Casio VZ Virtual Instrument:
A replica of the Casio VZ-1/VZ-10M music synthesizer

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See https://github.com/matthias-wolff/Casio-VZ-virtual-instrument/blob/master/Casio-VZ-virtual-instrument.pdf
for the latest version of this document.

Abstract

In this project I try to rebuild the vintage Casio VZ-1/VZ-10M music synthesizer in Reaktor 6 [6]. The primary goal is a fully functional player which is compatible with MIDI editor/librarian software like Midi Quest [8] or the like. My workplan is

1. make some debugging and development tools (waveform validator, envelope validator, etc.),
2. reproduce the 8 core waveforms of VZ-1/VZ-10M (1x sine, 5x sawtooth-like waveforms created by Casio's Phase Distortion Modulation, 1x white noise, 1x pitch-sensitive narrow-band noise),
3. implement the core sound engine (wavetable oscillators, phase and ring modulators, VCAs, oscillator circuits),
4. implement control signal generators (amplitude envelope, key following, layering, parametric sensitivity characterisitcs, etc.),
5. implement MIDI SysEx control capability, and
6. reproduce the factory voice and operation libraries.

I always strongly disliked the unpleasant—though most characteristic—aliasing and analog noise of the VZ-1. Hence, I will not attempt to reproduce this. Insofar, the remake is not intended to be perfect.
As a secondary goal I may want to reproduce the GUI of the original instrument. This would be a nice-to-have, however not necessarily of much practical use.

Contents

1 Goals and Prerequisites

In this project I try to rebuild the vintage Casio VZ-1/VZ-10M music synthesizer in Reaktor 6 [6]. The primary goal is a fully functional player which is compatible with MIDI editor/librarian software like Midi Quest [8] or the like. My workplan is

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1.1 The VZ-1/VZ-10M Music Synthesizer

[**TODO:** ...]

1.2 The Reaktor 6 Modular DSP Lab

[**TODO:** ...] [6]

1.3 The Midi Quest 12 Editor/Librarian Software

[**TODO:** ...] [8]

2 Development and Debugging Tools

2.1 Waveform Validator

[**TODO:** ...]

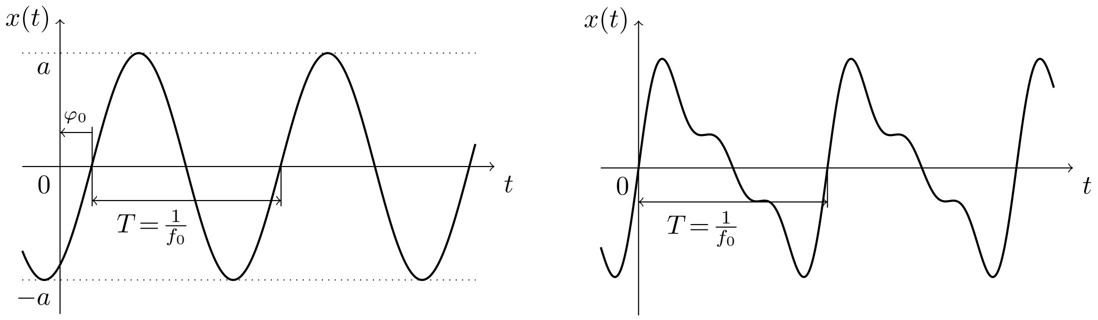
2.2 Envelope Validator

[**TODO:** ...]

3 Development and Debugging Tools

4 Core Sound Engine

VZ's sound engine is called "iPD (interactive phase distortion) modular sound engine" [2, p. 12]. According to Casio, this is an enhanced version of the phase distortion modulation introduced by the predecessor of the VZ-1 called CZ-1 [3, p. 39]. Actually, the VZ synths series seem to feature wavetable oscillators—with waveforms partly generated by the original PD synthesis—together with ordinary phase modulation and ring modulation.



