

WIND INSTRUMENT SYNTHESIS BY MEANS OF CYCLICAL SPECTRA

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ABSTRACT

Background: *The Variophon is a wind synthesizer, that was developed at the Musicological Institute of the University of Cologne in the 1970/80ies and at that time is based on a completely new synthesis principle: the pulse forming process. The central idea of that principle is, that every wind instrument sound can basically be put down to its excitation impulses, which independently of the fundamental always behave according to the same principles. In a recent project, supported by the German Research Foundation (DFG), it is planned to digitally rebuild the Variophon in an improved version.*

Aims: *The aim of the software-based modelling of that synthesis principle is both, creating an experiment system for analyzing and synthesizing (wind) instrument sounds, as well as building a synthesizer, that would be an alternative to comparable Physical Modelling applications, because on the one hand this sound synthesis technique accounts for the place where the sound is generated, on the other hand just a single breath controller is required to produce all the sound-nuances, that are possible on a real instrument.*

Method: *First of all the analogue circuits of the different instrument modules of the Variophon will be mapped onto a digital representation by means of the analogue circuit simulation software LTSpice. In a second step the Digital Variophon will be rebuilt in the modular environment Reaktor, made available by Native Instruments, and finally the experiment system will be programmed in C++ by means of the VST-Development Library (Virtual Studio Technology by Steinberg).*

Results: *The analogue circuit boards of trumpet and bassoon are already digitally implemented in LTSpice and NI Reaktor. Time and frequency domain analysis of some instrument specific generated static tones in pp, mf and ff as well as different intensity sweeps show an extensive concordance of Variophon and Digital Variophon. As expected in the current phase of the project, in comparison to an original trumpet or bassoon sound, spectral differences can be observed, resulting from the limited technical feasibility at that time.*

Conclusions: *A software-based Variophon makes it possible to bypass these restrictions, as for example, to synthesize the excitation impulses of original instruments by means of cosinusoidal or polygonal impulses, where the rising and falling edges of the impulses can be adjusted freely. Furthermore some important features of*

the sound production process, as the multiplicative interconnection between pulse forming and breath noise, can now be considered.

Keywords – timbre, sound synthesis, wind instruments, acoustics, pulse forming

1. INTRODUCTION

The pulse forming principle as a synthesis method for wind instrument sounds was developed in the 1970ies at the Musicological Institute at the University of Cologne, Germany, by Jobst Fricke and Wolfgang Voigt. The pulse forming can be seen as a kind of alternative or extension to the better known physical modelling. The central idea of that principle is, that every wind instrument sound can basically be put down to its excitation pulses, which independently of the fundamental tone always behave according to the same principles, and in which Karl Erich Schumann's Principles of Timbre are reflected (Schumann 1929, p.15-18, 98, 100). In 1975 Fricke (1975, p.407) and Voigt (1975, p.51,54) discovered the principles of generating wind instrument-like spectra with typical stable formant areas and spectral gaps evoked by the excitation pulses of double-reeds or lips.

2. CYCLICAL SPECTRA

Constant opening or closing times of the reeds and lips are the basic condition for stable formant areas, independent of the pulse frequency. That means, while the fundamental frequency may vary, the pulse widths have to remain the same. Besides the pulse width, there are several other factors, influencing the resulting cyclical spectra (Fricke 1989, p.115f.; Reuter 1995, p.75-84). Rather small changes of the pulse width or the pulse form cause a modification of the relevant spectrum and therewith an audible change of timbre.

A comparison of the excitation pulses in the time domain with corresponding spectra in fig.1a and fig.1b show, that the ratio of the pulse width τ and the cycle T determines the spectral gaps in the frequency domain. Having a pulse width of τ and a cycle of T one can find the spectral gaps at the partials $n \cdot (T/\tau)$ with $n \in \mathbb{N}$. This corresponds to Karl Erich Schumann's principle of formant areas: Independent from the pitch and without the necessity of any bandpass filter, the position of the spectral minima and maxima remain constant because of

a constant width of the excitation pulses (only at low frequencies a low pass filter effect can be found, caused by the sound-hole or bell, which in many cases is too small for the radiation of the lowest frequencies).

