Vibrato extent and intonation in professional Western lyric singing

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(Received 12 December 1996; revised 11 March 1997; accepted 14 March 1997)

Two important aspects of singers' $F0$ control have been investigated: vibrato extent and intonation. From ten commercially available compact disc recordings of F. Schubert's *Ave Maria*, 25 tones were selected for analysis. Fundamental frequency was determined by spectrograph analysis of a high overtone at each turning point of the vibrato undulations. It was found that the mean vibrato extent for individual tones ranged between ± 34 and ± 123 cent and that the mean across tones and singers amounted to ± 71 cent. Informal measurements on Verdi opera arias showed much higher figures. With regard to intonation substantial departures from equally tempered tuning were found for individual tones. A tone's vibrato extent was found to have a negative correlation with tone duration and a positive correlation with intonation. [S0001-4966(97)00707-8]

PACS numbers: 43.75.Bc [WJS]

INTRODUCTION

Vocal vibrato is an important aspect of professional opera and German ''lied'' singing in the Western cultures. Basically it corresponds to a frequency modulation of $F0$ characterized by its rate and extent. This modulation, in turn, causes amplitude modulations of the individual spectrum partials (see, e.g., Sundberg, 1987; Horii, 1989; Imaizumi *et al.*, 1994) which result in a modulation of the overall amplitude. This amplitude modulation may be both in phase and out of phase with the original frequency modulation.

A spectrogram of a sung tone shows a set of undulating wave patterns, of which the peaks and the troughs can be determined. Figure 1(A) shows one partial of such a tone. The fundamental frequency average can be seen to change slightly with time. In Fig. 1(B) the vibrato undulations have been isolated from the underlying gliding average shown in Fig. 1(C). This average, computed as a running one-vibrato-cycle mean of $F0$ represents the equivalent fundamental frequency of the tone (M. Metfessel in Seashore, 1932; Sundberg, 1978; Shonle and Horan, 1980; Brown, 1996). The departure of this mean from a target value reflects the intonation of the tone. Such departures can be measured as the deviation of the tone's running mean $F0$ from a target value, calculated according to equally tempered tuning, using the tuning of the accompaniment as the reference. Henceforth, this deviation, expressed in cent, will be referred to as $MF0$.

In the late 1920s and early 1930s, Carl E. Seashore and his co-workers explored in depth most aspects of vibrato thus establishing a platform for future studies in this field (Seashore, 1932, 1936, 1937, 1938). Although they designed and used instruments which were highly advanced for their time, accuracy and flexibility were limited as compared to present standards. After Seashore, many other studies dedicated to specific aspects of vibrato have been published (for reviews, see, e.g., Sundberg, 1987; Titze, 1994). However, it is sometimes difficult to compare results on vibrato extent from various studies, as it is often unclear what they relate to, amplitude or peak-to-peak, given in cent or as percentages of a tone or of a semitone. In the present investigation vibrato extent values refer to amplitude, preceded by ''$\pm$,'' and are given in cent.

In a previous investigation vibrato rate was studied (Prame, 1994). The aim of the present investigation was to examine two aspects of singers' $F0$ patterns. One is the variation of $MF0$, an almost unexplored field since the thirties, when Seashore (1937) published some articles on this topic (see, also, Sundberg, 1987; de Krom and Bloothooft, 1995). The other is vibrato extent, the description of which is still incomplete.

I. MEASUREMENTS

The same material was used for this study as in a previous investigation of vibrato rate, i.e., Franz Schubert's *Ave Maria*, D839 (Fig. 2), recorded on compact disc by ten prominent artists (Table I), all representing Western classical music tradition (Prame, 1994). The criteria for the selection of tones was the same in the present study as in the previous one, i.e., all tones should be long enough to provide reliable data. Thus the same 25 tones as before were selected for the analysis. The accompaniment was performed on different instruments. Of these, harp and piano did not interfere with the measurements of the solo voice while orchestra and choir occasionally caused minor difficulties.

