Acoustical characteristics of vocal modes in singing

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Acoustical characteristics of vocal modes in singing

Eddy B. Brixen[1], Cathrine Sadolin[2], and Henrik Kjelin[3]

[1] EBB-consult, Smorum, DK-2765 Denmark
ebb@ebb-consult.com

[2] Complete Vocal Institute, Copenhagen, DK-1128 Denmark
cathrine@sadolin.net

[3] Complete Vocal Institute, DK-1128 Denmark
kjelin@shout.dk

ABSTRACT

According to the Complete Vocal Technique four vocal modes are defined: Neutral, Curbing, Overdrive, and Edge. These modes are valid for both the singing voice and the speaking voice. The modes are clearly identified both from listening and from visual laryngograph inspection of the vocal cords and the surrounding area of the vocal tract. In a recent work a model has been described to distinguish between the modes based on acoustical analysis. This paper looks further into the characteristics of the voice modes in singing in order to test the model already provided. The conclusion is that the model is too simple to cover the full range. The work has also provided information on singers' SPL and formants' repositioning in dependence of pitch. Further work is recommended.

1.   INTRODUCTION

1.1.   Complete Vocal Technique, CVT

Complete Vocal Technique, CVT, is developed by Cathrine Sadolin over a period of 25 years. This work has been done in an attempt to encompass all sounds the human voice can produce in one singing technique model that will comply with knowledge from medical and acoustic science [1], [2]. Also that the model to a large extend cover the speaking voice.

1.2.   Vocal modes

A vital part of Complete Vocal Technique is the categorizing of any voice sound into one of four vocal modes which have different characteristics of sound, individual limitations according to pitch and vowel sounds, and different settings of the vocal tract.

The four vocal modes are:

Neutral - which is a 'non-metallic' usually softly characterized sound that might have a breathy quality to it.

Curbing - which is a 'half-metallic' slightly plaintive or restrained sound quality.

Overdrive - which is a 'full-metallic' - often direct and loud - sound with a more shout like character.

Edge - which is a 'full-metallic' light somewhat aggressive sound with a more screamy character. (This mode was formerly known as "Belting").

These modes are clearly identified both from listening and from visual laryngograph inspection of the vocal cords and the surrounding area of the vocal tract.

Also the modes to a large extent can be recognized visually from laryngograph waveform recordings.

However, until now there has not been presented any analysis on the frequency distribution of these modes. So for this and many other reasons (for instance creating vocal mode/training apps) it would be preferred to establish and apply the simplest possible acoustic analysis to identify the vocal modes. This could be used as a tool in the training and as definition of mode parameters.

1.2.1. Vocal modes vs. singer's formant

Since Wilmer T. Bartholomew in 1934 published his work on vocal efforts in singing: "Physical Definition of 'Good Voice-Quality' in the Male Voice" [3], much research has been done in that field. Most work has been related to classical singing. Johan Sundberg has provided consistent and important knowledge. He has identified and explained the phenomenon called "singer's formant" [4], [5], [6], [7], [8] sometimes also known as "voice ring". Others have followed with similar research [9], [10]. Initially this emphasis of frequencies in the 2.2-3.1 kHz range was only related to opera singers. However, it also has also been identified in the voice of singers performing other musical genres than classical singing as well as in the speaking voice [11], [12], [13], [14].

Basically the singer's formant is found to be a boost of the frequency band around 3 kHz. This is done by the aid of a resonator formed just above the vocal folds, between the glottis and the rim of the epiglottis.

In newer research it has been suggested that a second singer's formant can be found in the frequency range of 7.8 – 8.2 kHz [15], [16]. It has not yet been identified in which part of the vocal tract that provides this resonance.

The CVT emphasize the importance of separating technique from musical style and personal taste, and while the sound of the singer's formant is widely preferred in classical singing, there are many other styles of music where this sound is not perceived as appropriate. So the CVT is not directly aiming for singer's formant in the classical understanding of it. However, the vocal modes are basically identified using the same analysis methodology as previously has been used for the identification of the singer's formants and the major impact of the various vocal modes are observed in the same frequency ranges as the singer's formant is found.

1.2.2. Chest voice/ head voice/mixed voice

The terminology used to describe the quality of the singing voice remains problematic. Terms such as 'chest voice', 'head voice' and 'mixed voice' are widely used but not defined precisely. Originally the terms were used to describe a range of pitch, and did not necessarily refer to specific sound qualities. Chest voice is lower notes, and head voice is higher notes. A sound is produced in 'chest voice' when the singer can feel a resonance in the breastbone (sternum), chest resonance, which occur when singing lower notes. When singing higher notes the breastbone does not resonate, and many singers have instead a sensation of resonance in the head, hence the term 'head voice'. The interpretations of the terms have over the years developed simultaneously in multiple ways, and today many voice professionals interpret 'chest voice' and 'head voice' as a certain sound quality regardless of pitch. This is confusing, partly because of the different interpretations of the terms, and partly because the chest resonance does not take place at higher notes no matter the sound quality used.

