CZECH TECHNICAL UNIVERSITY IN PRAGUE

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Radioelectronics

Michal Vlk

A Novel Method of Noise Reduction in the Low-frequency Parametric Amplifier

Ph.D. Programme: Electrical Engineering and Information Technology

Branch of Study: Acoustics

Doctoral thesis statement for obtaining the academic title of “Doctor”, abbreviated to “Ph.D.”

Prague, november 2014

The doctoral thesis was produced in combined manner

Ph.D. study at the department of Radioelectronics of the Faculty of Electrical Engineering of the CTU in Prague

Candidate: **Michal Vlk**
Geomagnetic Observatory of the Geophysical Institute of the ASCR
Budkov 38, 384 22 Vlachovo Březí

Supervisor: **Doc. Ing Petr Skalický, CSc.**
Department of Radioelectronics
Faculty of Electrical Engineering of the CTU in Prague
Technická 2, 166 27 Prague 6

Opponents:

…..

…..

…..

The doctoral thesis statement was distributed on :

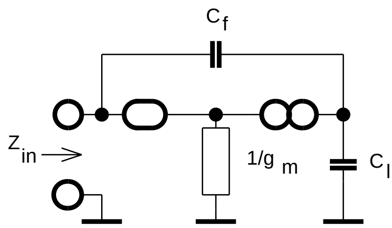
The defence of the doctoral thesis will be held on …....... at ….... a.m./p.m. before the Board for the Defence of the Doctoral Thesis in the branch of study Acoustics in the meeting room No. … of the Faculty of Electrical Engineering of the CTU in Prague.

Those interested may get acquainted with the doctoral thesis concerned at the Dean Office of the Faculty of Electrical Engineering of the CTU in Prague, at the Department for Science and Research, Technická 2, Praha 6.

Chairman of the Board for the Defence of the Doctoral
Thesis in the branch of study Acoustics
Faculty of Electrical Engineering of the CTU in Prague
Technická 2, 166 27 Prague 6.

1 Methodology

Consider a simple amplifier:



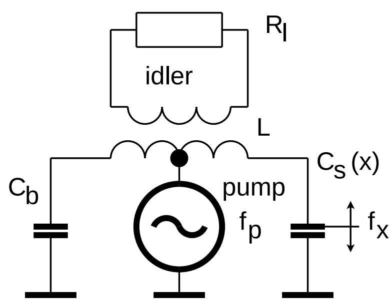
The input impedance of this circuit has the form:

$$Z_{in} = \frac{1}{p(C_l \| C_f)} \| \frac{C_f + C_l}{C_f g_m} \tag{1}$$

This is a parallel combination of resistor and capacitor. The noise factor of the resistor in this formula is dependent on noise factor of the resistor in the original circuit by the equation:

$$\gamma^{'} = \gamma \frac{C_f}{C_f + C_l} \tag{2}$$

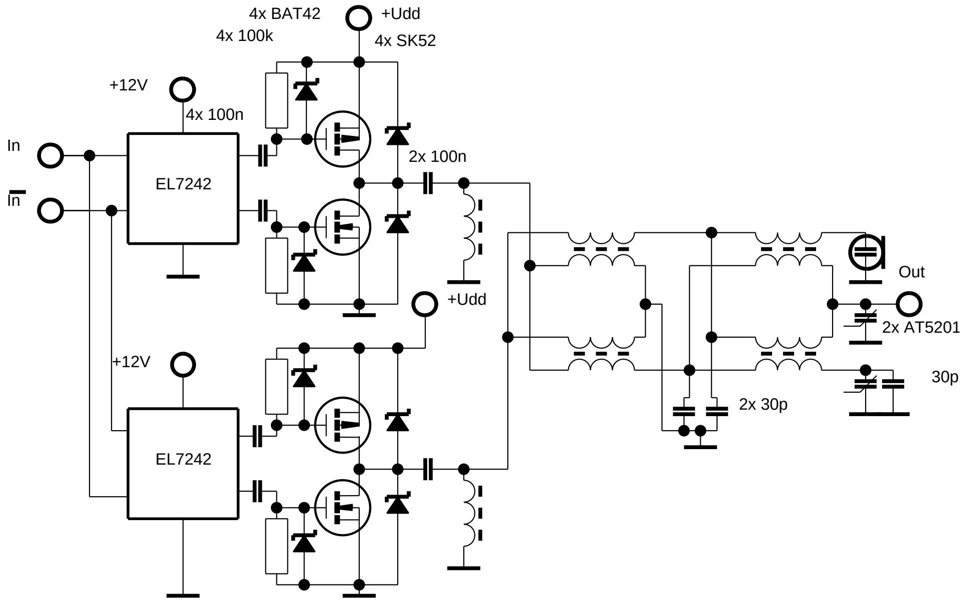
One can see, that the noise factor is decreased by a large amount. If the resulting noise factor is smaller than one, it has the same effect as cooling of the resistor to a temperature lower than that of the ambient. Author applied this fact for construction of special preamplifiers used for improving the noise parameters of low-frequency parametric amplifiers in the form:



