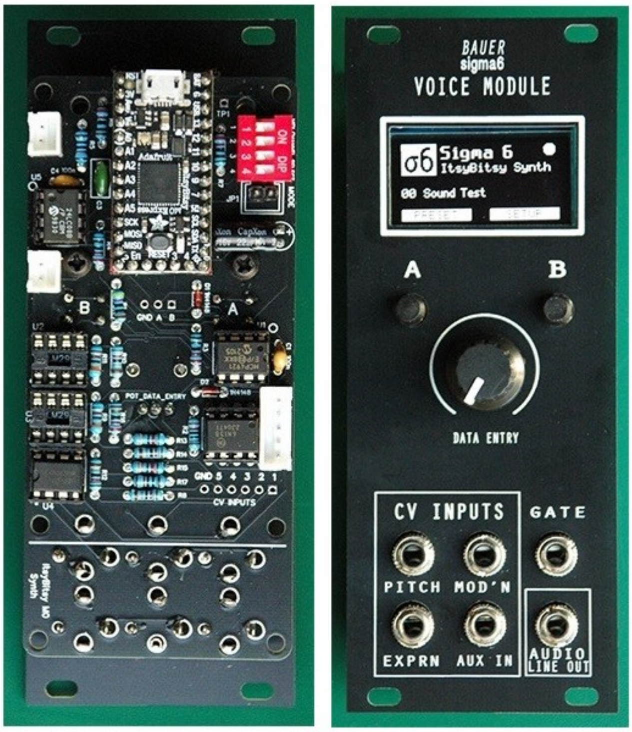
Bauer "Sigma-6" MIDI Sound Synthesizer

Design and Operation

Sigma-6 "Mother" Synth – based on PIC32MX MCU



"ItsyBitsy M0" Sigma-6 Voice Module – based on ATSAMD21 MCU

Overview

The "Sigma-6" is a MIDI-controlled digital monophonic sound synthesizer implemented entirely in software using a 32-bit micro-controller (without hardware floating point math). The synth can be played with any type of MIDI controller, for example a MIDI keyboard, wind controller (EWI) or MIDI sequencer.

Tone Generation

The synth model comprises 6 identical wave-table oscillators feeding into a mixer. Each oscillator generates a pure sinusoidal wave-form. The frequency of each oscillator is determined by the MIDI note number (from Note-On messages) multiplied by an "Oscillator Frequency Multiplier" factor (patch parameter). This parameter is settable to one of 12 fixed values, as shown in the table (next page).

An additive synthesis technique is applied to generate a desired sound timbre. The Sigma-6 synth engine provides 6 "partials" each settable to one of 12 frequencies relative to the fundamental. Moreover, each oscillator may be detuned independently. Although similar in concept to the Hammond "draw-bar" organ tone generator, an advantage of the Sigma-6 design is that it allows amplitude modulation of each oscillator independently, by a choice of modulation sources including MIDI modulation or expression CC messages, MIDI key velocity, 2 envelope generators ("contour" or ADSR), or low-frequency oscillator (LFO).

A problem which has plagued other simple digital synthesizer designs is aliasing of high-order audio frequency partials with the sampling frequency. The Sigma-6 firmware avoids this problem by calculating the frequency of each oscillator whenever a note is initiated and when its frequency is modified. If the frequency of any oscillator is higher than half the sampling rate (*aka* "Nyquist rate"), then that oscillator is muted. This process guarantees that the audio output signal will be devoid of aliasing artefacts.

User Interface

The front-panel user interface comprises a graphic LCD panel, six push-buttons and six potentiometers feeding into ADC inputs on the micro-controller.

The control pots allow adjustment of six patch parameters at a time. Which group of six parameters out of a total of 42 is determined by the row selected in the "Patch Parameter Matrix". (See table, next page.) The "active" group is selected by a push-button scrolling through the available groups. The six parameters in the active group (table row) are displayed on the LCD screen.

Patch parameters retain their stored (preset) values until a control pot associated with a particular parameter is moved. Then, that parameter value would be changed in accordance with the pot setting.

