$ audio power DAC or class D amplifier.

In the event shown in Figure 5, the difference of 4.4 dB between the RMS signals in 20 kHz bandwidth and measured according to the standard is reached. (THD of stimulated channel is only -64.4 dB or 0.06%). The third harmonic nearly reaches fundamental level: -0.8 dBc (absolute level -62.5 dBV).

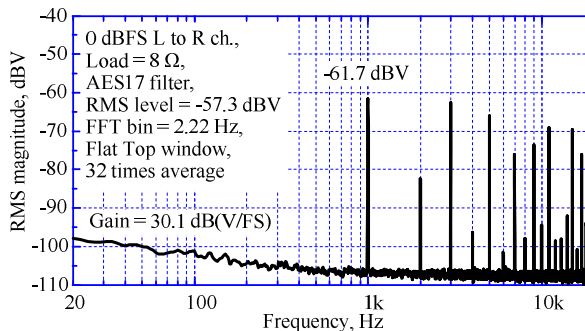


Fig. 5. The 1st example of the RMS spectrum

The worse case, where higher harmonics are of an incredibly high level, is shown in Figure 6. However, all of them will not be assessed by measuring the separation by the common method: the crosstalk will be -78.9 dBV after the application of 63 Hz 1/3 octave filter, notwithstanding the level of 5th harmonic is -62.1 dBV, and RMS level reaches -53.7 dBV. There are over 30 higher order harmonics exceeding the fundamental level.

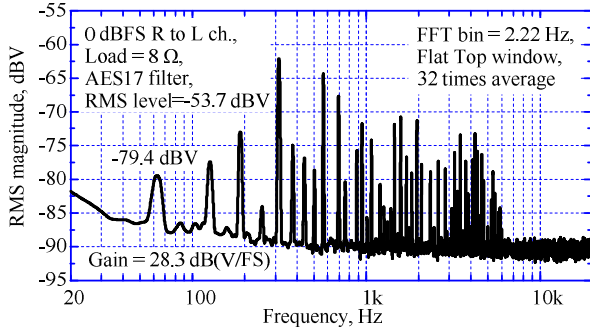


Fig. 6. The 2nd example of the RMS spectrum

In order to avoid inadequacy, interchannel separation can be measured by the proposed method graphically presented in Figure 7. It has all advantages over the previously mentioned (Fig. 4) common ICS measurement as total harmonic distortion plus noise (THD+N) versus THD: firstly, simplicity – no need for the 1/3 octave filter bank or the tunable 1/3 octave filter; secondly, informativity – high separation (or low crosstalk) values not only indicate that a direct stimulus signal does not penetrate much, but also it means that harmonious and non-harmonious components, interfering signals and wideband white noise are at or below the measured value. The main disadvantage is that the value of interchannel separation is lower in many cases. In some cases the difference may exceed 10 dB.

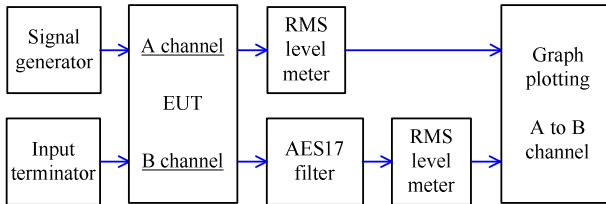


Fig. 7. The proposed evaluation method of interchannel separation

Besides, the main method with the AES17 bandpass filter (BPF), four alternative solutions for evaluation of an interchannel separation were provided and analyzed: with the AES17 lowpass filter (LPF) and the tunable highpass filter (THPF); with weighting CCIR-RMS filter; with advanced digital signal processing and with direct measurement from the RMS FFT spectrum. Some of the results from 8 different RMS spectra examples are shown in Table 3.

Δ_M – mean difference from the standard 1/3 octave filter measurement method result; Δ_{MD} – maximum difference; Δ_{MDMD} – maximum deviation from the mean difference; Δ_{AMD} – adjusted mean difference (excluding Δ_D value).

The AB class amplifiers were analyzed for the sake of comparison as well. Summarizing of the results from the examples of 6 RMS spectra of four different AB amplifiers are shown in Table 4.