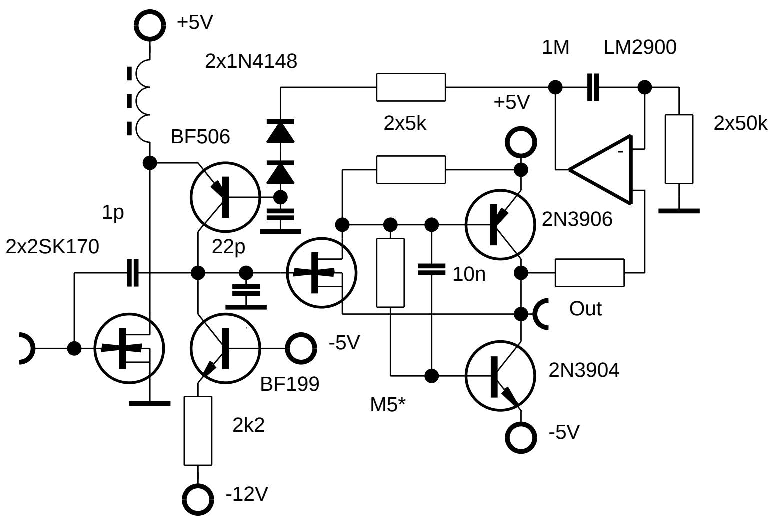
If the pump-generator is a hard-voltage source the only dissipative part is an idler-terminating resistor (which is in reality realised by the discussed circuit). To achieve this author used switched power circuits commonly used in radio transmitters.

2 Implementation

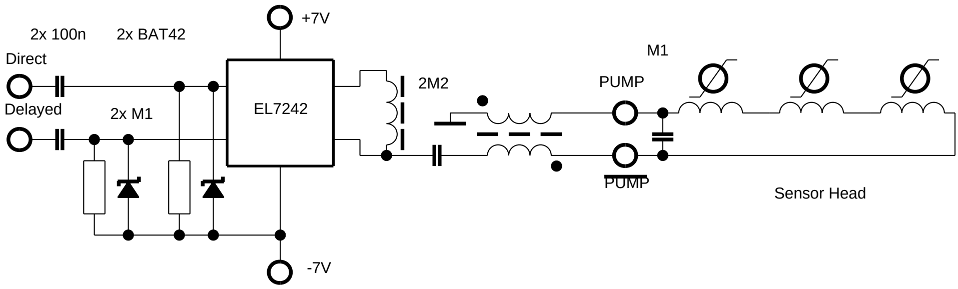
The first realised system was a capacitor microphone with a pumping circuit, which resembles a Westberg transmitter (where the drive impulses are non-overlapping):



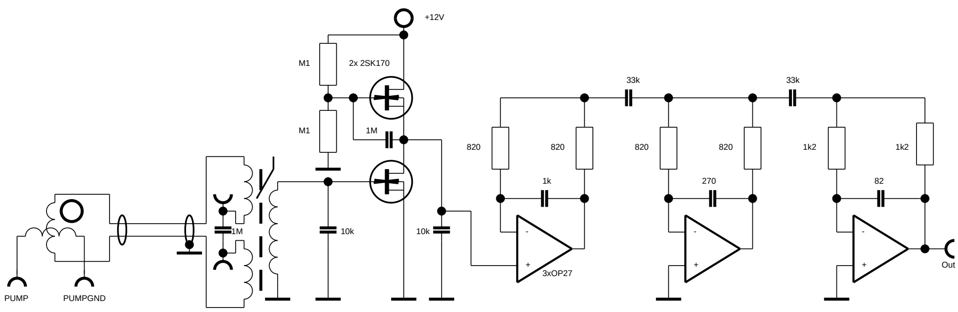
Here, the input amplifier has a form of the folded cascode, because used frequency is about 5 MHz and needed capacity C_f is much more smaller than the Miller capacity of the used device:



Another example is an second-harmonic fluxgate magnetometer where the author used original system for the pump-generator, which is more advantageous for a very low frequencies (16 kHz here), where the drive impulses are slightly overlapping:



Here, the input amplifier has a form of the simple CE stage, because Miller- capacity of the transistor is right-enough for the proper damping at frequency of 32 kHz. A band-pass filter-differentiator follows the input amplifier:



The amplified signal at the idler frequency is digitised, digitally band-pass filtered and demodulated by an envelope detector. The envelope detector uses digital first order all-pass filter to approximate Hilbert transformation $\tilde{x} = \mathrm{H}(x)$ and then a detector

$$y = \sqrt{x^2 + \tilde{x}^2}\,. \tag{3}$$

The signal is then decimated by a decimating chain and further processed in digital domain as needed. If the signal must be decimated plesiochronously (i.e. A/D converter has a free-running clock and output signal samples must be referenced to a global clock), it is advantageous to use plesiochronous resampling routine somewhere inside the decimation-chain. Author used routine based on a a FIR with a variable coefficients generated by an equidistant sampling of the continuous low-pass filter with a variable phase.

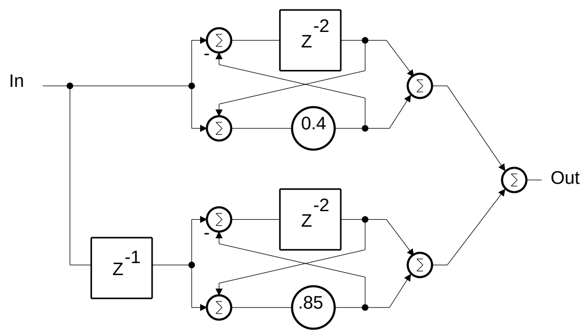
Suitable low-pass filters can be made by multiplying function:

$$\sin(\frac{\alpha\pi n}{T_s})/\frac{\alpha\pi n}{T_s} \tag{4}$$

and window:

$$1.0 - (0.35875 - 0.48829\cos(Q) + 0.14128\cos(2.0Q) - 0.01168\cos(3.0Q)) \tag{5}$$

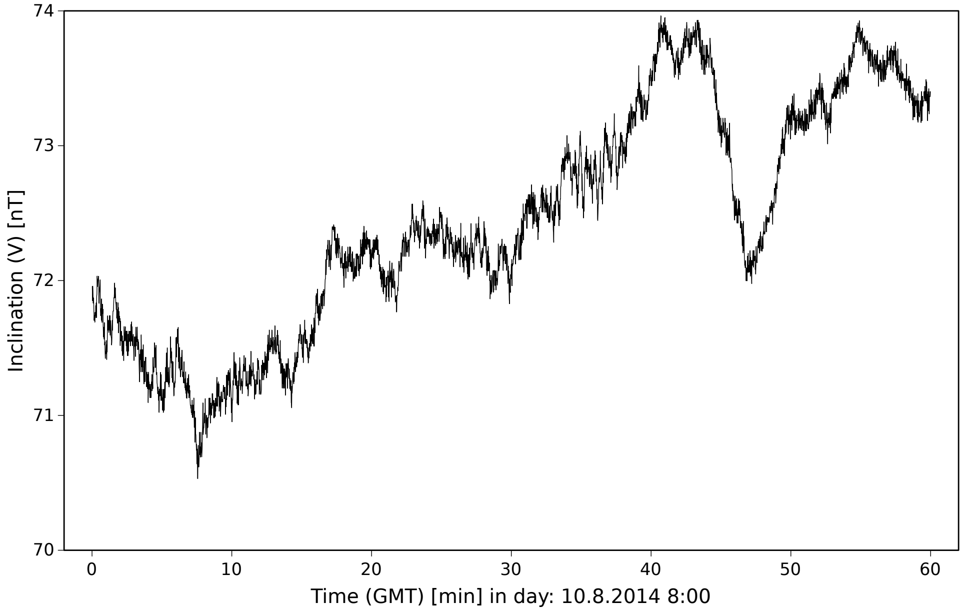
where α is smaller than 1 and represents the transient bandwidth of the filter (can be made narrower whether filter have more coefficients). Used Blackmann-Harris window gives yields good results and is noticeably simple (Q lies in the interval $0..2\pi$). Example of one decimator stage which decimates by two and is commonly used in today A/D converters is here:



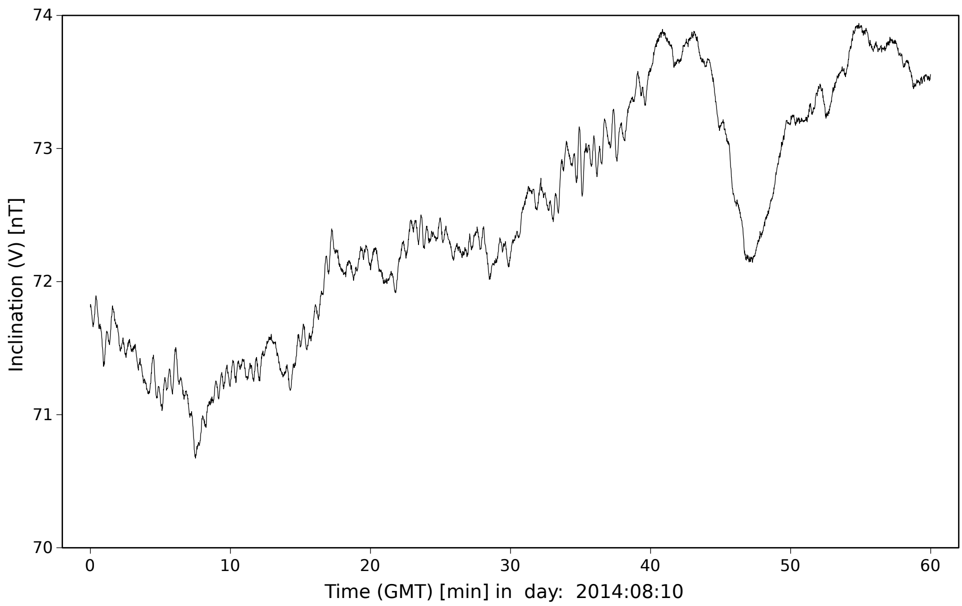
3 Results

Based on the above principles, triaxial fluxgate electronics was constructed for a spare NAROD-ACUNA ringcore probe. The instrument has been working over a year at the Budkov Observatory. An example of comparison with the standard observatory variometer GDAS (DMI magnetometer FGE) is given in the figures The Sampe data was taken with 1 sec. data in the I axis 8.10.2014 8:00-9:00 GMT. Using of Overhauser's PPM GSM90F1 (since 4-2014) as third instrument for noise intercalibration in F axis. Intercalibration was taken from whole-day one-second data of 8.10.2014; from band 350-450 mHz. Noise of the constructed instrument was estimated to 13.8 pT/$\sqrt{\text{Hz}}$. Noise of the GDAS (main observatory instrument since year 2002) was 61.3 pT/$\sqrt{\text{Hz}}$ and noise of PPM was 11.4 pT/$\sqrt{\text{Hz}}$.

GDAS instrument:



Constructed instrument:



4 References

Aschenbrenner, H.; Goubau, G.: Eine Anordnung zur Registrierung rascher magnetischer Stoerungen *Hochfrequenz-technik und Electroakustik* Vol. *47 (1936)* No. pp. 177-181

Acuna, M. H; Scearce, C. S.; Seek, J. B.; Scheifele, J. : *The MAGSAT vector magnetometer - a precision fluxgate magnetometer for the measurement of the geomagnetic field NASA Technical memorandum* No. *79656* Greenbelt, Maryland 1978

Arends, G.F.J.: De codensatormocrofoon met halfgleiders; *Polytechnisch Tijdschrift, Uitgave E*, Vol. *18(1963)* No. *7* pp. 241-247

Ballantine, Stuart: Reciprocity in electromagnetic, mechanical, acoustical, and interconnected systems; *Proc. IRE* Vol. *17 (1929)* No. *6 (June)* pp. 929-951

Baxandall, P.J.: New Low-noise Transistor Circuit for Electrostatic Microphone *Wireless World (1963)* No. 11-12, pp. 538-542;593-597

Blumlein, Alan Dower: Alternating Current Bridge Circuits; British pat. 323037 filled: *13.9.1928*

Bobrov, V.N.: Serija kvarcevych magnitnych variometrov *Geomagnetizm i aeronomija 2 (1962)* No. 2 p.348