Measurements were made on time spectrograms as displayed on a KAY DSP sonagraph, model 5500 (setup: frequency range: dc-4 kHz, analysis format: spectrographic display, transform size: 600 pts, analysis window: Hamming, and time axis: 400 or 800 ms). $F0$ was determined at all crests and troughs on the highest partial [U in Eq. (2)] that was distinctly displayed on the screen. As the frequency scale is linear, the obtainable resolution increases with the partial number. $F0$ values could not be adequately obtained

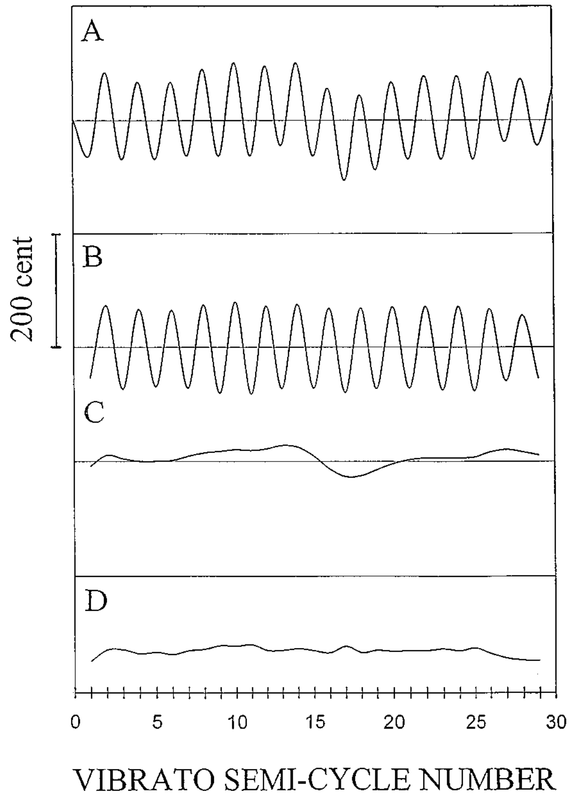

FIG. 1. Example of frequency modulation in a vibrato tone plotted in terms of $F0$ versus semicycle number. The original data is shown in panel (A). Panels (B) and (C) show the two components analyzed of the $F0$ variation, i.e., the vibrato modulation (B) and the running semicycle mean, $MF0$ (C). Panel (D) represents the envelope of the vibrato extent.

from 13 tones, mostly due to too low sound level. The total material thus included 237 tones.

The tuning of the accompaniment was determined by a listening experiment. The first bar of the accompaniment was repeatedly played over a loudspeaker. A professional violinist was asked to adjust the frequency of a complex tone so that it matched the pitch of the root of the chord. Three attempts were made for each recording, and the mean of the three readings was used as a measure of the tuning. The readings differed in average less than 1.4 cent from their respective means.

FIG. 2. Franz Schubert's song *Ave Maria* (D839) with the numbering of the 25 notes selected for analysis.

From $F0$ values of the type shown in Fig. 1(A) the vibrato extent (V) and the $MF0$ were calculated, see Fig. 1(B) and (C). The calculations for one vibrato cycle number n is found as the averages of two adjacent half-cycles, thus involving the three samples $n-1$, n, and $n+1$. Refer to Fig. 3 and the following formulas:

$$\nu_n = \left| \frac{[(-a_{n-1}+a_n)+(a_n-a_{n+1})]/(2\cdot 2)}{(a_{n-1}+2a_n+a_{n+1})/4} \right|$$

$$= \left| \frac{a_{n-1}-2a_n+a_{n+1}}{a_{n-1}+2a_n+a_{n+1}} \right|, \tag{1a}$$

$$V_n = 1200 \log_2\left[1 + \left| \frac{a_{n-1}-2a_n+a_{n+1}}{a_{n-1}2a_n+a_{n+1}} \right| \right] \text{ (cent);} \tag{1b}$$

$$MF0_n = 1200 \log_2\left[\frac{a_{n-1}+2a_n+a_{n+1}}{4\cdot W\cdot U} \right] \text{ (cent).} \tag{2}$$

These operations are then repeated in unit steps of n, i.e., for each half cycle. Eq. (1a) defines the vibrato extent as a fraction and Eq. (1b) shows the vibrato extent expressed in cent. W in Eq. (2) is the target frequency according to the tempered scale, using the tuning of the accompaniment as the reference, and U is the partial number selected for measurement. Finally, the vibrato extent envelope curve [Fig. 1(D)] was derived by rectifying (i.e., taking the absolute values of the turning points) and smoothing the curve shown in Fig. 1(B).