(a) A sine tone
$x(t) = a\sin(2\pi f_0 t + \varphi_0)$

(b) A tone composed of three sines
$x(t) = \frac{2}{3}\sum_{n=1}^{2}\frac{1}{n}\sin(2\pi n f_0 t)$

Figure 1: Examples for basic musical tones. The tone frequency—measured in Hertz—is denoted by f_0. We denote time by t and the duration of one cycle by T. Both are measured in seconds. The argument of the sine functions are called phase angles φ. One cycle corresponds to a phase difference of $\Delta\varphi = 2\pi$.

4.1 Theory

I assume that the reader is familiar with the basics of signal processing. Introductions can be found in [5] and [7].

4.1.1 Tones, Timbre, Frequency, and Pitch

A musical tone is a periodic sound. Fig. 1a shows an example of the most basic musical tone, a sine. Its mathematical representation is

$$x(t) = a\sin(2\pi f_0 t + \varphi_0), \tag{1}$$

where a denotes the amplitude, f_0 denotes the tone (or fundamental) frequency, and φ_0 denotes a phase offset.

Remark: Throughout this report I will assume continuous time signals $x(t)$ which, unless stated otherwise, take real values in $-1 \leq x(t) \leq 1$, even though we actually talk about digital signals of course. However, this simplification saves some notational trouble.

Fig. 1b shows an example of another basic tone composed by the mixture of three sine tones. The timbre of a musical tone can be described mathematically by the coefficients of its FOURIER series, i.e., the amplitudes and phase offsets of sine tones with frequencies $f = n \cdot f_0$ constituting the composed tone (see, e.g., [5, p. 102–113]). More complex tones comprise aperodic components (noise) and varying timbre over time.

As human perception of sound frequency is nearly logarithmic, Western music theory commonly uses the pitch

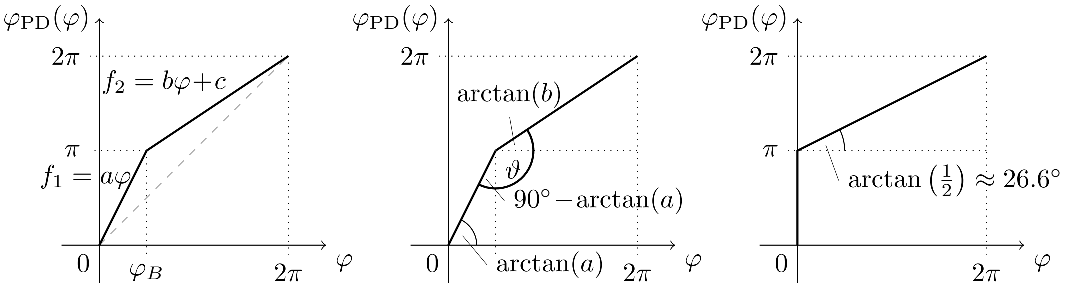
$$p = 1200 \cdot \log_2\left(\frac{f_0}{f_{\mathrm{a}^1}}\right) \tag{2}$$

measured in Cents (ct). The quantity in the denominator is a reference frequency. I will use the concert pitch $f_{\mathrm{a}^1} = 440\,\mathrm{Hz}$. Musical intervals can be measured in terms of pitch. E.g., a semitone spans 100 ct, a fith spans 500 ct, and an octave spans 1200 ct. Solving Eq. (2) for f_0, we obtain a formula for converting pitch to frequency:

$$f_0 = f_{\mathrm{a}^1} \cdot 2^{\frac{p}{1200}}. \tag{3}$$

4.1.2 Phase Distortion Modulation

Phase distortion modulation (PDM) was invented in the early 1980's by I. TOMITA, Y. TAKAHASHI and collegues of Casio Computer Ltd. for the CZ music synthesizer series [4]. Fig. 4 shows an example from the CZ manual. The VZ series uses wavetables basing on PDM.



