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VIBRATO FREQUENCY AND PHASE LOCK IN OPERATIC DUET QUALITY

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Abstract: For a 'bel canto' trained singer, 'vibrato' is defined as a periodic variation of the fundamental frequency of the sung note, with an intensity variation of the same period. 'Tremolo' is a variation in the intensity only. The locking of vibrato frequencies in unison soprano choirs has been reported and studied. A 1982 review article on the physics of the singing voice suggests that the pleasing or less pleasing quality of harmony in a vocal duet, for example, depends on whether or not the vibratos of the singers synchronise. This does not appear to have been investigated. Recordings of Dame Joan Sutherland singing the "Flower Duet" from the opera *Lakme* by Delibes with each of 3 different singers were studied. The powerful *SpectraPro* software was used for analysis. Our results show one singer locking in phase with Dame Joan, another locking in antiphase and another exhibiting phase wander. It is quite remarkable that such a complicatedly coupled system should behave so like a classically coupled oscillator system, for which in phase, and out of phase locking is possible, as is also phase wander. Psychophysical coupling clearly occurs.

1. INTRODUCTION

Aim

The aim of the acoustic analysis was to demonstrate firstly, that in operatic duet singing, the vibratos of the two singers can synchronise and secondly, to determine whether or not there was vibrato synchronisation in any of the chosen excerpts of the "Flower duet" from Lakme by Delibes. This aim developed out of expressed interest in this phenomenon by several voice researchers, namely, Troup [1] and Sacerdote [2].

Previous studies

The vibrato patterns of the solo singer have been studied by many people in great detail. Seashore [3] defined vibrato and tabled average rates and extents for famous singers. Choirs and larger ensembles have been examined with Sacerdote [2] reporting on the locking of vibrato frequencies in unison soprano choirs. It came to our attention that the locking of vibrato frequencies in duet singing had not been investigated. In a review on the physics of the singing voice published in 1981 by Troup [1], the following surmise occurs: "It may well be that the pleasing or less pleasing quality of harmony in a vocal duet for example, depends on whether or not the vibratos of the singers synchronise."

Why the interest in this topic?

One of the researchers is a singer and it was her experiencing first-hand this locking of vibratos that has interested us in this particular topic. She has performed the duet for mezzo and soprano from *Lakme*, by Delibes several times with at least four different mezzo partners. However, it has only been with one of the partners that there was an audible buzzing each time they sang together in certain passages of the duet. They were not singing the same pitch but we believed that their vibratos were synchronised and that this was creating the audible buzz. This type of vibrato locking in duet singing does not seem to occur a great deal but we feel that it is perhaps the key to a successful rendition of a duet with someone. It is the type of connection between two singers that composers probably visualise as they write their music but is seldom heard in reality.

Relevance of the study

The relevance of the results found so far in this study is quite considerable, for singers, teachers, directors, conductors and perhaps even composers. The results of the project may lead us to question some of the structures and traditions of vocal pedagogy as we know it. A structure which in focusing entirely on the solo voice, neglects to develop sensitivity to the different requirements of ensemble singing.

This project prompts the following questions. In duet singing we wonder how many singers consider how their vibrato contrasts or matches that of their partner. Do they alter their vibrato rate and extent at all, and if they do is this a conscious or a subconscious event? Do both singers alter their vibratos in order to attempt synchronisation, or only one of the singers? Is it accepted that either the higher or the lower voice makes the changes or does each singer remain constant? The study provides statistics proving that vibrato synchronisation or locking does indeed occur in duet singing.

It is also our belief that the synchronisation of the vibratos in a duet results in a fusion of the voices that is preferred by listeners. Further research is being conducted in order to examine the relationship between this synchronisation and preference rating of voice specialists. These results will not be discussed in this paper but we can say that results so far indicate that this is indeed the case. The implications will be most exciting for the opera world in the following ways:

- performers will have reason to consider their duet partner's vibrato rate and extent and will collaborate more often with their partner on phrasing and phasing of their vibrato;
- vocal pedagogues may consider training their students more often with differing partners and assessing aurally and also perhaps measuring acoustically how their students

synchronise when singing duets;

- directors will have to consider where they place the performers on the stage so that they can have the best possible chance of synchronising;
- conductors will have good reason to argue with directors over the staging if it interferes with balance and synchronisation of the vibratos of the two singers in the duet.