The accuracy of the measurements can vary, particularly depending on the frequency of the partial selected. An experiment was carried out to estimate the accuracy obtained by this method. A professional mezzo-soprano was asked to sing the song with piano accompaniment. Her singing was recorded from an audio microphone and also by an electroglottograph that produced a signal reflecting the vocal fold contact area. This recording was analyzed in two ways. The audio recording was analyzed by the Sonagraph procedure described above. The electroglottograph recording was analyzed by means of the SWELL pitch tracking program using the double peak picking strategy (Ternström, 1991). The agreement between the two methods was high, the mean discrepancy being 2.5 cent with s.d. 2.7 cent.

Equations (1b) and (2) above, do not completely eliminate the influence of vibrato on $MF0$. However, as we shall mainly restrict our analysis to means computed over entire tones, the accuracy will be satisfactory for our purposes. As three values are needed for the calculation of each data point in Eqs. (1) and (2) the total number of calculated points will be two less than the number of measurements for each tone.

II. RESULTS

Figure 4 illustrates the variation of vibrato extent for all artists' performance of tones 1 and 23 as function of vibrato semicycle. As can be seen in Fig. 2 these tones occur in a

TABLE I. The ten artists singing *Ave Maria* by Schubert.

Artist	Voice classification	Key	Age of artist	Recording year	Language	Accompaniment	Tempo (s) (quarter note duration)
1	soprano	Bb4	37	1975	German	piano	1.95
2	soprano	Bb4	42	1990	German	orchestra	2.18
3	soprano	Bb4	41	1984	Latin	harp	1.80
4	soprano	Bb4	41	1988	German	piano	2.13
5	soprano	Bb4	26	1971	German	piano	2.10
6	mezzo	Ab4	34	1936	German	piano	3.00
7	alto	G4	38	1971	German	piano	2.33
8	tenor	C4	38	1979	German	orchestra	2.10
9	tenor	Bb3	35	1968	Latin	organ/choir	2.13
10	tenor	Bb3	52	1987	Latin	piano	2.53

similar musical context, although tone 23 is different in the sense that it is the second time this context appears in the piece. A certain similarity can be discerned between each individual artist's rendering of these two tones. For example, artist 3 shows an increase of the vibrato extent during the tone while artist 8 keeps a basically constant vibrato extent throughout the tone.

The vibrato extent normally increases in the beginning and decreases in the ending of the tone. This is illustrated in Fig. 5 which displays the mean and s.d. for vibrato extent across all artists and tones as a function of vibrato semitones. In calculating these means only tones with a length of at least eight vibrato periods were included. The two curves are rather smooth and arch shaped; the tones' vibrato extent starts and ends well above zero, at 42 and 55 cent, respectively.

Artists' mean vibrato extent, calculated for each tone and then averaged across all tones, is another relevant aspect. Table II lists these means together with associated extremes and standard deviations for each artist.

Interesting observations can be made in Table II. The mean vibrato extent for individual tones ranged between ± 34 and ± 123 cent and the artist means varied between ± 57 and ± 86 cent. The mean across tones and singers was ± 71 cent. The s.d. averaged across artists for intratone variation and intertone variation are similar.

Figure 6 shows the variation of the semicycle *MF*0 for all artists' performance of tones 1 and 23. For some artists the deviations from equally tempered tuning show similarities between the two tones. For example, singer 2 shows a somewhat falling/rising curve shape, singer 4 adheres to the equally tempered tuning, and singer 10 exhibits a slowly rising curve. It is also interesting to note that singers 2 and 8 both show a *MF*0 gesture that is synchronized with the chord change at two thirds of the duration of tone 1. These observations suggest that intonation was used as an expressive means at least by some of the singers.

Also in the case of *MF*0 it is interesting to study artists' mean *MF*0, calculated for each tone and then averaged across all tones. Table III lists these means together with associated scatter data for each artist. Also, the tuning of the accompaniment *re*: 440 Hz is given for each recording.