(a) Piecewise linear phase charateristics

(b) Distortion angle ϑ, $135° \leq \vartheta \leq 180°$

(c) Minimum distortion angle $\vartheta_{\min} \approx 116.6\,°$, $a \to \infty$

Figure 2: Characteristic curve of phase distortortion

Core element of PDM is a phase distortion characteristic curve as shown in Fig. 2a [1, p. 20–21]. We see that the curve consists of two straight sections

$$f_1(\varphi) = a\varphi, \qquad 0 \leq \varphi < \varphi_B, \quad \text{connecting points } (0,0) \text{ and } (\varphi_B, \pi), \text{ and} \tag{4}$$
$$f_2(\varphi) = b\varphi + c, \quad \varphi_B \leq \varphi < 2\pi, \quad \text{connecting points } (\varphi_B, \pi) \text{ and } (2\pi, 2\pi). \tag{5}$$

The slope a of the first section is variable and can take real values ≥ 1. The start and end points of the sections define the following constraints

$$f_1(\varphi_B) = a\varphi_B = \pi \qquad \rightsquigarrow \varphi_B = \frac{\pi}{a} \tag{6}$$
$$f_2(\varphi_B) = \frac{\pi}{a}b + c = \pi \tag{7}$$
$$f_2(2\pi) = 2\pi b + c = 2\pi \tag{8}$$

From Eqs. (6) to (8) follows

$$b = \frac{a}{2a-1} \quad \text{and} \quad c = \frac{2a-2}{2a-1}\pi, \tag{9}$$

and finally

$$\varphi_{\mathrm{PD}}(\varphi) = \begin{cases} a\varphi & \text{for } 0 \leq \varphi < \frac{\pi}{a} \\ \dfrac{a\varphi + 2\pi(a-1)}{2a-1} & \text{for } \frac{\pi}{a} \leq \varphi < 2\pi \end{cases} \qquad \text{with } a \geq 1. \tag{10}$$

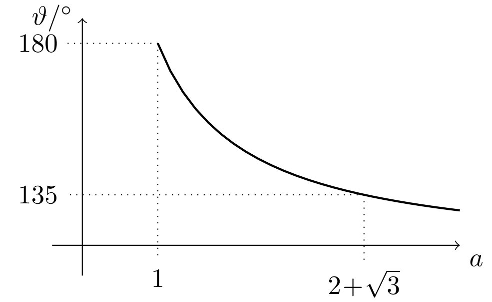
Modulation depth can also be expressed by the angle between the straight sections

$$\vartheta/° = 180 - \arctan(a) + \arctan(b) = 180 - \arctan(a) + \arctan\left(\frac{a}{2a-1}\right) \tag{11}$$

measured in degrees (see Fig. 2b). Literature states that the permissible range is $135° \leq \vartheta \leq 180°$ [4]. However, for the wavetable of the VZ series this restriction does not seem to hold. Measurement yielded angles down to 123° corresponding to slope parameters $a > 10$ (see `matlab/PDMwaves.mlx`). As I did not manage to solve Eq. (11) for a, I just plot the function and print a lookup table in Fig. 3.

Six out of eight VZ-1 wavetable samples are phase-shifted and phase-distorted sine waves:

$$x(\varphi) = \sin\left(\varphi_{\mathrm{PD}}(\varphi) - \frac{\pi}{2}\right). \tag{12}$$