Other examples of insufficient defined terminology widely used to describe the singing voice are: Projection, placement, natural voice, falsetto, voix mix, focused voice, singing in the mask, etc.

Due to these discrepancies these terms are not introduced in the CVT-training.

1.3. Automatic voice analysis

It was previously mentioned that the current work is to be regarded primarily as a documentation of the CVT. However, it also could become the basis for a simple feedback system for the singers although it is well

known that feed-back systems and systems for automatic voice analyses have been discussed, introduced, and used for a long period of time.

In [17] Howard et al. discuss the use of real-time displays in the singing studio.

In [18] Winkel expand his already introduced analysis device to include the analysis of vibrato (1976).

In [19] Zwan present his research for the design of an expert system for automatic quality assessment of singing voices. It is based on a large number of voice samples (untrained and trained classical singers). A number of parameters are extracted from the samples forming feature vectors used to train a neural network. The automatic system was tested against experts' assessment of the same set of voice samples.

In [20] Zwan and Kostek go further in detail regarding the results. In [21] a web presentation of this research can be found.

In [22] Mayor, Bonada, and Loscos outline a system that provides feedback to the singer. The intention behind this system is to provide the same kind of feedback as the singers' teacher would do. This system uses intra-note segmentation. It provides not only information on pitch but also timing and level. The implementation of visual feedback is discussed.

In [23] it was shown that a simple discrimination of the individual modes is possible based on 1/3 octave band analysis and a comparison between signal energy in groups of frequency bands. The vocal modes were detected from different individuals singing at the same pitch (male: C4, female: B4 (scientific scale)) and a given vowel (Neutral and Curbing: E; Overdrive and Edge: EH), providing a sufficient number of formants. This is however rather limited in relation to singers' pitch range and available vowels.

This paper describes the further work. An extended experiment has been carried out. Here a number of four singers have been recorded and analyzed.

The goal has been to investigate how well the simple model can provide sufficient results. It is known that not all modes apply to the full voice range. Also it is known, that the modes not equally fits all vowels.

Beside the primary results some "bonus" information has been established regarding the sound pressure level that singers produce when singing scales and applying the various vocal modes. Further, some observations regarding repositioning of formants (especially F1) as a function of pitch have been made.

2. SET-UP FOR THE STUDY

2.1. Subjects

For this study a number of four singers were recorded and analyzed: Two male and two female singers. All singers were familiar with the CVT principles.

2.2. Recording

The recording of the singers took place in a vocal booth; reverberation time here was <0.15 seconds in the regarded frequency range. No fixtures were applied between singer and microphone. However, the position of the microphone stand and the singer was marked on the floor. The distance between singer and microphone was 30 cm. It is important to keep distance constant when investigating voice spectra [24], [25].

Figure 1: Singers' and microphones' position in the vocal booth.

Two microphones were used for the recording: A pressure microphone (DPA4007) and a pressure gradient microphone (DPA4011). For these analyses only the signal from the pressure microphone was used. The recording system (Metric Halo) was set to 96 kHz/24 bit. The system (pressure microphone channel) was calibrated using a B&K acoustic calibrator.

2.3. Instruction of subjects

All subjects were instructed to sing a scale with a fixed interval of three semitones providing four tones per octave. The pitch range basically covered F2 (87.3 Hz) to B4 (987.8 Hz) to the extent it was within the ability of each singer. Each tone should have a sustained duration of at least 2 seconds.

Based on experience the following combination of vowels and modes was applied:

Neutral:
'EE'	is pronounced as in 'see' [i]
'OO'	is pronounced as in 'food' [u]
'AH'	is pronounced as in 'father' [ ]
'I'	is pronounced as in 'sit' [ ]
'EH'	is pronounced as in 'bed' [ɛ]
'A'	is pronounced as in 'cat [æ]
'O'	is pronounced as in 'woman [o]
'OH'	is pronounced as in beg. of 'so' [o]

Curbing:
'I'	is pronounced as in 'sit' [ ]
'O'	is pronounced as in 'woman [o]
'UH'	is pronounced as in 'hungry' [ ]

Overdrive:
'EH'	is pronounced as in 'bed' [ɛ]
'OH'	is pronounced as in beg. of 'so' [o]

Edge:
'I'	is pronounced as in 'sit' [ ]
'EH'	is pronounced as in 'bed' [ɛ]
'A'	is pronounced as in 'cat [æ]
'OE'	is pronounced as in 'herb' [ ]

No instructions regarding produced SPL were given. This was determined by what singers felt comfortable and necessary in order to produce the given tone.

## 3.	ANALYSES

### 3.1.	Frequency analysis

The frequency analyses were carried out using a FFT-based software (Smaart Live).