2. METHODOLOGY

The procedure was to acoustically analyse the three duets and to obtain the exact rate and extent of the frequency vibrato of each singer. The software used for this analysis was the SpectraPro 3.32A, a PC-based system with high-resolution FFT signal analysis, editing and playback of the sounds of speech and singing. The results were obtained using the Spectrograph display window with settings as follows: Sampling rate = 22050 Hz; FFT size = 1024; Window = Hamming; Averaging = 2. The material analysed consisted of three commercially available CD recordings of Delibes' "Flower Duet" from Lakme. Details are given in Table 1. The singers are all internationally renowned. Joan Sutherland is the soprano for each and the three mezzo-sopranos are Hugette Tourangeau, Marilyn Horne, and Jane Berbie. The score of the "Flower Duet" was examined and notes of crotchet duration or more were chosen for analysis. Ten pairs of duet notes in all were selected for analysis ranging from B4 to F#5 for the soprano and G4 to D#5 for the mezzo-soprano.

Table 1. Details of source recordings

Sutherland - Tourangeau	Classic Options CO3532
Sutherland - Horne	Virgin VVD780
Sutherland - Berbie	Decca 436305-2

The duet notes that were selected for analysis were the sustained notes of constant frequency, and in some instances the passage from one note to another (portamento), in which the singers are singing simultaneously. Rates were determined for each singer by selecting a high, clear partial from the spectrographic display of the note and plotting the peak and trough of each cycle in a graph format in seconds. The measurements were graphed using Microsoft Excel graph spreadsheets. This provided both the frequency vibrato rate and extent for each singer on these selected notes. For this paper we will concentrate on only one of the selected pairs of duet notes, namely, the pair identified as number 9. For the soprano the note is a dotted crotchet on F#5 using the French nasalised vowel [ã]. The note for the mezzo-soprano is a dotted crotchet on D#5, using the same nasalised vowel [ã]. The reason we have chosen this pair of notes is because by showing these three examples we can demonstrate the in-phase lock, antiphase lock and wandering that occurs between the vibratos of the two singers in duet. This pair of notes also provided the longest time period to observe the vibrato of the singers.

The second part of the acoustic analysis, was the analysis of the singers in a solo capacity. At the beginning of the duet both singers sing by themselves. We have analysed the longer notes of these solo passages and will be able to compare what the singer is doing in duet and solo on the same pitch and in some cases also the same vowel. This has proved very useful in determining whether the changes in the vibrato rates that occur in the duet singing also happen during solo singing or whether the changes are only affiliated with duet singing. We will discuss two of the selected solo notes. The notes are the same pitches that the singers sing in the duet notes we have analysed for this paper and it is for this reason that we will discuss the analysis of them. Because of length limitations we are only able to discuss the solo singing of one of the excerpts, namely the Sutherland - Berbie excerpt. The same procedure was applied to selecting the solo notes of each singer for analysis.

Whilst the research has measured both the frequency and extent of the singers' vibratos, in this paper we will only be discussing the vibrato rates of the singers. The vibrato extents shown on the graphs are only approximate. We can say that the frequency vibrato extents are still under assessment and will be a major part of the study.

3. RESULTS

Figure 1 demonstrates clearly the phase wandering pattern. The exact time period for the sung notes is 2.81 seconds for Sutherland and for Tourangeau it is 2.84 seconds. Essentially Sutherland is maintaining a vibrato rate between 5.26 and 5.88 cycles per second. Tourangeau is more erratic and her vibrato rate changes from 5.26 to 8.33 cycles per second. At the onset of the note Tourangeau begins at an averaged 7.87 cycles per second she then dramatically drops this rate to 6.10 cycles per second. At this point we see the two singers are in an anti-phase motion. The bracket shows this brief moment of anti-phase lock. This anti-phase lock is not characteristic for these singers. In the results of the other nine duet notes we see that for the tendency for these two singers is what appears to be a slow drift in relative vibrato phase. The singers then move through a series of motions throughout the rest of the note, almost in-phase, out of phase and then wandering and never coming back into any phasing at all.