Table 3. The results of interchannel separation methods for $\Sigma\Delta$ audio power DAC

Parameter	Method				
	AES17 BPF	AES17 LPF&THPF	CCIR-RMS	ADSP	FFT
Δ_M , dB	-11.4	-11.3	-11.1	-6.0	1.1
Δ_{MD} , dB	-25.2	-25.2	-25.4	-22.2	4.2
Δ_{MDMD} , dB	-13.8	-13.9	18.2	-16.2	3.1
Δ_{AMD} , dB	-9.5	-9.3	-13.7	-3.7	0.6

Table 4. The results of interchannel separation methods for AB class amplifiers

Parameter	Method				
	AES17 BPF	AES17 LPF&THPF	CCIR-RMS	ADSP	FFT
Δ_M , dB	-1.2	-1.2	6.1	0	0.2
Δ_{MD} , dB	-6.9	-6.6	24.9	-0.2	0.8
Δ_{MDMD} , dB	-5.7	-5.4	18.7	-16.2	0.6
Δ_{AMD} , dB	-0.1	-0.1	-3.7	0	0

In a situation where the strongest penetrating signal is not the test tone, it is advisable to use the strongest peak level in ICS calculations. This minimum derogation from the standard method allows avoiding the largest inadequacy.

Notwithstanding the fact that standard measurement fits for AB amplifiers and low power converters very well, sometimes it provides incorrect results for $\Sigma\Delta$ audio power DAC, which could be minimized by using proposed solutions.

4. Design, Simulation and Experimental Research of the Modified Twin-T Filter for Sigma-Delta Audio Power Digital-to-Analog Converter

Chapter 4 is focused on the proposed technique, which enables measurement of the intermodulation distortions with cheap lower dynamic range (10–14 or even 8 bit) analyzers using the modified Twin-T filter.

Two main tests for the high level non-linear behaviour of an audio power amplifier or DAC are harmonic distortion (THD, THD+N or signal-to-noise and distortion ratio (SINAD)) and intermodulation distortion (IMD) tests. However, THD+N cannot reveal the highest harmonic distortion products for digital audio systems which are band-limited. It may be a problem if one wishes to measure non-linearity due to slew-rate limiting.

IMD (including first 5 harmonics) could decline till –90 dB and lower for high quality sound devices. Levels of the individual IMD are yet lower. The solution – a notch filter for the main frequency suppression – may be used when the dynamic range of the analyzer is insufficient, which is usually applied in THD+N measurement. The main difference of the IMD measurement mentioned above is the requirement to suppress two strong tones. In such a case, a simple consecutive connection of the filters is not possible because the first stage will suppress only one tone, and the second stage will overload operational amplifiers of the same stage, when the dynamic range of the operational amplifiers is not exceptionally high. High order LCR filters are complicated and expensive. Here it will be more complicated to achieve the temperature stability; the size is considerable, no flexibility in relation to input impedance, etc.

The modified Twin-T filter enables solving the problem. The essence of the modification is based on separation of active and passive parts of the filter, with location of passive parts at the beginning and active parts subsequently (Fig. 8).

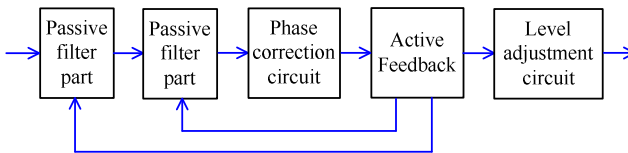


Fig. 8. The essence of modification

The filter was built on the FR-4 (woven glass and epoxy) plate and suites in the screened case with BNC connectors for protection from undesirable noise disturbances and interferences. The Size including connectors and switch is (W×L×H): 95×160×40 mm, weight – 430 g. A photo of the filter (scale M 1:2) is presented in Figure 9.

