CEBE IAB Meeting, October 3, 2010

Signals and Signal Processing in Broadband Impedance Measurements

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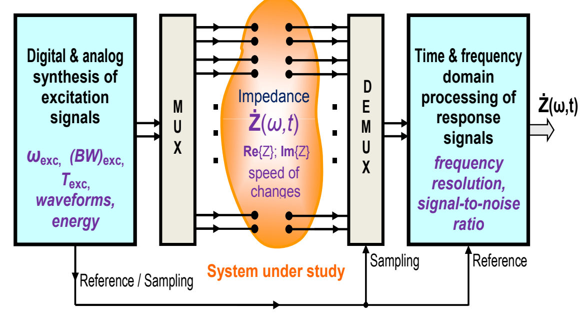
Preparatory research for the following reasearch projects –

P1: Application Specific Processors for Signal Processing in Biomedicine.
Coordinator: P. Ellervee, ATI Design Team. EMBEL-I: *principles for generation and processing of measurement signals.*

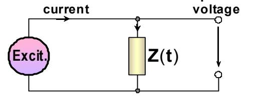
P3: Total Peripherial Resistance of Vascular System.
Coordinator: K. Meigas, TM Cardiology Team. EMBEL-I: *impedimetric methods for estimation of stroke volume and cardiac output, also methods for analysis of pulse wave dynamics and adaptive filtration/separation of signals, e.g., heart beating and breathing components.*

P7: Spectroscopy in Semiconductor Research (*New!*)
Coordinator: T.Rang, EMBEL-II Team. EMBEL-I: *broadband transient spectroscopy for semiconductor research.*

What do we do? Dynamic system identification!



Problems to be solved



Impedance spectrum of dynamic systems is **time dependent**.
Examples: (a) cardiovascular system; (b) pulmanory system; (b) microfluidic device.

Excitation must be:
1) **as short as possible** to avoid significant changes during the spectrum analysis;
2) **as long as possible** to enlarge the excitation energy for maximising signal-to-noise ratio.

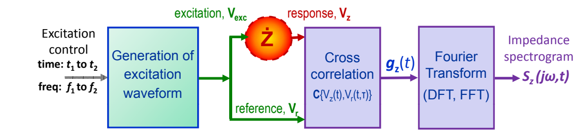
Unique property of chirp waveforms – **scalability** – enables to match the above expressed contradictory requirements (1) and (2) and match the needs for spectrum bandwidth (BW), excitation time (T_{exc}), and signal-to-noise ratio (S/N).

The questions to be answered:

a. Chirp wave excitation contains typically hundreds and thousands of cycles, if the impedance changes slowly. But what could be **the lowest number of cycles** applicable when very fast changes take place?
b. Are there any simpler **rectangular waveforms** to replace the sine waves and chirps in practical spectroscopy?

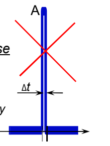
Signals and signal processing

Focus: finding the best excitation waveforms and signal processing methods for the fast and wideband, scalable, and time dependent spectral analysis: measurement of intensity (*Re* & *Im* or *M* & *Φ*) versus frequency *ω* and time *t*

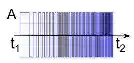


a – *short rectangular pulse*

- *very high* ***CF*** *(10 to 100)*
- ***BW*** *= 0 to 0.44(1/Δt),*
- *low level of spectral density*
- ***not scalable***



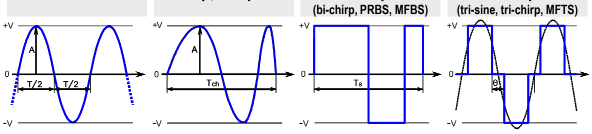
b – *chirp pulse (t_1 to t_2) covers wide BW (f_1 to f_2),* ***scalable****, acceptable* ***CF****=1.414*



c – *binary sequence (chirp pulse) from t_1 to t_2 covers BW from f_1 to f_2,* ***scalable****, ideal* ***CF****=1.0*

Crest factor CF = Peak / RMS

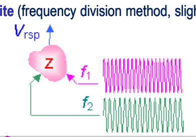
Excitation waveforms

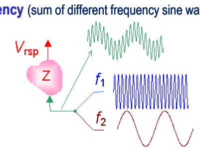
sine wave	chirp, chirplet	binari sequence (bi-chirp, PRBS, MFBS)	trinari sequence (tri-sine, tri-chirp, MFTS)
			