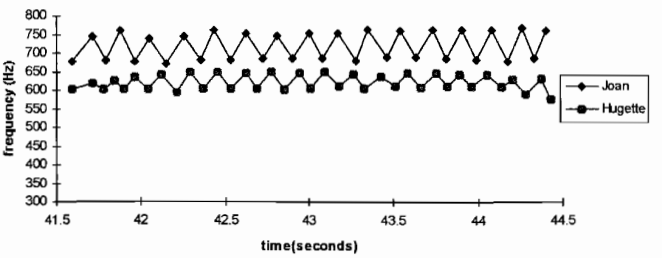

Figure 1. Pair 9 as sung by Joan Sutherland and Hugette Tourangeau.

Figure 2 shows a clear example of anti-phase lock occurring. The duration of the notes in this example are 2.74 seconds for Sutherland and 2.94 seconds for Horne. It takes almost 2 seconds for the pattern of anti-phase lock to emerge, but once it does the singers remain locked in this anti-phase mode until the end of the note which is for a further 0.74

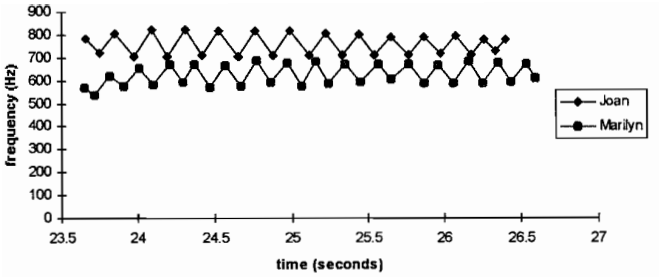

Figure 2. Pair 9 as sung by Joan Sutherland and Marilyn Horne

seconds. Although the singers' vibrato rates are obviously identical when they are in anti-phase lock the cycles are out of phase and this will still cause dissonance between the voices. The exact moment that anti-phase lock occurs is 1.99 seconds after Sutherland has begun to sing and 2 seconds after Horne has begun to sing. This point is at the time 25.65 seconds and is indicated by the arrow. We can see in this case that both singers change their vibrato rates significantly. If we break each of the notes into approximately 3 sections of almost 1 second each, we can see that this is the case. For the first second section the soprano is at 4.54 c/s, and for the second she is at 4.5 c/s. For the third second she is at an increase to 5.33 c/s. For the mezzo-soprano the first second section is at 5.43 c/s, the second section drops to 5.05 c/s and the third section increases again to match very closely with the sopranos third section at 5.31 c/s.

This anti-phase lock was a consistent characteristic for these two singers. In the 10 pairs of notes studied 5 of them exhibit cases of anti-phase lock which the most cases out of the three recordings.

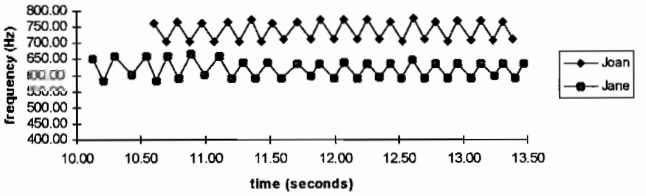

Figure 3. Pair 9 as sung by Joan Sutherland and Jane Berbie.

Figure 3 is most significant in that it depicts clearly what we recognise as vibrato synchronisation resulting in an in-phase lock. The two singers are Joan Sutherland and Jane Berbie. The duration of the notes in this excerpt are for the soprano 2.79 seconds and for the mezzo-soprano we captured 3.35 seconds. The perfect lock occurs on this time scale at the point 11.71 seconds which is 1.11 seconds after the soprano has begun her note and 1.59 seconds after the mezzo has begun her note. This point is indicated by the two arrows on Figure 3. The singers remain in a perfect lock for the rest of the duration of the note with only four exceptions. The four diversions from the perfect lock are only a difference of 0.01 of a second.

In order to see how this compares to when the singers are singing solo we will discuss the solo notes taken from the Sutherland - Berbie recording. These notes are the same pitch that the singers are singing in the duet notes we have already discussed.

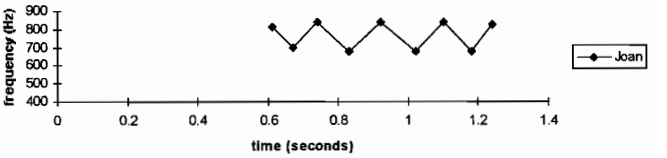

Figure 4. Note number 1 as sung by Joan Sutherland..

