Control of Synthesized Vibrato during Portamento Musical Pitch Transitions*

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Vibrato, the natural oscillation of musical pitch that is commonly associated with music performed by skilled singers and instrumentalists in certain musical styles, is an important aspect of realistic music synthesis. For synthesized singing particular care must be taken to ensure that the synthesized vibrato behaves naturally, especially in the vicinity of portamento pitch transitions. The appropriate fundamental frequency behavior by singers during legato transitions of musical pitch is examined, and an algorithm to produce realistic transitions for vocal vibrato synthesis is proposed.

0 INTRODUCTION

Vocal vibrato is a natural oscillation of musical pitch that is commonly associated with healthy vocal musculature and good vocal training [1]–[3]. For musical styles and contexts in which vibrato is customary, a singer employs vibrato as an expressive and musically useful aspect of the performance.

Existing systems for music synthesis typically allow vibrato to be specified among the allowable modulation features. Synthesized vibrato may include a user-selectable repetition rate, vibrato depth (fractional change in fundamental frequency), vibrato waveform, and time-varying vibrato parameters, such as a delayed onset or mapping of a controller to vibrato depth.

Research intended to better understand and characterize vocal vibrato dates back to the work of Milton Metfessel and Carl and Harold Seashore in the early 1930s at the University of Iowa [4]–[6]. Metfessel in particular noted the importance of vibrato in adding richness, warmth, and emotion to the musical performance, whereas Carl Seashore wrote [5]:

> A good vibrato is a pulsation of pitch, usually accompanied with synchronous pulsations of loudness and timbre, of such extent and rate as to give a pleasing flexibility, tenderness, and richness to the tone.

A skilled performer is able to manipulate the vibrato rate and depth in complicated ways corresponding to the musical context and mood. Indeed, it is often the subtle control of vibrato that separates a gifted singer from a merely competent one.

The particular vibrato context considered in this paper is the proper behavior during legato pitch transitions. The singer must maintain continuous phonation, known as portamento, when proceeding from one tone to the next. The natural vibrato behavior must therefore be understood if a convincing vibrato is to be produced by a music synthesis system. Specifically, the synthesis system must determine how to align the transitions from one note to the next in such a way as to maintain natural vibrato continuity.

The remainder of this paper is organized as follows. First we review several prior studies of vocal vibrato during portamento note transitions and develop a suitable analytical framework. Next we describe an experiment conducted with trained singers to ascertain the appropriate note timing and vibrato transition strategy for a synthesizer. Finally we conclude with several recommendations for implementing smooth musical pitch transitions to ensure vibrato continuity.

1 VOCAL VIBRATO AND PORTAMENTO TRANSITIONS

One of the musical contexts presenting a challenge for vibrato is a portamento transition from one musical pitch to another [7]–[9]. The portamento causes the vibrato's periodic frequency fluctuation to be superimposed on the musical pitch transition. The portamento frequency transition for vocal vibrato is found to occur in several different ways, as shown in Fig. 1 [6].

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A variety of questions arise when contemplating vibrato control during musical pitch transitions. Among these questions are whether the commonly observed acoustical properties are due to physiological phenomena (the behavior is a byproduct of natural singing and therefore “feels right” to the singer), psychological or aesthetic phenomena (the behavior is taught and learned, and therefore “sounds right” to the listener), or some combination of these influences. Furthermore, the situation can be complicated by the verbal context of the transition (such as vowel–vowel or vowel–consonant), the duration of the adjacent musical notes, the phrasing and style of the musical composition, the type of accompaniment, and so forth [10]–[13]. These issues have relevance in the assessment of human vocal performance, as well as in the design of systems to synthesize artificial singing while retaining realistic, natural qualities [14]–[16]. Although this investigation deals with the fundamental frequency modulation (FM) behavior of vocal vibrato, there are a variety of other vibrato-related effects. The 1990 reference by Maher and Beauchamp [14] and the more recent publication (2005) by Verfaille et al. [16] consider other vibrato characteristics, such as FM-induced amplitude modulation and random variations.

Harold Seashore’s study from the 1930s found that essentially all portamentos exhibited a fundamental frequency leaving the vicinity of the first musical pitch from the side opposing the transition and entering the vicinity of the second musical pitch by passing to the opposite extreme [6]. Specifically, Seashore found that the majority of the transitions were of types II, III, and V, as depicted in Fig. 1. Similar vibrato transition behavior has been noted by other researchers [8], [9], [12], [17], [18].

The crux of the problem is this: unless the vibrato cycle is somehow phase-locked to the rhythm of the music, the phase of the vibrato cycle will not generally match the desired transition pattern (for example, type II) at the instant of the note change, and therefore the transition behavior becomes ambiguous [8], [10]. This problem is depicted in Fig. 2.

If the desired transition pattern is to be accomplished, the singer must somehow align the transition from one note to the next with the rhythmic timing of the music. The singer could adjust the vibrato rate such that the proper transition phase works out—like a hurdler adjusting stride to be able to take off on the right foot—or the singer could alter the rhythmic timing to “wait” for the desired transition. This issue is considered in more detail in Section 3.