A sin(ωt), A = V, ω = 2π/T = const.	**ch(t)** = A sin[∫ω(t)dt], A = V, ω(t) = var, $ω_1$ to $ω_2$	**sign{ch(t)}** ω(t) = var, from $ω_1$ to $ω_2$	**tri{sin(ωt)}, tri{ch(t)}** ω=2π/T= const, or ω(t)=var
P = 0.5 V²	P = 0.5 V²	P = V²	P = (0.7...0.9) V²
RMS = 0.707 V	RMS = 0.707 V	RMS = 1.0 V	RMS= (0.85...0.95)V
P_{exc} / P = 100%	P_{exc} / P = 90...100%	P_{exc} / P = 65...85%	P_{exc} / P = 85...94%
P_{exc} = P = (0.5) V²	P_{exc} = (0.4...0.5) V²	P_{exc} =(0.65...0.85)V²	P_{exc} =(0.6...0.8)V²
Ideal S/N,	Very good S/N,	Low S/N, Plenty of higher harmonics,	Acceptable S/N, Much less higher harmonics,
easy to process	complicated processing	complicated processing !	easier to process !

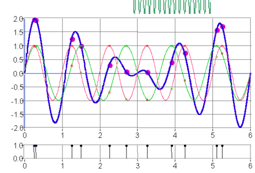
EP1786322B1: Sine wave signals and sampling – multisite and multifrequency simultaneously (P1)

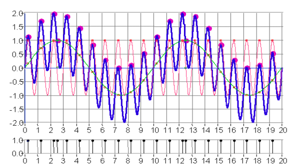
Multifrequency (sum of different frequency sine waves)

Multisite (frequency division method, slightly different f_1 and f_2)

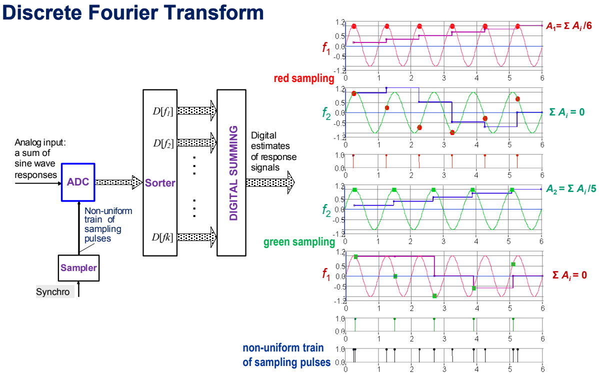






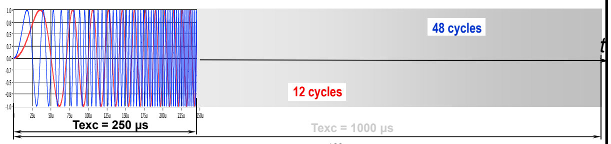


EP1786322B1: Signal processing – sorting and summing instead of Discrete Fourier Transform



Scalability of chirp function: two chirplets 1

A. Scalability in frequency domain: bandwidth BW changes, T_{exc} = const = 250 µs



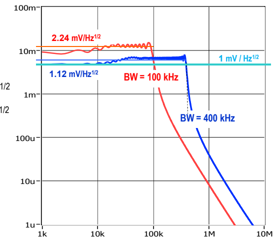
Excitation time **Texc = 250 µs** = const

Excitation energy **Eexc** = 0.5V² ·250 µs = **125** V²·µs

Voltage Spectral Density @ 100 kHz = **2.24** mV/Hz$^{1/2}$

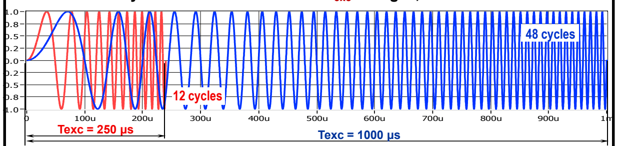
Voltage Spectral Density @ 400 kHz = **1.12** mV/Hz$^{1/2}$

