Approaching Microtonality in Spectral Music

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MUS 273: Spectralism

Introduction

The inception of spectral music ultimately cast a spotlight on the phenomenon of sound. By shifting the focus of composition from motive to model, composers of the spectral movement cultivated their musical grammar on physical and synthetic models of sound. These models, generally creating either harmonic and inharmonic spectra (Fineberg, 2000, pp. 85–95), were often based on the harmonic series—and its subsequent distortion—as well as frequency, amplitude, and ring modulation processes (for a list of other common models see Fineberg, 2000; Rose, 1996).

Due to this shift in compositional thought, the pieces composed in this style of music, when compared to pieces of music in the first half of the twenty-first-century and earlier, challenge our ears with novel harmonies and the abandonment of the all-too-familiar twelve-tone-equal-temperament. Furthermore, it is not uncommon for composers in the spectral school of though to raise or lower pitches by $\frac{1}{4}$ of a tone—even as little as $\frac{1}{8}$ of a tone—in an attempt to model their pre-compositional calculations.[1]

The deviation from equal-temperament introduces the listener to harmonic sonorities that may be contextually unfamiliar—for example, an orchestrated harmonic series played by orchestral instruments. But on the contrary, these sonorities may be entirely familiar on an implicit level. The harmonic series, for example, occurs far more frequently in every-day life than a listener may be aware of—one instance being the human voice, a sound experienced every day.[2]

Our familiarity with the harmonic series is the catalyst for this paper. Using four well-documented pieces of spectral music, I will compare the musicians' tuning in live performances to the composer's calculated as well as composed frequency spectra. The progression of pieces in the paper will begin natural and harmonic and end synthetic and inharmonic.

Beginning with Gérard Grisey's *Prologue* (1978) for solo viola and *Partiels* (1975) for 18 musicians, we can analyze the performed frequencies and measure if they tend to gravitate towards the calculated or the composed frequencies. I start with these two pieces because they both generate their pitch material with a natural harmonic series. I then analyze Tristan Murail's *Gondwana* (1980) for orchestra and Claude Vivier's *Lonely Child* (1980) for soprano and orchestra. These latter two pieces feature harmonic material that is generated using the process of frequency modulation resulting in an inharmonic spectrum. I chose both *Gondwana* and *Lonely Child* to measure if, in the presence of an inharmonic spectrum, performers tend to tune closer to the composed frequencies or if their ears can internalize the synthetic model and, instead, tune subconsciously to the calculated rather than the composed frequencies.

Method

For each piece discussed in this paper, I will apply the same analytical procedure. This procedure, which tracks decisions made at different stages of musical transmission—concept, realization, and transmission—allows me study three different pitch-related decisions: (a) the composer's decisions in rounding from calculated frequency to written pitch, (b) the performer's tuning of the pitch in comparison to the composer's written pitch, and (c) the performer's tuning of the pitch in comparison to the original calculated frequency.

First, I will generate the calculated frequency spectrum of the initial pitch material. This spectrum will be calculated from either the process that the composer has established as their generative process, or from an analyst who has identified the procedure used by the composer. The resultant frequency spectrum will then be applied to a Fast Fourier Transform (FFT) analysis.[3]

Next, I will refer to the pitches in the score and identify their frequency based on the table provided in Fineberg (2000, p. 83). Once the frequencies of the composed pitches have been identified, I will use them to generate a spectrum of sine-tones to produce a clear FFT analysis of the composed frequencies.

[1] These pre-compositional calculations can range from a harmonic spectrum, a distorted harmonic spectrum, a chord generated by frequency modulation, or even modeling a recorded sound.

[2] Depending on the shape of the mouth when speaking different phonemes, also known as formants (for more information see Moore, 2012, pp. 318–319), accentuate or diminish certain partials of the overtone series. These formants, acting as filters, shape how we listen to the harmonic series of the voice, but does not change the tuning or overtone structure of the voice.

[3] I exclusively use the FFT analysis instead of a spectrogram analysis because of the simplicity of the FFT's frequency representation. An FFT analysis also allows me to overlay multiple analysis for ease of comparison where a spectrographic analysis contains too much information.

Then, I will sift through as many live performances of the respective piece that I can find and extract the portion of audio relating to the spectrum analyzed in the previous two steps.[4] This audio will be analyzed using the FFT analysis, as described above. In some instances, the analyzed harmony makes multiple appearances in the score. In these situations, I will extract the audio from each of these repetitions to track how consistently performers tend to tune these spectral harmonies.[5]

The first two analyses, the conceptual and realized spectrum, will be superimposed onto the same graph to show the discrepancies—if any—between the calculated spectrum and the composed spectrum. Because there is only one concept and one composed spectrum, the FFT graph is the most efficient way to display the frequency deviations.

The analysis of the performed spectra, however, will produce a multitude of FFT analyses. It would be overwhelming and uninformative to try and overlay every instance of the live spectrum on top of the calculated and composed spectrum. Instead, I will apply a paired-samples T-test to measure if the difference between two means is statistically significant or not. Based on these results, I will plot the significant frequency differences against the conceptual and composed spectrum.