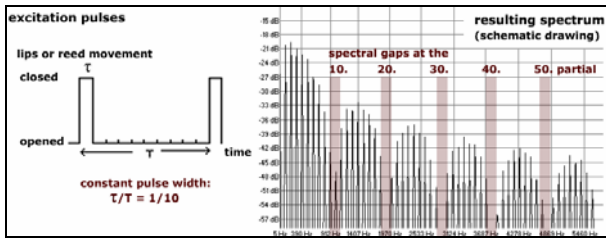


Figure 1a. Constant pulse width ($\tau/T=1/10$) and the resulting spectral envelope.

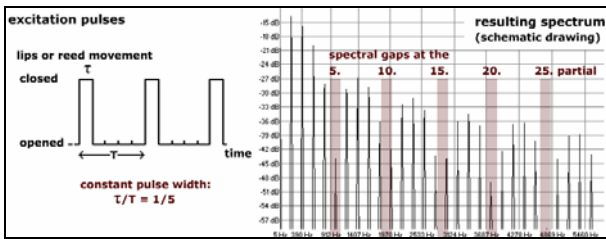


Figure 1b. Constant pulse width ($\tau/T=1/5$) and the resulting spectral envelope.

In fig.2 the pulse forming principle is schematically illustrated using an isosceles triangle pulse. Having a pulse width of τ and a cycle of T the spectral gaps can be found at the partials $2n \cdot (T/\tau)$ with $n \in \mathbb{N}$.

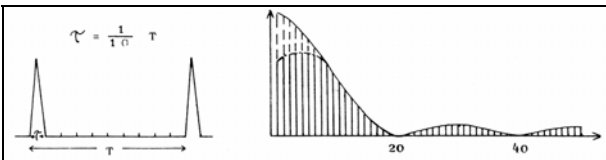


Figure 2. Constant triangle pulse width ($\tau/T=1/10$) and the resulting spectral envelope (after Voigt 1975, p.53)

If T/τ is no integer, the following functions describe the spectral distribution of energy for square pulses (1) and isosceles triangle pulses (2).

$$|C_k| = \frac{2F}{T} \cdot \frac{\sin \frac{\pi \cdot k \cdot \tau}{T}}{\frac{\pi \cdot k \cdot \tau}{T}}, k_o = \frac{T}{\tau} \quad (1)$$

$$|C_k| = \frac{2F}{T} \cdot \frac{2 \left(1 - \cos \frac{\pi \cdot k \cdot \tau}{T}\right)}{\left(\frac{\pi \cdot k \cdot \tau}{T}\right)^2}, k_o = \frac{2T}{\tau} \quad (2)$$

$|C_k|$ is the amplitude of partial k , F the pulse area and k_o describes the ordinal number, for which the partial's amplitude becomes a minimum for the first time (see Voigt 1975, p.52).

This demonstrates the spectral gaps' dependency on the exact pulse form. Concerning triangle pulse chains, Auhagen supplied evidence, that not the described ratio of pulse width and cycle duration is responsible for the spectral gaps, but the partition ratio of the rising and falling edges as shown in fig.3 (Auhagen 1987, p.710).

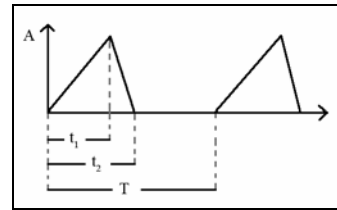


Figure 3. Triangle pulse chain (after Auhagen 1987)

That way, triangle pulses with different widths could produce spectra with the same spectral gaps, if the duration of one edge as a common divisor is kept constant. If $t_1 \neq t_2$, the gaps are unequally distributed, as it is shown in fig.4 (see Auhagen 1987, p.710).