Braun, Jaromír: *Kombinatorické metody v analýze a modelování elektronických soustav*; Prague: Academia *1990*

Braun, K. : Elektroakustische Vierpole; *TFT* Bd. *33 (1944)*, H. *5* pp. 84-95

Castigliano, A.: *Intorno ai sistemi elastici* Turin *1873* dissertation

Cerman, A.; Merayo, J.M.G.; Brauer, P.; Primdahl, F.: Self-Compensating Excitation of Fluxgate Sensors for Space Magnetometers *I2MTC - IEEE International Instrumentation and Measurement Technology Conference* Victoria, Vancouver Island *12.-15.5.2008*

Charkevič, Aleksandr Aleksandrovič: *Teorija elektroakustičeskych preobrazovatelej; Volnovyje processy*; Moscow: Nauka *1973*

Chireix, H.: High Power Outphasing Modulation *Proc. IRE* Vol. *23 (1935)* No. *11* pp. 1370-1392

Combes, Michel: *Un générateur paramétrable de multiplieur de fréquence utilisant des techniques numeriques* Paris: Université de Paris 06 *1994* - Doctoral thesis

Dement'jev, Jevgenij Petrovič: *Elementy obščej teorii i rasčeta šumjaščich linejnych cepej*; Moscow: Gosenergoizdat *1963*

Fakhfakh, Mourad -ed.: *Design of Analog Circuits through Symbolic Analysis*; Bentham e-books *2012*

Feussner, W.: Zur Berechnung der Stromstarke in netzformigen Leitern *Annalen der Physik* Vol. *15 (1904)* No. *12* pp. 385-394

Frederiksen, Erling: A method and a coupling for reducing the harmonic distortion of a capacitive transducer World patent WO 94/23547 published *13.10.1994*

Gouriet, G. G.: High-Stability Oscillator *Wireless Engineer (Apr. 1950)*

Griese, Hans Joachim: US. Pat. 3422225 pub. *1969* (compare with firm literature to add capacitor to complete Clapp circuit)

Guillemin, Ernst Adolph: *Introductory Circuit Theory* New York: J. Willey *1953*

Gyimesi, M.; Avdeev, I.; Ostergaard, D.: Finiteelement simulation of micro-electromechanical systems (MEMS) by strongly coupled electromechanical transducers *IEEE Transactions on Magnetics* vol. *40(2004)* no. *2 (march)* pp. 557-560

Hansen, S.T.; Ergun, A.S.; Liou, W.; Alud, B.A.; Khuri-Jakub, B.T.: Wideband micromachined capacitive microphones with radio frequency detection *JASA* Vol. *116 (2004)*, No. *2 (August)* pp.828-842

Harris, Frederic J.: On the Use of Windows fo Harmonic Analysis with the Discrete Fourier Transform *Proc. IEEE* Vol.*66 (1978)* No. 1 pp. 172-205

Hibbing, Manfred: Deutsche patent 4300379 publ.*1996* (Compare with firm literature to complete gamma LC with series inductor to tune the bridge.)

Hunt, Frederick V.: *Electroacoustics: The Analysis of transduction, and its historical background*; Cambridge: Harvard University Press *1954*

Jagoš, M.: Zmiešavač v spínacom režime *Súbor prednśšok z celoslovenského seminára rádioamatérov zväzarmu Vysoké Tatry 1989*

Korepanov, V.; Marusenkov, A.: Flux-Gate Magnetometers Design Peculiarities *Surveys in Geophysics* Vol.*33 (2012)* No. *5* pp. 1059-1079

Kvasil, Josef: *Mikroelektronické transformační bloky*; Prague: SNTL *1981*

Marie, G.: Amplificateurs paramétriques basses fréquences à commande magnétique orthogonale; *Acta Electronica*, Vol.*8 (1964)*, No. *1* pp 7-81.