Applications

Prologue

Prologue (1978), for solo viola, was written by Gérard Grisey as the first piece in the suite of pieces titled *Les Espaces Acoustiques*—though it was written after the following two pieces in the suite, *Periodes* and *Partiels*. Grisey was faced with a particular challenge when writing *Prologue*: conveying a harmonic spectrum in a monophonic context (Baillet, 2000, p. 99). Much like the rest of *Les Espaces Acoustiques*, *Prologue*'s pitch material comes from the spectrum of a trombone playing the pitch E_1.[6]

To reflect the spectrum of the trombone, Grisey composed this piece in a series of melodic cells based off of the harmonics of the trombone. Using the harmonics 1, 2, 3, 5, 7, 9, 11, and 13, he generates cells containing the number of pitches respective of the harmonic number (Baillet, 2000, pp. 99–100). For brevity, I will be focusing primarily on the opening five-note cell featuring partials 3, 4, 5, 6, 7, and 9 (see Figure 1).

We begin our analyses with *Prologue* because of its clear relationship to the harmonic series. Looking at the opening cell in Figure 1, Grisey composes partials 5, 4, 6 ,9, 7, and 3, respectively, with each tone sounding monophonically. Figure 2 shows the FFT analysis of the strict calculated frequencies generated with the formula $f_n = (f_{fund} \cdot n)$, where n is the partial number, f_{fund} is the fundamental frequency, and f_n is the frequency of the partial number n.[7]

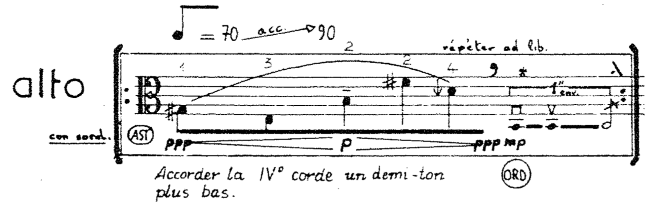

Figure 1
An excerpt of Prologue showing the composed notation of the first cell.

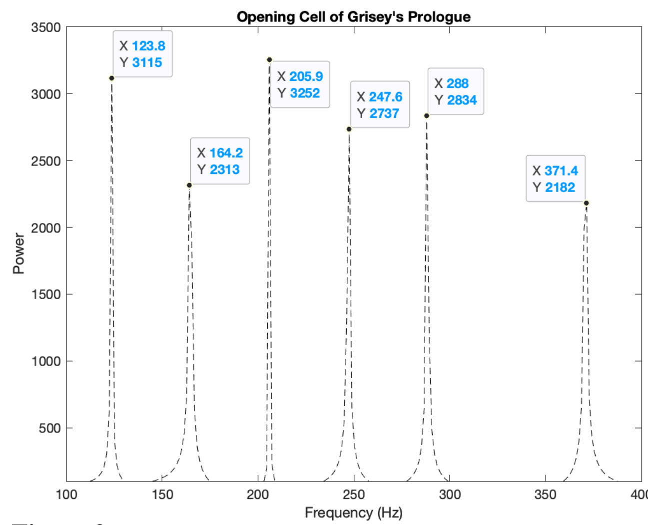

Figure 2
An FFT analysis showing the calculated partial numbers 3, 4, 5, 6, 7, and 9 with a fundamental frequency of 41.2 Hz.

Grisey, elects to round most of the pitches in this opening cell to their nearest $\frac{1}{2}$-tone with the exception of the D↓ (see Figure 1 above).[8] In Figure 3, superimposing the calculated spectrum's FFT analysis with the composed spectrum's FFT analysis it is clear how the pitches Grisey rounded to deviate from the calculated frequencies. Though there are noticeable deviations, the largest being 2.7 Hz in frequency bands 4 and 5, they are insignificant and virtually imperceptible.

To measure performers' interpretations of *Prologue* I ex-

[4]With the capabilities of recording, I avoid studio recordingsbecause they can potentially be dishonest due to possible pitch correction applied during post-production.

[5]This is in no way a measure of how correct or incorrect a performance is nor is it a measure of how good or accurate a particular performer or performance is.

[6]All octave numbers are labeled with middle C labeled as C_4

[7]The ordinate axis, power, is seldom considered in the analyses throughout this paper. Because of the need to manipulate calculations to better show the data, the power is often misconstrued at no detriment to the analysis.