Sampling Rate:	48 kHz
FFT size:	16 k
Window:	Hanning
Frequency resolution:	2.9 Hz
Averages:	16

All spectra were recalculated to form 1/3 octave band values. As it can be seen in figure 2, the individual tones are not matching the center frequencies of the standard ISO 1/3 octave bands. Most of the analyzed tones had a sufficient duration. However, some tones were looped to provide a duration needed for the analysis.

### 3.2.	Level analysis

The level was calculated from a summation of the measured frequency bands without any frequency weighting applied.

Band limits [Hz]	Center frequency [Hz]	F_0 [Hz]	Tone (scientific scale)
1130			
	1000	987.8	B5
880			
	800	830.6	Ab5
707		698.5	F5
	630		
		587.3	D5
565			
	500	493.9	B4
440			
	400	415.3	Ab4
353			
	315	349.2	F4
		293.7	D4
283			
	250		
		247.0	B3
225			
	200	207.7	Ab3
176			
	160	174.6	F3
141			
	125	146.8	D3
		123.5	B2
113			
	100		
		103.8	Ab2
88			
	80	87.3	F2
71			

Figure 2: The scale applied (right hand side) and its' relation to the 1/3 octave band filters.

3.3. Formant analysis

Formant analyses were carried out using dedicated software: Praat, by Paul Boersma and David Weenink.

4. RESULTS

4.1. Singers' SPL

As the singers did not receive any instructions regarding the acoustic level it was necessary to register the actual SPL performed. The analyses provide the acoustic level at the microphone, 30 cm from the singers' mouth.

The curves in Figure 3 show the average un-weighted SPL of each of the four vocal modes for each of the singers. It can be seen that the level ranges from around 50 to 110 dB re 20 µPa.

The curves to some degree approximate a straight line. In Table 1 below the slope of the best fitted straight line is calculated together with the correlation expressed as R^2. In this table the slope is calculated as dB/interval of three 3 semitones.

mode	M1		M2		F1		F2	
	slope [dB/interval]	R^2	slope [dB/interval]	R^2	slope [dB/interval]	R^2	slope [dB/interval]	R^2
O	3,0	0,983	3,9	0,958	4,6	0,990	4,1	0,968
E	2,2	0,970	3,1	0,945	3,4	0,972	3,4	0,962
C	2,4	0,945	2,5	0,844	3,7	0,967	3,0	0,979
N	3,0	0,983	3,7	0,977	4,2	0,982	3,8	0,977
Average	**2,7**		**3,3**		**4,0**		**3,6**	

Table 1: The table shows the relation between raised pitch and acoustic level of the four singers. The slope is here expressed as dB/interval. The interval is here a pitch raise of three semitones.

As the interval is 3 semitones the actual slope also can be expressed as 0.9-1.3 dB per semitone or 10.8-16 dB per octave (average: 3.4 dB per interval or 13.6 dB per octave).

This fact is of course known to many singers (sub-glottal pressure [26]) and affects their way of handling microphones when covering a large pitch range.
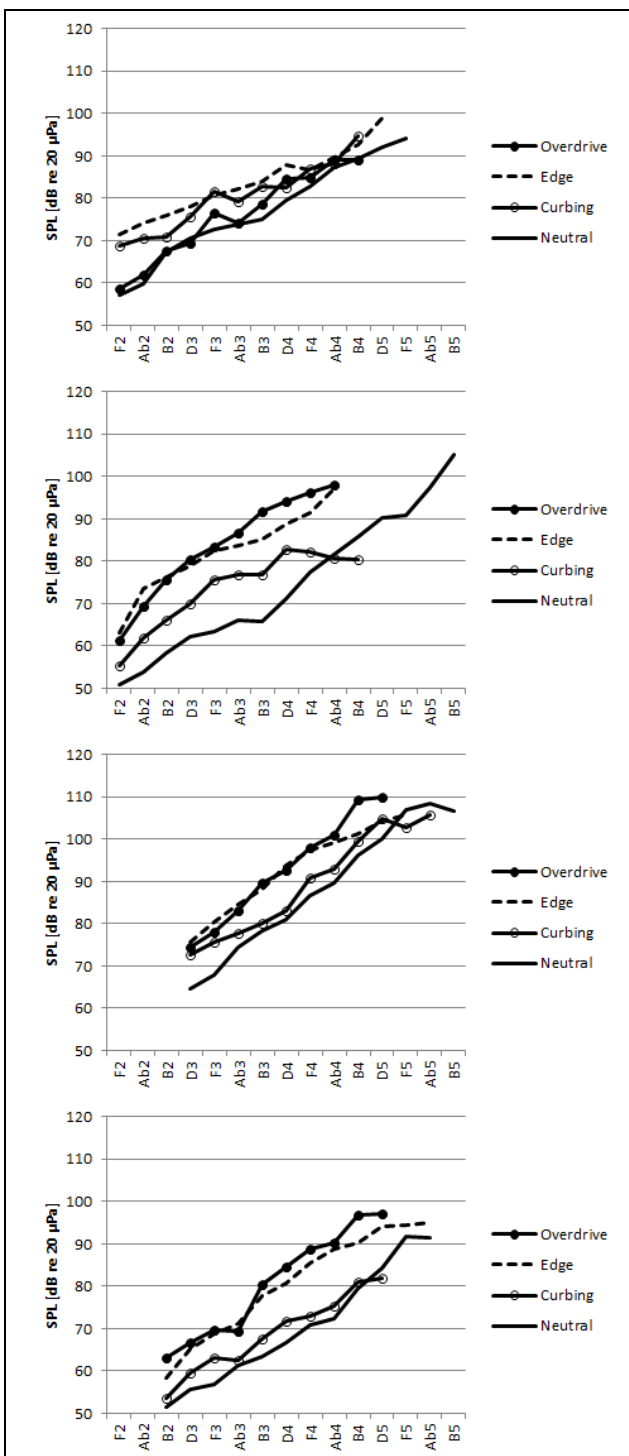