Table III shows that the mean difference across artists between sharpest and flattest intonation was 54 cent, the individual maximum amounting to 69 cent. Again, s.d. aver-

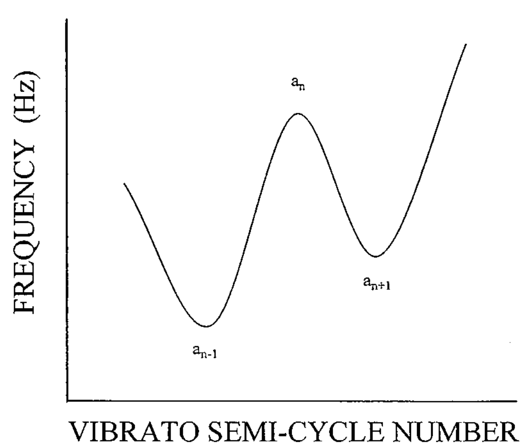

FIG. 3. Definition of the measuring points used in Eqs. (1) and (2).

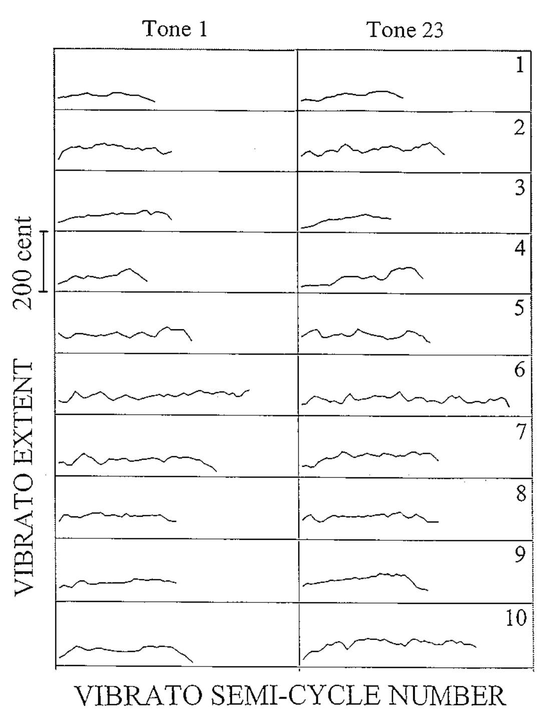

FIG. 4. All ten artists' vibrato extent envelope curves for tones 1 and 23 plotted as function of semicycle number.

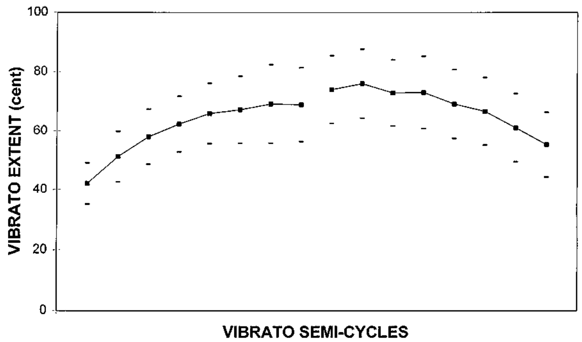

FIG. 5. Mean ± one s.d. for vibrato extent during the beginning and ending of tones, averaged across artists and tones, as function of vibrato semicycle. Only tones containing at least eight vibrato cycles are included.

aged across artists for intratone variation and intertone variation are similar. The artist mean deviation from the accompaniment varied between -20 and $+12$ cent.

A significant negative correlation between vibrato extent and tone duration was found for the 237 tones ($p<0.001$; $r=-0.44$); the longer the tone, the smaller the vibrato extent. Also, for the same 237 tones, a positive correlation was observed between mean vibrato extent and mean *MF*0 deviation ($p<0.001$; $r=+0.39$); the intonation of tones with great vibrato extent tended to be sharper. Note that as the number of measured tones is high (237), the significance levels can still be high ($p<0.001$) although the correlation coefficients (r) are rather low.

The above observations were based on measurements of sung performances of one single song, F. Schubert's *Ave Maria*. An interesting question is to what extent similar observations can be gathered from songs with different musical ambiance's. Vibrato extent was estimated from various tones in a set of performances of dramatic pieces, such as opera arias by G. Verdi and some dramatic passages from F. Schubert's *Erlkönig*. A typical variation range seemed to be ± 50 to ± 150 cent, approximately; thus, the vibrato extent was clearly wider than what was found for the *Ave Maria* song.

Informal measurements were carried out also on four violin performances of Schubert's song *Ave Maria*. The results indicated that the violinists had a much smaller vibrato extent than the singers, approximately half or less. Moreover, the violinists' variation of *MF*0 within tones was considerably smaller than that of the singers. Similar observations were previously reported by Meyer (1978).