[8]Grisey defines the accidental ↓ to indicate the lowering of a pitch by $\frac{1}{8}$ of a tone

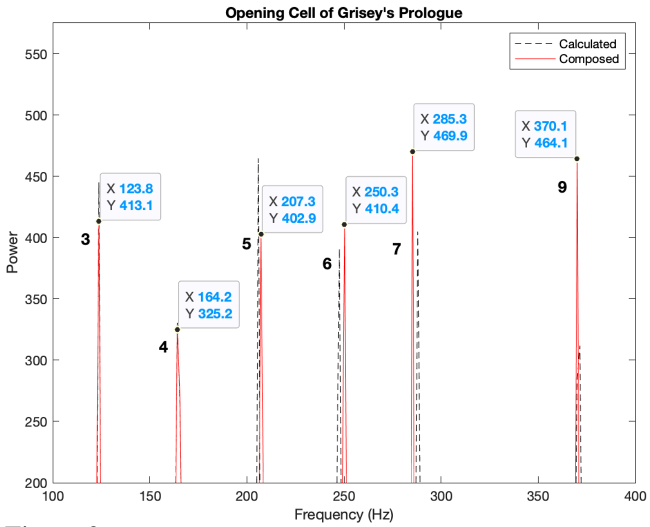

Figure 3

An overlay of the calculated and the composed spectra's FFT analyses. The frequency bands have been labeled with their partial number.

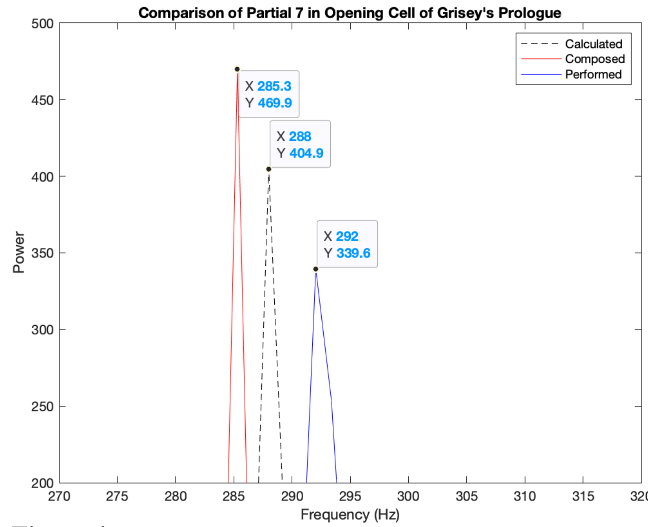

Figure 4

Comparison of the performed, calculated, and composed frequencies of the D↓.

tracted the audio from four different live performances.[9] I then sifted through each recording and extracted the audio for each D↓ to measure an instance of microtonality as it exists in a harmonic context.[10] After extracting the D↓ from each recording—twelve total for each recording—I measured the overall approach to tuning this pitch across all of the recordings using the paired-samples T-test. The frequency of this pitch, across all recordings, averages out to be 292.62 (± 3.58) Hz—1.04 Hz lower than a D♮.

According to Table 1, the live performance of this particular pitch had a 4.62 Hz, 95% CI [3.58, 5.66] and 7.32 Hz, 95% CI [6.28, 8.36] higher average frequency when compared to the calculated and compared target frequency, respectively. With a $t(47) = 8.94, p < .001$ and $t(47) = 14.170, p < .001$, the performed frequencies are statistically different when compared to the calculated and composed frequencies, respectively. Given these statistics, specifically the difference in means, performers are more likely to tune to the calculated, pure, frequency as it occurs in the harmonic series. Figure 4 shows the comparison of the performed, calculated, and composed frequencies.

Partiels

When writing *Partiels*, like *Prologue*, Grisey takes his pitch material from the E_1 harmonic series as played on the trombone. Instead of working in a monophonic context, *Partiels* reconstructs the overtone series through polyphonic orchestration. In general, the piece exploits the difference between harmonicity and inharmonicity through slow transitions between the two states. Starting in harmonicity, Grisey opens the piece with an orchestrated version of the harmonic series with a fundamental of E_1. For my analysis, I am choosing to focus on the opening chord because of its harmonic nature.

First, using the harmonic series formula, $f_n = (f_{\text{fund}} \cdot n)$, I generated a harmonic series. To identify which partials were used to generate the opening chord, I compared the frequencies of the written pitches in the score to the harmonic series. The partials that lined up were 2, 6, 10, 14, 18, 26, 30, 34, 38, 43, and 44. I then applied an FFT analysis to the calculated frequency spectrum generated from these partials.

When comparing the calculated and composed frequency spectrum in Figure 5, we see very little deviation. Between the calculated and composed spectra, the greatest frequency deviations occur are between 1236 Hz and 1244.51 Hz as well as between 1771.6 Hz and 1760 Hz, respectively. Although these discrepancies are larger than what we saw in *Prologue*, these differences, when considering the frequency range in which they occur, to changes of roughly $\frac{1}{16}$ of a tone.

To analyze the performed interpretation of this chord, I extracted the audio from every repetition of this chord from eight different performances for a total of 34 audio files. I applied an FFT analysis to each of the 34 audio files and took note of the performed frequencies for each pitch in the chord. When analyzing the audio from these different performances, due to a combination of recording quality and microphone placement (if any), not every pitch was identifiable

[9]Instead of extracting the entire piece, I extracted the first two-and-a-half systems—up until the first instance of the repetition of B_2

[10]Harmonic, in this context, references the harmonic/inharmonic binary.