Instrument Presets

The micro-controller provides persistent storage for a collection of "instrument presets", also known as "patch programs". Each preset is an array of 42 parameters defining a particular patch. The user interface provides a facility to save the "active" patch in non-volatile memory for later recall. Another function is provided to load one of many predefined presets (stored in flash memory) which then becomes the "active" patch. Each stored preset has an ID number and a short name associated with it.

A stored preset may also be selected by a MIDI "Program Change" message. Program numbers are shown in the GUI screen for Preset Selection. (Note: Program numbers may change with firmware version.)

Patch Parameter Matrix

OSC1 FREQ. MULT.	**OSC2** FREQ. MULT.	**OSC3** FREQ. MULT.	**OSC4** FREQ. MULT.	**OSC5** FREQ. MULT.	**OSC6** FREQ. MULT.
MODULATION SOURCE	MODULATION SOURCE	MODULATION SOURCE	MODULATION SOURCE	MODULATION SOURCE	MODULATION SOURCE
DETUNE	DETUNE	DETUNE	DETUNE	DETUNE	DETUNE
MIXER LEVEL	MIXER LEVEL	MIXER LEVEL	MIXER LEVEL	MIXER LEVEL	MIXER LEVEL
CONTOUR START LEVEL	CONTOUR DELAY TIME	CONTOUR RAMP TIME	CONTOUR HOLD LEVEL	ENV2 ^ DECAY TIME	ENV2 ^ SUSTAIN LEVEL
AMPLD ENV ATTACK TIME	AMPLD ENV HOLD TIME	AMPLD ENV DECAY TIME	AMPLD ENV SUSTAIN LEVEL	AMPLD ENV RELEASE TIME	AMPLD CTRL MODE #
LFO FREQUENCY	LFO RAMP TIME	LFO AM DEPTH	LFO FM DEPTH	MIXER O/P GAIN	LIMITER LEVEL

^ ENV2 (EG2) is a “transient” envelope generator with fixed (short) attack time; release time = decay time.

Oscillator FREQUENCY MULTIPLIER values*

0	1	2	3	4	5	6	7	8	9	10	11
0.5	1	1.333	1.50	2	3	4	5	6	7	8	9

* The “fundamental” frequency (x1) is determined by the MIDI note number

Oscillator Amplitude Modulation Source

0	1	2	3	4	5	6	7	8	9
None	CONT+	CONT–	ENV2	MOD’N*	EXPRN+*	EXPRN–*	LFO	VEL+	VEL–

* MOD’N = MIDI CC01 | EXPRN = MIDI CC-2, CC-7 or CC-11

Mixer Output Gain

0	1	2	3	4	5	6	7	8	9
0.2	0.3	0.5	0.7	1.0	1.5	2.0	2.5	3.3	5.0

Output Amplitude Control Mode

0	1	2	3
CONST (1)	CONST (0.5)	ENV1 * VEL	EXPRN*

* EXPRN = MIDI CC-2, CC-7 or CC-11

Patch parameter can be overridden by a global configuration parameter, to allow selection between amplitude envelope or expression (CC), without the need to adjust the patch parameter in each preset selected.

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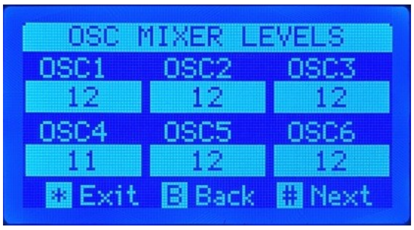
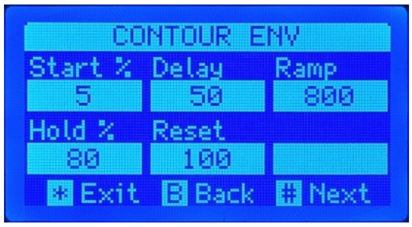
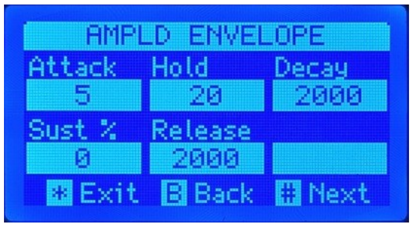
Following is a “map” of user-interface screens implemented in the Sigma-6 “Mother” model with six data entry pots. Note that the ‘ItsyBitsy M0’ synth has a simplified user-interface with only one pot.