Figure 3: Two upper diagrams: male singers, two lower curves: female singers. When singing scales, the general tendency is to raise the sound pressure level by approximately 1 dB per semitone or 13 dB per octave. The level is measured at 30 cm.

It can also be seen that the neutral mode in general is the softest of the four modes. Overdrive however in average is produced at a level 10 dB stronger.

4.2.   Pitch vs. formants

By tuning the resonances of the vocal tract the sound of the voice cords is filtered and thereby forming what is perceived as different vowels. In particular the first and the second formants (F1 and F2) are responsible for the vowels formed and perceived. In phonetics the specific position of F1 and F2 is important.

Compared to speaking, in singing the pitch is varying a lot (that's the basic idea of singing). This may leave the singer with a problem of producing certain vowels, especially when the pitch exceeds the first formant(s). Further it is interesting to investigate how much the formant's frequencies change with f_0.

In this study three vowels have been analyzed to find the F1/F2 values. Below is an example. The other subjects exhibit similar distribution of formants in dependence of pitch/f_0.
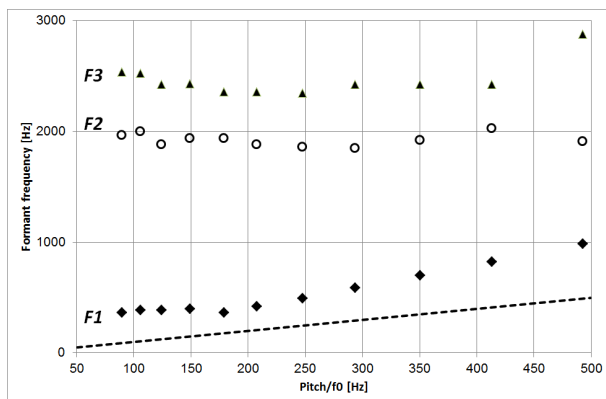

Figure 4: Subject: M1, vowel: EH, mode: Overdrive. F1/F2/F3 plotted against pitch. The dashed line shows the frequency of the pitch (f_0). It can be seen that especially the frequency of the first formant is increased with increasing pitch.

In phonetic science the Cardinal Diagram is a basic tool when vowels are defined. Here the F1 is plotted against F2. The frequency scales are inverted, because the diagram then largely defines the place of articulation /tongue position in the cavity of the mouth. Left hand side is the most frontal sound, closest to the lips.

In figure 5 all F1/F2 values for the vowels EE, OO and EH are plotted. (F1 is above f_0 in all cases).
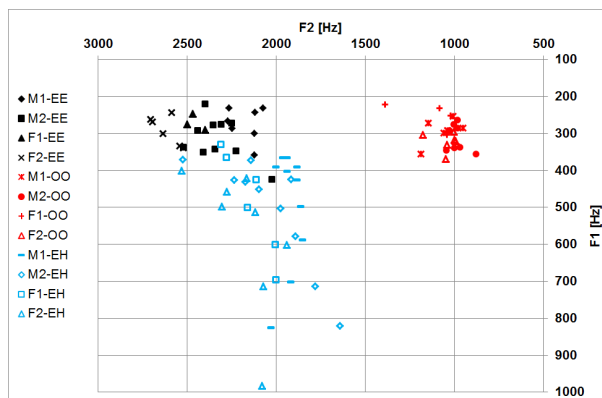

Figure 5: F1/F2 chart that present the values of the four subjects' three vowels: EE (upper left values), OO (upper right values and EH (lower left values).

The vowel EE is located upper/front, OO is located upper/back and the EH is located mid (low mid)/front.

It must be noted that there is a minimum spread in the upper vowel values of which the OO exhibit the most stable position. Regarding the EH however, the values are widely spread in the frontal area. This can be related to the application of the vocal mode Overdrive whereas the EE/OO-vowels were sung in Neutral mode.