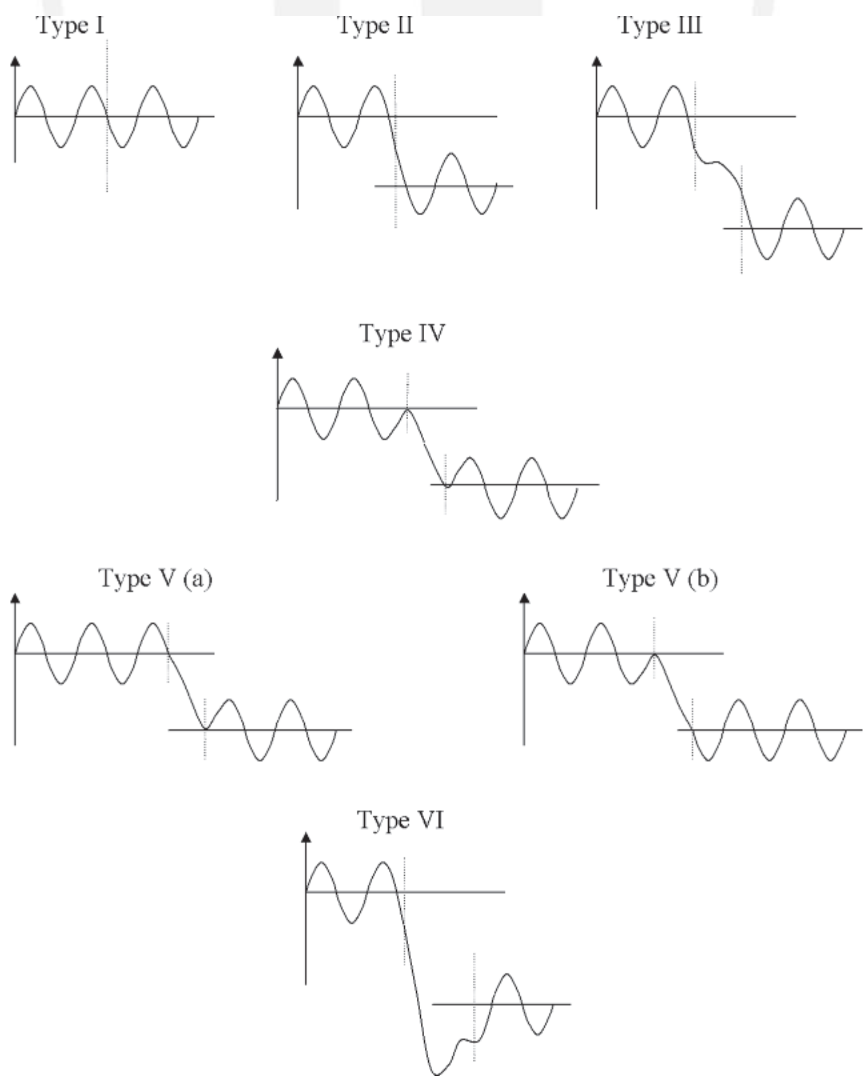

Fig. 1. Vibrato classification for note transitions (legato singing, fundamental frequency versus time). After Seashore [6], p. 70.

2 VIBRATO IN MUSIC SYNTHESIS

Frequency modulation for vibrato in music synthesis systems generally involves a simple two-oscillator patch diagram, as shown in Fig. 3. The default frequency f_0 for the primary oscillator is combined with the output d_v, of the secondary oscillator to create the desired vibrato effect. The secondary oscillator's amplitude setting A_v and its frequency setting F_v control the vibrato depth and vibrato rate, respectively. Expressing oscillator 2 in discrete-time form,

$$d_v[n] = A_v \sin(2\pi F_v n/f_s) \quad [\text{Hz}] \tag{1}$$

where n is the sequence index and f_s is the discrete-time sampling rate in hertz for the system. The vibrato depth is typically specified as a fractional deviation with respect to the primary oscillator's frequency, such as

$$A_v = \Delta_v f_0. \tag{2}$$

Common vocal vibrato shows a fractional deviation Δ_v in the range of 3–5%, or equivalently 50–84 musical cents (where 100 cents corresponds to one equal-tempered semitone, or $\Delta_v = 5.946\%$). Common vibrato rates are in the range of 5–6 Hz [14], [20].

Synthesis of a legato musical pitch transition (portamento) can be accomplished by slewing the primary oscillator's frequency control from the initial frequency $f_{0,0}$ to the frequency following the transition, $f_{0,1}$. The frequency slew rate depends on the musical context, but under normal conditions the transition is accomplished in a small fraction of the note duration so that the rhythmic timing is retained.