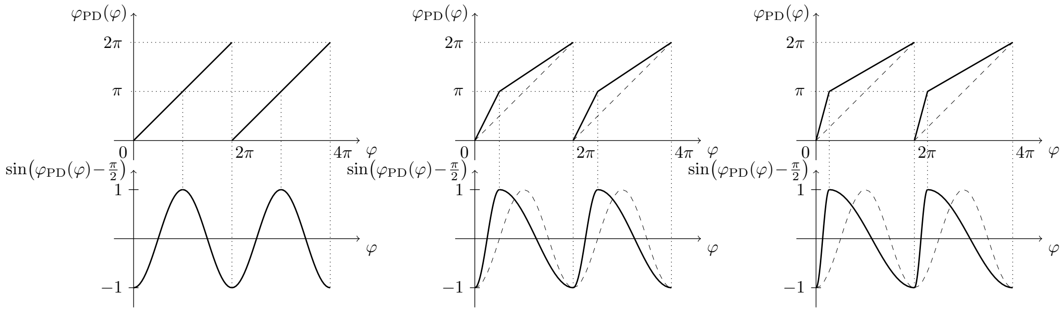


(a) Distortion angle parameter ϑ as a function of slope parameter a

$\vartheta/°$	a	$\vartheta/°$	a
116.6	∞	150	2.02
120	20.07	155	1.74
125	8.19	160	1.52
130	5.14	165	1.35
135	$2+\sqrt{3} \approx 3.73$	170	1.21
140	2.92	175	1.10
145	2.39	180	1.00

(b) Lookup table

Figure 3: Relation between distortion angle parameter ϑ and slope parameter a, see Eq. (11)



(a) $\vartheta = 180°$ $(a = 1)$ no modulation

(b) $\vartheta = 150°$ $(a \approx 2)$

(c) $\vartheta = 135°$ $(a \approx 3.73)$ resembling a sawtooth signal

Figure 4: Example of phase distortion modulation of the function $\sin\left(\varphi - \frac{\pi}{2}\right)$ adapted from [1, p. 20–21, Figs. 1–3]. Phase angles $\varphi < 0$ and $\varphi \geq 2\pi$ are wrapped into the base interval $0 \leq \varphi < 2\pi$.

Fig. 4 shows some examples.

Issue: Actually, VZ-1 seems to produce the inverted waveforms:

$$x_{\text{VZ-1}}(\varphi) = -\sin\left(\varphi_{\text{PD}}(\varphi) - \frac{\pi}{2}\right) = \sin\left(\varphi_{\text{PD}}(\varphi) + \frac{\pi}{2}\right). \tag{13}$$

Remark: An alternate phase distortion characteristic $f(x)$ with domain $0 \leq x < 1$ taking values $0 \leq f(x) < 1$ may be needed for Reaktor implementation:

$$f(x) = \begin{cases} ax & 0 \leq x < \frac{1}{2a} \\ \dfrac{ax + a - 1}{2a - 1} & \frac{1}{2a} \leq x < 1 \end{cases} \quad \text{with } a \geq 1. \tag{14}$$

4.1.3 Wavetable Osciallators

The original VZ-1/VZ-10M is apparently based on wavetable oscillators [2, p. 34]. Such oscillators contain a set of digital waveforms, each comprising exactly one signal period. Depending on the pitch, these waveforms are played back at different rates. **[TODO: ??]** shows an example of a VZ waveform (`SAW4`).

Formally, a single waveform can be expressed by

$$w(\varphi) \quad \text{with } 0 \leq \varphi < 2\pi, \tag{15}$$

where the argument φ is a phase angle. A oscillator based on this waveform uses a time-varying phase angle $\varphi(t)$. Its output signal can be written as

$$x(t) = w\big(\varphi(t)\big) = w\big(2\pi(f_0 t \bmod 1)\big) \quad \text{with } -1 \leq x(t) \leq 1 \tag{16}$$

where w denotes a waveform, $f_0 \in \mathbb{R}^{>0}$ denotes the note frequency in Hertz, and t denotes the time in seconds. Further, we denote by

$$x \mod 1 := x - \lfloor x \rfloor \quad \text{with } 0 \leq (x \mod 1) < 1 \tag{17}$$

the decimal fraction of the real valued quantity x. Hence, the argument $\varphi(t) = 2\pi(f_0 t \bmod 1)$ on the right side of Eq. (16) involves resetting the phase angle of the waveform to zero whenever the cycle length 2π is surpassed. [**TODO: ??**] shows an example.