In Figure 4 we see that in this example of solo singing Sutherland is singing at a rate of 6.24 cycles per second and at the same pitch in duet her singing was an average of 5.53 cycles per second. This demonstrates the theory that singers alter their vibrato rates in operatic duet singing in order to synchronise. Sutherland uses a slower vibrato rate when she is singing in duet. The same pattern is evident for Berbie. Figure 5 demonstrates this.

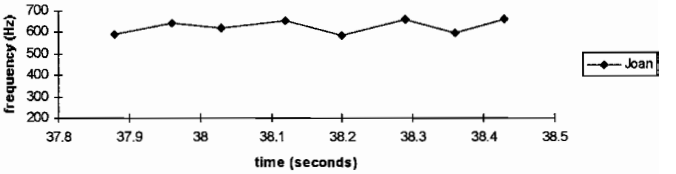

Figure 5. Note 14 as sung by Jane Berbie.

When Berbie sings at this pitch in solo her vibrato rate is an average of 6.54 cycles per second compared to an average of 5.35 cycles per second when she is singing at the same pitch in duet. The results of the full research indicate that this pattern is the same for the other singers.

4. INTENSITY CHANGE IN VIBRATO LOCK

The phase of intensity change with respect to frequency vibrato in the vibrato of individual singers has been extensively studied: a good summary of the literature and the findings is given by Horii [5]. There are singers with in-phase, others with antiphase intensity change with respect to frequency change, and still others with little or no intensity change. Horii explains this by considering what occurs to the fundamental and each harmonic when they interact with the vocal tract resonances (formants). A harmonic undergoing frequency vibrato will give rise to an in-phase intensity vibrato if the harmonic frequency is below the formant resonant frequency, and an antiphase intensity variation if the harmonic frequency is above the formant resonant frequency. At the resonant frequency there will be little or no intensity change at the vibrato frequency, but a small intensity change at the second harmonic thereof. Examples of this behaviour are given in Horii [5]. We have also observed in-phase and antiphase intensity change for various harmonics of the different singers studied. The intensity is shown in the Spectra-Pro presentation of spectra by either a grey scale, or a colour scale. It was found that the colour scale was preferable. In Figure 6 is shown an example of in-phase vibrato lock by Sutherland and Horne, in which one singer has an in-phase intensity change for a particular harmonic, and the other, an antiphase intensity change.

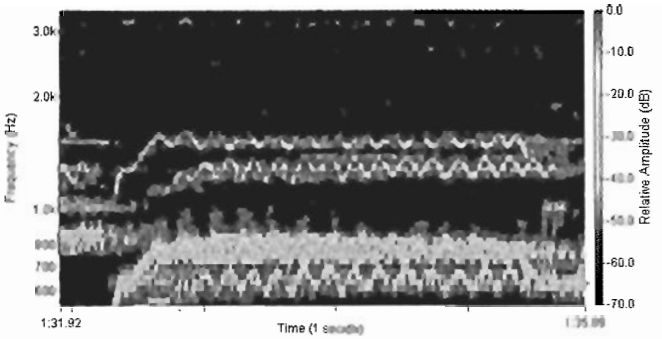

Figure 6. Spectrogram of a pair of notes sung by Joan Sutherland and Marilyn Horne, demonstrating vibrato phase lock.

5. CONCLUSIONS

The conclusions that we can draw from these results at this point are as follows. The aim of the paper was to demonstrate that locking of vibrato frequencies in duet singing can occur and to determine whether or not there was vibrato synchronisation in the chosen excerpts of the "Flower duet" from Lakme. This has been done. We have shown that the vibrato patterns of duet singers behave quite remarkably like a classically coupled oscillator system, for which in-phase, out of phase and also phase wander are possible. We can conclude that in one of the excerpts we have shown today that there is in-phase vibrato synchronisation. Results of the full acoustic analysis indicate that this exact synchronisation is a rare event and more common is phase wander and to a lesser extent anti-phase locking. However the results not yet published do reveal that this one case is not isolated and particularly in the Sutherland and Berbie recording there are several more cases of vibrato in-phase locking which prove that this was not a one off event.

