VIBRATO ANALYSIS IN BYZANTINE MUSIC

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ABSTRACT

In this work we study the vibrato rate, extent and intonation in Byzantine Music. Two methods of analysis have been applied: the first based on the analytical signal and the second on the crests and troughs of the waveform of the vibrato signal. Tones - samples were extracted from ascending and descending music scales, chanted by five famous singers for all the Greek vowels. The two analysis methods produced identical results in the level of significance, a=0.05, concerning the mean extent, the mean standard deviation of the rate and the mean intonation, while they differed in the rate (1.9-6.6%), the mean standard deviation of the extent (4-6 cents) and the standard deviation of intonation (0.46-1.20 Hz). Typical values of the average rate within a tone were found to be 5.35 Hz (SD: 0.96 Hz) and 5.13 Hz (SD: 0.95 Hz), while the most frequent values were 4.8 Hz and 4.5 Hz, for the first and second method, respectively. The average extent within a tone was 50 cents (SD: 18 cents). Moreover, the dependence of the vibrato parameters on pitch and sound intensity has been studied; there was no systematic relationship between them.

1. INTRODUCTION

The term “Byzantine Music” (BM) describes the contemporary church music of the Greek Orthodox Church, primarily, but also it refers to both the medieval sacred chant of Christian Churches following the Constantinopolitan Rite and the secular music in the Byzantine and post-Byzantine era. The eight-mode system of BM has affected the modern Greek folk and popular songs. In an effort of a comprehensive study of Greek singing, the study of BM is necessary, fundamental and of primal importance. Although musicologically, BM has been systematically studied [1], its acoustical attributes have not been thoroughly examined [2, 3, 4, 5].

The BM is purely vocal music and is performed without the accompaniment of musical instruments. Therefore, only the voice must satisfy the requirements for artistic musical ornaments, which embellish the melody in the music performance. Vibrato constitutes a characteristic ornament of the melodic voice [6]. It has been extensively studied in the context of various kinds of vocal music world-wide [7, 8, 9, 10]. Many of these studies had to do with the lyrical songs of Western opera, addressing the basic vibrato parameters rate and extent [10, 11, 12]. Also, dependencies were found between the appropriateness or not of vibrato with its rate, extent, periodicity and onset. Moreover, the relationship of poor or good vibrato with respect to the variability of its rate and extent has been studied [13]. In BM, the vibrato seems [14] to be a rather rare phenomenon, with rate and extent values to be different from those in Western opera. In that preliminary study [14] only average values of the rate, extent and vibrato duration were measured, by analyzing a single BM hymn.

In this work, the characteristics of BM vibrato rate and extent are studied in order: a) to assess their values in detail, and b) to search for any relationships with other voice features, such as fundamental frequency (f0) and sound intensity.

2. METHOD OF THE ANALYSIS AND MATERIAL

Vibrato analysis methods have been based on: a) studying the spectrogram under manually intervention of the user [11, 12], b) frequency analysis with a sliding window on the vibrato waveform [13], c) calculating the instantaneous frequency, resulting after the application of the Hilbert transform on the vibrato signal [15, 16].

2.1 The analytic signal

According to the last mentioned method above, vibrato is considered to be a time dependent signal of the form:

$$\hat{f}(t) = b(t) + a_v(t) cos\varphi_v(t) \quad (1)$$

where:

$$\varphi_v(t) = 2\pi \int_{-\infty}^{t} f_v(\tau) d\tau \quad (2)$$

The signals $\alpha_v(t)$ and $\varphi_v(t)$ correspond to the time varying parameters of the extent and the rate of vibrato, respectively. *b(t)* corresponds to the intonation of vibrato. It is known [15] that there is no single solution to the problem of determining these three signals, which constitute the time varying model in (1) and (2). The signal *b(t)*, could be obtained by passing the signal *f*(t) through a low pass filter with a cutoff frequency less than 3Hz, with the condition the vibrato rate to be equal or greater than 4Hz.