Changes in the frequency span BW reflect in spectral density



Scalability of chirp function: two chirplets 2

B. Scalability in time domain: duration T_{exc} changes, BW = const = 100 kHz



Bandwidth **BW = 100 kHz** = const

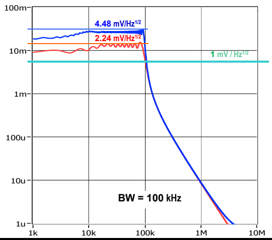
Energy $E_{250\mu s}$ = **125** V²·µs

Energy $E_{1000\mu s}$ = **500** V²·µs

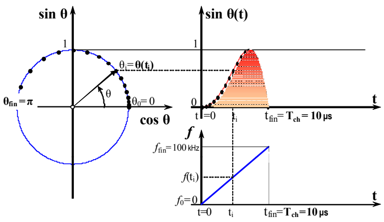
Voltage Spectral Density @ 250µs = **2.24** mV/ Hz$^{1/2}$

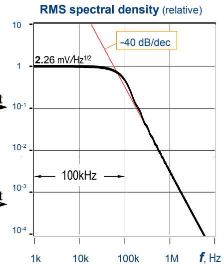
Voltage Spectral Density @ 1000µs = **4.48** mV/ Hz$^{1/2}$

Changes in the pulse duration T_{exc} reflect in spectral density



Half-cycle linear titlet (frequency grows linearly in time)





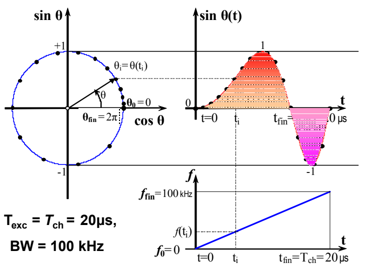
Texc = T_{ch} = 10 µs, BW = 100 kHz

Instant frequency $\omega(t) = \frac{d\theta(t)}{dt} = 2\pi \cdot f_2 \cdot t / T_{ch}$, rad/s

Current phase $\theta(t) = \int \omega(t) \cdot dt = 2\pi \cdot f_{fin} \cdot t^2 / 2T_{ch}$, rad;

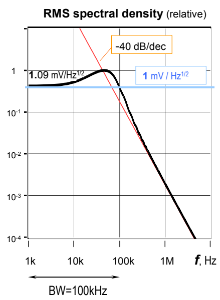
Final phase value $\theta_{fin}|_{t=Tch} = \pi$

Single-cycle linear titlet (frequency grows linearly in time)



T_{exc} = T_{ch} = 20µs,

BW = 100 kHz



Current phase $\theta(t) = \int \omega(t) \cdot dt = 2\pi \cdot f_{fin} \cdot t^2 / 2T_{ch}$, rad

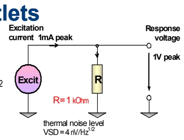
Instant frequency $\omega(t) = \frac{d\theta(t)}{dt} = 2\pi \cdot f_{fin} \cdot t / T_{ch},$ rad/s

Acceleration $d\omega(t)/dt = 2\pi f_{fin}/Tch = 2\pi\,(0.5\cdot10^{10})$, rad/s²

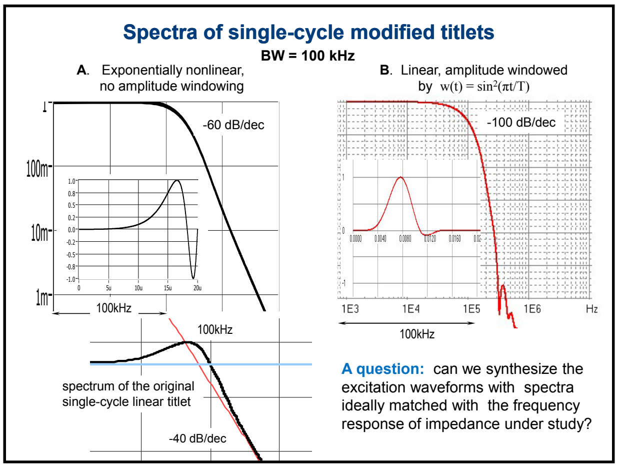
Final phase value $\theta_{fin}|_{t=Tch} = 2\pi$