In conventional music synthesis systems the primary oscillator generating the vibrato modulation is unsynchronized with the musical note transitions. This means that the actual frequency trajectory during the transition is not

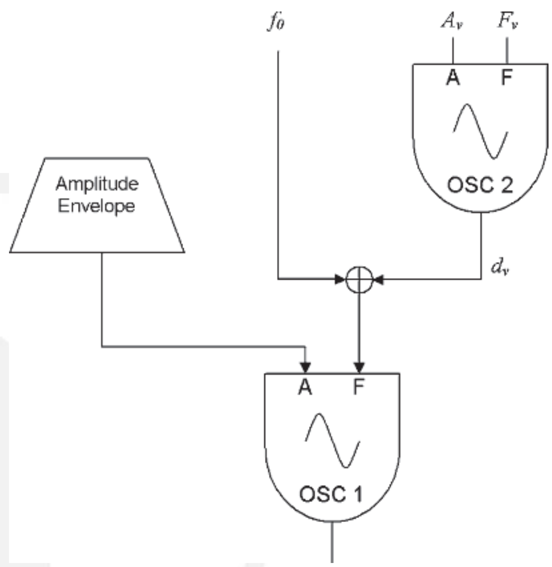

Fig. 3. Typical vibrato patch diagram.

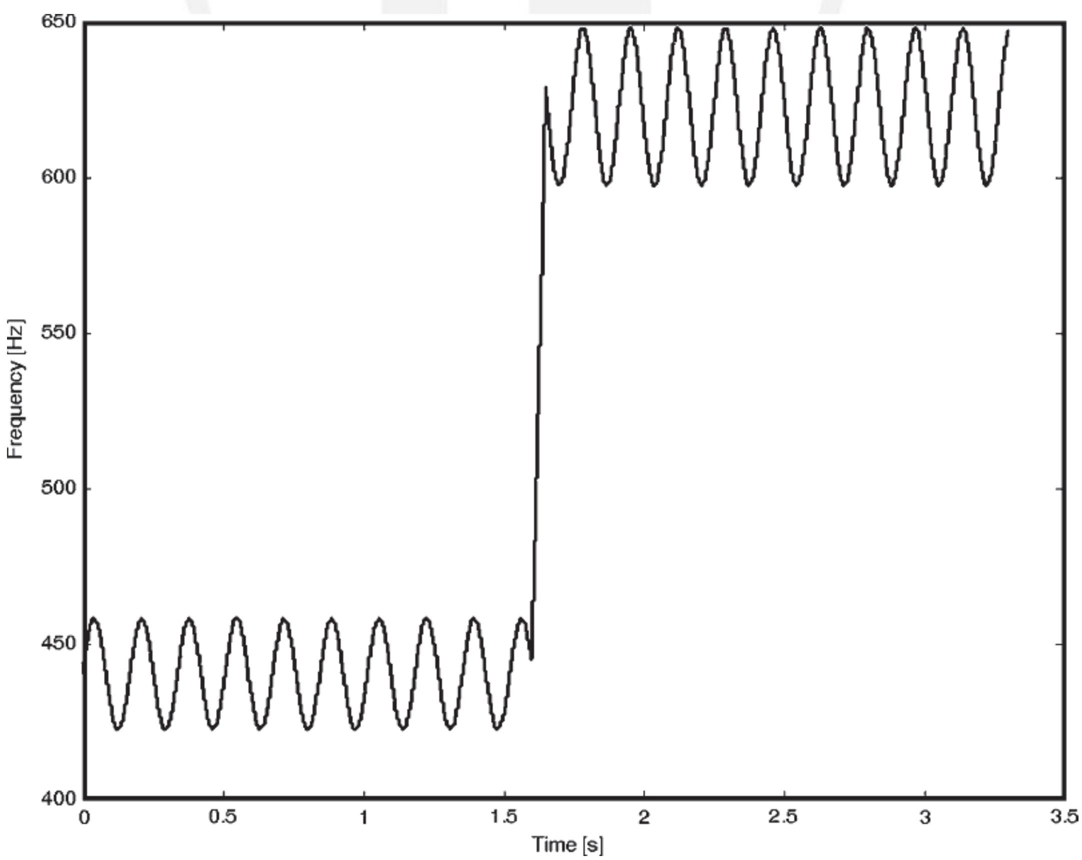

Fig. 2. Legato portamento vibrato transition with unsynchronized vibrato phase. Timing of transition dictated by rhythm does not necessarily align with smooth phase of vibrato cycle.

constrained to the smooth vibrato cycle (type II) unless additional decision logic is employed. Assuming that mimicking the natural frequency transition is desirable, the synthesizer has the same challenge as the singer: how to align the transition from one note to the next with the rhythmic timing of the music. In other words, should the synthesizer employ a strategy in which the vibrato rate is varied in anticipation of the note change to ensure the proper transition, or should the onset of the transition be delayed (or advanced) to align the desired phase of the vibrato waveform?

3 A VIBRATO EXPERIMENT

Asking a trained singer to explain vibrato behavior during a portamento transition is analogous to asking a runner whether the right foot touches the ground before the left foot is lifted when running at full speed. In both cases the individual does not actively control that physical parameter; it happens automatically as a side effect of singing (or running) and is therefore not introspectable. Thus we must somehow observe and analyze the natural vibrato behavior indirectly.