By subtracting the signal *b(t)* from *f(t)*, we get the pseudo-sinusoidal signal *s(t)*:

$$s(t) = f(t) - b(t) \quad (3)$$

Further analysis of the *s(t)* estimates the signals $\alpha_v(t)$ and $\varphi_v(t)$ through the analytic signal, which is defined as:

$$z(t) = s(t) + jH[s(t)] \quad (4)$$

where *H[s(t)]* is the Hilbert transform of *s(t)*.

The analytic signal *z(t)* can be expressed in polar coordinates as follows:

$$z(t) = A(t)e^{j\theta(t)} \quad (5)$$

In the case *s(t)* is a band-pass signal, then the amplitude and the phase derivative of the analytic signal define the amplitude and frequency modulation, respectively. The extent of the vibrato signal can be estimated from the amplitude *A(t)* divided by 2π. The rate of the vibrato signal can be estimated from the derivative of $\theta(t)$ divided by 2π.

2.2 The algorithm of this analysis

2.2.1 The first algorithm (analytic signal)

For the estimation of *b(t)* we have followed a different analysis method from that in [15]. Specifically, i) instead of low pass filtering the vibrato signal, first, the crests and troughs are located at the waveform and then the center of the vertical distance between two successive extremes is located, for all the maximum–minimum pairs. ii) The number of these central points is augmented via a cubic piecewise interpolation process, which preserves the shape of the data and respects monotonicity [17]. The resulting *b*(t) is a smoothed line following the slow changes in the vibrato waveform. We have followed the above estimation approach for the intonation for two reasons: a) Due to the rather low values of the vibrato rate in BM [14], a low pass filtering is not possible to be applied without loss of information that the vibrato signal conveys, and b) because part of the low pass filtering resulted in an intonation, which was not passing through the central points of the vibrato waveform, but instead it received values beyond the extremes. This last observation did not agree with the pitch perception of the vibrato tone.

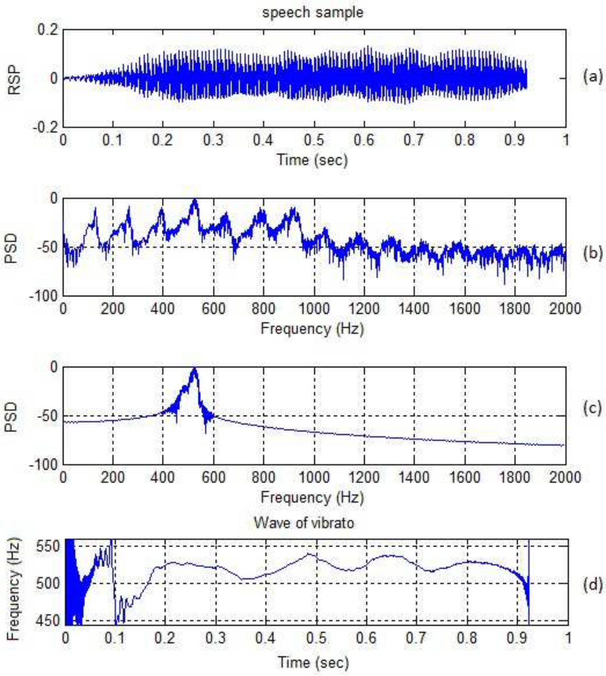

Figure 1. Signals for the first two steps of the analysis: (a-b) tone's waveform and spectrum, (c) fourth partial's selection and (d) vibrato waveform.

The steps of the first algorithm of the analysis are:

1) Compute the waveform of a partial of the voice signal, via band pass filtering. Select the partial, which shows the highest signal to noise ratio (Fig. 1a-1c).
2) Find the vibrato signal through the analytic signal based on the equations (4) and (5) (Fig. 1d).
3) Remove the rapid changes of the vibrato waveform through low pass filtering with a 20 Hz cutoff. Estimate the time indexes of its crests and troughs (Fig. 2a).
4) Compute the coordinates of the central points for each pair of successive extremes (asterisks in figure 2).
5) Estimate more points through cubic interpolation between the central points (Fig. 2a). (Compare the intonation time series with the low pass filtered with cutoff 2 Hz).
6) Subtract the intonation signal from the vibrato signal.
7) Compute the analytic signal with the equation (4).
8) Obtain the rate (instantaneous frequency) and the extent of vibrato from the relation (5) (Fig. 2b-2d).