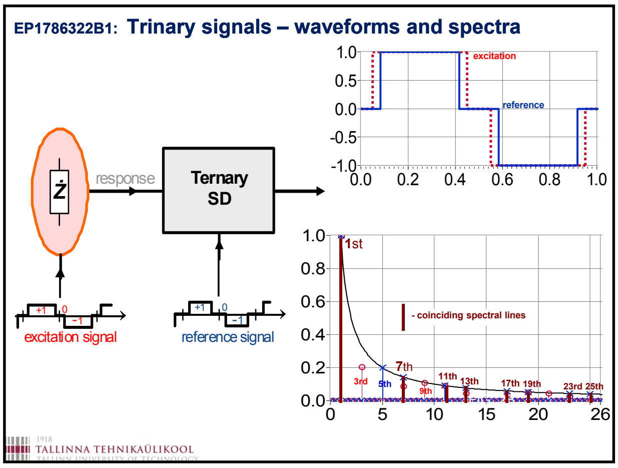
Energy and power of titlets

1. Energy of the generated signal $E = \int_0^{T_{ch}} v^2(t) \cdot dt$, V²·s
2. Average power of the generated signal $\overline{P} = \frac{1}{T_{ch}} \int_0^{T_{ch}} v^2(t) \cdot dt$, V²



Signal waveform v(t) BW=100 kHz	p number	Tch µs	E, V²·µs nJ @ 1 kOhm	EBW, V²·µs nJ @ 1 kOhm	EBW/E %	P, V² mW @ 1 kOhm
	1	20	8.25	7.74	94 good	0.41
	1/ 2	10	3.78	3.43	91 good	0.38
	1/ 4	5	1.52	0.81 very bad	54 bad	0.30
BW=100 kHz 0.5 power level	Not scalable	5	5.00	3.25	65 quite low	1.00 excellent


Spectra of single-cycle modified titlets
BW = 100 kHz
A. Exponentially nonlinear, no amplitude windowing
B. Linear, amplitude windowed by w(t) = sin²(πt/T)
-60 dB/dec
-100 dB/dec
100kHz
spectrum of the original single-cycle linear titlet
-40 dB/dec
A question: can we synthesize the excitation waveforms with spectra ideally matched with the frequency response of impedance under study?