Mason, W.P.: *Electromechanical transducers and wave filters* New York: D. Van Nostrand Comp.*1942*

Miller, G.: *Stylus-Groove Relations in Phonograph Records* Cambridge: Harvard University *1950* - Doctoral thesis

Mitra, S.K.: *Analysis and Synthesis of Linear Active Networks*, New York: J.Wiley *1963*

Motchenbacher,C.D; Fitchen, F.C.: *Low-noise electronic design* New York: J.Wiley *1973*

Moos, Petr: *Nulorové modely kvazilineárních a nelineárních elektronických prvků*; Prague: Academia *1983*

Musmann, G.; Anfassiev, Y.: Fluxgate Magnetometers for Space Research Norderstedt: Books on Demand *2010*

Mueller, R.; Holstein, P.: About a Digital RF-Condenser microphone; Convention Paper 6130 *116-th Convention AES* Berlin: *May 8-11 2004*

Narod, B; Russell, R.D.: Steady-State Characteristics of the Capacitively Loaded Flux Gate Sensor; *IEEE Trans. Mag.* Vol. *20 (1984)* No. *4* pp 592-597.

Narod, B. *NGL S-100 service manual*; Vancouver: Narod Geophysics Ltd. *1987*

Narod, B.: The origin of noise and magnetic hysteresis in crystalline permalloy ring-core fluxgate sensors *Geosci. Instrum. Method. Data Syst. Discuss. (2014)* No. *4* pp. 319-352

Otala, Matti: Circuit Design Modifications for Minimizing Transient Intermodulation Distortion in Audio Amplifiers *JAES 20 (1972)* No. 5 (June) pp. 396-399

Ott,H.W.: *Noise reduction techniques in electronic systems* New York: Wiley-Bell Tel. lab. *1976*

Oxborrow, Mark; Breeze, Jonathan D.; Alford, Neil M.: Room-temperature solid-state maser *Nature 488 (2012)* pp. 353-356

Paerschke, R.: Ein Hf- Kondensatormikrofon mit Transistoren *Funkschau 1965* No. *2* pp. 113-114

Parten, Michael E.: *Linear network analysis by Nullator-Norator residual networks* Lubbock: Texas Tech University(1972) - Doctoral thesis

Pastille, Holger: Ueber die Nichtlinearitaeten am Kondensatormikrofon unter besonderen Beruecksichtigung der Membran; Berlin, III. Fakultaet, 2011 - Doctoral thesis

Pedersen, M.; Olthuis, W.; Bergveld, P.: An integrated silicon capacitive microphone with frequency-modulated digital output *Sensors and Actuators* vol. A69 (1998) pp. 267-275

Penfield, Paul; Rafuse, Robert P.:*Varactor Applications* Cambridge: The MIT Press *1962*

Petterson, E.: *Magnetic wave amplifiing repeater* US PAT. 1884844 *1929*

Player, P.A.: Parametric amplification in fluxgate sensors *Journal of Physics D:* Vol. *21 (1988)* No.   pp. 1473-1480

Primdahl, Fritz: Temperature compensation of fluxgate magnetometers *IEEE Trans. Mag. 6 (1970)* No. 4 pp. 819-822

Radeka, V.: Signal, Noise and Resolution in Position-Sensitive Detectors; *IEEE Trans. Nucl. Sci.*, Vol. *21 (1974)*, No. *1* pp 51-64.

Rieger, F. : *Lineární Obvody*; Prague: SNTL *1967*

Ripka, Pavel : *Magnetometry s feromagnetickou sondou*; Prague: CVUT (Doctoral Thesis) *1988*

Russell, R.D.; Narod, B.B; Kollar, F.: Characteristics of the Capacitively Loaded Flux Gate Sensor *IEEE Trans. Mag.*, Vol. *MAG-19 (1983)*, No. *2* pp. 126-130

Sasada, I.: Symmetric response obtained with an orthogonal fluxgate operating in fundamental mode *IEEE Trans. Mag.*, Vol. *MAG-38 (2002)*, No. *5* pp. 3377-3379

Schroeder, Manfred R.:*Number Theory in Science and Communication* New York: Springer *2009*

Serson, P. H.; Mack, S.Z.; Whitham, K.: *Publ. Dom. Obs. Ottawa*, *19 (1957)* pp. 15 - 97

Seltzer, S. J.; Romalis, M. V. : Unshielded three-axis vector operation of a spin-exchange-relaxation-free atomic magnetometer *Appl. Phys. Lett. 85 (2004)* p. 4804

Soell, S.; Porr, B.: An Undersampling Digital Microphone Utilising Second Order Noise Shaping, *14-th. International conference MIXDES2007* Ciechocinek, Poland *21.-23. June 2007*

Sommerfield, A.: *Vorlesungen ueber theoretische physik, band III-Elektrodynamik*; Leipzig: Geest and Portig *1949* p.11