In step (5), the intonation time series, although it is very close to the low filtered vibrato waveform at four points (Fig. 2a), it deviates at the other points, especially at the edges. For this reason, the intonation waveform via cubic interpolation was preferred to the other. Specification of the time segment of the vibrato signal to be analyzed was implemented as follows: First, time borders were roughly defined, manually. Then, the time limits were marked precisely so that the left boundary is the midway of the distance between the two first successive extremes, in horizontal and vertical direction. The right border was found in the same manner for the last two successive extremes.

2.2.2 The second algorithm

To assess the accuracy of the above method, the vibrato characteristics rate, extent and intonation were also calculated by the following system of relations (6), (7) and (9). Henceforth we will refer to them as the second method of analysis. All the calculations in this method were based on the extremes in the waveform of vibrato. In Figure (2), the values obtained based on the extremes are represented together with the signals of the rate and extent as estimated by the first algorithm. The equations for estimation of the rate and extent through the second method are the following:

$$rate(m) = 1/\Big(2\big(t(k+1) - t(k)\big)\Big) \quad (6)$$

$$extent(m) = |a(k+1) - a(k)|/2 \quad (7)$$

where $t(k)$ and $a(k)$ are the instant and the value of the extreme k respectively. In this way, the rate and extent is computed for each semi-cycle of vibrato, by, roughly, doubling the number of the time instants.

However, since the variation of the values of the extent also increases, the mean between the two values of successive semi-cycles was calculated. (Fig. 2c, cycles). In a previous study [12], the extent was calculated as the percentage of the mean intonation between two semi-cycles, namely, based on the relation (8):

$$extent(m) = \left|\frac{a(k-1) - 2a(k) + a(k+1)}{a(k-1) + 2a(k) + a(k+1)}\right| \quad (8)$$

which can be obtained from the equation (7), as the ratio between the semi-sum of pairs of successive extreme values (two semi-cycles) and the mean intonation for these two semi-cycles. This value of the mean intonation is defined as:

$$intonation(m) = a(k) + a(k-1)/2 + (a(k+1) + a(k))/2 \quad (9)$$

where m takes values from 1 up to k-1.

The final values of the extent are converted in the music scale of semitones with frequency of reference the note of A3 (220 Hz), for any comparison in the psychoacoustic scale with previous studies, as well as because the order of the partial selected for the analysis varies among the tones.

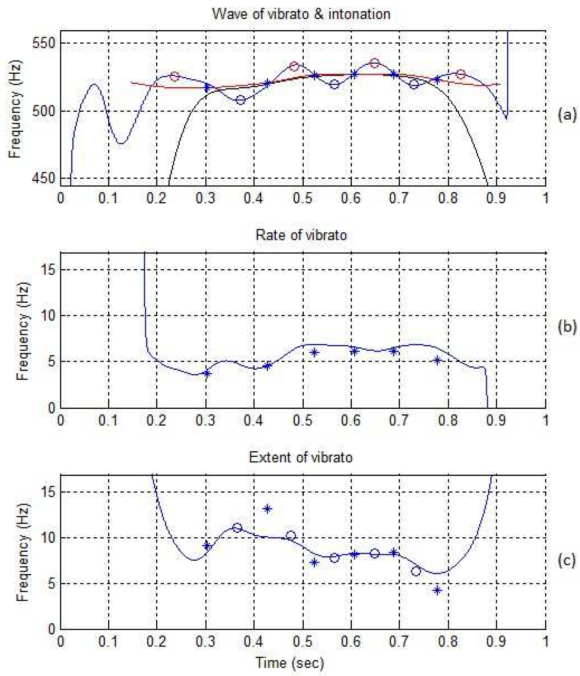

Figure 2. Signals and results of the algorithm of the analysis: (a) Intonation after low pass filtering (black line) and cubic interpolation (red line). Extremes at the smoothed waveform (red and blue cycles) along with the half-way distance points between them. (b) The values of the rate being estimated for each semi cycle of vibrato (asterisks) and the rate's waveform through the analytic signal. (c) Estimated values of the extent through the analytic signal (line), the equation (7) – asterisks and the equation (9) cycles.

