A Roughness Model Implementation to Analyze Sound Mass Composition: A Case Study in Ligeti's *Continuum* for Harpsichord (1968)

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Abstract. *We present in this paper an implementation of a roughness descriptor based on the model of Pantelis Vassilakis. We use the implemented descriptor to carry out a computer-aided musical analysis of György Ligeti's Continuum for harpsichord (1968). Our analysis establishes a parallel between the roughness model, concepts of sound mass composition, microtime perception, and Ligeti's ideas of timbre of movement and permeability. As a result, we display a graphical representation for the roughness computed from the Continuum's recording, propose a formal segmentation for the piece, and analyze its formal development from a musicological point of view.*

1. Introduction

In this paper, the implementation of a *roughness* descriptor is presented, aiming at the musical analysis of *sound mass* composition [1]. As a case study, a musical analysis of Ligeti's *Continuum* for harpsichord (1968) was carried out. This approach is justified in this context due to the perceptual characteristics of Ligeti's compositional poetics [2].

The use of audio descriptors in musical analysis is a well-known practice in the context of systematic and empirical musicology [3]. The graphical representation of audio descriptors provides extra insights into the formal aspects of a musical work, offering a complementary perspective with respect to the symbolic information from the score [3, 4]. Different types of audio descriptors have been also applied to investigate emergent and perceptual properties in the electroacoustic and live electronic music repertoire [5, 6, 7, 8].

An important characteristic of the *sound masses* is their *microtime* behavior [9, 10]. *Microtime* refers to a scale of sound perception, which Roads define as "Sound particles on a time scale that extends down to the threshold of auditory perception (measured in thousandths of a second or milliseconds)" [11, p. 4]. *Roughness* is a psychoacoustic model that represents the perception of very fast amplitude fluctuations in sound [12]. Therefore, we may understand *roughness* as a representative feature of *microtime* perception.

Ligeti's *Continuum* for harpsichord (1968) has been studied through the symbolic analysis of the score according to the *pattern-meccanico* technique [13] and the *Gestalt* model of perception [14]. From an experimental perspective, Douglas et al. used *auditory scene analysis* to study excerpts of *Continuum* and its *sound mass* characteristics [15]. *Microtime* perception in *Continuum* was also investigated using *audio descriptors* [10, 9].

In this study, we propose an implementation for a *roughness* audio descriptor based on Vassilakis' *roughness* model. Also, as a case study, we conduct an analysis of Ligeti's *Continuum* with the implemented descriptor. Considering *Continuum*'s very peculiar *sound mass* characteristics associated with its performance, we investigate how *microtime* features may be represented by the *roughness* descriptor. We describe how such a computer-aided musical analysis may lead to a segmentation of the piece that enhances the understanding of its formal development concerning *sound masses*. Therefore, we extend previous studies based on the symbolic analysis of *Continuum*'s score [13, 14, 15] by investigating singular characteristics of the chosen performance.

In Section 2 we present the central musicological concepts for this work: the idea of *sound mass* composition, Ligeti's concepts of *permeability* and *timbre of movement*, and an overview of his *Continuum* for harpsichord. In Section 3, we present the *roughness* model, its theoretical background, its mathematical formalization, and its proposed implementation. In Section 4 we present the guidelines and methodology for the musical analysis. In Section 5 we display results and in Section 6 we present a conclusion and a discussion about the perspectives for the computer-aided musical analysis of *sound mass music*.

2. Musicological Background

2.1. Sound Mass Composition

Sound mass composition aims to achieve the limits of the perception by exploring a large agglutination of sound in the time and frequency domains [15]. Composers like Karlheinz Stockhausen (1928-2007) have a contribution to the theoretical and aesthetics discussion of *sound*

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mass concept [16], and pioneer works with this approach became with composers like Iannis Xenakis (1922-2001), György Ligeti (1923-2006), and Krystof Penderecki (1933-2020). *Sound masses* could be achieved through many compositional techniques, like *sound clusters*, stochastic procedures, granular synthesis, *micropolyphony*, instrumental extended techniques, etc.