‘Home’ screen

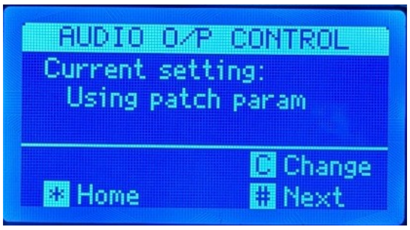
‘Patch’ screens

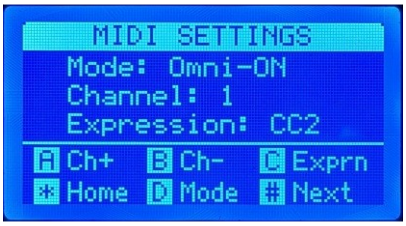






‘Config’ screens





‘Preset’ screens

‘Util’ & ‘Save’ screens

Note: Some screen-shots may be out-of-date with latest firmware release.

Configuration Options

The synth maintains a bunch of configuration options and control parameters which are independent of the selected preset. Examples: MIDI channel and message types recognised, audio amplitude control mode, vibrato control mode (auto, MIDI CC1 message, CV input), pitch bend mode, bend range, reverb level, etc.

Audio Output Amplitude Control

The Sigma-6 provides a choice of methods to control the overall audio output level (loudness). The choice depends on the type of instrument selected, which usually falls into one of two categories:

1. A percussive type of instrument such as a harp, piano, guitar, vibraphone, etc, where the audio level is best controlled by an envelope shaper, perhaps also responding to MIDI velocity data;
2. A wind instrument such as a flute, clarinet, oboe, etc, or an organ-like instrument, where the audio level may be best controlled by MIDI pressure or expression (control change) messages.

A patch parameter can be set to select either of these options. The setting therefore depends on the preset currently selected. However, the patch setting may be incompatible with the MIDI controller connected. For example, option 1 – envelope shaper and velocity control – is preferable for a MIDI keyboard or sequencer, whereas option 2 – pressure/expression control – is preferable for a MIDI wind controller (EWI).

To avoid needing to adjust the patch parameter for audio level control every time a different preset is selected, there is a “global” configuration parameter which overrides the individual patch settings. This setting can be found in the “Config” menu.

Presets and User Patch

In the Sigma-6 design, a “Preset” is simply a patch definition comprising up to 42 parameters stored in the MCU flash read-only memory (ROM). When a preset is selected, the patch parameters are copied from flash memory into data memory (RAM) where they can be modified using the Pot Control Panel. The RAM copy is called the “active patch”.

Preset zero is an exception… The “full-featured” Sigma-6 model (PIC32MX MCU) allows the active patch parameters to be saved in re-writable non-volatile memory (EEPROM). This is called the “User Patch”. To re-load the last User Patch saved, simply select Preset 0.

NB: The ‘ItsyBitsy M0’ Sigma-6 model does not support a User Patch, because only a small sub-set of active patch parameters are settable via the control panel (or via MIDI CC messages).

Explanation of Patch Parameters

Oscillator Frequency Multipliers

These param’s set the six oscillator frequencies relative to the fundamental which itself is derived from the MIDI note number whenever a note is initiated (or changed by legato). There is a choice of 12 frequency multiplier values, as given in the table below. Oscillator frequencies may be harmonics or sub-harmonics of the fundamental. In this context, a “sub-harmonic” is a frequency that is a non-integer multiple of the fundamental, e.g. 1/2, 3/2, 4/3. True harmonics are integer multiples of the fundamental, of course.