The values of the relative intensity level of the sound of the DAMASKINOS corpus [18] refer to the same distance from the microphone (30cm), for all recordings by using the same apparatus and settings. Intensity levels were calculated in relation to the loudness threshold. All the software developed for analysis was implemented in the MATLAB programming environment.

2.3 Material

Choosing the audio sample-tones for the analysis it was a difficult task, because of the rareness of the phenomenon of vibrato in BM. This is probably mainly due to stylistic reasons, an explanation that is supported by the short duration of vibrato [14] (less than 1.5sec, with an average 0.7sec). Assuming an average rate equal to 4.2 Hz (in BM hymns of medium rhythm) then the number of vibrato periods for analysis is approximately three, on average. For the purpose of finding possible longer tones for more accurate analysis, we selected those parts of the

DAMASKINOS corpus [18], which include chanted scales, both ascending and descending ones. The implicit assumption here is that the parameter values of vibrato will be approximately similar to those found in the musical performance of Byzantine Music [14]. Chanters were asked to chant each tone of the scale slowly and trying to keep its F0 invariable. In order to have a small representative set of subjects [19], five chanters were selected so as to be one chanter from each chanting category according to some classification, based on their spectra in a previous study [14]. The ages of these chanters ranged between 40 and 60 years, which were suitable to combine art experience with a cultured voice. The tones for each chanter were selected to belong to six frequency bands of 1 semitone width each and centers being defined by the notes C3, D3 #, F3 #, A3, C4 and D4 # (± 0.5semitones). Any tone contains only one vowel out of /a/, /o/, /i/, /e/ and /u/. Two tones were selected for each vowel and chanter, one from ascending and one from descending scale. The constant difference in frequency between the notes by three semitones was chosen in order to examine whether there are dependencies on the other logarithmically varying sizes (intensity level, extent and intonation).

3. RESULTS

Table (1) compares the two methods of vibrato analysis through a paired t-test between the mean values of the vibrato parameters, the rate, extent, intonation and their average standard deviations within each tone. The t-test reveals that the results of the two methods do not differ in the mean standard deviation of the rate, the mean extent and the mean intonation at the level of significance a = 0.05; however, they do differ in the mean rate and the mean standard deviations of the extent and intonation. Table (1) also shows the confidence intervals of the average difference between the values of the second and the first method, from which it follows that the maximum and minimum average difference in rate is 0.34 Hz and 0.1 Hz greater in the first method, respectively. In percentage terms, and taking into account the Table (2), these values correspond to 6.6% and 1.9% of the average of the second method, for all the tones.

	Mean of the rate (Hz)	**SD of the rate (Hz)**	**Mean of the extent (sem)**	**SD of the extent (sem)**	**Mean of the intonation (Hz)**	**SD of the intonation (Hz)**
h value	1,00	0,00	0,00	1,00	0,00	1,00
p value	0,00	0,78	0,34	0,00	0,99	0,00
CI lower	-0,34	-0,11	-0,04	0,04	-17,30	0,46
CI upper	-0,10	0,08	0,02	0,06	17,47	1,20
SD	0,74	0,57	0,19	0,07	108,41	2,30
t stat	-3,56	-0,28	-0,96	8,72	0,01	4,43
df	598,00	598,00	598,00	598,00	598,00	598,00

Table 1. Paired t-test between the two methods of vibrato analysis.

	Mean of the rate (Hz)	**SD of the rate (Hz)**	**Mean of the extent (sem)**	**SD of the extent (sem)**	**Mean of the intonation (Hz)**	**SD of the intonation (Hz)**
Mean (1st)	5,35	0,96	0,51	0,10	486,9	3,24
SD (1st)	0,69	0,46	0,18	0,06	114,3	1,99
Mean (2nd)	5,13	0,95	0,49	0,14	487,1	4,06
SD (2nd)	0,75	0,75	0,18	0,07	114,4	2,41

Table 2. Average values and their standard deviations of vibrato parameters over all subjects and pitches.