According to Douglas et. al. [15], "Sound mass exists when the individual identities of multiple sound events or components are attenuated and subsumed into a perceptual whole, which nevertheless retains an impression of multiplicity". The authors also point that the *sound mass* is comprised by the complexity of the sound organization, including rhythmic, melodic and spectral parameters of a composition [15]. This concept will be central in our study because the compositional techniques of György Ligeti are strongly related to the concept of *sound mass*. The details of this relationship will be clarified in the next topic.

2.2. Gyögy Ligeti's poetics

György Ligeti (1923 - 2006) is a composer born in Transilvania in a region disputed by Hungary and Romania during the world wars. He is a fruitful composer with a large number of works exploring a diversity of musical techniques and artistic movements. Most of his famous works, like *Atmosphères* (1961) and *Lux Aeterna* (1966), can be associated with the musical concept of *sound mass* composition [1].

Ligeti's *sound mass* compositions are linked with his interest in natural sciences, mathematics, acoustics, and psychoacoustics [17]. These interests are transposed to his musical thinking under musical concepts like *timbre of movement* and *permeability*.

Timbre of movement refers to the sound fusion, which occurs when the musical texture reaches such a level of complexity that one can not perceive individual events [18, p. 169]. Therefore, the listener's attention is led to global characteristics and inner movement of the musical texture.

Permeability refers to the absence of pitch perception in the musical texture. According to the composer: *"The loss of sensitivity to intervals is at the source of a state that could be called permeability"* [18, p. 123]. These concepts are operated in his composition by using techniques like *micropolyphony* [19], *pattern-meccanico* technique [13], and *sound clusters* [20]. The *Continuum for harpsichord* (1968) is a representative example of these compositional techniques.

2.3. The *Continuum* for harpsichord

Continuum is a consequence of Ligeti's interest in machinery, under the concept of *pattern-meccanico* technique [13]. Maybe, the most representative work that illustrates this concept is the *Poème symphonique* for 100 metronomes (1962). In this work, 100 metronomes with different velocities are displayed. The main remarkable sound result of this piece is the rhythmic behavior, which is a consequence of the emergent synchronicity between metronomes in time [21].

Also, *Continuum* is representative of Ligeti's interest in aural illusions [2]. According to Ligeti: *"I thought to myself, what about composing a piece that would be a paradoxically continuous sound, something like Atmospheres, but that would have to consist of innumerable thin slices of salami?"* [2]. According to Ligeti, he chose the harpsichord to create this piece because this instrument can play vary fast notes, and the plectrum in the strings produces *"quite a loud noise"* [2].

Continuum's score has only one rhythm with the instruction *"Prestissimo = extremely fast, so that the individual tones can hardly be perceived, but rather merge into a continuum. Play very evenly, without articulation of any sort"*. Therefore, the variation in the piece sound result comes from the variety of melodic profiles and *pattern-meccanico* technique written by Ligeti [13].

The musicological interest of Ligeti's *Continuum* resides in the manner that the constant patterns of the score lead to the emergence of *sound mass* perceptual characteristics during the performance [9]. According to Knop: *"Peitgen remarks on the compositional strategies that Ligeti applied to create what initially seem to be static textures which, however, develop into more differentiated rhythmical (and melodic) units"* [17]. Knop also highlights that this compositional strategy could be understood under Ligeti's interest in math and psychoacoustics [17]. So, in this context, we want to focus on the *microtime* perceptual characteristics, through the *roughness*' descriptor.

3. A model for *roughness*

3.1. Roughness model

The application of audio descriptors to analyze electronic and instrumental composition was largely explored in the computational musicology context (e.g. [22], [23],[24]). The choice of the descriptor that will be applied in the analysis is strongly related to the musical context of the composition and its musicological interest. We explore the main concepts of *the roughness model* to justify its choice for this analysis.

Previous studies have associated the *roughness* model with *microtime* perception in the context of *Continuum*'s *sound mass* composition [10, 9]. The first one applied the *roughness* model to perform a formal segmentation of the piece [10]. The second one investigates how the *pattern-meccanico* technique, proposed by Clendinning [19] leads to the emergence of *microtime* patterns in perception. By using the *roughness* model to analyze the *sound masses* of Ligeti's *Continuum*, we aim to describe microtime perceptual characteristics [11] of *sound masses* based on inner ear properties.