Table 1
Paired samples statistics comparing the average frequencies of the performed (perf) D↓ to the calculated (calc) and composed (comp) frequencies in Prologue

Paired Differences

			95% Confidence Interval of the Difference				
Comparison	Mean	Std. Deviation	Lower	Upper	t	df	Sig. (2-tailed)
Perf–Calc	4.62	3.58	3.58	5.66	8.94	47	.000
Perf–Comp	7.32	3.58	6.28	8.36	14.17	47	.000

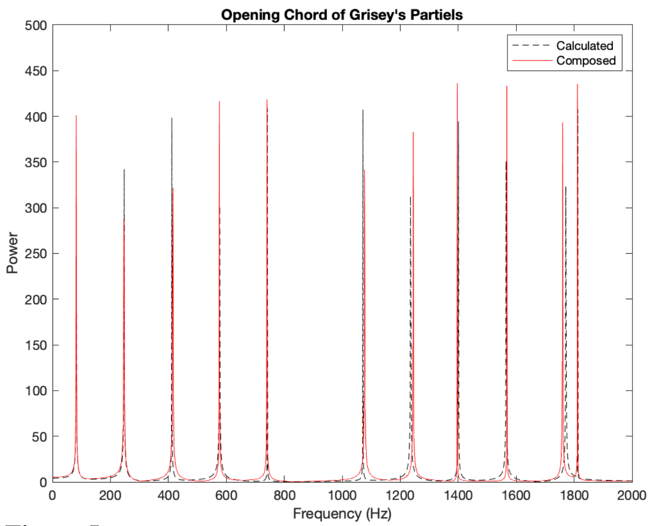

Figure 5
An overlay of the calculated spectrum's FFT analysis and the composed spectrum's FFT analysis.

across the range of recordings. Instead of guessing[11] what a particular frequency *might* be, I reduced the number of analyzed frequencies to those that were distinctly present in all 34 of the FFT analyses. These filtered frequencies translate to partials 2, 6, 10, 18, 30, 43, and 44. There was one particular frequency, due to its specific fine-tuning, that I wanted to measure that was not present in each of the recordings: the D↓ in the viola (partial 14).[12] Instead of the 34 data points, the D↓ frequency was analyzed from 26 recordings.

To determine if the differences between the average performed frequencies and the calculated and composed frequencies are statistically significant, I ran a paired-samples T-test comparing each individual frequency. I immediately removed partials 10 and 44 because the frequency differences weren't statistically significant. Partials 2 and 6 were removed because the frequency differences were less than 1.2 Hz, which I deemed aurally insignificant. Finally, due to the frequency of partial 43 (1771.6 Hz) and its maximum dynamic of *pianissimo*, the recorded frequencies were erratic with a standard deviation of 26.04 Hz—the second highest under partial 44 with a standard deviation of 59.06 Hz. With numbers as inconsistent as these, its difficult to say if it is a tuning or recording issue so I chose to exclude partial 43 from the analysis as well.

For the remaining partials, 14, 18, and 30, the paired-samples T-test resulted in statistically significant differences—with a $p < .001$—between the performed, calculated, and composed frequencies. Partial 18, an F♯$_5$ in the score, was performed (736.99 Hz) closer to the composed frequency (739.99 Hz) rather than the calculated frequency (741.6 Hz) with a mean difference of 2.99 and 4.6 Hz, respectively. Partials 14, and 30, however, were performed closer to the calculated frequencies. Partial 14, a D↓$_5$ in the score, when compared to the calculated frequency (576.8 Hz), deviated by 6.98 Hz from the performed frequency (583.78 Hz)—a difference of roughly $\frac{1}{6}$ of a tone—placing the performance of this pitch closer to an equal tempered D♮ (587.33 Hz). Of the three remaining partials, partial 30 contains the greatest difference between the performed (1228.71 Hz) and calculated (1236 Hz) frequencies and the performed and composed (1244.5 Hz) frequency: 7.29 Hz and 15.79 Hz, respectively. Figure 6 shows an FFT comparison of the three different stages of frequency transmission for partials 14, 18, and 30.

Gondwana

Unlike *Prologue* and *Partiels*, Tristan Murail's *Gondwana* (1980) features pitch material generated from an inharmonic process: frequency modulation. Frequency modulation (FM) follows the formula $F_i = |c \pm (m \cdot i)|$ where F_i is the resultant frequency of the index number (i), c is the carrier frequency,

[11] When analyzing an FFT of a complex audio file, frequencies with a tremendously low amplitude blend in to surrounding frequencies causing the frequency peak on the graph to be wide without a distinct "peak" frequency. Any frequency recorded for this broad frequency bands is potentially inaccurate and would reduce the accuracy of the reported data.