The average difference of the standard deviation of the extent is between 0.04 and 0.06 semitones, i.e. 4 and 6 cents, and in percentage values are 40% and 60% greater than the respective values of the first method, for all the tones. The confidence interval of the average difference of the standard deviation of intonation is (0.46 Hz, 1.20 Hz), i.e. (23.1%, 60.3%) greater than the values of the first method, for all the tones.

The average values for the entire set of tones, of the mean rate, mean extent and within the tone their standard deviations, for both methods are presented in Table (2). Moreover, the standard deviations of the within tone means for all tones are provided. The distributions of these values are presented in Figure (3). Although the within tone mean of the rate ± 1SD is 5.13 ± 0.95 Hz, for the second method, (5.35 ± 0.96 Hz for the first method) the value 4.5 Hz seems to have higher occurrence for the second method (4.8 Hz for the first method - Figure 3a) as the histogram is not symmetric in its maximum. The second method shows a tendency for slightly lower rate values compared to the first and this is not the case in the standard deviations (Fig. 3a, c). The intra-tone variation in the rate is greater than that for all tones and chanters (0.95 Hz versus 0.75 Hz - Table 2). For the rate, the largest percentage of values (mean ± 2SD) of the within tone standard deviation has a value less than 2 Hz (Figure 3c). The corresponding percentage for the rate has a value less than 7 Hz.

The extent shows approximately the same distribution of mean values within the tone (Figure 3b) and its standard deviations tend to be smaller in the first method than the second (Fig. 3d). The majority of values (mean± 2SD) of the mean vibrato extent over all tones vary within the range of 0.50 ± 0.36 semitones (Table 2). This finding is quite different from the values at the opera, where the extent reaches the maximum value of 123 cents [12].

Examining the dependency of the rate, the extent and their standard deviations on the f0, we observe that there is a negligible tendency for the within the tone mean rate to increase by 0.13 Hz per 100 Hz raise of the f0 (Fig. 4a). The regression analysis was based on the least squares and the assumption that there is a linear relationship between the dependent and independent parameter. In a total change by 300 Hz, the rate can be increased by 0.39 Hz, which corresponds to a change of less than the standard deviation (0.75 Hz -Table 2). For the same reason, the standard deviation of the rate is not affected by the change of the pitch (Figure 4b). Similarly, both the intra-tone mean extent and its mean standard deviation decrease by increasing the pitch by 0.7 cents/ semitone and 0.2 cents/semitone, for the mean and standard deviation of the extent, respectively. In a total change of f0 by 16 semitones, the reduction is 11.2 cents and 3.2 cents, for the mean and standard deviation of the extent, respectively.

The corresponding standard deviations across the tones are 18 and 7 cents, respectively, which are values greater than of the overall pitch change. The relationship between the intensity of the tone and f0 in semitones, as expected, is linear, with a slope of about 0.55 dB / semitone (Figure 5a). Also, the within the tone extent of vibrato and its within tone mean standard deviation show a linear relationship with a slope 1.2 semitones of extent / semitone of SD (Figure 5b). In other words, for an increase of 1 semitone in extent, its standard deviation increases by 0.83 semitones. Finally, the extent of the vibrato is not affected by the changes in intensity for all the tones as shown by the regressive analysis in Figure (5c).