According to Vassilakis [12], *roughness* is a perceptual feature related to the sense of very fast amplitude variation of the sound [12, p. 2]. It is partially conditioned by the sound stimulus and partially conditioned by the properties of the basilar membrane. This model is related to the concept of *sensory dissonance* in the context of western music [25, 23], but has also been explored in other non-tonal musical contexts, like Bosnian *Ganga songs* [12, p. 17].

The *roughness* models of Sethares [23] and Vassilakis [12] are based on Plomp and Levelt's dissonance curve [25], which displays a correlation between the sensation of dissonance and Zwicker's critical bandwidths model [26]. According to the results of Plomp and Levelt's experiment [25], the sensation of maximum dissonance for a pair of pure tones occurs when the distance between their respective frequencies is about a quarter of the critical bandwidth size [25]. Based on these results, Sethares [23] developed a model that consists of a parameterized curve for the dissonance values between a pair of pure tones, as we see in Figure 1. The *roughness* curve exhibits a profile with a peak in a quarter of critical bandwidth, which matches in this case with a semitone of the scale. Then, the *roughness* decreases until its minimum, in the final part of the *critical bandwidth*, around the major third of the scale (4 semitones).

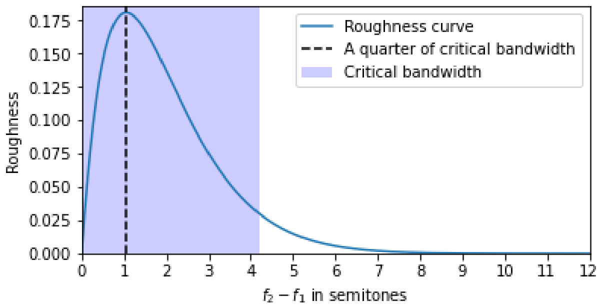

Figure 1: Roughness curve for two pure tones, in function of the twelve-tone equal-tempered scale with fundamental frequency 440Hz.

3.2. Roughness descriptor

The *roughness* value of a time frame is based on an approximation, proposed by Sethares [23] of the Plomp & Levelt's experimental dissonance curve[1] [25], and is defined for two pure sinusoidal tones with frequencies f_1 and f_2 as follows

$$r(f_1, f_2) = e^{\frac{0.84|f_2 - f_1|}{0.0207 f_1 + 18.96}} - e^{\frac{1.38|f_2 - f_1|}{0.0207 f_1 + 18.96}}. \qquad (1)$$

The formulation present in Equation 1 was revised by Vassilakis (Eq. 2) to incorporate the amplitude fluctuation characteristics in the sound stimulus on *roughness* perception, which were underestimated in Sethares' model

$$r(f_1, a_1, f_2, a_2) = (a_i * a_j)^{0.1} \left(\frac{2a_j}{a_i + a_j} \right)^{3.11} r(f_1, f_2), \qquad (2)$$

[1] For a full revision on *roughness* curves see [12, 27].

where a_1 and a_2 are amplitude values for the f_1 and f_2 components respectively.

For complex sounds, the *roughness* value can be computed using a formulation by Vassilakis [12], which combines all pairwise *roughness* values corresponding to pairs of sinusoidal partials

$$\text{Roughness} = \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{r(f_i, a_i, f_j, a_j)}{2} \qquad (3)$$

The computational implementation of the *roughness* descriptor is displayed in Algorithm 1. The magnitude spectrum is computed from the input signal x using the Short-Time Fourier Transform (STFT). Based on the spectral content, the frequency values and their respective amplitudes are obtained through peak selection for each time window. The frequency and amplitude values are then used to compute the *roughness* values as described in Equation 3.

Algorithm 1 Roughness descriptor

function ROUGHNESS(X)
  $X \leftarrow |STFT(x)|$
  $F, T \leftarrow \text{SIZE}(X)$ ▷ X is a $F \times T$ matrix
  for $t \leftarrow 1$ **to** T **do**
    freqs, *amps* ← PEAK_PEAK(*frame*)
    $R[t] \leftarrow 0$
    for $f1, a1 \in$ *freqs, amps* **do**
      for $f2, a2 \in$ *freqs, amps* **do**
        $R[t] \leftarrow R[t] + r(f1, a1, f2, a2)/2$
  return R

The source code for the implementation of the *roughness* descriptor and all the graphical analysis was done using Python[2] and the Jupyter[3] environment and are available at this Gitlab repository[4].