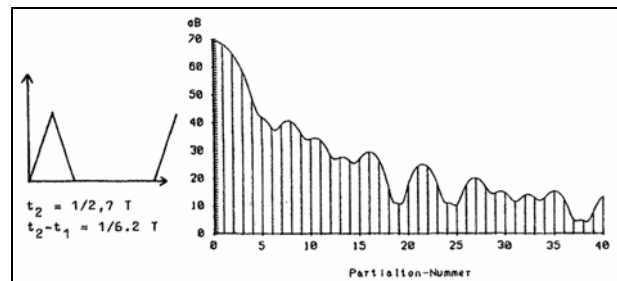


Figure 4. Triangle pulse ($t_2 = 1/2,7 T$ and $t_2 - t_1 = 1/6,2 T$) and the resulting spectral envelope (Auhagen 1987, 711)

Playing a tone on a double reed instrument in *ff*, the rising and falling edges of the pulses, representing the transition from opening to closing movements of the reeds and vice versa, are less smooth than they are, when playing a tone in *pp*. As can be seen in fig.5, a *pp* played tone has not only a more rounded shape than a *ff* played tone, but the higher partials are also less prominent than in the spectrum of a *ff* tone.

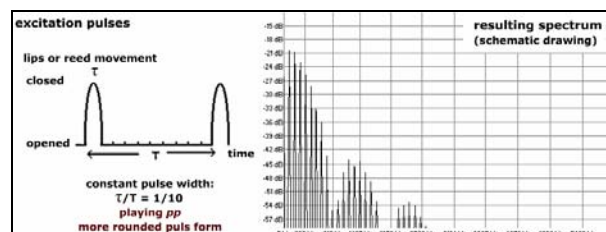


Figure 5. Constant pulse width ($\tau/T=1/10$) played *pp* and the resulting spectral envelope

With other words: The more squared the shape of the pulses, the stronger are the amplitudes of the higher partials. The shorter the width of the constant pulses, the more the spectral gaps and formant areas can be found at the higher partials. This corresponds to the principle of shifting and skipping formant areas found by Karl Erich Schumann.

3. THE VARIOPHON

The electronic technician Jürgen Schmitz saw the potential and possibilities of these pulse forming principles and he began to develop a wind synthesizer based on electronic pulse chains with constant widths modulated by a breath controller. Using that technology, he created the first prototype in 1977, the Martinetta, followed by the Variophon in 1979. Serialized by the Euskirchen Realton Company, the Variophon is the first and only synthesizer working on the basis of this natural pulse forming process. To keep the idea and the electronic circuit secret, he encapsulated the circuit boards of the single instrument modules into epoxy resin.

Unfortunately the disappearance of Schmitz caused the ruin of the Realton Company and also stagnancy in the scientific work on this field (exceptions: the experiments of Wolfgang Auhagen (1987) and Johannes Blens (1993)). Beside this he left behind an enigma in these epoxy resin encapsulated black boxes: how did it work? What was the electronic circuit which is the core of the whole synthesis principle and which is covered unresolved below this layer until now?



Figure 6a. Martinetta (1977)

4. THE DIGITAL VARIOPHON

In a recent project, supported by the DFG, it is planned to digitally rebuild the Variophon. In a second step, the sound production process, based on the pulse forming principle, ought to be improved, since a software-based version makes it possible to bypass some restrictions, resulting from the limited technical feasibility at that time, as for example, to synthesize the excitation impulses of original instruments by means of cosinusoidal or polygonal impulses, where the rising and falling edges of the impulses can be adjusted freely.

An important step in the rebuilding process was made, when diagrams of the circuit boards together with some unencapsulated instrument modules could be found and analysed. Now it was possible to measure the shape of the originally used pulses as well as the sound transformation in dependence of frequency and dynamic at every single point of the circuit.



Figure 6b. Variophon with supplies (1979)

To be able to modify any parameter of the circuit for the purpose of analysing the influence of the different units, it was necessary to map the analog circuit onto a digital representation by means of an analog circuit simulation software. To this end the switching regulator design program by Linear Technology, SwitcherCAD III and the circuit simulation engine LTSpice were used.

4.1. Formalisation

In a pilot study, the general framework of the pulse forming core on the circuit boards of the different instrument modules was analysed in order to formalise the so far gathered results within the circuit simulation engine. The formalisation is necessary to transfer the non-realtime model created in LTSpice to a realtime playable model in NI Reaktor.

