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Vibrato in music – physics and psychophysics

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ABSTRACT

Vibrato is a common feature of most present-day musical performances, from violins to opera singers, but its ubiquity has developed only since about the beginning of the nineteenth century. To some people it is an essential feature of musical performance while to others it is an unpleasant distortion of a musical experience. There are several different types of vibrato depending upon the person or instrument producing the sound, and the effect can vary greatly. This paper examines these various production techniques and their audible outcomes and then discusses the psycho-acoustic effects of vibrato on the listener.

INTRODUCTION

From the available evidence it seems that vibrato was not common in classical music until at least the eighteenth century. Musical instruments such as lutes and viols all had frets on the finger board so that note pitches were well defined, and the same was true, of course, of harpsichords, organs and other keyboard instruments. Scale tuning itself was also well defined with major and minor thirds tuned exactly to frequency ratios 5/4 and 6/5, rather than the compromise introduced by modern equal-temperament [1]. Bach's 48 preludes and fugues were composed to be played on a "well-tempered" instrument, perhaps using the Werckmeister III tuning, rather than with equal temperament. Because of the influence of pipe organs and the presence of boy's voices in choirs, a clear stable pitch was also the aim for vocal music.

But things changed during the eighteenth century, and more so during the nineteenth and twentieth. Violins, violas and cellos, all without fingerboard frets, replaced viols, so that note pitches were no longer fixed but could be easily varied, Flutes with easily varied lip embouchure replaced recorders, and trumpets with valves replaced 'natural' instruments. Most music was then played with somewhat flexible pitches and the regular pitch variation of vibrato became common. Something similar happened on the vocal scene as women's voices replaced those of boys in choirs and the narrative of operas became more emotional.

This leads to the questions: (i) Why did regular sound fluctuations with period in the range 5 to 10 Hz become popular? (ii) How are these fluctuations generated and controlled? (iii) What is their effect on human musical perception? This paper will address these questions.

First, however, it should be recognised that there are three basically different forms of vibrato. In the first, all that changes is the frequency, and thus the pitch, of the note. This is the idealised form recognised in musical terminology as 'vibrato'. In the second it is the amplitude and thus the loudness of the sound which changes, and this is known as 'tremolo'. Thirdly, there can be a rhythmic change in the spectral balance or timbre of the sound, a pattern for which there is no recognised separate musical term, so it is just called vibrato. As will be discussed later, however, there is generally a mixture of these three vibrato types, so that the naming refers only to the effect that is most prominent in human perception.

Most published discussions of the topic deal with vibrato in singing, since this is where it is most commonly noticed [2,3], but a few more general papers have appeared [4].

An approximate quasi-steady state representation of vibrato is adequate for the present discussion, since the sounds produced by most musical instruments consist of phase-locked harmonics of the fundamental. The nth mode then has a waveform

$$y_n(t) \approx a_n\ (1+\Delta_n \sin\Omega t)\sin[n\omega(1+\delta\sin\Omega t)] \qquad (1)$$

where ω is the unperturbed fundamental frequency, Ω is the vibrato frequency, δ the fractional vibrato amplitude in frequency space, and Δ_n is the vibrato amplitude in radiated sound pressure. Both Δ and δ are very much less than 1 and Ω is very much less than ω. To be completely realistic one might recognise that the vibrato is not precisely sinusoidal, but this need not be considered here.

BOWED-STRING INSTRUMENTS

The most straightforward form of vibrato is probably that used in playing bowed-string instruments such as the violin. The finger pressing the string to the fingerboard is simply rocked sideways so that it rolls back and forth along the string and varies its length in a periodic manner. The mathematical problem involved is actually quite complicated if treated rigorously, for the string becomes a moving-boundary problem. Fortunately, however, the relative motion of the boundary is small, as also is the boundary variation frequency (5–10 Hz) compared to the fundamental frequency of the string vibration (>100 Hz).

Since the finger movement is by a rocking motion, the change in string length produced is small, probably less than ±5 mm. A typical string length is about 30 cm, so that the change in length is less than about ±1/60, which is about ±20 cents or a fifth of a semitone. This estimate is verified by analysis of time-resolved spectra for solo violin performance. In some cases, of course, the vibrato may be smaller than this. The effect will be clearly heard, but the pitch deviation may not be very prominent. The vibrato frequency is typically around 5 Hz, but varies between performers. A typical; example with an expert player is shown in Figure 1.