St-Louis, Benôit, ed.: *Intermagnet Technical Reference Manual*; Edinburgh: BGS *2011*

Strnad, Ladislav: *Synchronizace sítí*; Prague: ČVUT publishing house *2013*

Sucksdorff, C.; Pirjola, R.; Häkkinen, L.: Computer production of K-indices based on linear elimination. *Geophys. Trans.* Vol. *36* pp. 333âĂŞ345

Suesse, R.; Civelek, C.: Analysis of engineering systems by means of Lagrange and Hamilton formalisms depending on contravariant, covariant tensorial variables; *Forschung im Ingenieurwesen* Bd. *68 (2003)* pp. 66 - 74

Swanson, Hilmer Irvin: *Amplitude modulator*, European Patent: 0083727 *1983*

Sýkora, Bohumil; Dudek, Pavel: Předzesilovače pro přenosku s pohyblivým magnetem *Amatérské radio A 68 (1990)* No. 1 - 2 pp. 65-70,105-108

Tomlinson, G.H. ; Galvin, P.: Analysis of skewing in amplitude distributions of filtered m sequences *Proc. of the IEE* Vol. *121 (1974)* No. *12* pp. 1475-1479

Vackář, Jiří: *Vysílače. 1., Teoretické základy* Prague: SNTL *1960*

Vágó, István: *Graph Theory : Application to the calculation electrical networks*; Budapest: Akadémiai Kiadó *1985*

Vorperian, Vatché: *Fast Analytical Techniques for Electrical and Electronic Circuits*; London: Cambridge University Press *2002*

Westberg, Jerry: *Phase to amplitude H-bridge switching circuit*, US Patent: 7092269 *2006*

Weynmann, G.: Di Messung kleinster Schalldruecke mit dem kondensatormikrophon *Elektrische Nachrichtentechnik* Vol. *20 (1944)* No. *6*, p. 149-158

Whittaker, Edmund Taylor; Robinson, George: *The Calculus of Observations: A Treatise on Numerical Mathematics* London: Blackie and Son Limited *1937*

Zell, Clemens: Einrichtung zur Umwandlung von ein- oder mehrphasigen Wechselstrom in Gleichstrom und umgekehrt mit Hilfe von Selbstinduktionsspulen mit polarisirtem Eisenkern German patent DE113992 (25.4.1899)

Van der Ziel, A.: *Noise* Prentice-Hall *1954*

Zuckerwar, A.;S hope, W.W.: A Solid-State Converter for Measurement of Aircraft Noise and Sonic Boom *IEEE Trans. Instrum. and Meas.* Vol. *IM-23 (1974)* No.*1* p. 23-27

5 Curriculum-vitæ

Michal Vlk has born 10.5.1979 a in small industrial city Pečky near Kolín

In 1994-1998 attended Secondary Technicall School in Kutná Hora; Branch of study: Electronic and Communication Systems.

In 1998-2005 attended master course at the Faculty of Electrical Engineering of the Czech Technical University in Prague; Branch of study: Radioelectronics - Electroacoustics. Master thesis: Noise properties of the ribbon microphone. (in Czech)

In 2005-2007 worked in TESLA company Prague in the Department of AM transmitters.

In 2007-2011 attended doctoral course at Department of Radioelectronics of the Faculty of Electrical Engineering of the Czech Technical University in Prague; Branch of study: Acoustics

In 2011-now work as a technician in Budkov Geomagnetic Observatory of the Institute of Geophysics of the Academy of the Sciences of the Czech Republic

His professional interests are low-noise and high-power low-to-middle-frequency electronics.

His free-time interests are electronic circuit breadboarding and choir singing.

6 Author's publications related to the thesis

6.1 Publications impacted and recensed

none

6.2 Patents

Vlk, Michal: Blumleinův můstek Czech patent *CZ 302207* granted: *5. 11. 2010*

6.3 Publications excerpted in WOS

none

6.4 Other publications

Vlk, Michal: Plesiochronní převodník vzorkovací frekvence *Proceedings of the regional AES meeting ˋATP´* Prague *2005*

Vlk, Michal: A Novel Analogy for Time-Domain Simulation of the Nonlinear Electrostatic Transducer *Procedings of the conference Poster* Prague *15.5. 2008*

Vlk, Michal: Condenser microphone as parametric electroacoustic system and its time-domain modelling via equivallent electrical circuit in SPICE software *Proceedings of the conference Acoustics 08* Paris *29.6-4.7. 2008*