0	1	2	3	4	5	6	7	8	9	10	11
0.5	1	1.333	1.50	2	3	4	5	6	7	8	9

* The “fundamental” frequency (x1) is determined by the MIDI note number

Oscillator Mixer Levels

The output “signals” (samples) from the 6 oscillators are added together by a “mixer” process. As in a real audio mixer, the 6 input levels are variable. Oscillator signal amplitudes can be adjusted relative to each other to obtain a desired sound timbre, i.e. harmonic spectrum.

Mixer level is quantized into 16 steps (plus zero) on a logarithmic scale. The steps are 3 decibels apart. A value of 1 represents attenuation of −45dB; a value of 16 represents 0dB attenuation (full-scale).

Oscillator Detune

The frequency of each oscillator may be further adjusted so that it is not a precise harmonic (or sub-harmonic) of the fundamental. The range of adjustment is up to 600 cents lower or higher than “normal”. De-tuning one or more oscillators can result in a range of effects from subtle “chorus-like” sounds to radical atonal inter-modulation effects. Note that two or more oscillators can be set to the same fundamental (or harmonic order) and de-tuned differently to create a richer or more nuanced sound.

Oscillator Modulation Source

The six oscillators can be amplitude-modulated independently. This feature allows the “timbre” (harmonic composition) of the sound to vary as the note progresses in time. There is a choice of 10 modulation sources including “none” (i.e. constant amplitude), Contour envelope (positive or inverted signal), ADSR envelope (ENV2) which has a short attack time and variable decay/release, or MIDI control change messages (modulation lever = CC01, or expression = CC02, CC07 or CC11), or low-frequency oscillator (LFO, 0.5Hz to 25Hz), or MIDI key velocity (positive or inverted signal). The table below gives a summary:

0	1	2	3	4	5	6	7	8	9
None	CONT+	CONT−	ENV2	MOD’N*	EXPRN+*	EXPRN−*	LFO	VEL+	VEL−

* MOD’N = MIDI CC01 | EXPRN = MIDI CC-2, CC-7, or CC-11 (config. Option)

Contour Envelope

The Contour Envelope signal is a linear ramp which varies as time progresses from a (settable) “Start Level” to a “Hold Level” in a specified “Ramp Time”. The Start Level is maintained for a (settable) “Delay Time” after a note is initiated, before the ramp begins. Start and Hold levels are represented as a percent of full-scale. Delay and Ramp times are specified in milliseconds (0 to 5000).

The Contour envelope can be used to “morph” the sound from one harmonic spectrum to another, in a way that subtractive synthesis (using filters) is not capable. This is achieved by setting one or more oscillators to AM by Contour+ (non-inverted) and other oscillator(s) to AM by Contour− (inverted).

Transient Envelope (ENV2)

In the same GUI screen as the Contour EG, there are 2 parameters provided for an “ADSR” envelope generator (ENV2) the purpose of which is to generate a “transient” for modulation of any oscillator(s). ENV2 has a fixed short attack time (10ms). Decay and Release times are variable, but set by the same parameter (range 0 to 5000 milliseconds). Sustain Level is entered as a percentage of full-scale.

Some organs (e.g. Hammond) can produce a transient on a single “harmonic” (draw-bar), typically the highest-order harmonic, while other harmonics are keyed in simple “on/off” manner.

Amplitude Envelope

The Amplitude Envelope shaper (ENV1) controls the overall audio amplitude at the output of the mixer, provided that the associated parameter ‘Amp Ctrl’ is set accordingly. See section: “Audio Output Amplitude Control” (page 5). The envelope generator profile comprises 5 segments: Attack, Peak-Hold, Decay, Sustain and Release, all settable parameters. Note that a zero "Hold" time setting will result in the Peak-Hold and Decay segments being omitted, i.e. the Attack segment will be followed immediately by Sustain.

Low-Frequency Oscillator (LFO)

The LFO can be applied to modulate the output amplitude of any (or all) of the 6 audio oscillators, and/or to modulate the frequency of all 6 oscillators together. The parameter '**Osc FM**' determines the amount of FM applied, also known as "Vibrato Depth", specified in "cents" (percent of a semitone).