We developed an experimental procedure involving two performance scenarios to investigate the ambiguity between the phase of the vibrato cycle and the timing of the note transition. In the first scenario the singer was invited to sing freely without an assigned rhythm. The singer was therefore able to make the transition whenever he or she desired. The second scenario differed in that a strict rhythmic meter was assigned, requiring the singer to perform the transition in synchrony with a specified musical beat. The research hypotheses tested are as follows.

Hypothesis 1 In the free-singing case the singer performs the pitch transition at a moment in the vibrato cycle that allows a smooth transition.

Hypothesis 2 In the strict rhythm case the singer adjusts the vibrato rate to anticipate and enable a smooth transition.

These hypotheses are consistent with presumptions that the singer is most comfortable with a smooth portamento, and that this type of transition is aesthetically the most pleasing.

3.1 Recording Procedure

The vibrato experiment was conducted with the assistance of the Department of Music, Montana State University–Bozeman. Eight student singers participated in the recording session (1 soprano, 2 altos, 3 tenors, and 2 baritones). None was a professional musician per se, but all had been invited to participate in the elite 16-voice vocal chamber ensemble of the university based on a competitive audition process. The subjects were told only that a musical acoustics study of vocal vibrato was being conducted to avoid the subjects' propensity, either conscious or unconscious, to alter their singing habits. The subjects were not attempting to sing without vibrato.

Each singer was asked to perform individually an ascending and descending arpeggio (major triad plus octave), using legato style, on the vowel /a/, beginning at a comfortable musical pitch. No musical beat or rhythmic cue was provided for the first recording. The subject was simply invited to "sing the arpeggio with each note held for several seconds" before the legato transition to the next note. For the second recording the subject was instructed to "sing each successive note exactly on the beat," and the investigator provided a conventional conducting gesture at 75 beats per minute to indicate the proper timing. A manual conducting gesture was used due to the singer's familiarity with this notion of rhythmic synchrony. Each individual singer was engaged in the experiment for less than two minutes. The monophonic recordings were obtained with 16-bit resolution at a 48-kHz sample rate (digital audio tape) and then transferred to a computer for processing.

3.2 Analysis Methods

A set of custom functions written in MATLAB automatically processed the vibrato recordings, calculated the short-time spectra, and analyzed the time-variant fundamental frequency behavior [21]–[23]. The vibrato parameters and characteristics for each recorded arpeggio were extracted automatically and then verified off-line for consistency by manual methods.

Each recording was processed using a Kaiser windowed short-time Fourier transform (STFT) procedure with an analysis frame rate of 46.875 frames per second. The resulting time–frequency resolution was found to be adequate for the vibrato examination. An example portion of the raw STFT data is depicted in Fig. 4. The fundamental frequency contour and the vibrato transition types were tallied using the definitions of Fig. 1. Note that it is often easier to evaluate the vibrato by treating the higher harmonic partials of the signal [21].

The note onset and transition times were identified for each recording by manually identifying the transition region and then allowing the MATLAB script to identify the adjacent extrema in the pitch contour. The duration of each note in the arpeggio was determined by identifying the time at which the musical pitch contour arrived at the nominal fundamental frequency, and the time from one onset to the next was measured.

The vibrato period measurement was repeated for several notes in the arpeggio sequence and then averaged to reduce any random variability, thereby producing a nominal vibrato period for subsequent comparisons. The corresponding vibrato rate was calculated as the reciprocal of the vibrato period.

3.3 Experimental Results

The measurement results for the eight subjects for free singing and metered singing are given in Table 1. None of the example transitions showed type III or type VI behavior. Type I, representing a vowel transition without a musical pitch change, was not relevant here.

3.3.1 Summary Observations

In the free-singing case the ascending transition pattern was generally a smooth cycle from the low-frequency extremum of the lower note's vibrato to the high-frequency extremum of the upper note's vibrato, while the descending transition was of the complementary form (high-frequency extremum of the higher note smoothly to the low-frequency extremum of the lower note). This corresponds to the type II and type V transitions defined in Fig. 1. Type II transitions were most common, and slightly more common in free singing than in metered singing. Under the conditions of this experiment the singers were remarkably consistent.

The distinction between types II and V is somewhat subjective, but has to do with the frequency deviation of the first extremum both before and after the legato transition. A full vibrato cycle depth is considered type II, whereas one or the other extremum reduced in depth is categorized as type V. An example of a type V transition is shown in Fig. 5. In this example the frequency trajectory for one of the spectral partials is highlighted for clarity. The extremum just prior to the transition is reduced in extent compared to the prior cycles, and thus the transition is judged to be type V.

A smaller percentage of transitions were found to be type IV (10% overall). A type IV example is shown in Fig. 6, again with the frequency trajectory for one of the partials highlighted for clarity. Note that the vibrato cycles both just prior to the transition and immediately following the transition are curtailed in extent, indicating the type IV classification.