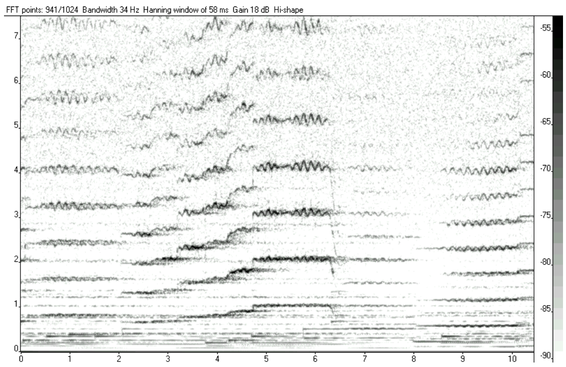

Figure 1. Time-resolved frequency analysis of an expertly played violin sound [4]. The time duration is 10 seconds and the frequency range 0–7 kHz. Vibrato amplitude is about 3% or about 50 cents.

If one examines the transfer function between bridge force and radiated sound for a violin, then resonances of the upper plate, enclosed air, and body are clearly seen and some are fairly sharply defined. This means that a variation in fundamental frequency necessarily carries with it variations in loudness and harmonic envelope or musical timbre, so that the total vibrato effect is a superposition of the three vibrato types, though with pitch variation dominating.

While bowed-string instruments often play solo parts, much of their effort is devoted to orchestral playing where there are typically six or more instruments playing the same notes. There is no desire to synchronise the vibrato motions of individual players, so that the resulting sound could almost be described as narrow-band noise centred on the note being played, though actually being more structured than noise. This 'chorus effect' is very pleasant and gives a rich quality to the sound, while individual vibratos are hidden.

WOODWIND INSTRUMENTS

Woodwind instruments must rely upon entirely different techniques to produce vibrato, since the length of the bore and the positions of the finger holes are all fixed. Any vibrato or other effect must therefore be developed by the interaction between the fixed air column resonances and variable properties of the air-pressure-driven nonlinear oscillator driving the sound production.

The obvious variable to change in order to produce vibrato is the air pressure in the mouth, since this can be influenced by contraction or relaxation of the abdominal muscles compressing the lungs. The oscillatory speed with which this can be done varies a little from one player to another, but is generally towards the lower end of the 5 to 10 Hz range. There are also other possible techniques that will be considered later.

The influence of varying blowing pressure varies somewhat from one instrument type to another. In the case of a reed instrument an increase in blowing pressure generally leads to a small increase in sound level with very little change in pitch, but if the blowing pressure is already high then increased blowing pressure may have the opposite effect since it will tend to close the reed and reduce its oscillation amplitude. Different woodwind instruments have developed different traditions in this regard, so that clarinets generally play with no vibrato while oboes usually use it, except perhaps when playing in duet mode with a clarinet. Bassoons generally play with small vibrato to match oboes. An oboe vibrato typically has a pitch range of about ±20 cents or a fifth of a semitone [4].

In the case of a flute, increased blowing pressure increases the speed of the jet and thus the speed of deflection waves upon it. These waves are generated by the incidence of the jet upon the upper lip of the embouchure and the phase relation between lip opening and pipe lip will be changed. This change can have a large effect upon the acoustic and aerodynamic interactions deflecting the jet and generating the harmonics. Thus, while the effect of pressure pulsations on total sound output may not be large, there may be a very significant influence upon the balance of harmonics in the sound. This timbre variation is confirmed by experiment [5] as being the major feature of flute vibrato, as shown in Figure 2. The amplitude of the fundamental is nearly constant and the pitch variation is typically only about ±10 cents.

There is also another way in which woodwind players can generate vibrato, and this is through the motion of the lips or mouth. The acoustic resonances of the mouth cavity are closely coupled to the reed vibration, so that a change in mouth volume can have an effect on both pitch and timbre. In the case of reed instruments the player can also vary the lip pressure on the reed which causes a periodic change in the equilibrium reed opening. This results in a change in vibration amplitude and so in sound amplitude, with only a small influence on pitch or timbre.

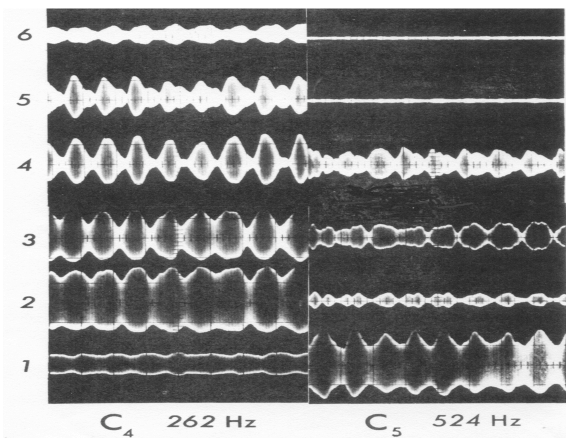

Figure 2. Waveforms of harmonics of two flute notes played with normal vibrato [5]. Note the variation in sound pressure amplitude of the upper harmonics, particularly for C_4.

