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The Alternators of the Telharmonium, 1906

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Thaddeus Cahill's Telharmonium, as completed in the Spring of 1906 at Holyoke, Mass., generated tones by means of power alternators. Their construction and deployment are described, showing how they produced both equal temperament and just intonation. Of special interest is the "phantom" octave, a 6th octave coaxed from a 5-octave range of alternators.

Construction of the Alternators
Thaddeus Cahill began constructing his full-sized commercial Telharmonium, for the generation and distribution of electrical music, in 1902. He first demonstrated the instrument to the public and the press in March, 1906. The tones were produced by alternating current dynamos of the inductor variety. As an iron tooth moved past an electromagnetic field, it generated an alternating current in the armature of the inductor. The stator was constructed to carry both the electromagnetic field windings, or coils, and the armature windings. The number of north and south pole pieces in the stator corresponded to the number of rotor teeth. Since the pole pieces were interspersed with armatures, the stators had to be cut with twice as many teeth as the rotors. The pole pieces were maintained in a state of constant excitation by a 185-hp constant-speed dc motor, which also rotated the pitch shafts bearing the massive alternators. As one rotor tooth would approach and recede from the stator, a current wave would be induced in the opposite armature coil. The current would rise continuously from zero to maximum positive value, then fall through zero to maximum negative value, and finally rise again to zero. Consequently, a sine wave would be induced in the armature coil. All the armature windings were in series, so the sum of currents generated at all the teeth in the alternator would be available at the output.[1]

In order to produce a sine wave, the teeth of the inductors had to be most carefully curved. This was common practice in the construction of alternators, but was difficult to achieve in the fabrication of the high-pitched units with their numerous small teeth. After cutting the teeth of an alternator, Cahill would run it and measure its wave shape. He could then further mill the teeth to attain more nearly the exact voltage curve desired.[2] He also found that simpler dish alternators, in which the armatures and pole-pieces (instead of teeth) were circumferentially mounted on rotating disks, were preferable to the toothed-cylinder type of inductor to produce the lowest fundamentals.[3]

Deployment of the Alternators
In the original patent design, there were 12 pitch shafts tuned to the equal-tempered scale. Each was to carry 7 fundamental alternators, 6 3rd-partial alternators, and 5 5th-partial alternators. The frequency relationships are shown in Table 1.[4] All the alternators on a shaft were to be tuned in just intonation. Each key would have up to 10 separate electrical contacts for the various harmonics of its note, to connect the keys to various alternators, all on the same pitch shaft. The pitch of a single al-

ternator could, of course, be routed to more than one key.[5]

Insofar as the dearth of harmonics in the upper pitches was concerned, Cahill asserted that this was not objectionable, since their presence would make the notes "sharp and cutting."[6] Furthermore, some weak 3rd and 5th harmonics would still be present, the sine waves of the higher frequencies not being perfectly pure. He admitted that mechanical and electrical difficulties militated against their production and limitations in receivers against their proper transmission.[7]

Only 8 of the projected 12 pitch shafts were eventually built (C, D, E^b, E, F, G, A, B^b), owing to their huge expense and the pressure to put the machine into service.[8]

Cahill had executed all of his original patent designs specifying a span of 7 fundamentals covering 6 octaves on one pitch shaft. The massive shafts were milled to accommodate 18 alternators each and no more, except for one shaft that could hold an additional dynamo. After they were fabricated, the indispensability of the 7th harmonic for brass synthesis surfaced.[9] In order to avoid constructing longer shafts to hold additional 7th-harmonic alternators (which would have necessitated a new mainframe, a more powerful motor, additional switchboards—essentially a rebuilt Telharmonium), 3 existing alternators were divested from each shaft in order to make room for 3 7th-harmonic alternators. One of those discarded was the lowest alternator, thereby decreasing the range bridged by the pitch shaft from 6 to 5 octaves (see Table 2).

If each pitch shaft encompassed only 5 octaves, and 7/8 octave be added in going up the scale, the result is a 6-octave range. Yet, in describing the machine in 1906, the science writer Addams S. McAllister stated: "The frequencies obtained vary from 40 to 4000 cycles."[10] That is very nearly 7 octaves. Furthermore, Cahill long afterwards implied that the instrument had a 7-octave range: "...experience shows that 8 octaves are much preferable to 7."[11]

The missing octave is at the low end of the range, since Cahill stated that the highest A-alternator of the instrument was tuned to 3480 Hz.[12] That would place the frequencies of the 5 A-alternators below at 1740 Hz, 870 Hz, 435 Hz, 217.5 Hz, and the lowest at 108.75 Hz, more than an octave above the instrument's putative stretch to 40 Hz.

How could a phantom octave be cajoled from a 5-octave pitch shaft? There was indeed a way, pointed by McAllister's careful disclosure: the frequencies of 40-4000 Hz were only *obtained*, not *generated directly*, by alternators tuned to those frequencies.