4.3.   Spectral distribution, 1/3 octave

In [24] the detection of modes was determined by the evaluation of 1/3 octave spectra. The model for discrimination is shown in figure 6 below.
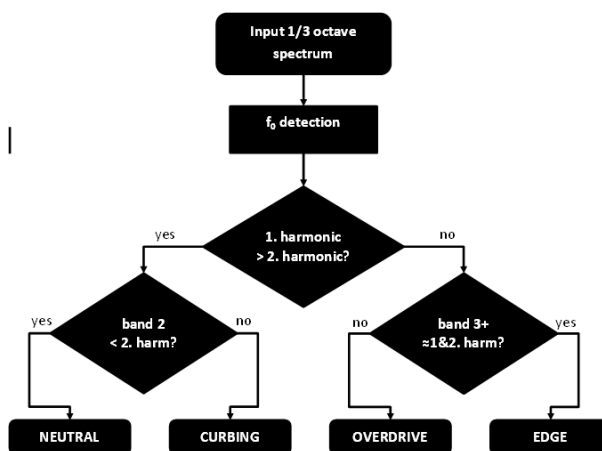

Figure 6: Determination of vocal modes based on 1/3 octave spectra as described in earlier work [23]. This applies basically only to midrange pitch (male C4 and female B4).

As the model indicates, the modes are defined by evaluation the 1st and 2nd harmonics and in addition two frequency bands (band 2: 2-4 kHz, and band 3: 8-10 kHz).

In this study the 1/3 octave analysis has been applied as well. Below in figure 7 is shown two series of spectra (subject M1, vocal mode: Overdrive, vowel: EH). The upper express the SPL measured. In the lower chart the absolute level is subtracted from each of the 1/3 octave values.
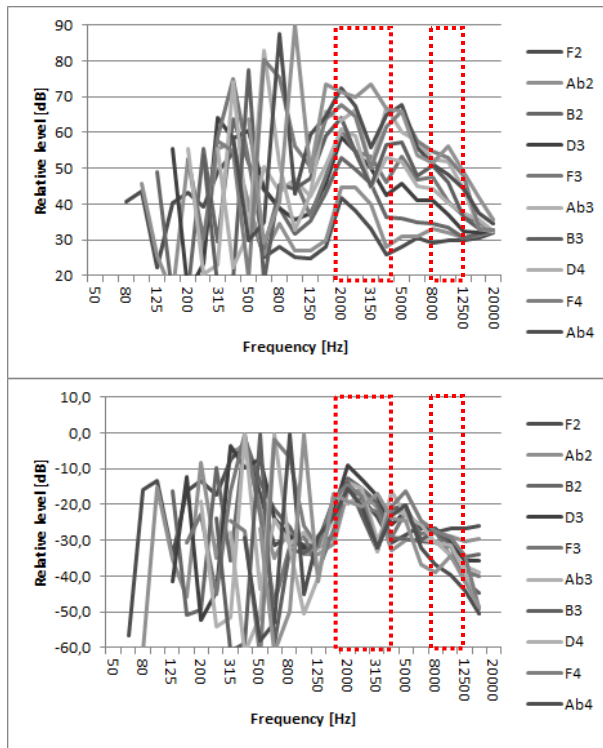

Figure 7: 1/3 octave spectra, subject M1, Overdrive, vowel: EH. Upper chart is the SPL as measured. In the lower chart the absolute level is subtracted from each of the 1/3 octave values (level normalization).