[12] The ↓ in *Partiels* indicates to lower the pitch by $\frac{1}{6}$ of a tone unlike in *Prologue* where it indicates lowering the pitch by $\frac{1}{8}$ of a tone

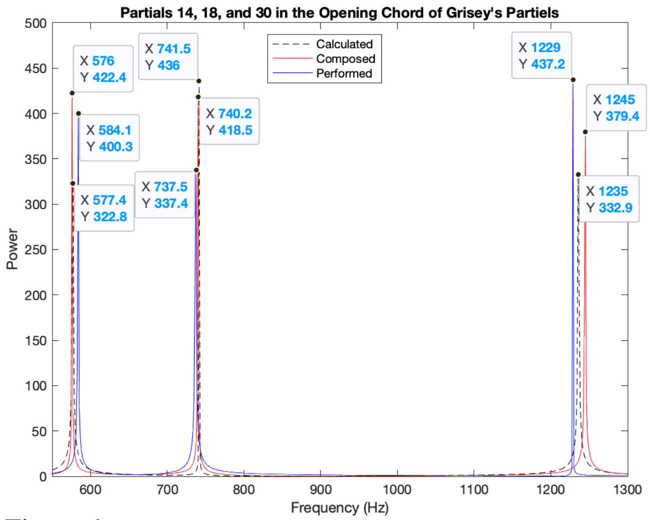

Figure 6

Comparison of the frequencies of partials 14, 18, and 30.

and m is the modulator frequency (Rose, 1996, p. 30). Because of this process, the resultant frequencies, depending on the m/c ratio (Rose, 1996, p. 30), often form an inharmonic spectrum.

Like the previous two case studies, the first step in the analysis is to replicate the spectrum based on Murail's calculations. According to Hirs and Gilmore (2009, pp. 96–97), Murail uses 392 Hz (G_4) as the carrier frequency and 207.65 Hz ($G\sharp_3$) as the modulator frequency with an index of 9. Applying these numbers to the FM formula generates the spectrum displayed in Figure 7.

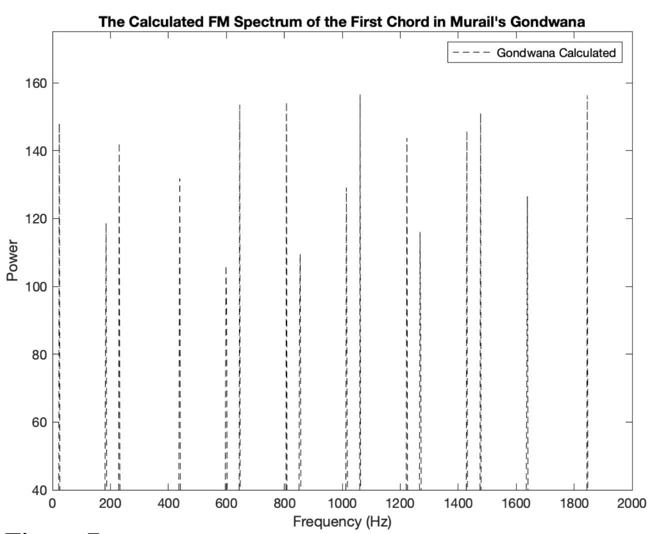

Figure 7

Calculated frequency spectrum of the opening FM chord in Murail's Gondwana*.*

According to Murail's *Questions de cible*, when handling frequencies that do not easily conform to equal tempered pitches, he chooses to round the pitches to the twelve-tone equal tempered scale *unless* the frequency falls "almost exactly" on a quarter-tone (as cited in Hirs & Gilmore, 2009; Rose, 1996). This conscious decision will cause the composed spectrum to deviate from the calculated spectrum above.

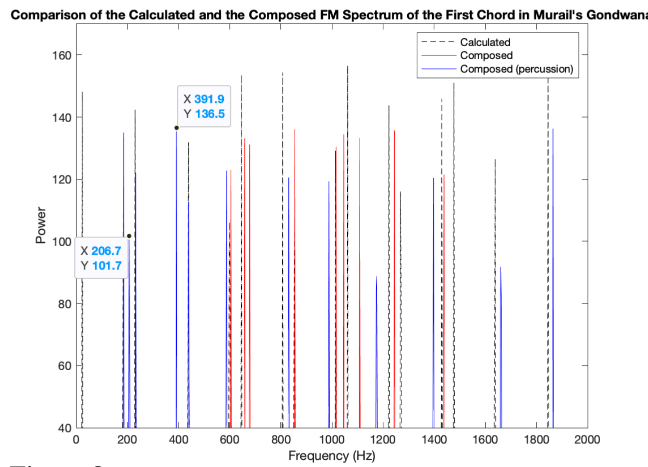

Figure 8

Comparison of the calculated and composed frequencies of the opening chord of Gondwana with percussion instruments (including piano) highlighted for their fixed tuning when compared to the performed spectrum.

Comparing the composed and calculated spectra (Figure 8) reveals not only the tremendous amount of rounding but also pitches that weren't generated by the FM formula. The first noticeable discrepency—with frequencies labeled in Figure 8—is the inclusion of the carrier and modulator frequencies (392 and 207.65 Hz, respectively).[13] Looking at the formula for FM ($F_i = |c \pm (m \cdot i)|$), the resultant frequencies are a result of manipulations of c and m and therefore, regardless of the index number, the frequencies of c and m will never appear in the FM spectrum. By including both of these frequencies in the opening chord of *Gondwana*, Murail models a process closer to Ring Modulation which, unlike FM, "is not hierarchic: there is not a carrier and a modulator which modifies it, but two equal sounds both of which are directly present in the resultant sound" (Fineberg, 2000, p. 97).[14]

In addition to the presence of the carrier and modulator frequencies, there are six pitches that deviate from the FM

[13]Note, with the FFT analysis. due to the bin size of the analysis, the frequency numbers are often adjusted as they fit into the analysis parameters.