Several informal observations can be made regarding the recorded performances, although further investigation will be needed to verify these subjective impressions. The singers appeared to increase vibrato depth for free singing compared to the metered case, although no systematic measurement has yet been made to verify this impression. Similarly, most of the singers appeared to allow their vibrato depth to swell slightly during each freely sung note before diminishing slightly prior to the transition. The metered singing, on the other hand, generally showed a relatively narrow vibrato extent and a slightly higher vibrato rate than in the free-singing case. This observation is consistent with the hypothesis that a singer attempts to adjust the vibrato phase to allow a smooth transition, which is presumably an easier task if the vibrato period is shorter (higher vibrato rate).

3.3.2 Research Hypotheses

The first research hypothesis was that the freely metered singer would choose to perform the note transitions in the smoothest possible manner (types II, IV, and V), and this hypothesis is clearly supported by the measured results in Table 1. The performers allowed the note transition to align smoothly with the vibrato action. The fundamental

Table 1. Vibrato transition observations for eight singers under free-singing and metered-singing conditions.*

Singer	Average Vibrato Rate [Hz]	Transition Type Tally (6 Transitions per Sequence)		
		II	IV	V
Sop_1 free	5.5	4	0	2
Sop_1 metered	5.5	5	0	1
Alto_1 free	5.4	3	0	3
Alto_1 metered	6.0	4	0	2
Alto_2 free	5.6	4	0	2
Alto_2 metered	5.7	3	0	3
Ten_1 free	5.4	4	1	1
Ten_1 metered	5.2	4	0	2
Ten_2 free	5.6	2	1	3
Ten_2 metered	5.7	2	2	2
Ten_3 free	5.5	2	0	4
Ten_3 metered	5.8	2	0	4
Bar_1 free	5.5	4	1	1
Bar_1 metered	5.6	1	0	5
Bar_2 free	6.6	4	2	0
Bar_2 metered	6.1	3	0	3
Total metered	5.7	24 (50%)	2 (4%)	22 (46%)
Total free	5.6	27 (56%)	5 (10%)	16 (33%)

* Transition types (II, IV, and V) refer to classification shown in Fig. 1.

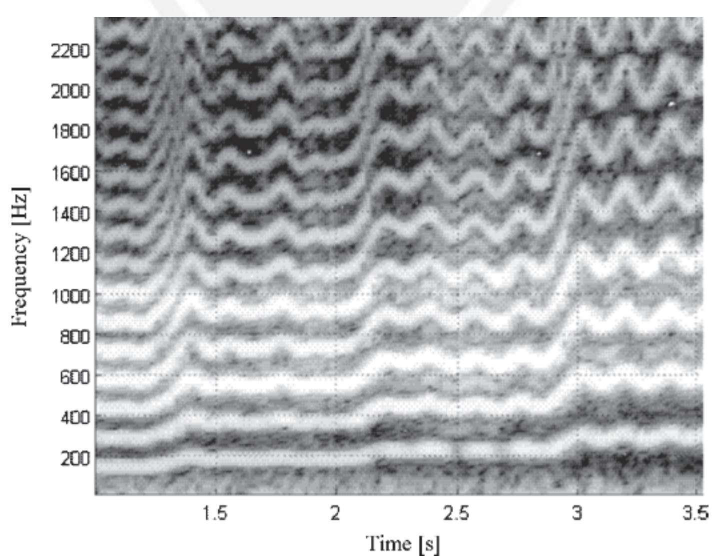

Fig. 4. Example raw output from short-time Fourier transform (STFT) procedure.

frequency traces were continuous, smooth, and generally uniform. There was no evidence that the singer halted the vibrato and restarted after the musical pitch transition.

The second research hypothesis was that the strictly metered singer would advance or retard the vibrato cycle (that is, vary the vibrato rate) such that the moment of transition would line up in time with the proper phase of the vibrato waveform. The data do not appear to support this hypothesis since the vibrato shape and rate were quite similar and regular even in metered singing. Instead, both the transition timing and the vibrato rate appeared to be adjusted slightly relative to the beat so that the type II transition was enabled within the vibrato cycle.

This result leads to the question of whether the singers are actually delaying or anticipating the transition by its synchrony with the vibrato cycle. To investigate this phenomenon, additional measurements were performed on the metered singing data to assess whether the singers were making a systematic delay or advance of the transition timing, or subtly changing the vibrato rate itself. The supplementary measurements are summarized in Table 2.

Table 2 shows the average note duration for each singer in column A. Next, the average note duration was used to predict the expected starting time if the singer was performing perfectly regularly, and the timing discrepancy between the measured start time and the predicted ideal starting time was computed. The average absolute value of the discrepancy is given in column B. For comparison, the duration of one-half the average vibrato cycle is given in column C, with the rationale that if the singer did not vary the vibrato rate and simply performed the legato transition at the nearest opportunity such that the vibrato phase was type II, the average start time discrepancy would be one-half the vibrato period—again, assuming that the metered note start times and the vibrato rate are independent.