Parameter '**LFO AM**' is the amplitude modulation index specified as percent of full-scale. Setting LFO AM to 100% will result in the oscillator(s) output signal swinging from zero to maximum. Lower settings result in a reduced swing, but the output signal is always "clamped" to the maximum signal amplitude. For example, setting LFO AM to 20% would result in a swing from 80% to 100% of maximum amplitude.

LFO frequency is variable over a range of 0.5Hz to 25Hz in 10 steps. For a typical "vibrato" effect, set LFO frequency between 3 and 7 Hz. Note that oscillator FM (vibrato) depth can be set to ramp up from zero to the level set by parameter 'Osc FM Depth' in a specified time, '**Ramp ms**', after a delay from 'Note On'. The ramp start delay time is also set by 'Ramp ms', so the total time from 'Note On' (trigger) to full FM depth is actually double the 'Ramp on' time setting. This works well for the "automatic" vibrato mode.

Mixer Gain

When the 6 oscillator output signals are "mixed" (added together) the mixer output signal amplitude could be higher or lower than the output of any individual oscillator, depending on the relative oscillator frequencies and their corresponding mixer input levels. To compensate for a possible large deviation from the desired output level, a "Mixer Gain" parameter is provided. Set the value as high as possible to obtain a satisfactory overall loudness without "clipping" (overload, resulting in audio distortion).

If the output signal is not loud enough with a mixer gain of x10 (maximum), then consider increasing the mixer input levels of each oscillator in proportion. Increasing all oscillator input levels by the same number of steps will not change the sound timbre (i.e. the relative partial levels). Aim to have the maximum oscillator level at step 14, 15 or 16. If clipping (distortion) occurs, reduce the Mixer Gain setting.

Amplitude Control Mode

The audio signal amplitude at the output of the synth can be controlled by a choice of options, selected by the patch parameter '**Amp Ctrl**'. For details, refer back to the section: "Audio Output Amplitude Control".

Note: If the reverberation effect is enabled (reverb level set to non-zero), then the audio signal may persist after the "final" audio signal drops to zero. It may also exceed the "clipping" level.

Amplitude Limiter

Limiter Level is a patch parameter. When the mixer output signal exceeds the limiter level, it will clip, resulting in distortion. The distortion could be desirable… or not! The limiter functions like "overdrive" in a guitar amplifier. Adjust Mixer Output Gain and Limiter Level to achieve the desired effect. To disable the limiter, set the level to zero. This has precisely the same effect as setting the clip level to 97%.

How to modify or add a Preset/Patch

Patch definitions (presets) are stored in flash program memory. The only way to add a new preset is to enter the parameter data into the program source code and re-build the firmware. Patch definitions are written in the C source file: "sigma6_synth_data.c" (PIC32MX) or "ItsyBitsy_M0_synth.ino" (SAMD21).

Find the array initializer named "g_PresetPatch[ ]". Each preset definition takes this form:

```
{
  "Instrument Name",               // ##  <--preset number
  { 0, 1, 4, 6, 7, 10 },           // Osc Freq Mult index (0..11)
  { 0, 2, 0, 2, 0, 0 },            // Osc Ampld Modn source (0..7)
  { 0, 0, 0, 0, 0, 0 },            // Osc Detune cents (+/-600)
  { 14, 12, 0, 6, 0, 12 },         // Osc Mixer level/step (0..16)
  5, 20, 1000, 0, 300, 2,          // Ampld Env (A-H-D-S-R), Amp Mode
  0, 0, 200, 100,                  // Contour Env (S-D-R-H)
  200, 25,                         // ENV2: Dec, Sus %
  70, 5, 0, 70,                    // LFO: Hz x10, Ramp, FM %, AM %
  10, 0,                           // Mixer Gain x10, Limit %FS
},
```

The location and purpose of each constant value in the preset definition follows the format of the table "Patch Parameter Matrix" on page 3. Note that the values entered on the line "Osc Freq Mult index" are not the actual Oscillator Frequency Multiplier values. A number (index) identifying the required 'Osc Freq Mult' value is written in this group. Index values are given on the top row of the table titled "Oscillator FREQUENCY MULTIPLIER values" on page 5. Likewise, the "Osc Ampld Mod'n source" value is encoded.