In the flute, a similar technique allows oscillatory variation in the lip aperture, which will change overall loudness, or alternatively a variation in lip configuration, which changes the direction of the air jet and consequently varies the balance between harmonics generated by the jet. Both of these techniques are possible, but are not favoured by professional players or teachers.

The vibrato frequency typically varies a little between players, and this is most noticeable in the flute where the harmonic content of the sound is less than in reed instruments. While the range is typically between 5 and 8 Hz, the vibrato frequency often aids in the recognition of performance by a particular player. Vibrato frequency and amplitude are, however, not fixed quantities for a given player, and there are often subtle changes within a single sustained note, with the vibrato amplitude and frequency either increasing or decreasing through the note duration depending upon whether it is the beginning or the ending of a phrase.

BRASS INSTRUMENTS

In brass instruments, once again, there is a resonator with fixed mode frequencies coupled to a highly nonlinear oscillator, the player's vibrating lips, which act as a valve to inject a periodically varying volume flow of air. It is possible for the player to vary the lung pressure driving the airflow or to vary muscular tension in the lips, which will affect both their vibration amplitude and frequency, though the frequency variation is limited by the resonances of the air column.

Another limitation is the fact that brass instruments often play notes based upon higher modes of the relatively long air column. This has the consequence that any substantial modification of the natural vibration frequency of the lips may cause a jump to a neighbouring mode, which is not what is desired in vibrato.

For these reasons brass instruments are usually played without vibrato in orchestras, and indeed when a vibrato or tremolo is introduced it tends to sound "unnatural" or even unpleasant..

KEYBOARD INSTRUMENTS

In a keyboard instrument one might expect there to be no opportunity for vibrato in the sound, but in fact there is. In the case of the clavichord, where the string vibration is excited by the impact of a small metal plate which deflects the string, it is possible to vary the plate position a little by changing the force on the key, thus causing slight pitch variations. In the piano no such control is possible since the hammer hits the string and rebounds, but surprisingly the fact that there are generally several strings for each note, the interaction between the string vibrations at the bridge, which is not completely rigid, causes an oscillatory variation in loudness which is under the control of the piano tuner rather than of the player [6]. In both cases there is also a temporal variation caused by interaction of the two polarisations of string vibration which combine to form a slowly-rotating ellipse.

None of these effects can be produced on the pipe organ, but many organs have a rank called either "vox angelica" or "vox celeste" which produces an oscillatorily varying sound modulation. This is accomplished at the will of the designer and builder, for these ranks contain two pipes for each note and the tuner typically adjusts these to produce a beat at about 8 Hz.

THE HUMAN VOICE

The most studied form of vibrato is that of the human voice, excellent reviews having been given by Sundberg [2] and by Titze [3]. The main reason is the great freedom allowed for the technique because the vocal tract air column does not control, or even significantly influence, the vibration frequency of the vocal folds but rather acts as a resonant filter for the higher harmonics. This filter action produces bands of emphasised harmonics known as formants, and the pattern of these formant frequencies is what differentiates the various vowels in human speech.

Vibrato in human song is produced by oscillatory variation of the tension in the muscles linked to the vocal folds, this variation changing their position and tension and thus vibration frequency. While vibrato frequency is generally in the range 5.5 to 7.5 Hz for different singers, the frequency for an individual is usually almost fixed, independently of the music being sung. The vibrato frequency is quite important in identifying particular singers, and the reasons for its restricted range are clear from both physiological and musical viewpoints. While a vibrato rate slower than 5 Hz could easily be achieved, it begins to cease sounding like a vibrato and is perceived as simply a pitch change and is not attractive. At the other extreme, a vibrato that is faster than about 20 Hz is no longer perceived as an oscillatory pitch change but rather as a "roughness" in the sound of the note, which is again unattractive.

A particular feature of sung vibrato is the large variation in pitch frequency compared with vibrato in musical instruments. This is illustrated in Figure 3 for a distinguished soprano soloist Typical frequency variation in singing is in the range ±1–2 semitones, which is ±6–12% or ±100–200 cents compared with only 20–50 cents or so in wind instruments. Sung vibrato with a frequency variation greater than ±2 semitones is often called "trillo" because it sounds more like a transition between two notes.

As mentioned before, very young singers of either sex do not use vibrato at all, but it appears to emerge spontaneously in professional singers, though perhaps encouraged by existing performance norms and the preferences of teachers. There is, however, one notable advantage of vibrato and that concerns pitch accuracy in singing. If a steady 'pure' tone is used, either in solo or choral singing, then very accurate pitch is required or the result will sound 'out of tune'. Singers using vibrato, on the other hand, can get away with much larger inaccuracies in pitch, which is certainly an attractive feature from a performance viewpoint. Some other features of vibrato will be discussed in the next section.