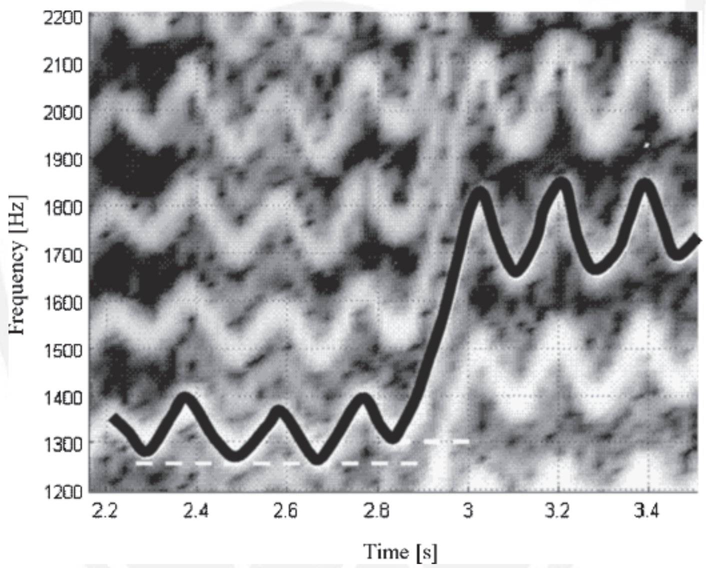

Fig. 5. Example STFT depicting a type V transition: vibrato cycle just prior to note transition is of lesser extent than prior cycles.

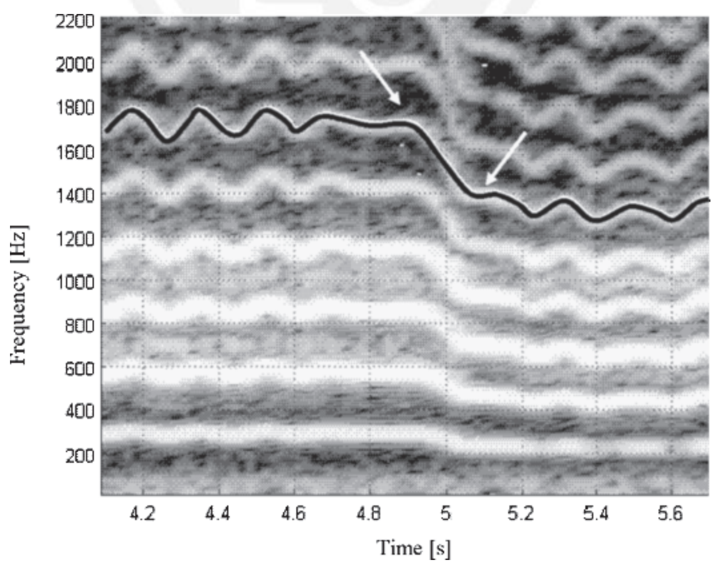

Fig. 6. Example STFT depicting a type IV transition: vibrato cycles just prior to note transition and immediately following transition are of lesser extent than regular cycles.

Since the average timing discrepancy was found to be substantially less than half the vibrato period, it appears likely that the singer actually employs some active control over the transition timing and vibrato rate, as observed by Sundberg [17, p. 73]. Moreover, because the vibrato rate for each singer actually varied somewhat with time, the use of time averages may be misleading in this respect. Further work is needed to understand the natural timing relationships between the vibrato and the rhythmic behavior [19].

The slight delay or advance of the note transition to accommodate the vibrato cycle is blended by the slightly variable duration of the legato (portamento) glide of the fundamental frequency, and therefore the musical timing and internote phrasing do not seem to be hampered by a singer's technique. Informal listening to the recordings does not reveal a noticeable timing irregularity.

4 VIBRATO SYNTHESIS IMPLICATIONS

The singers in the free versus metered singing experiment use a strategy that allows a legato pitch transition to occur with a smooth vibrato trajectory. Thus a music synthesizer attempting to reflect natural vibrato behavior should use a similar strategy.

Table 2. Transition timing measurements for the metered-singing case. For comparison, the duration of one-half the average vibrato cycle period is given in Column C.

Singer	Average Note Duration [ms] (A)	Average Start Time Discrepancy [ms] (B)	Average ½ Period [ms] (C)
Sop_1 metered	810	1	9
Alto_1 metered	790	2	8
Alto_2 metered	740	2	9
Ten_1 metered	840	3	10
Ten_2 metered	770	1	9
Ten_3 metered	790	3	9
Bar_1 metered	760	1	9
Bar_2 metered	840	2	8

A trained singer knows the rhythmic requirements of a particular song, even if sight-reading the notes. Likewise, a synthesizer playing a predetermined musical score will also know the note duration and transition times in advance. The synthesizer can take advantage of the timing information to adjust the vibrato rate and transition times to arrange a favorable vibrato phase at the transition. On the other hand, a real-time synthesis may not be able to anticipate the exact moment a transition will be requested, for example, a new key is pressed on a keyboard. In this case a perfect vibrato transition may not be feasible, but the synthesizer could still attempt to find the best compromise between transition rate and vibrato shape. One approach for aligning the vibrato phase during a synthesized transition is described next.

4.1 Ascending Portamento Vibrato Synthesis Strategy

First consider again the synthesized transition example (instantaneous frequency versus time) shown in Fig. 2. In this example the vibrato rate and the note duration are not commensurate, resulting in an abrupt and awkward transition in musical pitch.