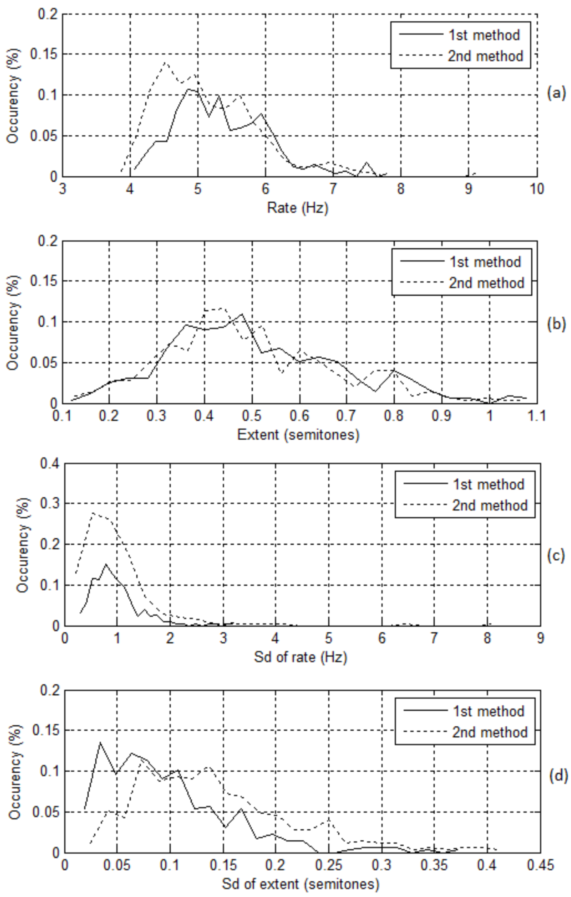

Figure 3. Histograms of the estimated values for the rate (a), the extent (b), the SD of the rate (c), and the SD of the extent (d), by the two methods of analysis.

4. DISCUSSION

The two methods of vibrato analysis give identical results concerning the within tone mean standard deviation of the vibrato rate, the mean intra-tone vibrato extent and the mean intra-tone intonation. Although it seems that do not agree to each other in the intra-tone mean rate, the maximum difference of 0.34 Hz is rather

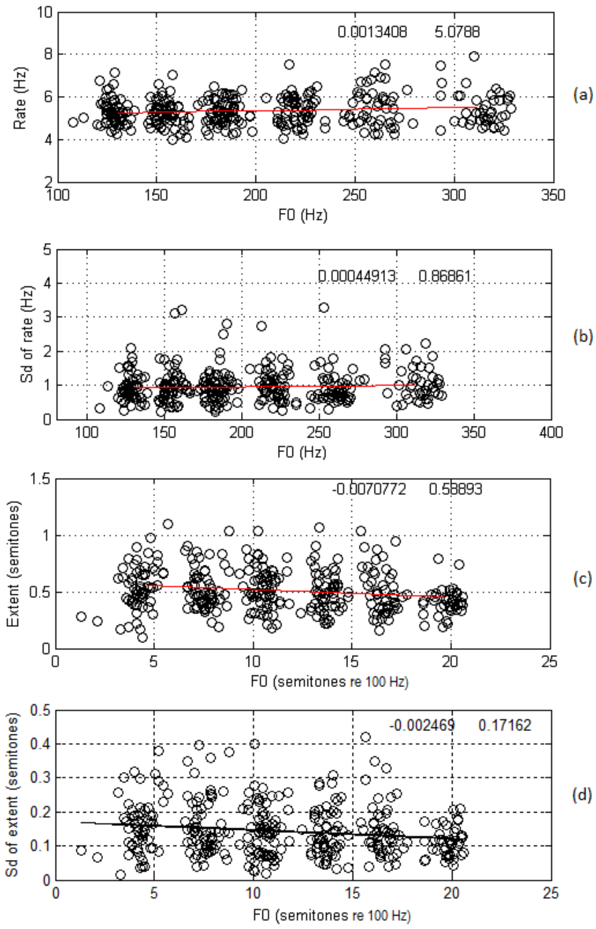

Figure 4. Values of vibrato characteristics in BCM for the (a) rate, (b) SD of the rate, (c) extent, and (d) SD of the extent, in relation to f0 for all the tones analyzed. Straight lines of Least Squares fitting are shown along with their parameters.

small, provided that the intra-tone standard deviation is 2.5 times greater. The major cause of this difference is due to improper placement of the extremes of vibrato waveform, despite the smoothing of the analysis algorithm. This measurement error of the rate mainly affects the second method. Also, there may be changes in the rate values due to the pseudo-sinusoidal waveform of vibrato, which, although they are taken into account in the first method, do not affect the values estimated by the second one (see Figure 2b, time 0.2-0.4sec). The difference between the two methods in the intra-tone mean standard deviation of the extent by 6 cents (at most), is obviously due to the estimation of the intonation time series. Since the within the tone mean standard deviation of intonation is a bit bigger in the second method by 1.2 Hz (at most) and the mean difference between the two methods is also about 1.2 Hz, this difference could be ascribed mainly to the intonation time series. Improvements in the analysis algorithm could be made by applying a better smoothing of the vibrato waveform, for the second method and another way of estimation of the intonation time series for the first method.