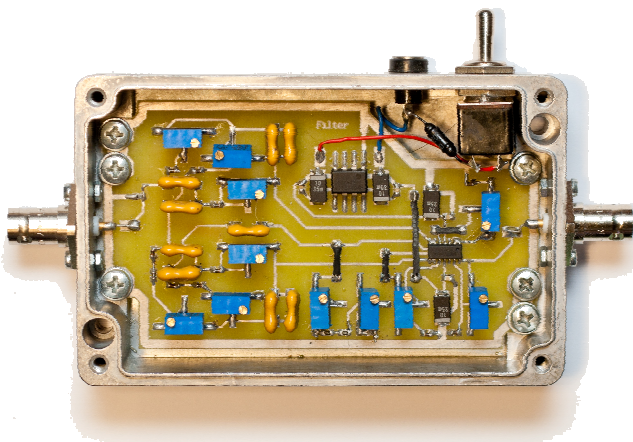


Fig. 9. The prototype, M 1:2

The most informative and underlying feature of the performance – frequency response – is presented in Figure 10. Simulation results obviously justify the strategy of separation of active-passive parts. Unfortunately, experimental results are not in good agreement with the simulation results. The filter quality is obviously too low: the suppression at dominant third intermodulation harmonics (16 kHz and 22 kHz), accordingly, is 16 dB and 19 dB. Yet the gain exceeds 30 dB, because the pair of the test tones is suppressed nearly by 50 dB.

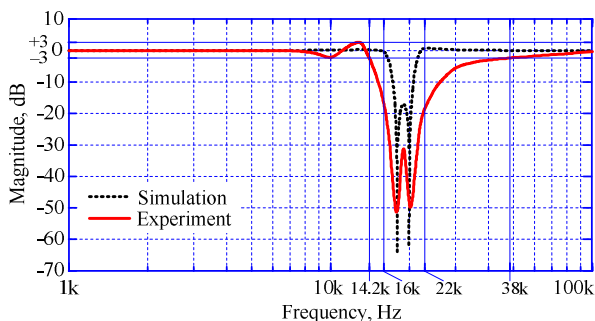


Fig. 10. Frequency response with OPA4134

Good simulation results were achieved with Elantec EL2424, EL2444, EL2445; Texas Instruments THS4032, THS4061, THS4062; and family of Linear Technology LT1357–LT1365, etc.

The transient simulations have shown that the filter does not prevent correct operation even when amplitudes of the test tones were by 30 dB above its power supply voltage. The simulation result looks as shown in Figure 11, after the fast Fourier transform has been made.

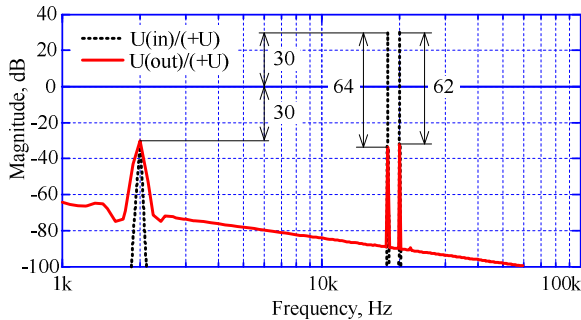


Fig. 11. Fast Fourier transform of the signals

LT1365 was chosen for the next experimental study. The main changes of the frequency response (Fig. 12) were achieved at the passband slopes, i.e., the filter quality was increased. The experimental curve was drawn near the simulation curve. Suppression of the tone pair has undergone no changes.

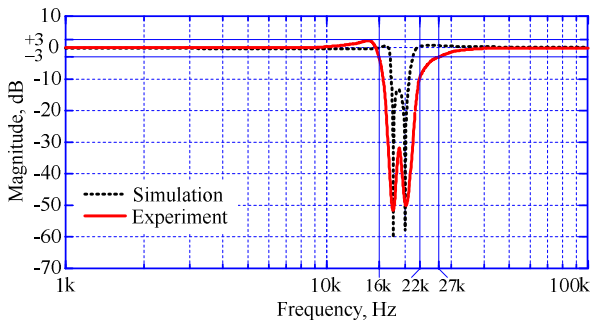


Fig. 12. Frequency response with LT1365

The aim of the second supplementary study is simplification of filter circuits. Now there are only two operational amplifiers in the circuit and, without level regulation and no need for buffering, only one operational amplifier is sufficient.