For typical musical vibrato rates, the vibrato period is on the order of 175 ms. This represents a duration too long simply to delay the transition until the next favorable alignment with the vibrato cycle without corrupting the rhythmic pattern of the music. However, by carefully choosing the vibrato rate so that an integral number of cycles fit within the note duration, it is possible to prearrange for the desired vibrato phase at the transition, as shown in Fig. 7. This example of synchronized vibrato was achieved by choosing a slightly lower vibrato rate so that the transition fits the preferred contour.

This concept leads to a practical algorithm for synthesized vibrato synchronization. The proposed algorithm re-

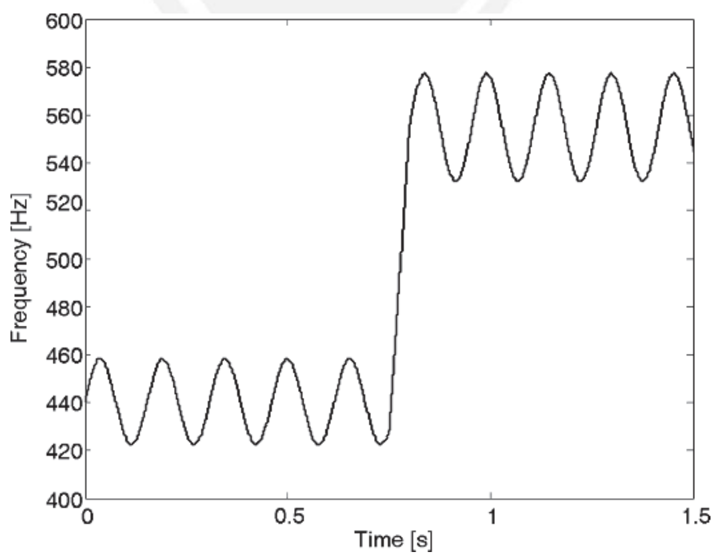

Fig. 7. Synthesized portamento vibrato transition with synchronized vibrato phase.

quires several subjective choices, including the allowable vibrato rate range ($F_{v,min}$ to $F_{v,max}$), the vibrato depth (A_v or Δ_v), and the minimum allowable transition time. The vibrato rate range should be kept sufficiently small so that the maximum rate change from one note to the next is not musically objectionable, while still being sufficiently large to allow a high likelihood of finding a smoothly synchronized transition.

The algorithm can be summarized as follows. For a note duration denoted by τ (seconds) and an ascending portamento pitch transition between two musical notes, the allowable number of vibrato cycles C contained in τ is given by

$$\tau \cdot F_{v,min} \le C \le \tau \cdot F_{v,max}. \tag{3}$$

If this range spans an integer, then there exists at least one allowable vibrato rate that fits the smooth ascending pattern at the transition. In other words, defining the integer $\hat{C}$ as

$$\hat{C} = \{\mathrm{floor}(\tau \cdot F_{v,max}) - \mathrm{floor}(\tau \cdot F_{v,min})\} \tag{4}$$

we see that if $\hat{C} > 0$, then there exist $\hat{C}$ vibrato rates F_v such that the ascending vibrato transition will be synchronized, assuming that the vibrato waveform is a sine wave with zero phase at the onset of the note. The synthesizer can choose the rate closest to this nominal (desired) rate.

If $\hat{C} = 0$, the combination of note duration and the allowable range of vibrato rates does not permit a perfect ascending transition, so the synthesizer must settle for a nonoptimal transition shape, a modified note duration, or force an out-of-range vibrato rate. This situation occurs predominantly for short-duration notes ($\tau < 2/F_{v,max}$). The perceptual importance of vibrato is less significant for these short-duration notes, so for synthesis purposes the nonoptimal transition is generally acceptable.

4.2 General Portamento Vibrato Strategy

Descending vibrato transitions are synthesized using a similar approach, except that the required cycle alignment must now enable the descending trajectory. Similarly, when a sequence of legato notes of differing durations and musical pitches is synthesized, the vibrato rate and transition calculations must be repeated for each successive note. Moreover, the required vibrato phase at each transition must be taken into account so that the smooth type II transition is produced.

For example, if there is an ascending portamento to the current note and a descending portamento to the next note, the phase of the sinusoidal vibrato is zero radians at the start of the note (ascending pitch slope), but the vibrato phase must be π at the end of the note (descending pitch slope).

An example musical phrase with unsynchronized vibrato is shown in Fig. 8. In this example the musical pitch sequence is {G5, A5, B4, E5, D5, A4}, the note durations are arbitrarily chosen to be {0.8, 0.99, 0.41, 0.49, 0.865, 1.6} seconds, and the vibrato rate is fixed at 6 Hz. This result shows the lack of vibrato phase alignment at the note boundaries, which would be typical of a conventional synthesizer with independent vibrato generation.