A glance at the scheme of alternator tooth counts (Table 2) shows that the lowest 7 alternators possessed teeth in increments of 2 (4, 6, 8, 10, 12, 14, 16). In addition to their employment as various lower-order harmonics, these alternators also constitute the 2nd through 8th harmonics of the frequency of a non-existent 2-toothed alternator. That fundamental frequency, an octave below the 4-toothed alternator, could be formed as a difference tone. Any 2 or 3 adjacent harmonics, especially towards the lower compass of the series, sounded louder than *mezzo forte*, will create the sound of their fundamental. This is generated by simple addition and subtraction, in the reproducing system as well as directly in the ear. In fact, all of the harmonics in the series will be produced as sum and difference tones, or combination tones, reinforcing the sound of the fundamental. With up to 7 harmonics as the generating set, and

Table 1. Vibration Frequencies of All Alternators on One Pitch Shaft

Hz	Fundamental	3rd Partial (Perfect 5th)	5th Partial (Major 3rd)
3072		96n (288)	
2560			80n (240)
2048	64n (192)		
1536		48n (144)	
1280			40n (120)
1024	32n (96)		
768		24n (72)	
640			20n (60)
512	16n (48)		
384		12n (36)	
320			10n (30)
256	8n (24)		
192		6n (18)	
160			5n (15)
128	4n (12)		
96		3n (9)	
64	2n (6)		
32	n* (3)		

* n is the lowest in pitch of the fundamental alternators. The number of cycles per revolution of the shaft, which also equals the number of teeth or pole pieces on each alternator, is shown in parentheses.

Table 2. Number of Teeth on Each Alternator

	Hz	Fundamentals, 2nd, 4th, 8th Harmonics	3rd & 6th Harmonics	5th Harmonics	7th Harmonics
C	4138.4	128			
G	3103.8		96		
E	2586.5			80	
C	2069.2	64			
B^b	1810.6				56
G	1551.9		48		
E	1293.3			40	
C	1034.6	32			
B^b	905.28				28
G	775.96		24		
E	646.31			20	
C	517.31	16			
B^b	452.64				14
G	387.98		12		
E	323.32			10	
C	258.65	8			
G	193.99		6		
C	129.33	4			

Oscillation frequencies and tooth counts of the 18 alternators on the C-shaft. Note variances from the design described in Cahill's patents (Table 1): the range has been truncated and the 7th harmonics added.[13]

with their amplitudes carefully regulated to progressively diminish upwards, a reasonably convincing "two-toothed" fundamental would result. The individual pitches would more or less blend, although not disappear altogether, and would cause a brand new phantom note to appear.

Organ builder Robert Hope-Jones wrote of the Telharmonium: "It is interesting to observe how the resultant C [fundamental] is still heard when the ground tone has been practically all shut off and nothing but a chord of harmonics is left sounding."[14]

Cahill's patent descriptions make no mention of this technique. It must be remembered, however, that it was a familiar scheme with acoustic instruments. Helmholtz mentioned the phenomenon, which was particularly evident on the harmonium. Builders of this small reed organ even installed tuned resonators to enhance the effect.[15]

One pitch shaft had a 5-toothed alternator installed.[16] Exactly which shaft was not reported, so there is uncertainty about the pitch supplied. Such a tooth count would yield a major third above the lowest alternator. The second octave had no F#, G#, or C# , and the first of these cavities was probably the most painful. A 19th alternator on the D-shaft brought the total complement (18 x 8, + 1) to 145 alternators. The numbers 144 and 145 were constantly both reported as the full count throughout the instrument's entire tenure at Telharmonic Hall in New York from 1906 to 1908.

With 4 missing pitch shafts, a complete 12-tone tempered scale was unavailable on the Telharmonium. The 1st, 2nd, and 6th octaves did not even possess the full chromatic scale. However, there was great flexibility of pitch selection in the midrange: 4 separate frequencies could be tapped for the notes G and D, and 3 for each E, F, A, B^b, and C. These were employed for just-intonation intervals, usually major or minor thirds, in various keys. Every Telharmonic performance was a compromise, neither fully equal-tempered nor just-intoned, but a mix of the two.

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[1] John Grant, "The Electrical Generation of Music," *The American Telephone Journal*, October 27, 1906, XIV:17, page 269; Addams Stratton McAllister, "Some Electrical Features of the Cahill Telharmonic System," *Electrical World*, January 5, 1907, XLIX:1, page 22.

[2] Application of Thaddeus Cahill for letters patent to the Commissioner of Patents, April 26, 1915, filed April 27, 1915, National Archives no. 241, 1,213,804, page B15.

[3] *Ibid.*, pages B16, B17.

[4] *Ibid.*, pages B11-B12.

[5] *Ibid.*, pages B20-B22.

[6] *Ibid.*, page B22.

[7] *Ibid.*

[8] "Magic Music from the Telharmonium," *The New York Times*, December 16, 1906, part 3, page 3.

[9] Thaddeus Cahill, "The Electrical Music as a Vehicle of Expression," *Papers and Proceedings of the Music Teachers' National Association at Its Twenty-Ninth Annual Meeting, Columbia University, New York City, December 27-31, 1907*, 1908, page 209.

[10] McAllister, page 22.

[11] Application from Thaddeus Cahill, page B100.

[12] Thaddeus Cahill, "The Electrical Music as a Vehicle of Expression," page 208.

[13] "Magic Music from the Telharmonium," page 3; Daniel Gregory Mason, "Electrically Generated Music," *The New Music Review*, March, 1907, 6:64, page 239.

[14] Robert Hope-Jones, "The Future of the Church Organ," *The New Music Review*, February, 1908, 7:75, page 175.

[15] Hermann Ludwig Ferdinand Helmholtz, *On the Sensations of Tone*, Second English Edition, translated and conformed to the Fourth German Edition of 1877 with notes by Alexander J. Ellis, 1885, reprinted with an introduction by Henry Margenau, New York: Dover Publications, Inc., 1954, page 157.

[16] "Magic Music from the Telharmonium," page 3.