Vlk, Michal: Kondenzátorový mikrofon jinak *Proceedings of the 77-th Acoustic seminary of the Czech Acoustical Society* Zlenice *7.-9.10. 2008*

Vlk, Michal: Koncové stupně digitálních vysílačů *Proceedings of the conference Radiokomunikace* Pardubice *4.-6.11. 2009*

Vlk, Michal: Modernisation of the Narod fluxgate electronics at Budkov Geomagnetic observatory *Poster presented at EGU General Assembly* Wien *7.-12.4. 2013*

Hejda,P.; J. Horáček, J.; Vlk, M.; Bayer, T.: ON THE THUNDERSTORM OF 10 JULY 2011 AT MAGNETIC OBSERVATORY BUDKOV *Boletin ROA San Fernando* No.*3 2013*; Author's participation 30 %

Vlk, M.: Obvodové modely indukčnostního teslametru *Proceedings of the 89-th Acoustic seminary of the Czech Acoustical Society* Šlovice *7.-9.10. 2014*

7 Author's publications not related to the thesis

none

8 Responses to author's publication

not known

9 Summary

This thesis concerns low-frequency parametric amplifiers. These systems have been widely used in power electronics since semiconductors replaced it. Today, they are used only in systems where the low 1/f noise corner is the main interest. The schematic diagrams of these systems are still in the style of 1960. Several methods are presented to improve electronic circuits and also the noise property of parametric amplifier circuits and allow using the power of todays personal computers used as data-loggers.

- The method of singular elements can significantly simplify circuit analysis. It gained popularity in the late 1970s because monolithic integrated circuits do not allow coils to be used inside the structure. Here, this method is used as a tool to analyse a simplified circuit of the input amplifier to improve its property as an electronic idler cooling element and to improve its stability.
- Switched MOS power amplifiers with external commutation are discussed and used as a source of the pump signal with wery low output impedance.
- The software radio is used to process parametric amplifier idler signals. Since the idler signal is at intermediate frequency, the system 1/f noise is not affected by the 1/f noise of DC amplifier or A/D converter. A linear envelope detector is used instead of a phase-sensitive detector which eliminates the sensitivity of the spurious phase-drift which occurs in ferroresonant pump circuits and tuned idler circuits.
- Plesiochronnous signal processing is used to eliminate the need of a synchronised oscillator as an A/D converter frequency source if the data sampling rate must be synchronised to the global time - source.

The use of these techniques is illustrated on two case studies: high-frequency condenser microphone and second harmonic fluxgate.

10 Résumé

Práce pojednává o zlepšení šumových vlastností nízkofrekvenčních parametrických zesilovačů. Tyto systémy byly používány před nástupem polovodičů ve výkonové elektrotechnice, v současné době se používají jen v systémech s velkými nároky na 1/f šum. Obvodová řešení takových systémů se od šedesátých let mnoho nezměnila. V práci předkládám několik přístupů k modernizaci obvodových schémat, které by zlepšily parametry a umožnily využít výkonu současné výpočetní techniky v roli akvizičního systému.

- Metoda singulárních elementů, která dovoluje výrazně zjednodušit analýzu zejména idealizovaných obvodů, dosáhla maxima své popularity v sedmdesátých letech dvacátého století z důvodu masového nástupu analogových monolytických integrovaných obvodů, které nemohou mít ve své struktuře skutečné cívky. Zde je tato metoda použita pro syntézu vstupního zesilovače speciálních vlastností - tedy nefiltračního obvodu.

- Spínané výkonové zesilovače osazené tranzistory MOS s vnějšími komutačními obvody ve spojení s oscilátorem s velkou fázovou čistotou umožňují snížit vliv budicích obvodů na celkový šum soustavy jednak zmenšením tlumicího odporu a jednak zvětšením reaktančního výkonu pumpovacího zdroje.

- Digitální zpracování signálu na kmitočtu idleru umožňuje využít optimalizací známých v konsturukci mezifrekvenčních zesilovačů a odstranit vliv 1/f šumu A/D převodníku.

- Plesiochronní zpracování signálu umožňuje použít volně běžící oscilátor bezprostředně u A/D převodníku, což zjednodušuje konstrukci a snižuje fázový šum hodin převodníku.

Použití těchto technik je ilustrováno na dvou studiích: vysokofrekvenčním kondenzátorovém mikrofonu a indukčnostním magnetometru.