FM Synthesis VI, a virtual carillon bell

multiple sets 'simple FM'

An addition of multiple sets 'simple FM' offers the greatest freedom to design the overtones in a sound. We are going to discover this on the basis of a sound simulation of a carillon bell.

overtone characteristics of the bell sound

One of the first bell sound simulations with FM was the 'tubular bell' preset from the Yamaha DX7. This sound can be reduced to a set of 'simple FM' `c : m ratio 1 : 3.5`. According to the 'summation trick' (see FM Synthesis II) this yields the following side bands or overtones.

```
        (1+3.5=) 4.5 (+3.5=) 8 (+3.5=) 11.5 (+3.5=) 15 (+3.5=) 18.5 (+3.5=) 22
1
        (|1-3.5|=) 2.5 (+3.5=) 6 (+3.5=)  9.5 (+3.5=) 13 (+3.5=) 16.5 (+3.5=) 20
```

all partials put in order:

```
1       2.5     4.5     6       8       9.5     11.5    13      15      16.5    18.5    20
```

A spectrum with a mixture of harmonic partials (the integer frequency ratios) and the inharmonic partial frequencies, the partials with decimal numbers. From psycho-acoustics we know that harmonic overtones tend to fuse into an integer pitch sensation, fusion named. The smaller the integer numbers the greater the fusion. In this example, the harmonics in the spectrum, `1, 6, 8, 13, 15, 20, 22` do not form a real stable fusion into one integer timbre. This ambiguous timbre is due to the fact that the harmonic partials do not form a compact series, but rather form a non-compact series with consideral gaps. In short, the result yields a distinct bell-like sound with characteristics of fusion: a pitch impression. But also with characteristics of 'splitting', fission. Besides the basic pitch experience, we also hear more or less independent overtones accompanied by a noticeable pitch. That is, in this case, very obvious for the first overtone (`ratio 2.5`), which has a large interval (a tenth) above the fundamental (1). All in all characteristics that we also encounter in the sound of carillon bells.

the strike tone

Another important perceptual characteristic of (western church and carillon) bells sounds is called the strike tone. That is the metal-like sound at the time of the attack which determines the bell's pitch impression. Remarkably, this pitch sensation does not necessarily correspond to one of the partials of the bell. It is a psycho-acoustic phenomenon. If we mix pure tones, sine tones with simple or approximate harmonic frequency relationships, our perception is a pitch sensation corresponding to the great common denominator of these ratios. When we look on 'sound analysis of a carillon bell', we see that the octave, the twelfth and the triple octave, at the time of attack are very loud with frequency relation of `2 : 3 : 4`. The pitch that we percieve now is the called the virtual `1`, the strike tone. Notice: this is one octave below the octave partial.

the spectrum of a carillon bell

Below (in table 1) we see the partials of a carillon bell. Some bell partials have fixed names (in Dutch), these are also included in the table. We also see the initial loudness (in music notation) at the attack. The right column gives an impression of the relative decay times. The strongest harmonics are bold, obviously suggesting these are most important for the 'sound identity bell'. Table 2 is an abstaction of table 1, only the most important partials are included. When we hear a bell at a great distance it still is unmistakably a bell. In this case only the strongest partials are heard. The others are not observed. Due to the large listening distance they are below the hearing threshold. Piet van Egmond simulated bell sounds already in the sixties of the last century on the organ. In table 3 we see that he used only four organ pipes, two very wide open labials for the fundamental and the minor tenth, and two principal stops with rich overtones for the octave and the twelfth (according to my own aural analysis). Together with the reverberation in the church and playing style: fundamental and minor tenth sustained (sometimes with additional tremulant stop) and the principals rhythmically played as 'bim-bam' provided, certainly in those days, spectacular results.