Notwithstanding the simplified circuit, the frequency response in the lower frequency band (to 16 kHz) has undergone almost no changes (Fig. 13) – the whole response curve is lying in the range of ± 3 dB. Unfortunately, the slope in the higher frequencies range is more low-pitched: suppression is 14 dB at 22 kHz instead of the previous value of 9 dB; still it is by 5 dB better in comparison with the original prototype, operational amplifier OPA4134.

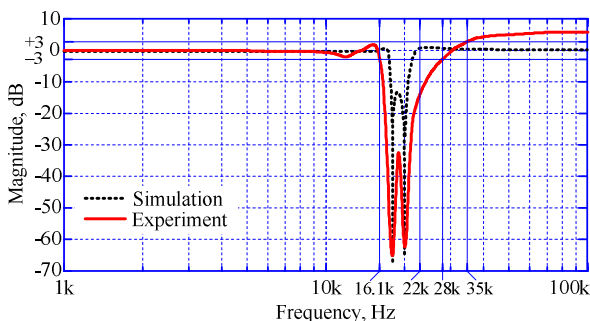


Fig. 13. Frequency response when two operational amplifiers are used

The experimental results of tone pair suppression rebate in relation to the simulation results only for by 2 dB and achieve accordingly 64 dB and 62 dB at the frequencies of 18 kHz and 20 kHz, i.e., yet 12 dB better than previous versions. Therefore, such features allow using even 8 bit inexpensive analyzers, i.e., Pico Technology PicoScope series, Hantek DSO and CWAV USBee families, BitScope analyzers, MicroTec TiePieScope series, Cleverscope, LeCroy, Tektronix, and many others.

The filter is characterized by the following advantages (prototype parameters in parentheses): compact – small size (W×L×H: 95×160×40 mm, without power supply), light weight (430 g, without power supply); achieved impedance exceeds 20 kΩ; temperature stability ($<\pm 0.1$ Hz @ 10–75 °C, with silver mica capacitors); stable operation by strong tested tone pair signals (18 kHz and 20 kHz, >50 V); sufficient suppression (especially the version of 2 operational amplifiers) for the usage of 8–12 analyzers; no inductive components; high dynamic range operational amplifiers are unnecessary; inexpensive (<60 Euros, without prototype remaking).

In spite of many advantages, some disadvantages can be mentioned. The main ones are: power supply is required; frequency response is not ideal, especially in the higher frequency band. The latter disadvantage may be compensated by digital processing in the same analyzer (digital filter calibration).

In spite of the drawbacks mentioned above, the results of the study confirm that separation of passive and active parts of the filter yields expected results, and this was the main aim of the experiment.

General Conclusions

The following scientific and practical results in the electrical and electronic engineering science were obtained during preparation of the dissertation:

1. The improved interpolator of Sigma-Delta audio power digital-to-analog converter has been designed. The simulation and experimental study of characteristics of two interpolator variants have been carried out. The main properties of the interpolator were improved. The first version: the total number of non-zero coefficients – 43 (instead 44); the stopband attenuation of Sigma-Delta audio power digital-to-analog converter – 66 dB (instead 49 dB); ripple at passband edge (19.4 kHz) – <0.1 dB; the resources of field-programmable gate array have been reduced to 777 Slices. The second (adapted) version: the stopband attenuation of Sigma-Delta audio power digital-to-analog converter – 99 dB (instead 49 dB); the resources of field-programmable gate array have been reduced to 761 Slices.

2. It has been shown by adapted interpolator that by simulating power spectral density of the whole system (interpolator + modulator + output filter) it is possible to identify the places of the interpolator where hardware resources could be saved in this way reducing clock speed or the chip area occupied by the converter. The stopband attenuation of the system has been increased by 33 dB (from 66 dB to 99 dB) after the application of the maxim.

3. The method of interchannel separation evaluation of Sigma-Delta audio power digital-to-analog converter has been improved, which evaluates nonlinear crosstalk and is suited for the D class audio equipment. The method is verified by research on the root mean square spectrum and total harmonic distortion. The main advantages of the method are: simplicity – no need for the 1/3 octave filter bank (31 fixed frequency filters for 20 Hz – 20 kHz span) or the tunable 1/3 octave filter; informativity – high separation (or low crosstalk) values not only indicates that a direct stimulus signal does not penetrate much, but also it means that harmonious and non-harmonious components, interfering signals and wideband white noise are at or below the measured value.