The frequency and amplitudes values were obtained from the magnitude spectrogram using the Librosa [28] library, with a window size of 4096 samples and a hop length of 1024 samples.

4. Methodology

With the following methodology, we aim to apply the *roughness* psychoacoustic model to represent the *microtime* characteristics [11] in the *Continuum* through the analysis of the performance recording shown in Table 1, enlarging the proposal of previous studies [29, 30].

We hypothesize that this descriptor could represent the concept of *timbre of movement* and *permeability*, as well the *microtime* behavior of the *sound masses*. These concepts could be associated with the principles of *minimum masking* and *limited density* [31], which states that

[2] https://www.python.org/
[3] https://jupyter.org/
[4] https://gitlab.com/Feulo/ligetis-continuum-analysis

Album	Requiem / Lontano / Continuum
Composer	György Ligeti
Performer	Antoinette Vischer
Year	1968
Country	France

Table 1: Metadata of the chosen performance recording.

the higher the level of spectral information in the auditory nerves, the lower the ability to perceive musical pitches and intervals. These principles of *minimum masking* and *limited density* were already associated with the concept of *sound mass* [1]. Starting from this point of view, we argue that the *roughness* model will provide a one-dimensional representation that will reflect:

(A) *The density level and agglutination of the spectra in the frequency domain*- The *roughness* model is based on the level of the energy into the *critical bandwidths*, the higher the density and agglutination of the sound spectra, the higher the level of *roughness*.

(B) *Perceptual features related to microtime amplitude fluctuation*- As already pointed, the *roughness* model presented is based on subjective tests and properties of the inner ear aligned with the subjective perception of sound amplitude fluctuation [12].

Based on the above guidelines, we conducted the musical analysis of the chosen performance recording of the *Continuum* as follows:

1. *Roughness calculation from the audio data:* By applying the algorithm presented in section 3.1, a *roughness* curve of the *Continuum's* recording will be generated.
2. *Segmentation of the piece:* Based on the *roughness* curve levels, we propose a segmentation of the piece based on the *local minimums* of the curve. It provides an overview of the temporal development of the sound material through the composition.
3. *Musicological considerations:* In this step, we perform the analysis starting from the musicological information about the *Continuum* and the *roughness* descriptor representation.

5. Results

We disclose in this section the results of the analysis, divided into the three steps we present above in section 3.2. The analysis is anchored in the graphical representation of Figure 2, which displays the *roughness* in blue and its respective moving average, for 20 samples, in orange. The formal segmentation of the piece is represented by the dotted vertical black lines, as we will detail below.

1. Roughness calculation

By plotting the *roughness* curve in function of the time of the Continuum, we could observe a decreasing profile of the curve through the piece, with the highest value around 25 seconds, and the lowest values in the final part of the piece. Also, we observe a pattern-like behavior during the piece, with an increasing and decreasing behavior with local maximums and minimums in time.

2. Segmentation of the piece

We propose a segmentation of the *Continuum* using as criteria the local minimums in time, which leads to the following initial time of Table 2 for the segments from A to F, as shown in black dotted vertical lines in the Figure 2.

A	B	C	D	E	F
00:00	01:02	01:41	02:17	02:45	03:25

Table 2: Initial time for each proposed segment of the *Continuum*'s recording.

So, we may observe that the segmentation of the piece highlights the *roughness* patterns inside each of the segments.

3. Human conducted musical analysis

The analysis of the Continuum with a *roughness* descriptor allows us to speculate about the perceptual outcome of Ligeti's compositional strategy. First, we may notice an overall strategy: the manipulation of the tension of the *sound mass* through the *roughness*. Second, in terms of the development of the material in time: a kind of pattern in each segment of the piece could be the source of a perceptual coherence in the composition. Third, by observing the descending profile of the roughness in the composition, this analysis reinforces the filtering strategy of the musical texture, as already pointed by [9]. Thus, we may conclude that the diversity of the melodic patterns of the Continuum does not dazzle a kind of coherence at the perceptual level. This is achieved by an internal coherence in each segment and an overall directionality during the piece.