Next we apply the proposed vibrato transition synchronization method on the same sequence of musical pitches and note durations. With allowable vibrato rates chosen to be between 5.5 and 6.5 Hz, the vibrato transition algorithm calculates vibrato rates as {6.50, 5.85, 6.50, 5.68, 6.14, 5.81} Hz, respectively, resulting in a favorable vibrato transition between each note. The resulting synthesized vibrato pattern with synchronized vibrato phase is shown in Fig. 9. Compared to the unsynchronized behavior of Fig. 8, the proposed alignment algorithm shows smooth and natural vibrato alignment with the portamento transitions.

An informal evaluation of this portamento vibrato synthesis strategy yields a general agreement that the vibrato transitions sound smooth, clean, and natural. The algorithm is straightforward to implement, and very suitable for inclusion in synthesizers using precalculated note durations, such as MIDI files.

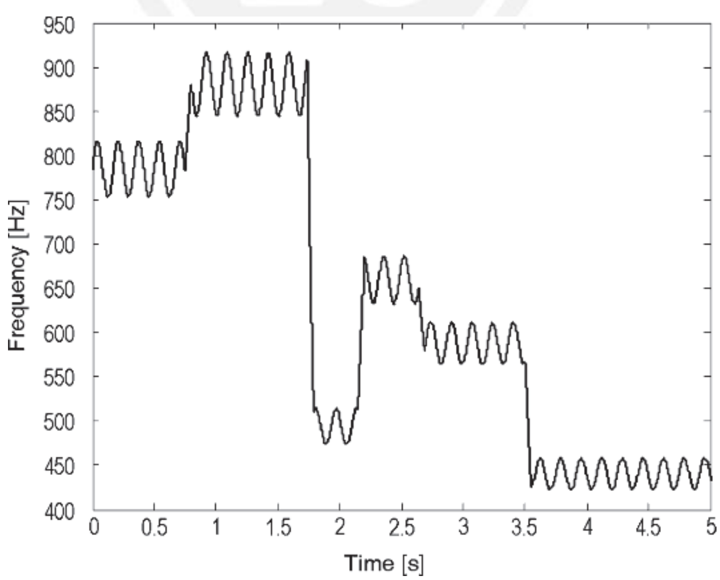

Fig. 8. Synthesized musical phrase with unsynchronized vibrato, 6-Hz vibrato rate.

5 CONCLUSIONS

The vibrato measurements for portamento transitions show a preference for aligning the note transition to the natural shape of the vibrato cycle in both the free-singing and the metered-singing regimes. It appears that in the metered case the singer may be concentrating more closely on the temporal aspects of singing and is therefore more inclined to regulate the vibrato process.

This apparent preference for vibrato continuity over timing accuracy raises the question of its physiological or psychological origin. It is tempting to comment on the apparent psychological aspects, although this experiment was designed to treat only the acoustical characteristics present in the recordings. Our conjecture is that the musculature involved in the vibrato interacts with the vocal fold tension in such a way as to make the singer "feel right" when the transition occurs with synchrony. It is not known whether this behavior is learned by listening to other trained singers or comes naturally as part of unconscious instinct. We have not found a vocal instructor who is consciously aware of this particular nuance of vibrato, yet it seems to be quite pervasive.

Among the motivations for this work was the desire to obtain more natural and realistic qualities for artificial synthesis of singing and other musical sounds [14]. In most current synthesis systems the vibrato generator is a separate and largely independent component of the synthesis architecture, and therefore the vibrato during portamento transitions is not generally confined to the type II behavior of natural singing [19]. It is possible that the decoupling between the note transitions and the vibrato behavior may contribute to the synthesized singing being judged unnatural, although definite conclusions in this regard will await further study.

The proposed smooth portamento vibrato transition strategy uses the allowable vibrato rate range as a parameter, thereby choosing the rate that will allow a near-optimal vibrato phase at the transition point without notable timing errors or unnatural variations.

6 ACKNOWLEDGMENT

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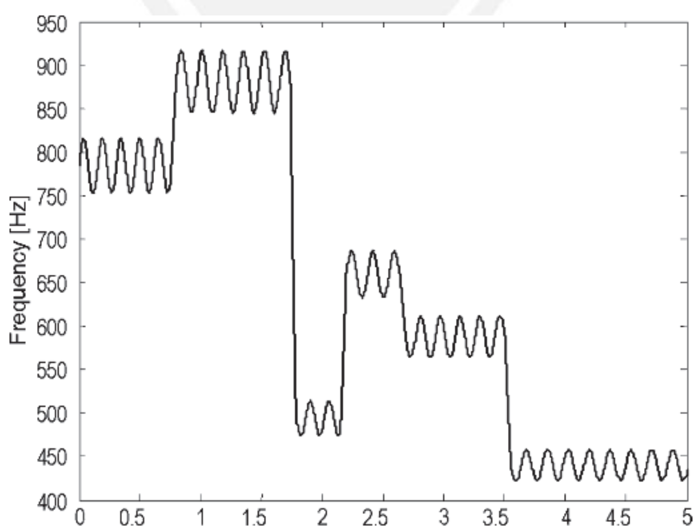

Fig. 9. Synthesized vibrato with proposed synchronization algorithm.

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