4. Alternative solutions for evaluation of ICS were provided and compared, which enables reducing the emerging inadequacies of interchannel separation in Sigma-Delta audio power digital-to-analog converter.

5. A method for testing intermodulation distortion of Sigma-Delta digital-to-analog for audio power amplifiers was proposed and investigated by using modified Twin-T filters. The method is characterized by the following advantages: it enables measuring ultra-low values of intermodulation distortion (40–60 dB below the lower limit of the analyzer); it enables using lower dynamic range (8–12 bits) inexpensive analyzers, in the range from –80 dB to –120 dB.

6. Simulation and experimental study of frequency response characteristics of Twin-T filters have been carried out by using structures with four and two operational amplifiers. The principle of filter development may serve for creation of newer filters with even better characteristics.

7. Results of the research and proposed methods may be used for design of power digital-to-analog converters, pulse and digital (Sigma-Delta, Pulse Width Modulation) amplifiers, for design, research and optimization of interpolators, design of the amplifier measurement equipment, preparation of measurement methodologies and investigation of technical properties of amplifiers. It may also be a stimulus for additional research in order to improve D Class amplifiers.

List of Published Papers on the Topic of the Dissertation In the Reviewed Scientific Journals

Puidokas, V. 2010. Ekonomiškas interpoliatorius $\Sigma\Delta$ SA keitiklyje, iš *Elektronika ir elektrotechnika*: Mokslas – Lietuvos ateitis. Straipsnių rinkinys. Vilnius: Technika, 2(1): 32–35. ISSN 2029-2341 (Index Copernicus).

Puidokas, V.; Marcinkevičius, A. J. 2008. Structure and Features of Sigma-Delta Modulators, *Electronics and Electrical Engineering*. Kaunas: Technologija, 4(84): 39–42. ISSN 1392-1215. (Thomson Reuters ISI Web of Science).

Puidokas, V.; Marcinkevičius, A. J. 2008. Research on Characteristics of Audio DAC Sigma-Delta Modulator on Field Programmable Gate Array, *Electronics and Electrical Engineering*. Kaunas: Technologija, 5(85): 39–42. ISSN 1392-1215. (Thomson Reuters ISI Web of Science).

Puidokas, V.; Marcinkevičius, A. J. 2009. Interpolator in a Sigma-Delta Digital-to-Analog Converter, *Electronics and Electrical Engineering*. Kaunas: Technologija, 2(90): 99–102. ISSN 1392-1215. (Thomson Reuters ISI Web of Science).

Puidokas, V.; Marcinkevičius, A. J. 2010. Analysis of Digital audio D-class Power Amplifiers Characteristics, *Electronics and Electrical Engineering*. Kaunas: Technologija, 2(98): 41–44. ISSN 1392-1215. (Thomson Reuters ISI Web of Science).

Puidokas, V.; Marcinkevičius, A. J. 2010. High Resolution High Power Low Frequency Digital-to-Analog Converter, *Solid State Phenomena*. Switzerland: Trans Tech Publications, 164: 133–138. ISSN 1392-1215. (Thomson Reuters ISI Web of Science).

Puidokas, V.; Marcinkevičius, A. J. 2011. Filter for Intermodulation Distortion Measurement of Audio Power Amplifiers, *Electronics and Electrical Engineering*. Kaunas: Technologija, 8(114): 47–50. ISSN 1392-1215. (Thomson Reuters ISI Web of Science).

In the other editions

Puidokas, V. 2008. Skaitmeninis triukšmo formavimas skaičiaus analogo keitiklyje, iš *Elektronika ir elektrotechnika*: 11-osios Lietuvos jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis“. Teminis konferencijos Elektronika ir elektrotechnika (2008 m. kovo 14 d.) straipsnių rinkinys. Vilnius: Technika, 52–66. ISBN 978-9955-28-373-7.