It is interesting to remember in this context that the roughness model is related to the accumulation of energy into the critical bandwidths. So, we may argue that the sound masses allow different levels of pitch perception, as stated by the concept of *permeability*. Thus, strategies of blurring are at a source of the inner movement of the sound masses in the composition.

6. Discussion and Conclusions

In this paper we presented an implementation of a *roughness* descriptor, applying it in the context of Ligeti's *sound mass music*. With that, we privilege a perceptual approach in the musicological study. The *roughness* descriptor is a feature that, combined with other audio descriptors and symbolic information of the score, could provide a broader methodology of musical analysis of the *sound mass* characteristics.

It is important to notice that the segmentation through the *roughness* profile displays a great convergence with the segmentation anchored in a symbolic analysis of the score performed by Clendinning [13]. It means that the

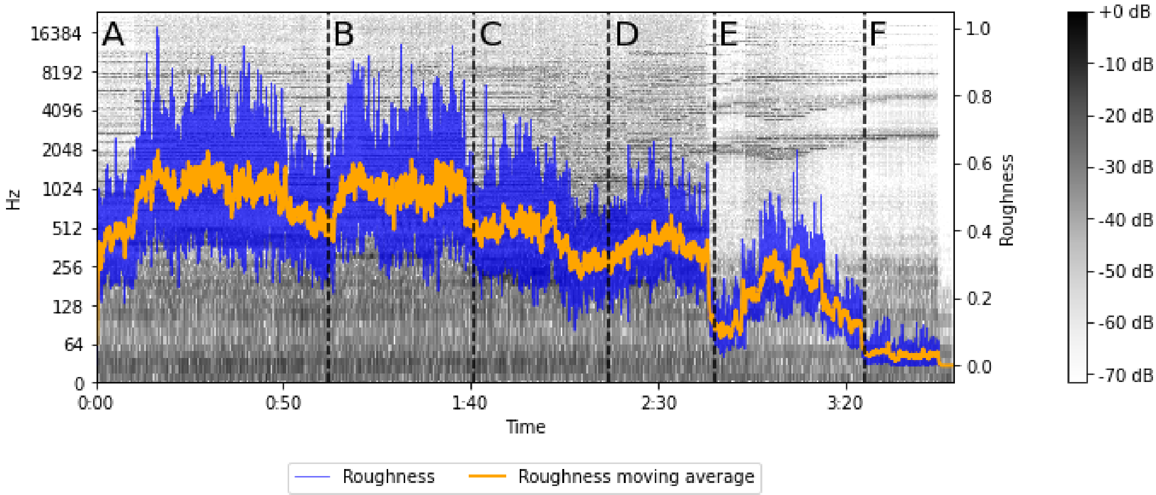

Figure 2: Roughness for the *Continuum*'s recording (blue) and its moving average(orange). The black dotted lines represent the proposed segmentation of the piece. The spectrogram is displayed in the background.

roughness descriptor could provide a meaningful musical representation in the context of *sound mass* composition which explores a great variety of *sound clusters*.

As already demonstrated, the *roughness* profile of the *Continuum* shows an oscillatory pattern through the segments, which is a consequence of the of *sound mass* behavior. Therefore, future musical analysis of the *Continuum* could investigate in more detail the relationship between the *pattern-meccanico* technique detected in the symbolic analysis from the score and psychoacoustic patterns obtained through audio descriptors.

Due to the diversity of techniques and instrumental ensembles in the context of *sound mass* music, we need to improve audio signal processing strategies to represent properly the psychoacoustic features. Also, the use of more accurate time-frequency representations could provide better for the *roughness* descriptor computation.

The musical analysis methodology exposed in this paper could be applied in other musicological contexts. Firstly, by enlarging the perceptual knowledge of a musical performance from the audio data, the *roughness descriptor* fills a gap in the context of psychoacoustic descriptors that could be particularly interesting to the musicological field. Second, the *roughness* provides relevant information about the energy concentration of the frequencies in the musical texture that could be used to enlarge the understanding of invariant properties of the *sound masses*.

Future works may perform a comparative analysis between the audio features of the Continuum's performance with a symbolic analysis of the score, to verify how the melodic patterns lead to these psychoacoustic characteristics. Also, experimental works with expert and non-expert listeners could provide more information about the accuracy of the Roughness feature in the segmentation of the piece.

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