III. DISCUSSION

Our investigation was based on commercially available recordings of ten singers of world fame, all performing one and the same German lied. Therefore our material should be representative of lied singing. As the frequency range of *Ave Maria* is no more than 13 semitones, each singer could be assumed to sing in a comfortable pitch range. Given the musical character of the piece, it could be further assumed that the same was true with regard to intensity and tempo. Thus, the data can be assumed not to be influenced by any extreme vocal conditions.

The present investigation concerned two distinct aspects of fundamental frequency control in singing, viz. vibrato extent and *MF*0, the tones' mean departures from equally tempered tuning. In the following, these two aspects will be discussed separately.

With regard to *vibrato extent* our results are in reasonable agreement with those previously published in comparable investigations. Our values are, however, higher than Seashore's commonly quoted average of ± 50 cent with a typical variation range of ± 30 to ± 70 cent. Seashore also reported that extreme values can reach ± 150 cent, which is similar to our findings.

How should a mean value for the vibrato extent of a tone be defined? In the present investigation we have applied a straightforward definition, the average of all calculated vibrato semicycles of a tone. In performances of Verdi's opera

TABLE II. Vibrato extent values for the ten artists. Column 1. Vibrato extent first averaged over all vibrato periods within each tone and then averaged across all 25 tones; Columns 2 and 3. Extreme values among the 25 tone means; Column 4. s.d. of the 25 tone means; Column 5. Mean s.d. across the 25 tones; Column 6. Mean vibrato rate (Hz) according to Prame (1994). In each column the extremes are marked with bold.

	Vibrato extent					
Artist:	Mean (cent)	Max (cent)	Min (cent)	Intertone s.d. (cent)	Intratone s.d. (cent)	Rate Mean (Hz)
1	72	106	38	**17**	14	5.6
2	84	105	59	12	**18**	6.5
3	71	99	42	16	13	6.3
4	73	102	50	16	13	6.0
5	64	85	36	13	10	5.9
6	**57**	**71**	44	**8**	10	**6.7**
7	72	88	51	9	10	5.9
8	**86**	**123**	**66**	15	14	**5.4**
9	60	80	**34**	11	**10**	5.6
10	70	111	48	14	12	5.8
Average	71	97	47	13	13	6.0
s.d.:	9	16	10	3	3	0.4

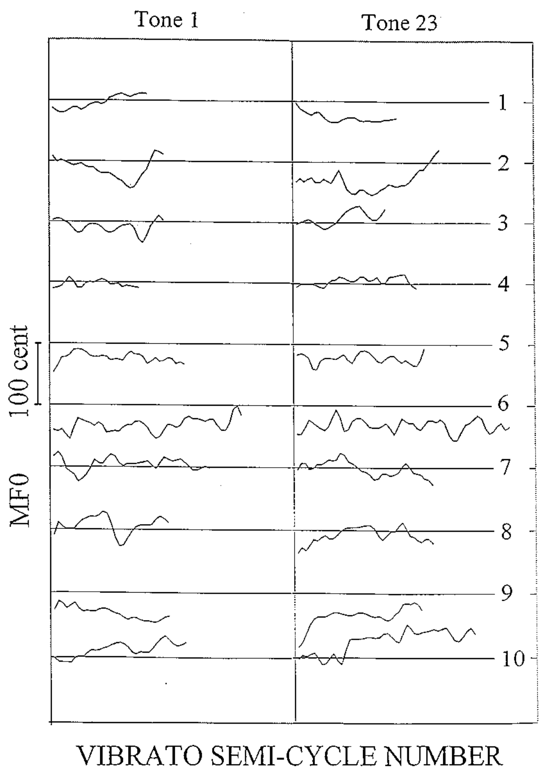

FIG. 6. All ten artists' $MF0$ curves for tones 1 and 23 plotted as function of semicycle number.

arias and in most recorded performances of the *Ave Maria*, the vibrato extent tends to start at a rather high value of the tone, as illustrated in Fig. 5. In performances of, e.g., early baroque music, the vibrato extent may be small or even close to zero during the first part of the tones. The means calculated from such tones cannot be compared with the values reported in the present investigation. Indeed, no one of our ten singers used the early music vibrato type.