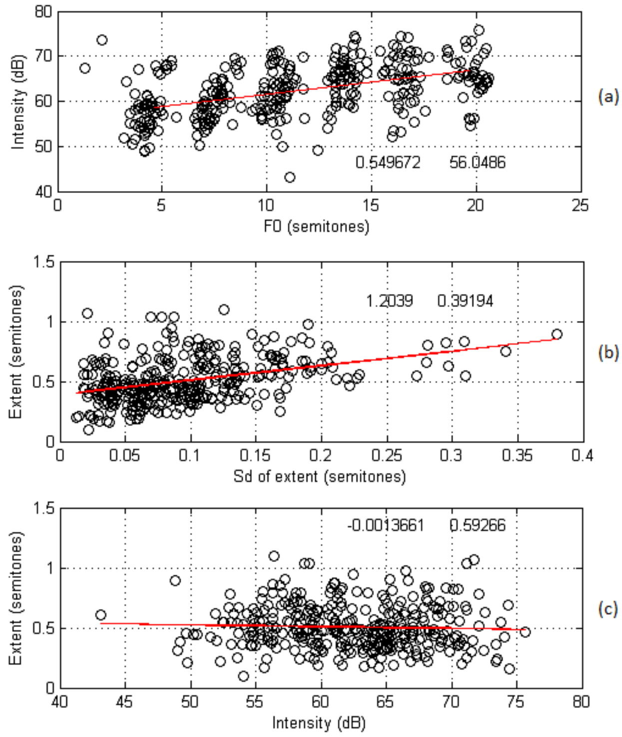

Figure 5. Correlograms for all analyzed tones between: (a) relative intensity and f0, (b) extent of vibrato and SD of extent and, (c) extent of vibrato and relative intensity. Straight lines of Least Squares fitting are shown along with their parameters.

It is obvious that the standard deviation across the chanters and vowels is smaller than that within the tone. This may suggest that the vibrato rate depends mainly on the stylistic characteristics of BM rather than the individual characteristics of the chanters. Yet, the fact that this is not affected by the pitch change inside the pitch range of the "average" chanter is in line with the literature, where no systematic differences have been observed [10]. The maximum value of vibrato extent in BM of 86 cents, has been also found in a previous study [14], which was implemented with a different sample of chanters and is likely due to low pitches in BM. This follows from the fact that the intensity varies depending on the pitch (Figure 5a); also it was observed that whenever it increases, the extent of vibrato increases too.

However, when the intensity decreases, the extent tends to remain stable, while exhibiting a maximum in the middle pitches [20]. In this study, the extent does not change with the increase of intensity within the pitch range of the "average" chanter. This may be explained by the fact that in the entire set of tones, half came from descending scales and furthermore these changes are different for each chanter. The marked decrease in the average value over the frequency range (302.3Hz -320.2 Hz: D4 # ± 0.5 semitones) reveals that a maximum exists in the extent values somewhere in the previous middle pitches. Both the rate and extent of vibrato differ slightly between the tones of musical scales and those of musical performance [14] by 4.5 or 4.8 Hz versus 4.1 Hz and 0.5 semitones versus 0.6 semitones, respectively. In [14], tones extracted from a single Byzantine hymn (of melodic sticheraric type [1]) were analyzed questioning these differences between musical scales and performance. Further investigation is needed for these in order to be considered systematic. Besides this, reverse differences have been reported between sustained tones and real performance of a song. More specifically, lower rate values have been found in sustained notes than inside a song [21]. In addition, these differences in vibrato rate and extent in BM could also be due to the method of the analysis. In the current work other than the autocorrelation method was used and issues such as rate and extent time series, vibrato intonation and various dependencies on f0 and intensity were considered here.

5. CONCLUSIONS

Two methods of vibrato analysis applied in BM showed identical results although with slight differences in the mean intra-tone rate and variability of the standard deviations of the intensity. There was no systematic dependence of the vibrato parameters on the f0 and BM intensity. There is a need to investigate further the variation of the characteristics of BM vibrato in every tone per chanter and by increasing the sample for analysis, by including more singers and tones.

Acknowledgments

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