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SIGMA-DELTA SKAITMENINIŲ-ANALOGINIŲ KEITIKLIŲ GARSO GALIOS STIPRINTUVAMS PROJEKTAVIMAS IR TYRIMAS

Mokslu problemos aktualumas

Garso įrangoje taikomi AB klasės garso galios stiprintuvai pasižymi mažu naudingumo koeficientu, didele mase ir nemaža kaina. Kita stiprintuvų klasė – impulsiniai stiprintuvai, kurių eksploatacinės charakteristikos geresnės: mažesni, lengvesni, gerai dirba esant kompleksinėms apkrovoms, žymiai didesnis naudingumo koeficientas. Vienas poaibių – skaitmeniniai Sigma-Delta

($\Sigma\Delta$) garso galios skaitmeniniai-analoginiai (SA) keitikliai – ypač perspektyvūs, nes iki paskutiniųjų pakopų yra pilnai skaitmeniniai. Darbe nagrinėjami tokių keitiklių ypatumai, struktūros, parametrai ir charakteristikos.

Tyrimų objektas

Skaitmeninis Sigma-Delta garso galios SA keitiklis: sandaros tobulinamas, charakteristikų skaičiavimas, vertinimas bei eksperimentinis tyrimas.

Darbo tikslas ir uždaviniai

Darbo tikslas – patobulinti skaitmeninio Sigma-Delta garso galios SA keitiklio interpoliatoriaus struktūrą ir keitiklio analizės metodus.

Darbo tikslui pasiekti, darbe reikia spręsti šiuos uždavinius:

1. Atlikti Sigma-Delta garso galios SA keitiklio struktūrų bei charakteristikų palyginamąją analizę bei suformuluoti darbe spręstinas problemas.
2. Suprojektuoti aparatinių išteklių požiūriu ekonomišką interpoliatorių skaitmeniniam Sigma-Delta garso galios SA keitikliui ir atlikti charakteristikų modeliavimą, ekonomiškumą patikrinti eksperimentiniu tyrimu.
3. Patobulinti Sigma-Delta garso galios SA keitiklio tarpkanalio atskyrimo įvertinimo metodą, pagrindžiant eksperimentiniais efektinių verčių spektrų ir netiesinių iškraipymų tyrimais. Pateikti alternatyvių sprendimų palyginimą bei įvertinimą.
4. Pasiūlyti ir ištirti Sigma-Delta garso galios SA keitiklio taromoduliacinių iškraipymų testavimo metodą panaudojant modifikuotus Twin-T filtrus. Pateikti supaprastintus alternatyvius tyrimo įrangos variantus.
5. Atlikti Twin-T filtro struktūrų su keturiais ir dvejais operaciniais stiprintuvais dažnių amplitudės charakteristikų modeliavimą bei eksperimentinį tyrimą.

Praktinė vertė

Tyrimų rezultatai gali būti naudojami projektuojant garso galios SA keitiklius, D klasės ($\Sigma\Delta$, PWM) stiprintuvus; projektuojant, tiriant ir optimizuojant interpoliatorius, projektuojant stiprintuvų matavimo įrangą, sudarant matavimų metodikas bei tiriant stiprintuvų techninius parametrus. Taip pat gali būti akstinas papildomiems tyrimams D klasės stiprintuvų tobulinimui.

Mokslinis naujumas

1. Suprojektuotas ir ištirtas Sigma-Delta garso galios SA keitiklio aparatinių išteklių požiūriu ekonomišką interpoliatorių, užtikrinantis 99 dB sistemos slopinimą nepralaidos juostoje, vietoje 66 dB ar 49 dB X. Huang

variante. Projektavimo principas sudaro prielaidas naujų ekonomiškų filtrų kūrimui.

2. Ištirtas paprastesnis ir informatyvesnis Sigma-Delta garso galios SA keitiklio tarpkanalio atskyrimo (TA) bei kryžminių trukdžių (KT) įvertinimo metodas, labiau tinkantis D klasės garso įrenginiams.

3. Pasiūlytas modifikuotas Twin-T siaurymės (pleištinis, režecinis) filtras skirtas Sigma-Delta garso galios SA keitiklio tarpmoduliacinių iškraipymų analizei ir įvertinimui. Filtras suprojektuotas, sumodeliuotas ir eksperimentiškai ištirtas. Parametrai daugelių aspektų geresni už analogiškos paskirties filtrų. Filtro sudarymo principas gali pasitarnauti naujų, dar geresnių charakteristikų filtrų kūrimui.