We will use the circuit symbol [**TODO: . . .**] for a wavetable oscillator.

4.1.4 Phase Modulation

4.1.5 Ring Modulation

4.2 VZ Hardware

The VZ series features eight waveforms: sine (`SINE`), five sawtooth-shaped waveforms created by phase distortion modulation (`SAW1`–`SAW5`), white noise (`NOISE1`), and narrow-band noise (`NOISE2`).

4.3 Replica

4.3.1 Voltage-Controlled Oscillators (VCO)

In order to read the wavetable out of my VZ-1, I proceeded as follows

1. Initialize a new voice,
2. Mute all oscillator modules except `M1` and configure line `A` as `MIX` in `MENU 1/00`,
3. In `MENU 1/02`, set `M1` to a fix pitch of [**TODO:** `OCT=??`, `NOTE=??`, `FINE=??`] to generate tones with a frequency of $46^7/_8$ Hz (see below),
4. Configure all amplitude controls of `M1` for maximum signal output and set a trivial amplitude envelope mimicking a mere gate signal,
5. Disable all LFOs and MIDI controllers on `M1`.

I recorded with the Komplete Audio 6 sound interface at a sampling frequency of $f_S = 48\,\text{kHz}$. Each waveform in the wavetable shall contain $K = 1024$ samples for one full cycle. Hence, the "natural" frequency of the waveforms—i.e., when reading out at 48 kSamples per second—is

$$f_0 = \frac{f_A}{K} = \frac{48000\,\text{Hz}}{1024} = 46^7/_8\,\text{Hz} \tag{18}$$

which corresponds to the musical note F#1 + 23 ct. Using the fix pitch settings above, one cycle of the waveform being recorded is exactly 1024 samples long and no resampling is necessary.

4.3.2 Voltage-Controlled Amplifiers (VCA)

5 Control Signal Generators

6 MIDI SysEx Control

Issue: Reaktor 6 does not seem to support MIDI SysEx. Circumvent by control automation?

7 GUI Replica

- LCD dot matrix display 96×64 pixels

References

[1] Casio Computer Co., Ltd. *Casio CZ-1 Operation Manual*, 1987. Available online: https://www.manualslib.com/download/1156999/Casio-Cz-1.html.

[2] Casio Computer Co., Ltd. *Casio VZ-1 User Manual*, 1988. Available online: https://www.manualslib.com/manual/358586/Casio-Vz-1.html#product-VZ-1.

[3] S. de Furia and J. Scacciaferro. *Power Play VZ - The Essential Guide to Practical Applications*. Hal Leonard Publishing Corp., 1989. ISBN 0-88188-871-0. Available online: https://www.manualslib.com/manual/358586/Casio-Vz-1.html#product-VZ-1.

[4] H. Gerdes. Workshop: Casio CZ/VZ und die Grundlagen der Phase Distortion Synthesis. Online: https://www.amazona.de/workshop-casio-czvz-und-die-grundlagen-der-phase-distortion-synthesis/, Dec. 2009.

[5] Rüdiger Hoffmann and Matthias Wolff. *Intelligente Signalverarbeitung 1 - Signalanalyse*. Springer Vieweg, 2nd edition, 2014. ISBN: 978-3-662-45322-3.

[6] Native Instruments GmbH. Reaktor 6 Modular DSP Lab. Online: https://www.native-instruments.com/en/products/komplete/synths/reaktor-6. retrieved: Aug. 30, 2019.

[7] A. V. Oppenheim and R. W. Schafer. *Discrete-Time Signal Processing*. Pearson, 3rd edition, 2014. ISBN: 978-9332535039.

[8] Sound Quest Inc. Midi Quest 12. Online: https://squest.com/Products/MidiQuest12/index.html. retrieved: Aug. 30, 2019.