The formalisation process is exemplarily described for the bassoon instrument module. The pulse widths of the square pulses were measured at the timer device on the circuit board (NE555) for every pitch from A1 (55 Hz) to E4 (329,6 Hz). The dynamic value that usually is determined by the manually blown breath controller was controlled by an adjustable power supply unit (100 mV steps from 1000 mV [pp] to 3200 mV [ff]). As the first analyses revealed, the pulse width gradually changes with the dynamic value but there are only 3 different pitch registers, where different pulse widths could be found. A low register from A1 to C#3, a mid register from D3 to G#3 and a high register from A3 to E4. The pulse height was for every pitch and dynamic value constant around 4,5 V (see fig.7).

The exact structure of the functions determines the timbre gradient and therefore the specific character of the instrument sound. The oboe for example has only two registers with completely different pulse widths for the corresponding dynamic values, whereas at the trumpet instrument module not only the pulse width

function is different but also the height of the pulses varies.

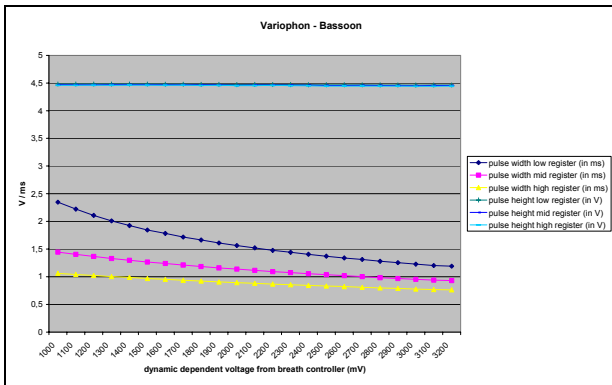


Figure 7. pulse widths and heights of the Variophon bassoon module in dependency of pitch and dynamics

4.2. The pulse width formula

By applying a polynomial regression for the measured values of every register, one got the following manageable set of functions (3,4,5) for the low register ($f(x)_{low}$), the mid register ($f(x)_{mid}$) and the high register ($f(x)_{high}$) for $1 \leq x \leq 23$ and x being the dynamic value.

$$f(x)_{low} = -0,00009x^3 + 0,0053x^2 - 0,1292x + 2,4576 \quad (3)$$

$$f(x)_{mid} = -0,00001x^3 + 0,0011x^2 - 0,0419x + 1,4832 \quad (4)$$

$$f(x)_{high} = -0,000004x^3 + 0,0004x^2 - 0,0213x + 1,083 \quad (5)$$

When implementing these equations in a NI Reaktor framework, the core function of the original Variophon bassoon sound module is already usable in realtime as a digitised model. But to realize an even more natural instrument it is necessary to abandon the concept of different registers and develop a function that includes pitch as a continuous parameter. In the following equation (6) i is the pulse width in ms, c is the pitch range in cent (for example $c=3100$ for a pitch range from A1 to E4), y is the played pitch in cent with the lowest pitch within the defined pitch range as 0 cent and k is an exponent for defining the kind of pitch dependency (for example a logarithmic or exponential dependency).

$$i_{x,y,c,k} = f(x)_{low} - \left((f(x)_{low} - f(x)_{high}) \cdot \frac{y^k}{c^k} \right) \quad (6)$$

5. DISCUSSION

The specific functionality of the Variophon was unsolved a long time, but by means of the newly-discovered material it is now possible to build the Variophon as a software synthesizer. For this reason

research can be continued, that abruptly ended 25 years ago.

Besides the possibility of synthesizing more realistic excitation impulses by means of sinusoidal or polygonal impulses, where the rising and falling edges of the impulses can be adjusted freely, the described formalisation is another example for the potentiality resulting from the transfer to the digital platform.

The developed software should furthermore be capable to serve as an experiment system for analyzing and synthesizing wind instrument sounds, though the pulse forming principle should work for other wind instruments, where typical formants can be found.

6. ACKNOWLEDGEMENTS

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