Tyrimų metodika

Darbe taikomi skaitmeninio modeliavimo (Matlab, G, C, Spice, VHDL, Verilog), įvairūs optimizavimo metodai bei eksperimentiniai tyrimai.

Skaitmeninėms grandinėms modeliuoti taikyti MW Matlab bei Simulink, Xilinx ISE, MG ModelSim, HDL Works Ease. Analoginėms grandinėms – Spectrum MicroCap, Cadence PSpice, TI Tina bei FilterPro, NuHertz Filtre Solution, Tanne Elsie, LT Filter CAD, Schematica Wiz Pro. Spausdintinėms plokštėms projektuoti taikytas Altium Designer paketas. Eksperimentiniai tyrimai buvo atlikti disertacijos rengimo eigoje sukurta programine įranga.

Ginamieji teiginiai

1. Patobulinta ir eksperimentiškai ištirta Sigma-Delta garso galios SA keitiklio interpoliatoriaus struktūra užima mažiau lauku programuojamos loginės matricos išteklių (lyginant su X. Huang variantu) bei pasižymi geresnėmis perdavimo charakteristikomis (slopinimas nepralaidos juostoje 17–50 dB didesnis).

2. Pasiūlytas metodas, skirtas Sigma-Delta garso galios SA keitiklio tarpkanalio atskyrimo parametrų analizei, yra paprastesnis (nereikia perderinamo 1/3 oktavos filtro arba 1/3 oktavos filtrų banko – 31 fiksuoto dažnio filtro, norint perdengti 20 Hz – 20 kHz dažnių juostą) ir informatyvesnis (aukšta TA – arba atitinkamai žema KT – vertė ne tik parodo, jog tiesioginis testavimo signalas mažai prasiskverbia, bet taip pat harmoninės ir neharmoninės dedamosios, interferenciniai trukdžiai bei plačiajuostis triukšmas yra ties KT įverčio riba arba žemiau jo).

3. Modifikuotas Twin-T siaurymės filtras, skirtas Sigma-Delta garso galios SA keitiklio tarpmoduliacinių iškraipymų analizei, leidžia praplėsti analizatoriaus dinaminį diapazoną (40–60 dB), įgalinant panaudoti mažo dinaminio diapazono (8–12 skilčių) analizatorius matuojant nuo –80 dB iki –120 dB lygio vertes.

Darbo apimtis

Darbą sudaro įvadas, 4 skyriai, išvados, literatūros sąrašas ir autoriaus publikacijų sąrašas. Bendra apimtis – 116 puslapių, 80 iliustracijų, 9 lentelės, 56 numeruotos formulės ir 106 literatūros šaltiniai.

Pirmasis skyrius skirtas Sigma-Delta garso galios SA keitiklio struktūrų palyginamajai analizei, parametrų įvertinimui bei disertacijos uždavinių formulavimui.

Antrajame skyriuje nagrinėjamos Sigma-Delta garso galios SA keitiklio interpoliatorių schemos, sudaromi matematiniai modeliai ir analizuojami modeliavimo rezultatai.

Trečiajame skyriuje analizuojami Sigma-Delta garso galios SA keitiklio tarpkanalio atskyrimo įvertinimo metodai, pasireiškiant netiesiniams kryžminiams trukdžiams pasyviame kanale. Pateikiami eksperimentiniai efektinėms vertėms normuotų spektrų pavyzdžiai, bei tuo metu stimuliuojamame kanale pasireiškiantys netiesiniai iškraipymai; aptariami kryžminių trukdžių įvertinimo būdai.

Ketvirtajame skyriuje aprašoma pasiūlyta Sigma-Delta garso galios SA keitiklio tarpmoduliacinių iškraipymų testavimo metodika naudojant modifikuotus Twin-T filtrus. Analizuojami dažniųjų amplitudės charakteristikų modeliavimo ir eksperimentinių tyrimų rezultatai, pateikiami suprastinti alternatyvūs analizės variantai.