When these spectra in figure 7 are tested against the model they all are detected correctly except from the highest note. Most "Overdrive-spectra" actually are detected correctly. However, it seems like the model does not fit with the same consistency in the other modes. The following figures show the spectral distribution for M1. Although the graphics are not ideal, the surface charts can provide some kind of impression of the characteristics of each combination of tone, vocal mode and vowel.
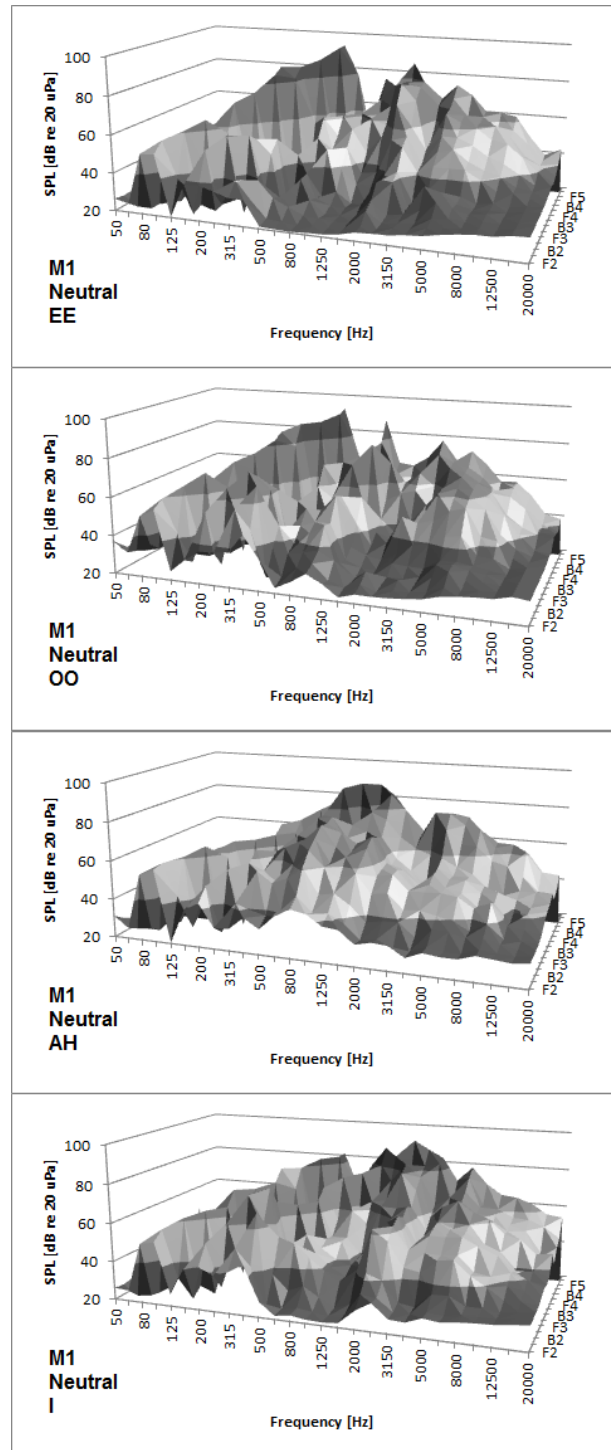