Sigma-6 "Mother" (PIC32MX-based) Synth

The Sigma-6 "Mother" synth provides a utility function to output the "active patch" parameter values in a format suitable for copying into the C source file as a Preset definition. The data is transmitted via the console serial port. You will need to connect a PC running a serial Terminal application, for example "PuTTY" for Windows (free to download). Set the terminal baud rate to 57600.

From the Home screen, press button [**#**] to show the "Misc. Utility" menu. Then press button [**A**] to run the serial output function. Your terminal screen should show a listing something like this:

```
{ 1, 6, 9, 8, 0, 11 },          // Osc Freq Mult index (0..11)
{ 0, 0, 7, 0, 0, 0 },           // Osc Ampld Modn src (0..9)
{ 0, 33, -35, 0, 0, 0 },        // Osc Detune, cents (-600..+600)
{ 9, 13, 13, 0, 0, 0 },         // Mixer Input levels (0..16)
5, 100, 2000, 0, 2000, 2,       // Amp Env (A-H-D-S-R), Amp Mode
5, 20, 500, 95,                 // Contour Env (S-D-R-H)
500, 50,                        // ENV2: Decay, Sus %
30, 500, 10, 20,                // LFO: Hz x10, Ramp, FM%, AM%
10, 0,                          // Mixer Gain x10, Limit %FS
```

If you intend to re-build the firmware, copy and paste the text from the terminal screen into the source file. Add a line above with the new preset name, using the same structure as the existing patch definitions.

Be sure to email me the patch data for any appealing new sounds you create!

Addendum – How to Emulate Hammond Organ Sounds (approximately)

The Sigma-6 sound "engine" has similarities to the Hammond organ tone-wheel system. Whereas a typical draw-bar organ provides up to 9 harmonic frequencies added together in variable proportion, the Sigma-6 provides a maximum of 6 oscillator frequencies added together. Both systems are capable of generating a diverse range of sound timbres. However, the Sigma-6 software tone-generator differs from the Hammond electro-mechanical tone-wheel system in several ways, as follows:

- The mixer input level of each oscillator is adjustable in 16 steps (logarithmic scale, 3 dB apart), compared to 8 steps (approx. 4 dB apart) in the Hammond draw-bar system.
- Each of the 6 oscillators can be set to one of 12 frequencies relative to the "fundamental", including sub-harmonics at 1/2, 4/3 and 3/2 of the fundamental, plus harmonics at the 7thand 9thorder. (The Hammond system generates harmonics up to the 8th-order, but omits the 7th order.)
- Each of the 6 oscillators can be de-tuned independently up to +/- 600 cents (half an octave). (The relative tuning of the 9 partial frequencies in the Hammond system is not adjustable, although the tone-wheels are not precisely synchronized, which contributes to the Hammond's unique and appealing sound.)
- The amplitudes of the each of the 6 oscillators can be modulated independently by a choice of modulation signal sources, including MIDI modulation or expression CC messages, 2 envelope generators ("contour" or ADSR), or a low-frequency oscillator (LFO). This feature allows the timbre (harmonic composition) of the sound to vary as the note progresses in time.

Note that emulation of the Hammond tone-wheel system was **not** a design objective for the Sigma-6 synth. Nevertheless, the Sigma-6 is capable of generating sounds reminiscent of some Hammond-like sounds, plus a whole raft of sounds that the Hammond system is not capable of, due to its design limitations.

Draw-bar organs use a numeric "short-hand" notation to represent draw-bar settings, also known as the "registration". This is written as a set of 9 digits, each in the range 0 ~ 8. For example, 00-8050-200 sets the fundamental to level 8 (maximum = 0dB), the 3rd harmonic to level 5 (approx. −12dB) and the 5th harmonic to level 2 (approx. −24dB). All other harmonics have zero amplitude. This is a rough approximation of a descant recorder spectrum.