[14]The similarity to Ring Modulation is lost after the inclusion of the carrier and modulator frequencies. Ring Modulation is often used with complex signals, each of which contain overtones, and the modulation occurs between each pitch's respective spectrum.

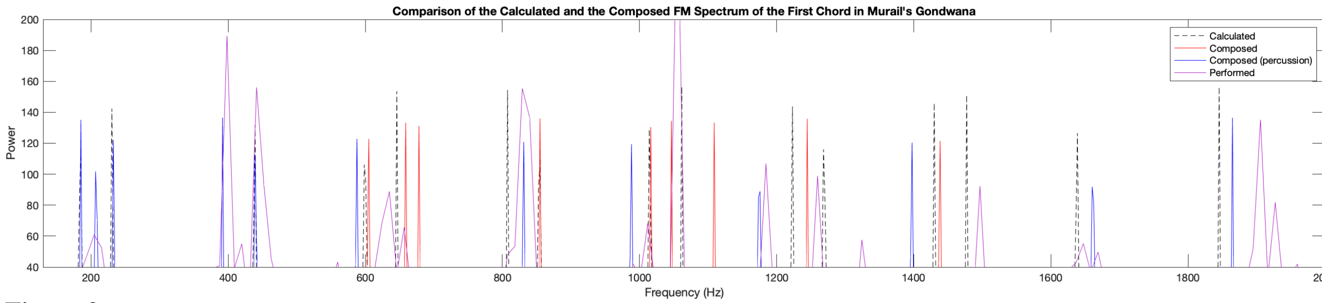

Figure 9
Comparison of the performed, calculated, and composed frequencies in the opening chord of Gondwana.

calculation entirely: $E\uparrow_5$, $G\sharp_5$, B_5, $C\sharp_6$ D_6, and F_6—678.57, 830.61, 987.77, 1108.73 1174.66, and 1396.91 Hz, respectively.[15] It can be argued that these pitches are the result of rounding from closest $\frac{1}{4}$-tones, but Figure 8 shows that, in all but one case ($G\sharp_5$ at 830.61 Hz), rounding from the calculated frequencies has already been accounted for in the composed spectrum. Without an explicit comment from Murail on these pitches, the addition of these pitches could be an attempt at making the resultant sound more dissonant by adding more pitches in close proximity to others.

Without the harmonic series as an aural grounding, I am particularly interested in how performers tune inharmonic spectra such as the ones produced in *Gondwana*. Unfortunately, I've only been able to locate one recording of this piece and it is not a live recording so statistical analyses of the deviations are impossible to perform. Aside from the absence of some frequencies, possibly from the instrumentation or recording processing, Figure 9 shows a relatively consistent tuning to the composed frequencies with a few notable exceptions.

The strong presence of 635.2 Hz, a slightly flat $E\downarrow_5$, looks as though trumpet 3 tuned their written $D\uparrow_5$ too high because their respective frequency, 604.54 Hz, is absent from the spectrum. The presence of 1324 Hz is a little more troubling; this frequency translates to a slightly sharp $E\natural_6$ which is nestled between the $E\flat_6$ and $F\uparrow_6$ in oboes 2 and 1, respectively. Their frequencies on the FFT can be accounted for at 1260 and 1497 Hz—both of which tuned closer to the calculated frequency than the composed frequency. The only other instrument in this frequency range is the F_6 in the piano. If this frequency occurred in the piano, it would most likely be tuned sharp in comparison to its 1396.91 Hz on account of its stretched tuning (Fletcher & Rossing, 1998, p. 335). More likely the case, this erroneous 1324 Hz frequency is simply an overtone of the second trumpet's E_5. The last drastic frequency discrepancy is the strong 1906 Hz. This is one of the few frequencies that fall closer to the composed than the calculated spectrum. Representing a slightly flat $B\downarrow_6$, this pitch aligns closest with the flute's $A\sharp_6$ (later joined in unison by the piccolo).[16]

Lonely Child

Similar to *Gondwana*, Claude Vivier generates *Lonely Child*'s pitch material through the inharmonic process of frequency modulation—coincidentally with similar creative deviations to the process like Murail—that Vivier labels these generated chords as *les couleurs* (Gilmore, 2007, p. 6). Starting at measure 24 in the score, Vivier implements this process using the sustained G_3 in the cello and calculates the *couleur* harmonies by combining the frequency of the cello pitch (196 Hz), acting as the carrier frequency, with the changing pitches of the soprano melody, acting as the modulator frequency.