EP1786322B1: Trinary signals – waveforms and spectra
excitation
reference
response
Ternary SD
excitation signal
reference signal
1st
- coinciding spectral lines
3rd
5th
7th
9th
11th
13th
17th 19th
23rd 25th
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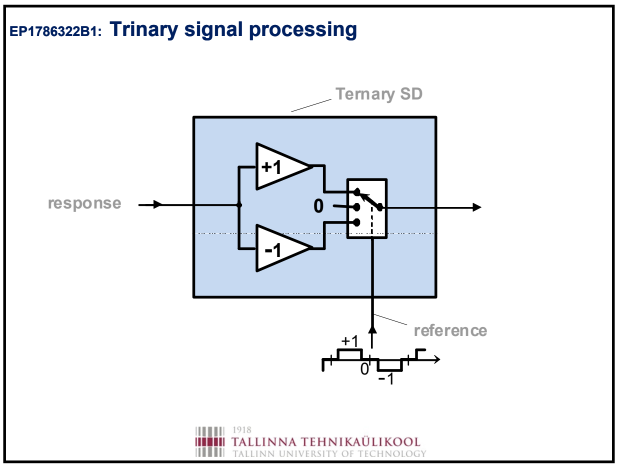
EP1786322B1: Trinary signal processing
Ternary SD
response
+1
0
-1
reference
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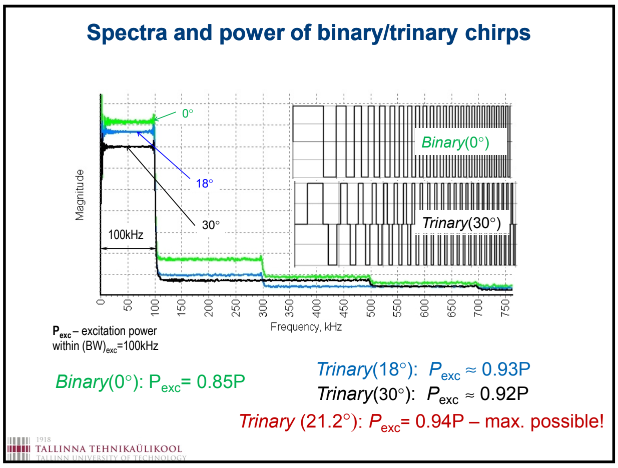
Spectra and power of binary/trinary chirps
Magnitude
0°
18°
30°
100kHz
Binary(0°)
Trinary(30°)
Frequency, kHz
Pexc – excitation power within (BW)exc=100kHz
Binary(0°): Pexc= 0.85P
Trinary(18°): Pexc ≈ 0.93P
Trinary(30°): Pexc ≈ 0.92P
Trinary (21.2°): Pexc= 0.94P – max. possible!
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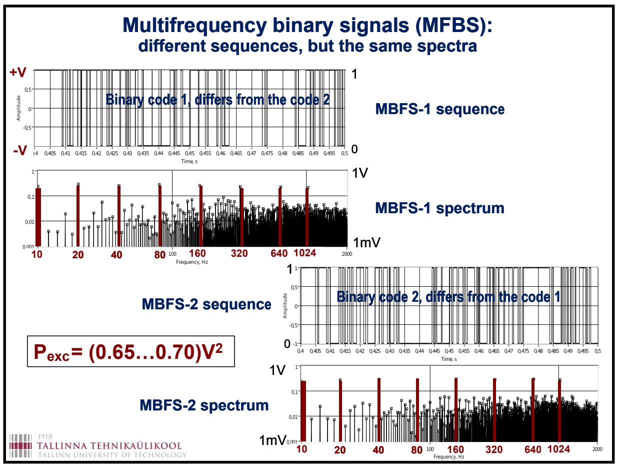
Multifrequency binary signals (MFBS): different sequences, but the same spectra
+V
-V
Binary code 1, differs from the code 2
MBFS-1 sequence
1V
MBFS-1 spectrum
1mV
10 20 40 80 160 320 640 1024
MBFS-2 sequence
Binary code 2, differs from the code 1
Pexc= (0.65…0.70)V²
MBFS-2 spectrum
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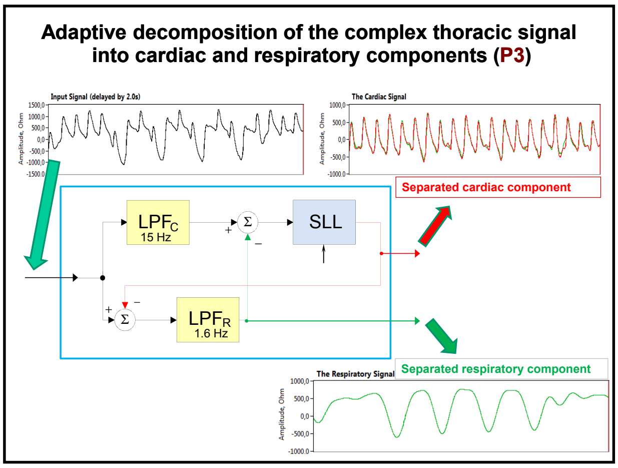
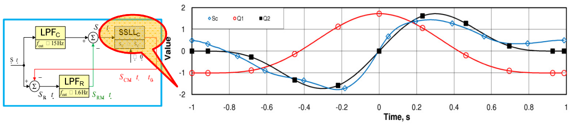

Adaptive decomposition of the complex thoracic signal into cardiac and respiratory components (P3)
Input Signal (delayed by 2.0s)
The Cardiac Signal
Separated cardiac component
LPFC 15 Hz
Σ
SLL
LPFR 1.6 Hz
The Respiratory Signal
Separated respiratory component

Cardiac Signal Model



Application-specific orthonormal basis (ASOB) has been designed applying the N^{th} order **Gram-Schmidt Process**

$$W^{A,B}(t) = (1 - t)^{A}(1 + t)^{B}$$ - **Jacobi weight function**

Summary

Short rectangular pulses in time domain spectroscopy cover a wide range spectrum, but the the spectral density of excitation energy is low. Also, there is no possibility to choose the **excitation time** and **frequency range** independently (no scaleability)

Simultaneous applying of several sine wave excitations with different frequencies (**multisine**) is a better, but complicated solution.

We propose specific chirp based excitation signals as **chirplets** and **titlets**, also **binary and ternary chirps and chirplets** for carrying out the fast and wide band scalable spectroscopy of dynamic objects.

Also **multi-sine binary and ternary** (trinary) **signals** are proposed for excitations in impedance spectroscopy and tomography.

Synthesis of the above mentioned excitation signals enables to provide independent, both **time and frequency domain scalable spectroscopy**, which can be adapted to the given measurement situation (speed of impedance variations, frequency range, S/N level, etc).

Synthesis of the **application specific orthonormal signal basis** enables to separate the signals with partly overlapping spectra.

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