Bendrosios išvados

1. Suprojektuotas patobulintas interpoliatorius Sigma-Delta garso galios SA keitikliui. Atliktas dviejų interpoliatoriaus variantų charakteristikų modeliavimas ir eksperimentinis tyrimas. Pagerinti pagrindiniai interpoliatoriaus parametrai. Pirmajame variante pagerinti šie interpoliatoriaus parametrai: bendras nenulinių koeficientų skaičius – 43 (vietoje 44); Sigma-Delta garso galios SA keitiklio slopinimas nepralaidos juostoje – 66 dB (vietoje 49 dB); netolygumas ties pralaidos juostos riba (19,4 kHz) – $<0,1$ dB; lauku programuojamos loginės matricos loginių celių skaičius sumažintas iki 777. Antrajame variante sistemos slopinimas nepralaidos juostoje padidintas iki 99 dB (vietoje 49 dB) ir lauku programuojamos loginės matricos loginių celių skaičius sumažintas iki 761.

2. Pritaikytuoju interpoliatoriumi parodyta, jog modeliuojant pilnos sistemos (interpoliatoriaus + modulatoriaus + išėjimo filtro) spektrinio tankio charakteristikas, galima nustatyti zonas, kuriose interpoliatoriaus filtrų vietose įmanoma sutaupyti aparatinių išteklių, sumažinant taktinį dažnį arba užimamą plotą integrinio keitiklio grandyno luste. Tuo pasinaudojus, sistemos slopinimas nepralaidos juostoje padidintas 33 dB (nuo 66 dB iki 99 dB).

3. Patobulintas Sigma-Delta garso galios SA keitiklio tarpkanalio atskyrimo (TA) įvertinimo metodas, įvertinantis netiesinius kryžinius trukdžius (KT) ir pritaikytas D klasės garso įrenginiams. Metodas patikrintas efektingoms vertėms normuotų spektrų ir netiesinių iškraipymų tyrimais. Pagrindiniai metodo privalumai: paprastumas – nereikia 1/3 oktavos filtrų banko (31 fiksuoto dažnio filtro, norint perdengti 20 Hz – 20 kHz dažnių juostą) arba persiderinančio 1/3 oktavos filtro; informatyvumas – aukšta TA (arba atitinkamai žema KT) vertė ne tik parodo, jog tiesioginis testavimo signalas mažai prasiskverbia, bet taip pat harmoninės ir neharmoninės dedamosios, interferenciniai trukdžiai bei plačiajuostis triukšmas yra ties KT įverčio riba arba žemiau jo.

4. Pateikti ir palyginti alternatyvūs TA įvertinimo sprendimai, leidžiantys sumažinant pasireiškiančius tarpkanalio atskyrimo neadekvatumus Sigma-Delta garso galios SA keitiklyje.

5. Pasiūlytas ir ištirtas naujas Sigma-Delta garso galios SA keitiklio tarpmoduliacinių iškraipymų testavimo metodas, panaudojant modifikuotus Twin-T filtrus. Metodas pasižymi žemiau išvardintais privalumais: galima matuoti ypač mažas (40–60 dB žemiau analizatoriaus apatinės ribos) iškraipymų vertes ir panaudoti mažesnio dinaminio diapazono (8–12 skilčių) analizatorius, matuojant nuo –80 dB iki –120 dB lygio vertes.

6. Sudarytos modifikuoto Twin-T filtro struktūros su 4 ir 2 operaciniais stiprintuvais, atliktas dažninių charakteristikų modeliavimas ir eksperimentinis tyrimas. Eksperimento metu išmatuotos dažninės amplitudės charakteristikos patvirtina modeliavimo rezultatus.

7. Tyrimų rezultatai ir pasiūlyti metodai gali būti naudojami projektuojant galios SA keitikius, impulsinius bei skaitmeninius ($\Sigma\Delta$, PWM) stiprintuvus, projektuojant, tiriant ir optimizuojant interpoliatorius, projektuojant stiprintuvų matavimo įrangą, sudarant matavimų metodikas ar tiriant stiprintuvų techninius parametrus.

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FOR AUDIO POWER AMPLIFIERS

Summary of Doctoral Dissertation
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SIGMA-DELTA
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PROJEKTAVIMAS IR TYRIMAS

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