Following the calculations presented by Tannenbaum (as cited in Christian, 2014), I generated The calculated spectrum using the soprano's $B\flat_4$.[17] According to Gilmore (2007), the generation of this chord follows the formula $f = (c + m \cdot x)$ where $x = [1, 2, 3]$. This formula, however, does not translate correctly to the entire chord for if the process continued with $x = [4, 5]$, the final two pitches are tremendously different than the pitches Vivier composed—too different to claim Vivier rounded to equal-tempered pitches. To correct this, Peter Tannenbaum proposed a series of calculations based on Gilmore's, with modifications: $(c+m)$, $(c+2m)$, $(2c+m)$, $(2c+3m)$, and $(3c+3m)$ (as cited in Christian, 2014). When using this set of five equations, however, I noticed that there is an additional discrepency that Christian does not address or correct: the equation $(2c + 3m)$ is backwards. With $c = 196$ Hz and $m = 440$ Hz, for example, $(2c+3m) = 1712$ Hz which is roughly $A\downarrow_6$[18] when that particular equation should result in an F_6. After the equation is flipped to $(3c + 2m)$, however, it results in a frequency of 1520.32 Hz which is 3 Hz lower than the F_6 in the score. These are the frequencies—including the corrected

[15] In the context of this paper, ↑ represents the raising of a $\frac{1}{4}$-tone.

[16] Having the flute and piccolo in unison could also account for the 1927 Hz frequency, though it is impossible to tell which frequency belongs to which instrument.

[17] When using the soprano's A_4, the *couleur* chord featured mostly equal-tempered pitches.

[18] The ↓ in this context indicates lowering the pitch by $\frac{1}{4}$ of a tone.

equation—I chose to generate the calculated frequency spectrum.

I then took the frequencies of the written chord in the score to generate the composed frequency spectrum. Like in *Gondwana*, Vivier elects to include both the carrier and modulator frequencies in the score which, as mentioned above, reflects the practice of ring modulation rather than frequency modulation. Figure 10 shows the frequency comparisons between the calculated and composed spectra for the chord generated from the soprano's $B\flat_4$ when modulated against the cello G_3 in measure 24–27.

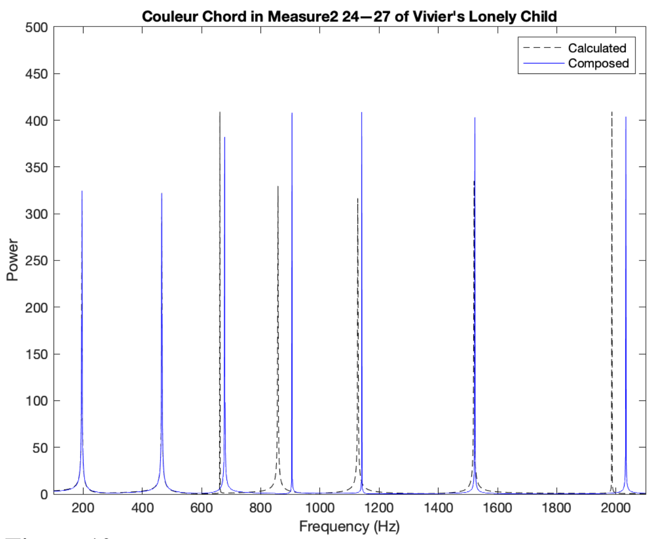

Figure 10
Comparison of FFT analyses of the calculated and composed frequency spectrum in measure 24–27.

Measuring the performed frequency spectrum for *Lonely Child* is interesting for the same reasons as in *Gondwana*: how do performers handle synthetic spectra that deviate from the pure harmonic series? I extracted the audio from the four instances of this particular chord in measures 24–27 in two performances for a total of 8 audio files.[19] Across these eight audio excerpts, the $D\downarrow_6$ and $B\uparrow_6$ were not consistently present in all of the files so I excluded them from my analysis.

The carrier and modulator frequencies, when comparing the performed, calculated, and composed frequencies, did not show a statistically significant difference which means that performers consistently performed those pitches as they were intended by Vivier. The difference between the performed $A\uparrow_5$ (average 911.6 Hz) was also not statistically significant when compared to the composed $A\uparrow_5$ (905.79 Hz). Like the G_3 and $B\flat_4$, this lack of significance shows that performers are more likely to perform the $A\uparrow_5$—albeit an average of 5.81 Hz sharp—as written in the score. When compared to the calculated frequency (858.16 Hz), the performed frequency was 53.44 Hz higher, roughly $\frac{1}{2}$ of a tone which, though a statistically significant difference, is far too wide to be considered aurally significant.

For the remaining two pitches, $F\downarrow_5$ and $G\downarrow_6$, the paired-samples T-test considered the difference between the performed and calculated and the performed and composed frequencies statistically significant. The performed $F\downarrow_5$'s frequency (an average of 699.11 Hz), fell closer to the composed frequency (678.57 Hz) rather than the calculated frequency (662.16 Hz). This is an interesting difference because Vivier, instead of rounding the calculated frequency of 662.16 Hz to an $E\natural_5$)—only 2.9 Hz difference—rounded up to an $F\downarrow$.[20] This significant difference between the performed and composed frequencies seems to stem from performers trying to follow the score but more consistently played the equal-tempered $F\natural_5$ (698.46 Hz) instead of the written $F\downarrow_5$. The performance of the $G\downarrow_6$, although showing a statisitically significant difference from both the calculated and composed frequencies, deviated roughly 129 Hz which translates to difference of about $\frac{3}{4}$ of a tone. This large of a difference seems aurally insignificant and subsequently was removed from my analysis. I have plotted the averaged performed frequencies in Figure 11 to show the comparison to the calculated and composed frequencies.