Figure 8A-8D: The charts show spectral distribution of four vowels when singing applying Neutral mode. At the highest notes the tones are detected as curbing, according to the model.
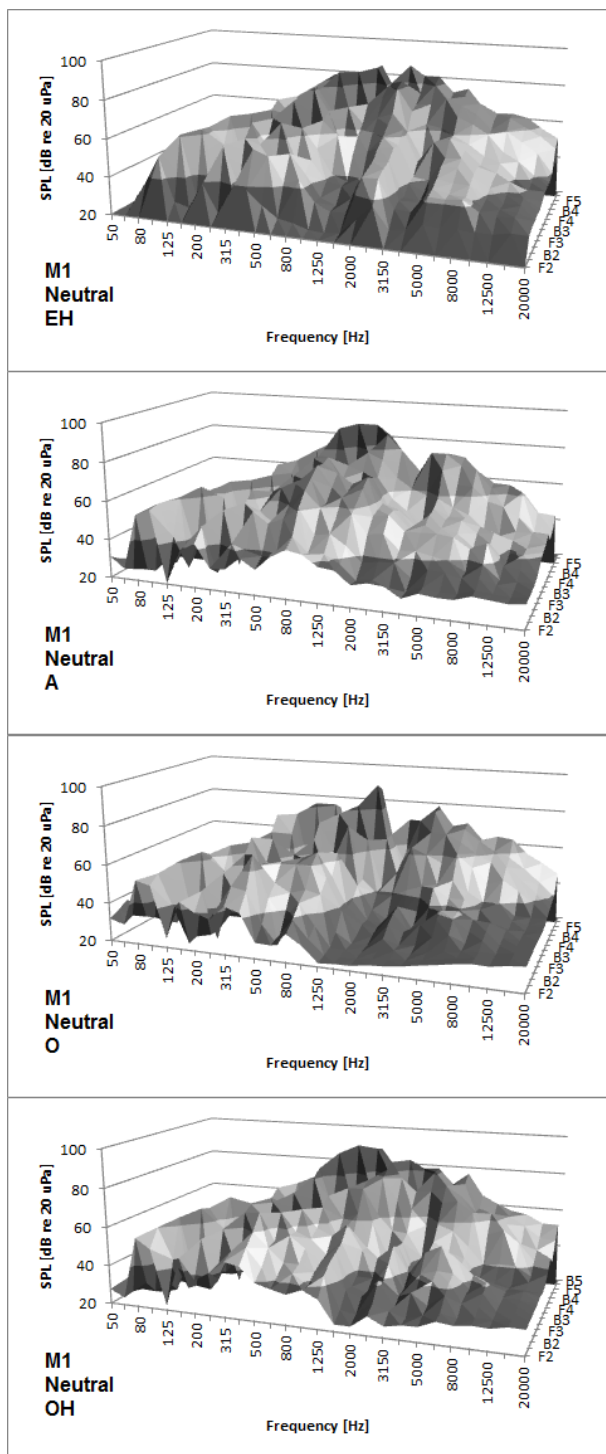
Figure 8E-8H: These four Neutral spectra as performed by subject M1. At low notes the mode is detected correctly by the model. But it does not apply at the higher notes. Here the spectra are detected rather as Overdrive.
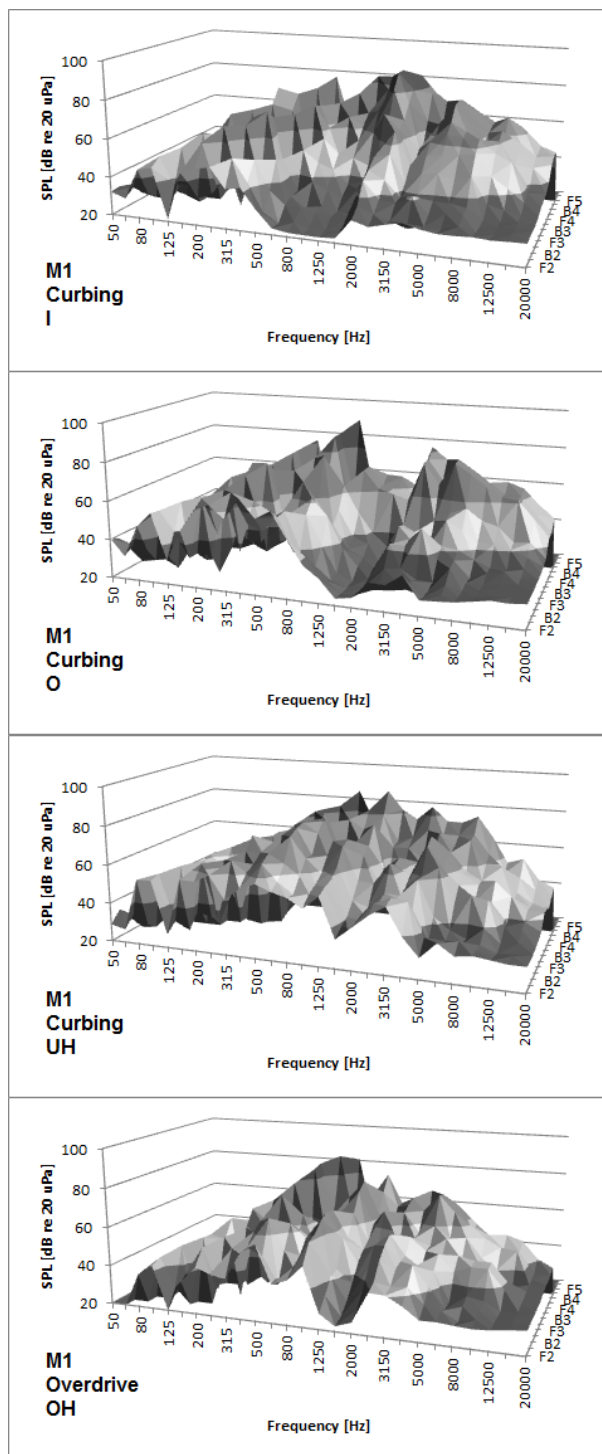
Figure 8I-8L: The spectra of the three upper charts show what should be regarded as Curbing. At low notes the mode is hardly detectable. However, it works better at higher notes. The lowest chart show Overdrive that is detected correctly.
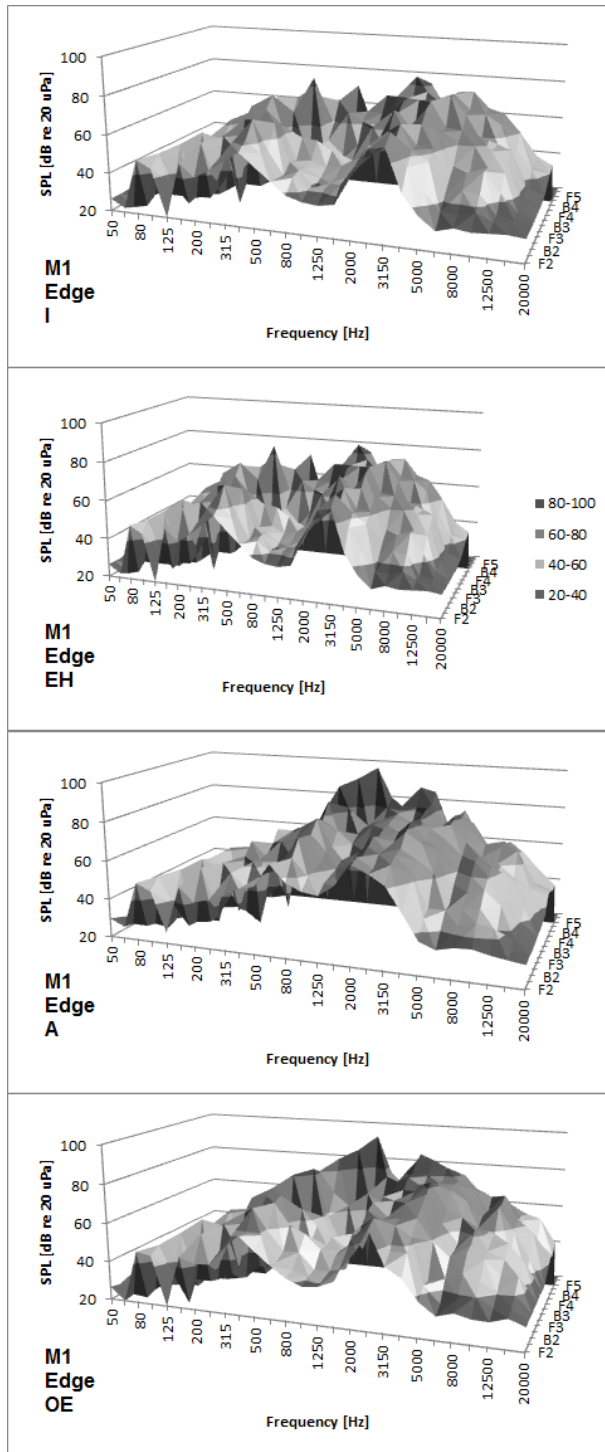
Figure 8M-8P: These charts all show the spectra of four vowels performed in the vocal mode Edge. The two upper vowels however are detected as Overdrive. The third chart (vowel A) show spectra that are predominantly correctly detected.