A few of the questions raised in the relevance of the study can be answered. It is possible to say that in duet, singers do alter their vibrato rates. The results of the three examples described here show that a pattern has emerged. Results obtained by comparing notes of the same frequency from duet and solo notes analysed are further support to this hypothesis. Berbie and Sutherland significantly slow down their vibrato rates when singing in duet. The comparison of the 15 pairs of notes that are the same frequency in solo and in duet show that in 13 of the cases this occurred. The overall mean rates for the singers in solo, and duet are shown in Table 2, indicating that throughout the entire excerpt the trend is the same.

Table 2. Overall mean vibrato rates for solo and duet singing - 1968 recording

SINGER	Solo Singing	Duet Singing
Sutherland - 1968	6.38c/s	5.61c/s
Berbie	6.24c/s	5.5c/s

In the Sutherland/Tourangeau recording we find that of the 8 pairs of solo and duet notes compared in Sutherland's singing, 7 of the cases demonstrate that the trend towards slowing the vibrato rate when singing in duet is evident in this recording. Sutherland's overall duet note vibrato rate is again significantly slower than her overall solo note vibrato rate. Tourangeau exhibits the trend in only 3 of the 7 pairs of notes compared. In fact Tourangeau is quite significantly faster in some of her duet notes than her solo notes of the same frequency. This is the reason for the lack of in-phase synchronisation within this excerpt. Further evidence that supports this statement is the fact that in the duet notes number 3 and number 9 of the Sutherland - Tourangeau recording there is in-phase vibrato synchronisation and it is in duet notes 3 and 9 that Tourangeau has slowed her duet vibrato rate to less than her solo vibrato rate on the same note. Table 3 indicates that Tourangeau's overall duet vibrato rate is only marginally slower than her overall solo note vibrato rate. In summary it plausible that the lack of in-phase vibrato synchronisation within the Sutherland - Tourangeau recording is likely to have been caused by Tourangeau not slowing down her duet vibrato rate.

Table 3 . Overall mean vibrato rates for solo and duet singing - 1976 recording

SINGER	Solo Singing	Duet Singing
Sutherland - 1976	6.10c/s	5.78c/s
Tourangeau	6.85c/s	6.75c/s

In the Sutherland - Horne recording in all of the 15 pairs of notes compared, the duet notes have a slower vibrato rate than the solo notes of the same frequency. Both singers have overall duet note vibrato rates slower than their overall solo note rates and this is shown in Table 4.

This recording had the most examples of vibrato locking (8) occurring between the 10 duet notes that were analysed. Only 3 of the notes exhibited in-phase vibrato locking, the other 5 were examples of anti-phase locking. This demonstrates that the vibrato rate is only part of the equation when it comes to achieving in-phase vibrato lock. Even though these two singers were able to lock together their vibrate pulse rates, the majority of examples show an anti-phase locking. It still demonstrates that when singers slow their vibrato rates in duet the are more likely to achieve vibrato synchronisation.

Table 4. Overall mean vibrato rates for solo and duet singing - 1986 recording

SINGER	Solo Singing	Duet Singing
Sutherland - 1986	5.85c/s	5.29c/s
Horne	6.07c/s	5.80c/s

In regard to which voice is responsible for the lock we can say the following. In the first example it was the mezzo-soprano who altered her vibrato rate significantly. In the second example both of the singers had fluctuating vibrato rates and in the last example it is again the mezzo-soprano who alters her vibrato rate, this time with good result as the singers find perfect vibrato synchronisation. Overall results of analysis of the duet notes from all three recordings indicate that it is the

mezzo voice that consistently seems to be responsible for the significant changes in rate which result in an in-phase synchronisation.

The three examples shown in this paper indicate that in order for singers to demonstrate vibrato in-phase lock two things must happen:

- the rates of vibrato in cycles per second of the two singers need to be the same; and
- the phases of the cycles of the two singers needs to be synchronised.

This raises the question of whether singers in a duet can hear if they are out of phase with their partner and if so whether they can alter the cycles per second in order to synchronise the cycle phase. Research published by Coleman [4] has concluded that when singing a sustained note in unison, two singers singing a duet adjusted their frequency modulation extent to less than 50% of that used in solo singing, presumably to "blend" into one tone. It is this conclusion that lead us to believe that singers would certainly do the same with their vibrato frequency rate in order "blend" or synchronise their cycles. The results indicate agreement with this hypothesis. When singing in duet, as opposed to solo singing, the singers used in this research reduced their vibrato rate cycles per second. We believe that this was in order to synchronise with their singing partner.

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