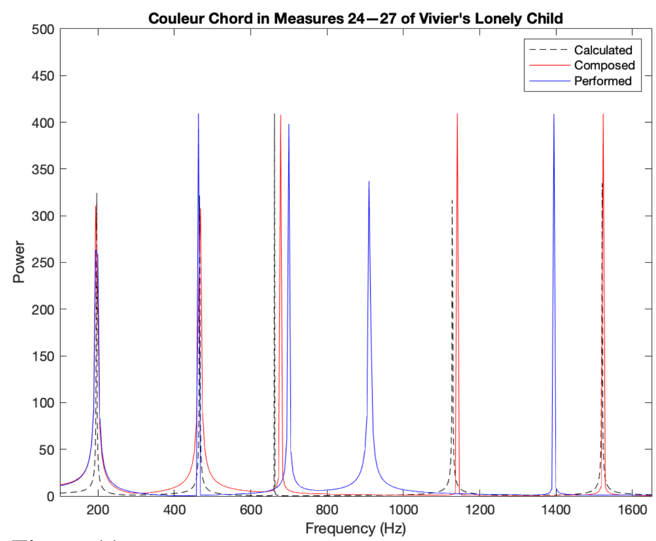

Figure 11
Comparison of FFT analyses of the average performed, calculated and composed frequency spectra in measures 24–27.

Discussion

Before commenting on the findings from the above analyses, it is important to note that none of the process existed in

[19] I stopped at measure 27 because the harmony changes in measure 28.

[20] Vivier is known to spontaneously round pitches in unexpected ways to generate more colorful harmonies (Christian, 2014).

an appropriately controlled environment; though, with that being said, some of the results are worth noting. With the exception of one frequency in *Partiels*, when looking at the two harmonic examples, the performed pitches that were extractable were generally closer to the calculated frequencies than the composed frequencies. This result, though not conclusive, points towards a performer's implicit grounding in the harmonic series, regardless of a how a composer may represent it in musical notation.

Because *Prologue* and *Partiels* realize the harmonic series in a monophonic and polyphonic context, respectively, this also measures the performers tuning ability in the context of horizontal and vertical scene organization. Horizontal and vertical scene organization is our ability to discriminate between multiple signals, such as frequencies, that belong together and those that do not. This organization can be measured both in a melodic (horizontal) and harmonic (vertical) context (Pressnitzer & McAdams, 2000, pp. 50–51). The performers' susceptibility to tune the frequencies to an imagined—arguably implicit—model (the harmonic series) is also a commentary on their ability to group necessary and ignore unnecessary stimuli while performing the piece in question.

Even more impressive is the tuning results from *Gondwana*. With the exception of one frequency—again, not entirely conclusive—the musicians, on average, tuned their pitches closer to the calculated frequency modulation spectrum. As mentioned above, the only available recording for this piece was a studio recording, so it is possible that these pitches were either addressed or corrected across multiple takes to produce the final recording.

Of the analyses conducted in this paper, Vivier's *Lonely Child* is the only piece with disappointing results. This is partly at the due to the fact that Vivier's choice of pitch rounding, with the exception of one, was so close to the calculated frequencies. With little difference between the composed and calculated frequencies, it would be incredibly difficult to claim a performed frequency was closer to one or the other. The one exception where there was an aurally significant difference between the calculated and composed frequencies, F$\downarrow_5$ in the score, the average performed frequency fell closer to the written pitch.

Future Directions

To further explore these results, I will create an experiment that will take the listener's preferences into consideration. Focusing on the monophonic/polyphonic and harmonic/inharmonic models, the participant's data will be collected from their choices made on chordal and melodic discrimination, tuning, and creation tasks.

To measure the polyphonic variable, the participant will be asked to select from a pool of multiple spectrally-tuned chords which chord sounds the most "correct." They will also be asked to tuned one to several pitches within a spectrally tuned chord with the instructions to "correct the chord." For the monophonic variable—much like the polyphonic tasks—they will select the most "correctly" tuned melody and tune specific notes of a melody. Their final task will be to generate spectral harmonies of their own. They will be provided with a bank of pitches gathered from various spectral chords from the literature and I will measure the frequencies of the pitches they choose.

These tasks will allow me to measure the ability of a large population of participants to generate harmonic or inharmonic chords. In addition to their accuracy, it will test if they gravitate towards harmonicity or inharmonicity as well. Though the experiment is in the developmental stages, results from the analyses performed above support the creation of this experiment. The analyses above strongly suggest that performers often tune to an imagined model and the experiment will investigate this model's significance on a greater population.

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