4.4. Identification rate

Running all spectra through the model provides the following results:

Mode	Vowel	M1 [%]	M2 [%]	F1 [%]	F2 [%]	All [%]
Neutral	EE [i]	46	33	27	33	35
Neutral	OO [u]	46	73	73	75	67
Neutral	AH [ ]	42	40	18	50	38
Neutral	I [ ]	38	53	36	36	41
Neutral	EH [ɛ]	23	40	36	33	33
Neutral	A [æ]	42	33	36	33	36
Neutral	O [o]	46	67	55	67	59
Neutral	OH [o]	46	40	73	8	41
Neutral	OE [ ]	31	67	73	67	59
Curbing	I [ ]	33	18	60	45	39
Curbing	O [o]	0	0	27	18	12
Curbing	UH [ ]	0	0	30	10	9
Overdrive	EH [ɛ]	91	80	89	60	80
Overdrive	OH [o]	100	80	89	90	90
Edge	I [ ]	27	56	0	55	34
Edge	EH [ɛ]	25	50	10	58	38
Edge	A [æ]	67	56	40	73	60
Edge	OE [ ]	25	33	10	45	29
Total		44	47	39	41	44

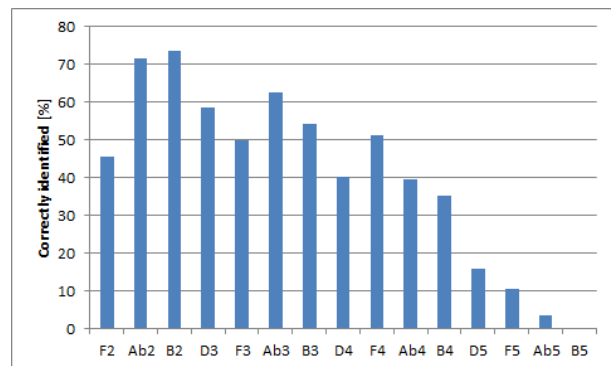**Table 2: Identification rate (pct.) of the individual modes per subject and in total.**

Figure 9: Identification rate (pct.) as function of note (all subjects).

5.   DISCUSSION

Based on the results presented it is obvious that the model is far from perfect. It can be seen that in general it fails with increase of pitch. There are several reasons for that. One reason is the fact that the level of the second harmonic at higher pitch is affected by the formants of certain vowels. Corrections may be introduced in the model.

Looking at the spectra and listening to the voice samples leaves the impression that it is not certain whether this is solely caused by the model being too primitive or the reason in some cases might be the singers not performing the modes/vowels perfectly despite the intention to do so. In that case the model works as intended.

In extension of this work is needed a test that combines the model with an extensive listening test to revalidate each voice sound sample.

6.   CONCLUSION

This paper reports the outcome of a study on characterization of vocal modes. Four singers performed full range scale-singing.

The recorded signals have been analyzed and tested against a model formerly established. It showed that the model in general detected overdrive very well. However, detection of other modes did not exhibit the same overall consistency especially at high pitch.

Some bonus information has come out of the project.

1: When singing scales, the singers' sound level is increased by approximately 13 dB per octave (raising pitch) as a result of the related sub-glottal pressure.

2: The formants are relocated in dependence of pitch, especially 1st format when generated front / low mid.

7.   ACKNOWLEDGEMENTS

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