table 1, sound analysis of a carillon bell

Reminder! European pitch notation, thus c1 equals C4 international

partial number		pitch with offset in cents	loudness	decaytime
1	**fundamental**	**c1 +31**	**mf**	**100%**
2	**priem**	**c2 +31**	**f**	**55%**
3	**kleine terts**	**dis2 +40**	**ff**	**75%**
4	kwint	g2 +23	mp	20%
5	**octaaf**	**c3 +31**	**fff**	**30%**
6	grote deciem	e3 +58	p	
7	1e undeciem	f3 -34	p	
8	2e undeciem	f3 -14	p	
9	**duodeciem**	**g3 +9**	**ff**	**20%**
10		a3 +2	pp	
11		b3 +32	pp	
12	**dubbeloctaaf**	**c4 +91**	**f**	**15%**
13		cis4 +13		
14		cis4 +22		
15		d4 +45		
16		dis4 +29		
17		e4 +60		
18	**dubbelundeciem**	**f4 +56**	**mf**	**10%**
19		fis4 +57		
20		fis4 +64		
21		g4 +11		
22		g4 +31		
23		gis4 +65		
24		a4 +18		
25		**a4 +46**	**mp**	**7.5%**
26		ais4 -7		
27		ais4 +16		
28		ais4 +36		
29		b4-6		
30		b4 +53		
31		c5 -30		
32		c5 -11		
33		c5 +17		
34	**trippeloctaaf**	**c5 +82**	**mp**	**5%**
35		cis5 +12		
36		cis5 +37		
37		cis5 +58		
38		cis5 +60		
39		d5 -4		
40		d5 +29		

After André Lehr from:
Leerboek der campanologie, Nationaal beiaardmuseum, Asten, 1976
also in
Campanologie, Koninklijke Beiaardschool Mechelen, België, 1996 ISBN 90-75832-01-X

(The analysis was based on a bell with fundamental pitch gis+31 cents. For convenience and comparison I transposed all partials up to fundamental pich c1)

table 2, the loudest and most important partials of a carillon bell and their names

fundamental	C4
prime	C5
minor third	D#5
octave	C6
twelfth	G6
double octave	C7

tripple octave C8

table 3, the notes and organ stops Piet van Egmond used for bell simulation on the organ

fundamental	C4	wide open labial
minor third	D#5	wide open labial
octave	C6	principal
twelfth	G6	principal

sideband bands generated by a 'simple FM' algorithm with
`c : m = 1 : 3`

N.B. European pitch notation

Ratio	offset (MIDI) note#.cents	note name (+/- cent)	bell partial
1	0	c1	**fundamntal**
2	12	c2	**prime**
4	24	c3	**octave**
5	27.86	e3 -14	**tenth**
7	33.69	ais3 -31	
8	36	c4	
10	39.86	e4 -14	
11	41.51	fis4 -49	
13	44.40	a4 +40	
14	45.69	ais4 -31	
16	48	c5	
17	49.05	cis5 +5	
19	51	dis5	
20	51.86	e5 -14	
22	53.51	fis5 -49	
23	54.28	fis5 +28	

sideband bands generated by a 'simple FM' algorithm with
`c : m = 2.38 : 8.38 (reduced to it's basic form: 1 : 3.52)`

Ratio	offset (MIDI) note#.cents	note name (+/- cent)	bell partial
2.38	15	dis2	**minor tenth**
6	31.02	g2 +2	**twelfth**
10.76	41.13	f3 +13	
14.38	46.15	ais3 +15	
19.14	51.10	dis4 +10	
22.76	54.10	fis4 +10	
27.52	57.39	a4 +39	
31.14	59.53	c5 -47	
35.90	62	d6	
39.52	63.65	e6 -35	
44.28	65.62	fis6 -38	

Notice the simmilarity between the two (transposed) spectra generated by respectivily almost identical `c : m ratios, 1 : 3` and `1 : 3.52`.
Mixed together these two spectra fuse into quite a convincing carillon bell sound.
A more convincing synthesis can be made by addition of a third spectrum with `c : m ratio` = `2 : 6` (notice i.e. basic ratio: `1 : 3`), thus this spectrum lies one octave higher than the first spectrum generated by `c : m = 1 : 3`).

The actual synthesis implementations for Clavia Nord Modular G2 (*Virtual Carillon.pch2*) and G2Demo (*Swinging Bell.pch2 and 3-Bells Peals.pch2*) may be down loaded form this website.

literature

'Leerboek der campanologie',
André Lehr
Nationaal Beiaardmuseum, Asten, 1976

CAMPANOLOGIE,
dr André Lehr
Koninklijke Beiaardschool "Jef Denijn" Mechelen, België, 1996
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Partial groups in the bell sound
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