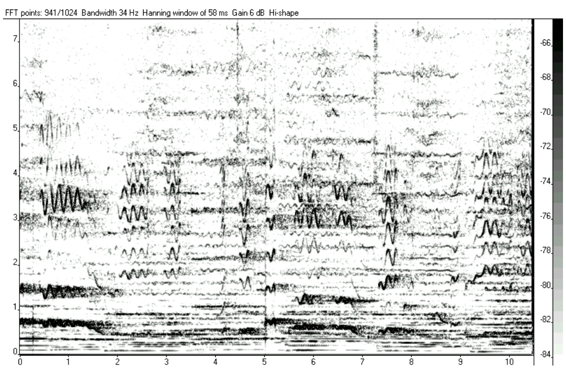

Figure 3. Time-resolved spectrogram of a distinguished soprano singing a quite unemotional piece [4]. The time duration is 10 seconds and the frequency range 0–7 kHz. Note the great frequency amplitude of the vibrato.

PSYCHOPHYSICAL BASIS

Music in general has a strong interaction with human perceptions and many different influences can be conveyed, ranging from the discipline of army marching bands through the pleasure of dancing and the emotional excitement of opera to the calming effects of a peaceful lullaby. The neural and perceptual phenomena underlying these influences have been examined in depth by Zwicker and Fastl [7].

Perhaps the most obvious property of vibrato, as exemplified in the operatic singing of sopranos, is that it adds an emotional character to the musical line. Of course there is more to it than this, but emotion is an important clue to the popularity of vibrato and suggests that there may be some psychological effect related to it. This is supported by the fact that the vibrato frequency is typically in the range 5 to 10 Hz, or a time period 0.1 to 0.2 s, which is the onset time of many human neural and muscular responses. Even more importantly, the frequency range nearly coincides with the 8–12 Hz frequency range of the 'alpha rhythm' of brain-cell oscillation as detected by electro-encephalography. It is therefore not unreasonably to expect some sort of maximal effect within this frequency range.

Examples of other neural/muscular responses of significance are the tremor frequency associated with Parkinson's disease and the triggering of epilepsy in susceptible people by repetitive light flashes at about 6 Hz. Although these responses are associated with neural defects, they do indicate a characteristic oscillatory timing for the human neuro-muscular system, and this supports the view that stimuli within this frequency range may be particularly influential.

SUBJECTIVE EVALUATIONS

Part of the perceptual influence of vibrato stems from the human mental process of categorical perception. A musical note with vibrato will then be mentally classified as either a constant pitch with a varying character, or as a varying sequence of pitches. Loudness and timbre vibratos will generally fall into the first category, while pitch vibratos will be perceived as one or the other depending upon the magnitude and speed of the pitch variation.

Particularly in the case of song, there may also be an influence from the perceptual environment in which the musical note or phrase is embedded – a pure uninflected note matches well with a peaceful and relaxed environment while a note with substantial vibrato is suited to an environment with high emotional content. Pure uninflected tones are therefore favoured in the environment of a cathedral – it is difficult to imagine a satisfying performance of Allegri's *Miserere* with vocal vibrato – or in songs describing a peaceful view of the countryside. Intense vibrato, in contrast, is appropriate in emotional environments such as love scenes or conflicts in an opera. If the music is heard in an unmatched environment, such as listening to an operatic soprano on the radio with the volume low while reading a book by the fireside, the emotional categorisation may not be aroused, so that the singer sounds simply like someone with an unpleasantly "wobbly" voice.

The sounds of musical instruments rarely reach into the highly emotional character of opera, so that vibrato is perceived simply as a character of the musical tone and judged accordingly. There is therefore a preference for moderately fast vibrato with rather small amplitude in terms of the variation imposed upon the original tone.

CONCLUSIONS

Musical vibrato is a very subtle modification of tone quality that may either enhance or detract from the quality of the sound as perceived by the listener, depending upon the acoustic environment and the emotional content of the music. Many singers and other musicians tend to use a fixed vibrato quality independently of these factors and this can detract from the quality of the performance as judged by the listener. On the positive side, however, a judicious use of one or other of the forms of vibrato can enhance the impact of the music and give individuality to the performer.

Vibrato appears to be entrenched as a performance attribute of classical and contemporary music as played today, with the possible exception of the clarinet and some brass instruments. It is good, however, to find that performances of "Early Music" using no vibrato are also becoming popular and that choirs using boy sopranos still sing in some cathedrals and university chapels. The co-existence of these two performance styles enhances the impact and enjoyment of them both.

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