The correlation between vibrato extent and tone duration was found to be negative. This is surprising, taking into account that the vibrato extent during onset and decay was typically smaller than in the middle of the tone. Hence, mean values for short tones could be expected to be small. Still the opposite was observed. This implies that the maximum extent value of a short tone is considerably greater than that of a long tone.

The maximum and minimum values of the individual singer's vibrato extent differed by a factor of 2 or more. Similar observations were made by Keidar *et al.* (1984). This suggests a substantial influence of a number of factors including musical context, tone length, and probably also musical expression (Sundberg *et al.*, 1995). In addition, musical and performance style also influence vibrato extent. For all these reasons, it is difficult to attribute a typical vibrato extent value to an individual singer, if the above mentioned factors are not taken into consideration. Vibrato rate, by contrast, is much less varying within as well as between singers (Prame, 1994).

The results regarding $MF0$ are interesting. The greatest tone mean departures from equally tempered tuning were $+42$ and -44 cent, and within a singer the greatest difference between sharpest and flattest tone mean was no less than 69 cent. Also some artists' $MF0$ tends to consistently depart from the accompaniment; for example, for artists 5 and 6, the mean deviation from the accompaniment was -20 cent and for artist 10 it was $+12$ cent. Taking into consideration that these values are means across 25 tones, the departures are remarkable. Indeed, some of these deviations exceed by an order of magnitude the just-noticeable difference for frequency discrimination (Wier *et al.*, 1977).

The $MF0$ is obviously highly relevant to whether or not a tone is perceived as in tune. This aspect has been examined in a different investigation (Sundberg *et al.*, 1996). The field of $MF0$ variation in sung performance seems to hide interesting and as yet unknown phenomena which invite further investigation.

TABLE III. Tuning data for the ten recordings analyzed. The accompaniment columns show means of accompaniment's departures from $A4=440$ Hz in cent and in Hz, respectively. The $MF0$ variation columns concern the singers intonation. The Deviation column shows mean deviation of $MF0$ from accompaniment, first averaged over all vibrato periods within each tone and then averaged across all 25 tones. The Max-min column lists the difference between sharpest and flattest tone mean. Intertone and intratone s.d. refer to the singer's deviation across and within the 25 tone. In each column the extremes are marked with bold.

	Accompaniment		$MF0$ variation			
Artist:	(cent)	(Hz)	Deviation (cent)	Max-min (cent)	Intertone s.d. (cent)	Intratone s.d. (cent)
1	15	+3.9	5	60	15	9
2	11	+2.8	7	66	**17**	11
3	9	+2.3	−7	45	12	11
4	3	+0.9	10	47	13	9
5	20	+5.1	**−20**	45	**10**	**8**
6	**−2**	**−0.4**	−20	57	13	8
7	10	+2.6	5	**42**	10	10
8	**34**	**+8.7**	9	**69**	16	**14**
9	1	+0.3	−14	52	14	9
10	8	+2.0	**12**	60	13	12
Average	11	+2.8	−1	54	13	10
s.d.:	10	2.6	13	9	2	2

IV. CONCLUSIONS

A great number of data on vibrato extent and $MF0$ was assembled from recordings of ten singers of world fame performing Schubert's *Ave Maria*. The mean vibrato extent for individual tones ranged between ± 34 and ± 123 cent. The artist means varied between ± 57 and ± 86 cent. The mean across tones and singers amounted to ± 71 cent. Informal measurements of opera arias by G. Verdi showed higher figures, ranging between ± 50 and ± 150 cent, approximately.

$MF0$ revealed remarkable departures from equally tempered tuning. The greatest tone mean departures from equally tempered tuning amounted to $+42$ and -44 cent, and within a singer the greatest difference between sharpest and flattest tone mean was 69 cent. The difference between the artist's mean intonation and the accompaniment ranged between -20 and $+12$ cent. A tone's vibrato extent was found to have a negative correlation with tone duration and a positive correlation with $MF0$.

ACKNOWLEDGMENTS

Johan Sundberg and Johan Liljencrants are gratefully acknowledged for their helpful and stimulating discussions, Johan Sundberg also for assistance in preparing this manuscript, and Lars Frydén for patiently and accurately determining the tuning of the accompaniment. Some of the above results have been presented at the 15th International Congress on Acoustics (ICA95) in Trondheim 1995.

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