To translate a draw-bar registration to the Sigma-6 patch scheme, first choose up to 6 harmonics with the highest amplitude settings. Many Hammond registrations use 6 or less of the 9 available "harmonics". These translate easily to the Sigma-6 scheme. From the table below, note the relative frequencies of the harmonics required. Set each of the oscillators in the Sigma-6 to one of these frequencies, then set the corresponding mixer input amplitude to match the respective draw-bar setting.

Draw-bar number	1	2	3	4	5	6	7	8	9
Harmonic order	0.5	1.5	1	2	3	4	5	6	8
Sigma-6 Freq. Mult.	0.5	1.5	1.0	2.0	3.0	4.0	5.0	6.0	8.0

This table gives approximate equivalent Sigma-6 mixer levels corresponding to the 8 draw-bar settings used in Hammond organ registrations:

Draw-bar setting	0	1	2	3	4	5	6	7	8
Attenuation (dB)	X	−28	−24	−20	−16	−12	−8	−4	0
Attenuation (Av)	0	0.04	0.06	0.10	0.16	0.25	0.40	0.63	1.0
Sigma-6 mixer setting	0	7	8	9	11	12	14	15	16

Example: Translate the draw-bar registration **80-7654-030** to Sigma-6 patch parameter settings.

Solution:

Draw-bar number	1	2	3	4	5	6	7	8	9
Draw-bar setting	8	0	7	6	5	4	0	3	0
Sigma-6 Oscillator #	1	x	2	3	4	5	x	6	x
Sigma-6 Freq. Mult.	0.5	x	1.0	2.0	3.0	4.0	x	6.0	x
Sigma-6 mixer setting	16	x	15	14	12	11	x	9	x

Selection of popular Hammond organ registrations with equivalent Sigma-6 parameter settings:

Instrument Name	Draw-bar Registration	OSC1 Freq. Mult Mix Level	OSC2 Freq. Mult Mix Level	OSC3 Freq. Mult Mix Level	OSC4 Freq. Mult Mix Level	OSC5 Freq. Mult Mix Level	OSC6 Freq. Mult Mix Level
Bright Accomp.	87-8000-456	0.5 16	1.5 15	1.0 16	5.0 11	6.0 12	8.0 14
Full Swell Organ	30-7645-2xx	0.5 9	1.0 15	2.0 14	3.0 12	4.0 11	5.0 8
Melody Organ	80-0808-000	0.5 16	2.0 16	4.0 16	X 0	X 0	X 0
Electric Oboe	00-4675-300	1.0 11	2.0 14	3.0 15	4.0 12	5.0 9	X 0
Rock Organ	88-8800-000	0.5 16	1.5 16	1.0 16	2.0 16	X 0	X 0
Jazz Organ #1	30-5060-040	0.5 9	1.0 12	3.0 14	6.0 11	X 0	X 0
Jazz Organ #2	40-6160-040	0.5 11	1.0 14	2.0 7	3.0 14	6.0 11	X 0
Meditation	00-7800-453	1.0 15	2.0 16	5.0 11	6.0 12	8.0 9	X 0
Mellow Reed	00-8042-660	1.0 16	3.0 11	4.0 8	5.0 14	6.0 14	X 0
Pink Floyd	74-0004-000	0.5 - 14	1.5 - 11	4.0 - 11	0.5 + 14	1.5 + 11	4.0 + 11
Recorder	00-8271-200	1.0 16	2.0 8	3.0 15	4.0 7	5.0 8	X 0
Sumkinda Pipe	00-8360-400	1.0 16	2.0 9	3.0 14	5.0 11	X 0	X 0
Stopped Flute	00-7540-000	1.0 15	2.0 13	3.0 11	X 0	X 0	X 0
Swell Diapason	00-7866-540	1.0 15	2.0 16	3.0 14	4.0 14	5.0 12	6.0 11
Theatre Organ	87-8656-000	0.5 16	1.5 15	1.0 16	2.0 14	3.0 12	4.0 14

[X = Don't care, Osc. not used | +/- = Osc. de-tuned]